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PREDICTIONS OF RELATIVE SEA LEVEL CHANGE AND SHORELINE EROSION OVER THE 21ST CENTURY ON TANGIER ISLAND, VIRGINIA

ABSTRACT

For approximately 300 years, Tangier Island, located in the middle of the Chesapeake Bay, USA has been continuously populated by up to 1000 residents. It is one of two islands in the Bay that continues to have a resident human population. The island is very flat, with the highest elevation at less than 2 meters above mean sea level (msl). The residents live on three sandy "ridges" with elevations of about 1.0 to 1.5 meters above msl. Over the past century of recorded data, the relative sea level there has risen about 31 cm. This is more than twice the global rate of sea level increase, in part due to the estimated subsidence of the island (in other parts of the Bay as well) at a rate of about 18 cm per century. As the level of the sea continues to rise in the 21st century, and as shoreline erosion continues, the very existence of the island is in jeopardy. In this study, projections are made to the year 2100 in terms of how sea level rise and continued shoreline erosion will impact the island. Historical sea level changes were examined at locations up and down the Chesapeake Bay, where periods of record of nearly 100 years were available. Over the periods of record examined, the relative sea level increases were remarkably consistent from station to station. Sea level rise projections were made to the year 2100 using a climate change model. Low, moderate, and high climate sensitivities were examined. These projections were generally within the envelope provided in IPCC (2001). Adjusting for island subsidence, the projected relative rates were calculated. To evaluate the impacts of these changes, several years of historical tidal levels (data were collected hourly over each year) were extrapolated to the year 2100, using the predicted sea level changes. The historical tidal levels were chosen from years when either hurricanes or Northeasters occurred in the Bay. These are two frequently occurring storm types that have a short term, but dramatic effect, on tidal levels. For each of the three climate scenarios, analyses of these data were made in terms of the number of hours in the year 2100 that the levels of the tide exceeded critical elevations on the island, such as the elevation of the houses where people live. Also, the number of individual events per year was calculated. These predictions were compared to the observed levels in year 2000 to show the effects of relative sea level change. Due to the marshy nature of much of the

island, the sea level changes were manifested in the disappearance of land at low points within the island, as well as more frequent flooding of residences. Shoreline erosion was also examined, which is caused primarily by wave action and enhanced as sea level rises. Historical maps that date from as far back as the 17th century were examined to help make estimates of rates of erosion. However, the first map with enough accuracy to correctly depict temporal changes in shoreline was in 1850. That map of Tangier Island was compared to more recent ones, including an aerial photograph taken in the year 2000, to estimate the rate of shoreline erosion. It was found that erosion was much more severe on the western shore, due to the longer fetch over which wind-generated waves could develop. The estimated rates were remarkably constant up until the 1940s, and appear to have accelerated over the past several decades. Finally the implications for continued human habitation to the year 2100 were examined, and the future island size was projected, assuming no additional human intervention beyond what has been implemented to date.

INTRODUCTION

Tangier Island is located in the middle of the Chesapeake Bay, the largest estuary on the east coast of the United States (Figure 1). The island is located about 20 km from the mainland on the Eastern Shore of Virginia, and 30 km from the western shore, just below the Virginia-Maryland state boundary (Figure 2). English settlers populated Tangier Island sometime during the 18th century. The abundance of artifacts, such as arrowheads, around the island is evidence that Tangier may have been inhabited many years earlier by native Americans, when sea level was much lower than today (Figure 3) and the island was likely part of a peninsula connected to the Eastern Shore of Maryland. As shown in Figure 3, the level of the sea has been rising over the past 10,000 years in the Chesapeake Bay (Ellison and Nichols, 1974), following the last glacial maximum about 15 thousand years ago. The sea level rise has not been uniform over that time but was greatest in the first few thousands of years following the last ice age. Today, the sea level within the bay appears to be increasing again. However, the main reason now is due to steric effects associated with a warming ocean. Figure 4 illustrates the major components of sea level rise in the Chesapeake Bay over the past century. The sum of the three effects shown (steric, tectonic, and post-glacial response) constitutes the relative rate of sea level rise, about 37 cm over the past century. More than half of that is due to steric effects, and the remainder is due to post-glacial subsidence and tectonic movement of the earth's crest. In the Chesapeake Bay area, relative sea level rise is about twice the rate that would occur in parts of the world where the land is not moving vertically.

Today about 700 people live on the island. The major industries on the island are the seafood industry (the seafood industry consists primarily of blue crabs, oysters, and fin fish) and tourism. The highest point on the island is approximately 2 m above mean sea level (msl), and homes are built on one of three "ridges" that are about 1 m to 1.5 m above msl. Figure 5 shows the topography of the island and the bathymetry in the vicinity of the island. The cross-sections shown in the figure suggest that only the tip of what was a much larger island remains today. Also shown on the cross-sections are approximate relative sea levels 400 and 2000 years ago to illustrate the potential extent of Tangier

Island in the distant past (a cautionary note: these estimates are based on today's bathymetry, which differs from the bathymetry centuries ago).

Figure 6a shows a map of the island drawn in 1850. While earlier maps exist, such as these drawn by Captain John Smith (Global Sales Publications, 1996) in the 17th century and Fry and Jefferson in the 18th century (Fry and Jefferson, 1791), this appears to be the first accurately drawn map. Three sandy ridges are identified on the island, locations where homes have been built and remain today. A 1986 USGS topographic map shown in Figure 6b identifies the three ridges (West Ridge, Main Ridge, and Canton Ridge), and homes built on each of these three ridges. Note that the island has been bisected by a channel (Tangier North Channel) that is routinely dredged to maintain navigational integrity. The 76° 00' W meridian shown in both Figure 6a and 6b helps to provide a marker to quantify the amount of shoreline erosion that occurred between years 1850 and 2000. Quantification of the erosion rate is provided subsequently in this paper.

In Figure 6c, an aerial photograph of the island, taken in March 2000 by the United States Army Corps of Engineers (USACE) is shown. The Tangier Island Municipal Airport on the western side of the main island can clearly be seen, and has been extended since 1986. Also, a seawall was constructed by the USACE in 1990 to protect the airport from the eroding shoreline. The extent of the seawall is indicated in the figure.

Due to the relative increase in the sea level in Chesapeake Bay over the past 100 years of tide gage records, and the projected continued increase over the 21st century, it is expected that both shoreline erosion and sea level rise will increasingly diminish the size of the island, and further limit locations where people can live. Accordingly, the objectives of this report are to:

- Examine the rates of relative sea level rise over the past century as well as projected future sea level rise over the 21st century.
- Analyze several years of tidal data that include a range of storms (hurricanes and Northeasters) to project tidal levels to the end of the 21st century using a range of plausible relative sea level changes at Tangier Island.
- Quantify the rates of erosion of the island's shoreline, and project future erosion rates over the 21st century.
- Identify options that could mitigate these impacts, and the implications for continued human habitation of the island.

The Exhibit at the end of this paper contains a series of photographs that document erosion-related issues on the island. The aerial photograph taken in year 2000 by the USACE is used to show where the other photographs in the exhibit were taken, and the direction towards which the camera was pointing. The first eight photographs illustrate erosional issues associated with the main channel and land. Photographs 9 through 14 were taken at the southern end of the seawall, and along the sand spit that extends further south. They document erosion that has occurred since the seawall was constructed in 1990, and continuing erosion and movement of the sand spit. Photograph 15 shows a large ship traveling north in the shipping lanes to the west of Tangier Island, and photograph 16 is a bed and breakfast on the island that caters to the tourist industry.

METHODS

Relative sea level rise data were compiled for four locations in the Chesapeake Bay (Hampton Roads, near the mouth of the Bay; Solomons Island; Annapolis, and Baltimore). These stations had periods of record that ranged from 60 to nearly 100 years. A power analysis was performed on the data to determine major periodicities. Information on the occurrence of hurricanes and Northeasters in the bay was gathered, and from that information, specific years with storm events (1933 and 1998) were chosen to evaluate sea level rise impacts. This was done by predicting sea level 100 years into the future using MAGICC (Hulme et al., 2000) and accounting for uncertainties in sea level rise by examining low, moderate, and high climate change sensitivities. Hourly tidal data for the two years chosen were then extrapolated to the year 2100 by combining the MAGICC results and historical tidal information. Frequencies of tidal elevations above levels that would be of concern to the residents of the island were calculated.

Shoreline erosion on Tangier Island was evaluated by collecting historical maps, charts and aerial photographs that spanned the years 1850 to 2000. The historical maps were obtained from different sources. The maps for years 1850-1905 were purchased from NARA Map Scan. These maps were originally created by the U.S. Coast and Geodetic Survey. The maps from 1942 and 1968 were obtained from the USGS archived files. The map for 1986 was downloaded from the USGS website (www.usgs.gov). All historical maps came as digital raster images except for years 1942 and 1968, which were scanned and saved as TIF images. Using a Geographic Information System (GIS), temporal changes in Tangier Island's shoreline were calculated. Further the change in the percent of internal water was estimated using the same overlay technique. Using the GIS, the digital maps were geo-referenced to a common projection – UTM NAD 27, Zone 18. A set of prominent land marks on the maps, such as road intersections, lighthouses, and the 76º west meridian, were used as control points in the process. By overlaying the maps of different time periods on top of each other, changes were identified and quantified.

The topographic data used are from 7.5 min USGS Digital Elevation Models (DEM) (www.usgs.gov). The bathymetric data used were from the National Ocean Service (NOS) Estuarine Bathymetry Products, and were downloaded from NOS's website (http://spo.nos.noaa.gov). The two digital data sets were imported into Vertical Mapper software and merged together to form a contiguous map of land surface topography and underwater bathymetry.

Wind speed and direction data were collected for the years 1997-2001 and processed to determine wind speed and direction variability. This information, along with bathymetric data and fetch information, was used to estimate wind generated waves, using techniques described in U.S. Army Corps of Engineers (1984). Ship generated waves were also estimated using methods described in Weggel and Sorenson (1984). Subsidence of Tangier Island due to local pumping was estimated using linear extrapolation of the data from Davis (1987). All analyses, other than those performed using MAGICC, were performed by developing and implementing MATLAB programs (The Mathworks, 2000).

RELATIVE SEA LEVEL CHANGES

Figure 7a shows 20th century relative sea level changes at four locations throughout the Chesapeake Bay based on tide gage information obtained from the Permanent Service for Mean Sea Level (PSMSL) (Proudman Laboratory, 2002). The locations were selected both for their spatial distribution and long periods of records (over 60 years at Solomons Island to over 95 years at Baltimore). Note the general similarities in trends at the four locations. Averaged over a century, the relative sea level increases from 31 cm/century at Baltimore to 38 cm/century at Solomons Island. These rates are about twice the rates of global sea level increase (approximately 15-20 cm/century) as discussed earlier. Subsidence in the Chesapeake Bay area has been estimated to be about 18 cm/century (Kearney and Stevenson, 1991). Major causes of the large-scale subsidence includes post-glacial response of the land following the last Ice Age over 15,000 years ago and tectonic activity of the earth's crust. Removing the subsidence from the recent relative sea level increases would indicate that the global sea level increase is about 13 cm/century to 20 cm/century, within estimates of global sea level rise provided by IPCC (2001). Figure 7b shows five-year running averages at four locations within the Chesapeake Bay. Similarities between stations are evident and long-term fluctuations are apparent (and similar) in all records. These dramatic fluctuations illustrate the risk of using short-term records to estimate rates of sea level change.

In addition to the long-term trend in sea level, it is seen from Figure 7a that the sea level changes cyclically over each year. A power analysis was performed of the data to examine this periodicity. The results are shown in Figure 8. Sea levels exhibit a strong annual cycle. The maximum sea levels typically occur during the summer months, and the minimums occur during the winter. These patterns are caused by both thermal expansion (summer) and contraction (winter) when the water temperatures change from about 28 ºC to 5 ºC, respectively, and by changes in volumes of freshwater in the Bay due to seasonal runoff, where often peaks in runoff rates often occur at two different times during the year.

While long-term sea level data are not available for tide gages located on Tangier Island, some limited hourly tidal data are available. One month of tidal data in July and August 1999 was plotted against the tidal data for Hampton Roads, Solomons Island, and Baltimore (Figure 9). The data indicate that the tidal range is considerably greater near the mouth of the Bay at Hampton Roads than further up the Bay. The ranges at both Solomons Island and Baltimore are similar to that at Tangier, although the phase has shifted. Since the phase is immaterial for this study, tidal data for both Solomons Island and Baltimore are used in subsequent analyses.

Several years of historical tidal data were selected for use in extrapolating sea level changes to the year 2100. To determine which data to extrapolate, historical storm activity in the Chesapeake Bay was examined. Examples of severe storms that have struck the Bay are summarized in Table 1. Comparisons of maximum water surface elevations and durations of those elevations are shown for Hampton Roads (near the mouth) and Baltimore. The unnamed hurricane of 1933 produced the highest elevations in recorded history of the Bay, although the duration of the extremely high water was only 3 to 6 hours. Northeasters (extra-tropical storms that produce strong and sustained winds from the northeast) have also produced extremely high tides. A number of Northeasters occurred during the winter of 1998, and produced tidal heights of up to 1.7 m above msl. While not as high and as wide spread as the tidal heights from the hurricane of 1933, the duration of high water was longer. Based on these results, the years 1933 and 1998 were used in the predictions to follow. The entire yearly sea level data for Baltimore and for Solomons Island are provided in Figure 10. Data points that correspond to the Hurricane of 1933 and Northeasters of 1998 are noted in those figures.

To extrapolate sea levels to the year 2100, the model MAGICC (Hulme et al., 2000) was used, and simulations were performed under low, moderate, and high climate sensitivities. Sensitivity refers to the global temperature change that results from a doubling in atmospheric greenhouse gas concentrations, at attainment of an equilibrium condition. The model results are shown in Figure 11, along with the time series of sea level changes at Baltimore with and without adjustment for subsidence. It is seen that the relative rate of sea level increase without adjusting for subsidence is similar to the present rate of global sea level increase for high climate sensitivity, while the relative rate adjusted by removing subsidence is closer to the low sensitivity rate. In turn the low sensitivity rate is close to the historical rate of 15-20 cm/century, as depicted by the blue line that extends over the 21st century.

In the following predictions, results from the low and moderate sensitivities are emphasized, but several high-sensitivity results are also shown. The low climate sensitivity is very similar to the historical trend, and is referred to as the historical trend in the following. The first set of results is shown in Figure 12, using both Baltimore (1933 and 1998) and Solomons Island (1998) historical data. In the top panel of the figure, the single spike shown represents the unnamed hurricane of 1933. It is immediately obvious that this was a rare storm, when the tidal elevations from that event are compared with all others. To generate the year 2100 data, the historical data were extrapolated to the present using historical trends, and then into the future using the MAGICC results. Island subsidence was assumed to continue at the present rate.

To interpret the results of rising sea level, Figures 13, 14, and 15 were prepared. In Figure 13 yearly tidal data, both historical and predicted, were sorted from low to high and plotted as cumulative distribution functions. The tidal elevations are shifted to the right with increasing time (that is, from 1933 to 1998 to 2100) and with increasing climate sensitivity (low sensitivity, essentially a continuation of the historical trend, and moderate climate sensitivity). In Figure13a (based on Baltimore records), the historical relative sea level rise from 1933 to 1998 is shown by the two left most curves. Over this time interval (65 years) the historical relative sea level has increased by about 20 cm, as measured by the 50th percentile tides. This is equivalent to about 31 cm/century. Predictions for the year 2100 show that the median tidal level will increase by about 30 cm (continuation of historical trend) to 60 cm for moderate climate sensitivity. Figure 13b is a similar plot for Solomons Island, but includes a shorter time frame, 1998-2100. The predicted sea level increases are very similar to those in Figure 13a.

In terms of predicting impacts on the human population of the island, Figure 14 has been prepared that shows the amount of time per year that certain critical tidal elevations are exceeded. Figure 14a uses the 1998 Baltimore data as the base year, Figure 14b is based on using 1998 Solomons Island data as the base year, and Figure 14c is based on using 1933 Baltimore data as the base year. Each figure uses the elevations of 0.8 m, 1.0 m, 1.5 m, and 2 m above msl. When the tidal elevation is 1 m to 1.5 m above msl, the ridges on which the houses are built begin to flood, as the elevations of these ridges are about 1 m above msl. When the tidal level is greater then 2 m above msl the entire island is underwater. In 1998 the tidal elevation was 1 m above msl for only 3 hours of that year (Figure 14a). Extrapolating to the year 2100 for either a continuation of the historical trend or for moderate climate sensitivity, the 1 m elevation would be exceeded much more, 80 hours to 1494 hours, respectively. For the high climate scenario, the 1 m above msl elevation would be exceeded about 4400 hours, or 50 percent of the time. Very similar results are obtained using the 1998 Solomons Island data (Figure 14b). Figure 14c uses the year 1933, the year of the unnamed hurricane, as the base year. The major difference in using this year is that tidal elevations would exceed 2 m above msl, in which case the island would have been underwater for 8 hours in 1998, increasing to 12-18 hours in the year 2100 depending on the rate of sea level rise.

Figure 15 shows the number of predicted events during the year when the tidal elevations would be above the levels indicated. Each event is defined to begin when the tide reaches a specified level, and continues until the tide recedes below that level. The number of events when tides exceed 1 m above msl would increase dramatically for the year 2100 for both the moderate and high climate sensitivity cases, regardless of which data are used in the extrapolation. Note at the lower limit of tidal elevations used in Figure 15 (0.8 m above msl), the number of events at the high climate sensitivity actually decreases relative to the number of events at moderate sensitivity. This is due to the increased duration of each event.

SHORELINE EROSION

Shoreline erosion has been occurring on Tangier Island for as long as documented records are available. Much of the shoreline on the island consists of a water-marsh interface, with little or no beach sand [except for the sand spit at the southern tip of the island (Figure 6c)]. The marshy soil is composed of cohesive clays and silts, and organic matter. Just offshore, the bay bottom is sandy with median sand size of 0.25 mm close to shore and 0.50 mm further off shore. The sandy bottom material is steadily transported to the south, and helps to maintain the sand spit at the southern end of the island. The depths of water within a few hundred meters of the island are much greater than can be accounted for by relative sea level rise, so that the bottom sand apparently is being scoured and transported to the south faster than it can be replenished.

As shown below, the erosion is worst on the western side of the island, where the island is exposed to longer stretches of open water, and wind generated waves are larger. Figure 16 shows a polar plot of wind speed and direction at a location 60 km north of Tangier Island for the five years 1997-2001. Also identified on the plot are a hurricane (Hurricane Floyd) and northeaster that occurred during this time period, which were responsible for some of the highest wind speeds. Analysis of the data show that the wind blows from 270° - 360° 31 percent of the time (the most of any quadrant), and from 0° - 90° 20 percent of the time (the least of any quadrant). Figure 17 shows the distribution of wind speeds by quadrant. When the winds are blowing from 270° to 360°, they typically blow harder than when blowing from the other quadrants.

Figure 18 illustrates typical relationships between wind speed and direction, and tidal height. During northeasters (low pressure systems) the tidal heights tend to increase, as shown earlier in Table 1, and illustrated in Figure 18. When the wind direction shifts to the northeast the tides increase accordingly, as more water is pushed into the Bay during this time. Two different northeasters are boxed in Figure 18: the first around January 28, 1998 and the second around February 4-5, 1998. Both illustrate how the tidal elevation increases as the wind blows from the northeast.

Figure 19 illustrates the fetch by direction at Tangier Island. The longest fetches are to the northwest of Tangier, which is also the direction from which winds blow more often, and at higher speeds. Figure 20 shows how fetch influences wave height. In that figure, predicted wave heights are shown as a function of water depth and wind speed for two different fetches (42 km and 20 km). These fetches are representative of open-water distances from the northwest and from the east, respectively. Wave heights of up to 80 percent higher result from the longer fetch. For example at a water depth of 30 m and wind speed of 20 m/sec, the predicted wave heights at fetches of 42 km and 20 km are 2.7 m and 1.9 m, respectively. To illustrate combinations of fetch, depth, and wind speeds required to produce waves of two specified heights (1.5 m and 2.0 m) Figure 21 was created. It is clearly seen that conditions for 2 m waves to occur are much more limited than for 1.5 m waves. For example, 2 m waves do not occur for fetches under 25 km, while 1.5 m waves can occur for fetches as short as 13 km.

Numerous maps of Tangier Island are available and accurate enough to permit the estimation of shoreline erosion for over 150 years. The maps used to make estimates of shoreline erosion are:

- 1850 and 1905 T-charts (manuscript topographic charts)
- 1942, 1968, and 1986 USGS topographic quadrangle maps
- 2000 aerial photograph taken by the United States Army Corp of Engineers

Although several earlier maps were located (John Smith's 1608 rendition of the Chesapeake Bay, and Jefferson Frye's 1750 rendition of the Bay) neither showed enough detail of Tangier Island to allow shoreline erosion estimates to be made. Based on the above-mentioned charts and aerial photographs, the relative change in island size was first visually documented. An example is shown in Figure 22 that compares the island in 1850 to 2000. The 76° 00´ W meridian was used to assist in aligning the two maps. Practically all of the island west of 76° 00´ W has been eroded. It is apparent that significant erosion of the western shore has occurred over the past 150 years all up and down the shoreline. The sand spit at the southern end of the island has migrated eastward as the shoreline has eroded and wind has blown the sand eastward. On the eastern side of the island shoreline erosion has also occurred but to a far lesser degree. The effect of the seawall in abating shoreline erosion is shown by examining Figure 6c. Note the erosion that has occurred just to the south of the seawall over the ten years from 1990 to 2000.

To assist in quantifying the erosion rates, ten points were added to both the western shore and eastern shore of the island in the 1850 rendition, at locations were erosion rates were calculated. Erosional distances were estimated, and are shown plotted in Figure 23. Figure 23a shows those locations not influenced by the seawall constructed in 1990, and Figure 23b shows the remaining locations on the western shore. Examining Figure 23a, it appears that the rates of erosion began to increase beyond historical rates at all locations at least by 1968, and at some locations by the 1940s. Similar accelerations are noted in Figure 23b as well (with the exception of location 9).

Figure 23d shows the erosional rates on the eastern side of the island. Due to uncertainties in the shoreline, only the first (1850) and last maps (2000) were used to make these estimates. The erosional rates on the eastern side of the island are about 10 to 20 percent as high as on the western side.

Changes in the interior water within Tangier Island were also examined. Due to the increasing level of the sea and due to the potential die-off of interior marsh grasses if vertical accretion rates do not stay up with relative sea level rise, it is expected that ponds would appear and enlarge, and channels would widen as sea level rise accelerates. This has been documented to occur on the Eastern Shore of Maryland over the past decade (Leatherman et al., 1995; Stevenson et al., 2002). The graphics in Figure 24 confirm this. This figure compares the amount of interior water in the same portion of the island between the years 1850 and 2000. In 1850, this portion of the island contained about 18 percent interior water; in 2000 the same area contained about 33 percent interior water. As more interior land is converted to shallow water, these shallow ponds and channels provide conduits for accelerated shoreline erosion once the shoreline impinges on these interior waters. For example, Toms Gut is likely to connect directly to the open bay waters within a few years, exposing more of the interior of the island north of the main channel, and increasing erosion potential. Qualitatively similar results were found on Tangier Island south of the main east-west channel through the island. However, quantitative estimates were not made of the percent internal water there, even though attempts were initiated to do so. This was because of the poor resolution of the earlier maps at resolving narrow channel widths and small ponds, predominant on this part of Tangier Island.

There exist a number of causative factors that could explain the increased erosional rates observed around the island. They include the processes identified below:

- Increasing relative sea level due to land subsidence and steric contributions that bring the erosive power of the waves further inshore (Downs et al. 1994; Bruun, 1983).
- Accelerated loss of the protective marsh on the island that results if the vertical accretion rate of the marsh is not great enough to keep pace with the increasing rate of sea level (Kearney et al., 2002; Stevenson et al., 2002). This results in increased amounts of interior pond development and channel widening.
- Increasing shipping traffic in the Bay (Hampton Roads to Baltimore) over the years, and increased vessel size that generate larger waves.
- Subsidence of land due to increased regional and local groundwater withdrawals (Kearney and Stevenson, 1991).
- Loss of submerged aquatic vegetation (SAV) over the past decades as the Bay has eutrophied (Bay Journal, 2002).
- Salt marsh die-off from periwinkle snails due to over harvesting of snail predators, such as blue crabs (Silliman and Bertness, 2002).

Together these forces combine to attack the island both from its exterior (at the shoreline) and its interior (increased amounts of interior water widen channels). Of these two modes of attack on Tangier Island, it is the shoreline erosion that is most obvious and impactful. As the relative level of the sea rises, due to global sea level rise and island subsidance, the same wind generated waves bring their energy at elevations that are higher than before, and provides more energy to dislodge marsh grass and to erode the shoreline. The effects such as sea level rise and regional subsidence have been well studied and documented as causes of shoreline erosion (Kearney, 2002; Downs et al., 1994; Brunn, 1983). However, it is not clear what effects (major, minor, or none at all) other contributions (such as increased shipping traffic in the bay, subsidence of the island related to local groundwater withdrawals, loss of submerged aquatic vegetation around the island, and salt-marsh die-off from periwinkle snails) have on exterior and interior land-lost processes. Below, these are briefly analyzed.

Presently, approximately 27,000 vessels call on the Port of Baltimore each year. Of these, approximately 10 percent are large ocean-going vessels that travel in the deep channel west of Tangier Island (Figure 26). The frequency associated with the passage of these ships past Tangier Island is about 15 trips per day, both up and down the bay. Given that each ship generates multiple sets of waves, the amount of wave energy generated over the coarse of a year by these ships is significant. Further, satellite imaginary has shown that ship-generated waves can travel significant distances laterally (scale of kilometers) before completely dissipating.

Over the past 50 years, the size of ocean going vessels that ply the Chesapeake has significantly increased. Figure 27 illustrates the evolution of container ships within the bay for nearly 50 years. Pre-1960 vessels displaced approximately 20,000 tons, while the largest vessels today displace more than 175,000 tons. In the Exhibit, photograph 15 shows an example of a large ship traveling in the ship channel just west of Tangier Island (c.1975).

To evaluate potential impacts of these vessels on Tangier Island, the following analyses were conducted. The cross-section of the bay shown in Figure 26 was used. Also shown on that figure are drafts of the smaller and larger container ships. The larger ships are constrained to stay within the 5 km wide channel, while the smaller ships can operate over a channel width of about 10 km. Based on their cross-section and personal observations it appear that large ships approach to within about 10 km of Tangier Island.

The approach to analyzing the effects of these waves on Tangier Island is based on a method of Weggel and Sorenson (1984). They developed dimensionless ship-parameter groups and fit observed wave data to quantify unknown coefficients. Figure 28 shows the predictions in terms of maximum wave heights versus lateral distance from the ship. Curves are shown for both 25,000 ton displacement vessels and 200,000 ton displacement vessels. For the smaller vessels, maximum wave heights drop off to less than 0.5 m in about 1 km, and to about 0.25 m in 10 km. However, for the larger vessels, wave heights greater than a meter persist for about 2 km, and are about 0.55 m at a distance of 10 km. Thus, the larger vessels are expected to produce significantly larger waves that potentially impact Tangier Island. However, due to the relatively small number of these vessels currently in the bay (less than 25 percent of the container ships fall in this range) and the predominance of larger wind-generated waves, it is not expected that the waves from these large vessels are significant with respect to shoreline erosion on Tangier Island.

Significant small boat activity also exists around Tangier Island from the many oyster, fishing, and crab boats. A recent study has shown that boat generated waves might impact seagrass habitat (Koch, 2002). However, it is unlikely that these small waves would have significant impacts on the shoreline erosion, as evidenced by the uniformity of the erosion up and down the island, suggestive of the importance of a larger-scale phenomenon, such as uniformly sized wind generated waves.

The next possibility that may affect erosion is subsidence of the island due to local groundwater pumping. Pumping from deep artesian wells has been ongoing for decades on the island. Eight wells have been drilled on the island over the past 42 years at depths between 930' to 1033' into the Lower Cretaceous Aquifer beneath the bay. While pumping records are not known for all years, during the time frame 2000-2002 the average amount of water pumped was 380 m^3/day. It is expected that the amount pumped in years previous to those would be similar or slightly greater, since the population on the island over the years has not significantly exceeded the present day population for long periods of time.

Davis (1987) evaluated the localized effects of groundwater withdrawals on land subsidence in southeastern Virginia, with emphasis on two pumping areas in West Point and Franklin. Figure 29 shows those areas of subsidence, along with subsidence in other areas of the Chesapeake Bay due to vertical coastal movements (in mm/yr). Note that away from the heavy pumping zones the vertical land subsidence (independent of pumping) is about -1.6 mm/year. However, near the larger pumping centers, additional subsidence is occurring such that total rates are between -3.2 mm/yr (West Point) and -4.0 mm/yr (Franklin). For the major locations of pumping, the following subsidence to head declines have been observed (Davis, 1987):

Location	**Subsidence/Head Decline (mm)**
West Point, VA	0.0024
Franklin, VA	0.0033
Dover, DE	0.0024

Assuming linear rates of subsidence, the estimated subsidence on Tangier Island is calculated based on the following relationship:

$$\Delta z = \alpha \cdot H_1 \cdot \left(\frac{T_2}{T_1}\right)\left(\frac{Q_2}{Q_1}\right)$$

where

α = specific subsidence (subsidence/head decline), m/m
H_1 = actual subsidence at location 1, m
T_1, T_2 = pumping duration, years
Q_1, Q_2 = pumping rates, m^3/yr
Δz = predicted subsidence at location 2 (Tangier Island)

Using the data from West Point:

H_1 = 49 m (West Point)
T_2 = 100 year (assumes today's pumping rate has been constant on Tangier Island)
T_1 = 40 year
Q_1 = 380 $m^3 day^{-1}$ (assumes today's pumping rate has been constant on Tangier Island)
Q_2 = 95,000 $m^3 day^{-1}$
α = 0.0024

The predicted subsidence is $\Delta z = 10^{-3}$ m = 0.1 cm in 100 years. Thus subsidence from local pumping over a 100 year period is negligible.

The amount of SAV (submerged aquatic vegetation) or seagrass in the Chesapeake Bay today is approximately 35,000 ha. This is about 13 percent of the 272,000 ha thought to be in the bay a century ago. Typically SAV is present in water at depths of less than about 1 m, due to light limitations that reduce photosynthetic activity at greater depths, assuming other factors (such as low wave energy) are favorable. (In the past when water clarity was greater in the Bay, SAV was found at depths of up to 2 m.)

Since 1971 Chesapeake Bay SAV has been mapped from aerial photography. However, SAV around Tangier Island has been mapped for most years only since 1978. Figure 30 illustrates the locations of SAV around Tangier Island for three of those years: 1978, 1992, and 2001. In all years the SAV is located predominately on the eastern side of the island, where it offers some protection against erosion by absorbing and transmitting wave energy to the bed. On the western side of the island SAV is absent, however. It is not known whether SAV was present there prior to 1978. Discussions with local waterman suggests it was not. Note that the water gets deeper than 2 m close to shore, which reduces the opportunity of SAV to survive there. The bottom at these locations near the western shore appear to be erosional areas, since the water depths there are far greater than could be accounted for by sea level rise. From the available data, it can not be concluded that SAV was present on the western shore. As shown earlier, rates of shoreline erosion there have been significant since data were available (see Figure 23) beginning in 1850. The accelerated rate observed between 1985 to present does not appear to be related to changes in SAV coverage during that time.

Recently, the role of periwinkle snails in the die-off of salt marshes has been examined (Silliman and Bertness, 2002). Prior to the work of Silliman and Bertness, it was thought that salt marsh plant communities were bottom-up regulated communities, dominated by physical conditions and nutrient supplies. However Silliman and Bertness showed that consumers (e.g., periwinkle snails) could exert a strong top-down control. At the extreme, the grazing periwinkle snails were capable of denuding marshes into barron mudflats within 8 months. They conclude that over-harvesting of snail preditors (e.g., blue crabs) may be an important factor in contributing to massive salt marsh die-off in the southeastern United States. However, their study was a controlled experiment in two different marshes, and applicability to Tangier Island was not an objective of the research. Over the years, indicators of blue crab abundance in the bay have varied considerably, without any known explanation (Figure 31). Yet evidence (based on historical maps, photographs, and conversations with local watermen does not show similar patterns with respect to marsh grass die-off and regrowth.

REMEDIAL OPTIONS FOR TANGIER ISLAND

Assuming rates of erosion and sea level rise continue over the next century at present rates (which is likely to be conservatively low as the rate of sea level rise is likely to increase), the approximate configuration of the island in 2100 should be similar to that shown in Figure 32. The island boundaries were drawn by extrapolating erosion rates and by considering the existence of interior water, and the likely accelerated erosion of small parcels of marsh on Uppards as they become more exposed to the bay waters. One of the major impacts of the loss of Uppards is that the main channel through the island, where boats are harbored and crab houses exist, would be exposed to the open water. Under such conditions the harbor would no longer be able to function as a safe haven. The town of Tangier Island, which borders the harbor, would then be exposed to the severe wave forces generated within the bay. Photographs 5 and 6 in the Exhibit illustrate how the town is built next to the channel, and structures exist on both sides of the channel.

Prior to discussing potential remedial alternatives for Tangier Island, several examples of island remediation projects within the Chesapeake Bay are discussed to provide examples of what is being done elsewhere. The first example is Poplar Island, MD, located across the bay west of Annapolis, MD. Figure 33 shows a sketch of the proposed remediation. Today Poplar Island is a cluster of marshy knolls and tidal mudflats, that once occupied 1,000 acres (around 1850). To restore the island, over 10 km of dykes will be constructed to hold 500 ha of dredged materials. The use of dredged materials is a large-scale effort to manage dredged materials from within the Bay as a resource rather than as a waste. Both marsh and upland areas are being created on the island. The project is expected to take 25 years and cost over $437 million. The project is for ecosystem restoration.

On Smith Island, shown previously in Figure 2, a project to protect the shoreline at Tylerton (one of three towns on Smith Island) was recently completed (Figure 34) and additional projects are planned that would start in 2005 focused on the Martin National Wildlife Refuge (Figure 35). At Tylerton, a 820 m long bulkhead was completed in 2001 along the town's western shore to prevent further erosion at the shoreline. Along the southern edge of the town, a seawall was built to slow erosion and to protect nearby wetlands and submerged aquatic vegetation. At the Martin National Wildlife Refuge (the northern most island of the Smith Island complex), the project proposed for implementation in year 2005 emphasizes wetland and SAV protection (Figure 35). This project consists of the following:

- A series of breakwaters built to protect approximately 3,000 m of the western shore. Sand would be placed behind the breakwaters to create tidal marsh.
- Stone breakwaters with sand backfill built to protect and restore Fog Point Cove and to create wetlands and habitat.
- Segmented breakwater built along the northern and southeastern peninsulas of Back Cove.

The remedial actions for Martin National Wildlife refuge are for ecological purposes, while those around Tylerton serve both to protect the town as well as to restore and protect ecological resources.

On Tangier Island, the major remedial project completed to date was the seawall constructed in 1990 at a cost of $3.7 million. The location of this seawall was shown in Figure 6c and photograph 9 in the Exhibit, and was designed to protect the airstrip and western shoreline from further erosion. Two additional projects have also been approved for implementation by the USACE:

- Jetty construction of 75 m length on the northwest end of the main channel of Tangier Island to protect the harbor from encroaching waves when the wind blows from the northwest (see photographs 7 and 8 in the exhibit that show the waves generated at the entrance to the harbor when the winds are blowing from the Northwest), and to project the shoreline from further erosion. This project was authorized in 1996, but funds have not yet been appropriated.
- Ecosystem restoration on Uppards that includes attempts to reestablish SAV in the protected channels prevalent there.

To date there does not appear to have been developed an island-wide approach to protect Tangier Island's population and ecological resources. Ultimately to protect the island from vanishing, a two-part approach to remediation approach is needed:

- Part I: Arrest shoreline erosion and minimize the rate of land loss.
- Part II: Evaluate whether the interior salt marsh is accreting enough to stay up with relative sea level change, and evaluate approaches to raise the elevations of the three ridges on the island.

Regarding shoreline erosion, the northern island is quickly eroding away. Once Toms Gut is breached, the erosion should accelerate. After Uppards erodes, the safe inner harbor will become exposed to the open bay waters. Relocation of the harbor, crab houses, and many other shoreline structures that are present in the harbor to another part of the island does not appear to be an option, due to the small remaining available island space.

Regarding salt marsh accretion, the amount of interior water, has increased over time. This suggests that salt marsh accretion has not been able to stay up with relative sea level rise. Given that the rate of relative sea level rise is likely to increase in the future, it will become important to determine whether the marsh can be managed stay up with relative sea level changes. If not, then options could be investigated to augment accretion rates.

Eventually, options to increase the ridge elevations also need to be explored. Sand that is migrating along the sand spit could provide a natural material from the island itself to rise the ridge elevations.

In addition to the technical issues associated with the implementation of any remedial alternatives, other considerations must be considered as well:

- The cost of implementing alternatives vs. the benefits, including the alternative of abandoning the island and relocating at nearby locations on the eastern or western shores. Costs will be a significant issue, given that the existing seawall, which offers no protection to Uppards, cost $3.7 million in 1990. Major construction projects on the island of the scale to minimize erosion would likely cost tens of millions of dollars. Given that the funds to construct a 75 m stone jetty at a cost of $1.8 million to protect the entrance to the island's harbor have not been appropriated, it is uncertain that the funds for large scale remediation would ever become available. Further, erosion minimization, without addressing the increasing interior water, would only delay the loss of the island.

- The issue of whether the bay itself can continue to offer the island residents a way of life, given the dwindling stocks of oysters, crabs, and fin fish. The tourist industry (which numbers about 20,000 people each year) has to date provided a partial replacement.
- The willingness of the residents, particularly young people who are concerned about the future of the island, to remain on the island

SUMMARY AND CONCLUSIONS

Tangier Island, located just south of the Virginia-Maryland state line in the Chesapeake Bay, is home to approximately 700 residents. The island has continually been eroding since accurate maps became available in 1850, and erosion appears to have accelerated over the past several decades. The most likely cause is the acceleration of relative sea level rise. Projections made in this paper suggest that Uppards, the island to the north of the main east-west channel, will erode by year 2100 unless some remedial action is taken. Once that island has eroded, the town of Tangier will be directly exposed to waves generated by winds blowing from northerly directions. The presently safe harbor will disappear, and no viable alternative exists. No island-wide remedial plan presently exists designed to protect against both shoreline erosion and increasing interior water. Costs will be high to implement such a plan. The option of abandonment should be evaluated as well, based not only on costs, but also on the declining seafood industry within the bay.

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Table 1
Examples of Severe Storm Activity in Chesapeake Bay

Event	Hampton Roads	Baltimore
Unnamed Hurricane		
Date	August 22-23, 1933	August 23-24, 1933
Max water surface height (msl)	2.1 m	2.2 m
Duration >2 m	3 hr	6 hr
Hurricane Hazel		
Date	October 15, 1954	October 15-16, 1954
Max water surface height (msl)	0.9 m	1.5 m
Duration >1 m	0 hr	10 hr
"Ash Wednesday" Northeaster		
Date	March 6-8, 1962	March 7-8, 1962
Max water surface height (msl)	1.9 m	1.1 m
Duration 1 m	28 hr	4 hr
Winter '98 Northeasters		
Date	Jan 28; Feb 4-5	Feb 5; March 9-10
Max water surface height (msl)	1.7 m	1.1 m
Duration >1 m	32 hr	3 hr

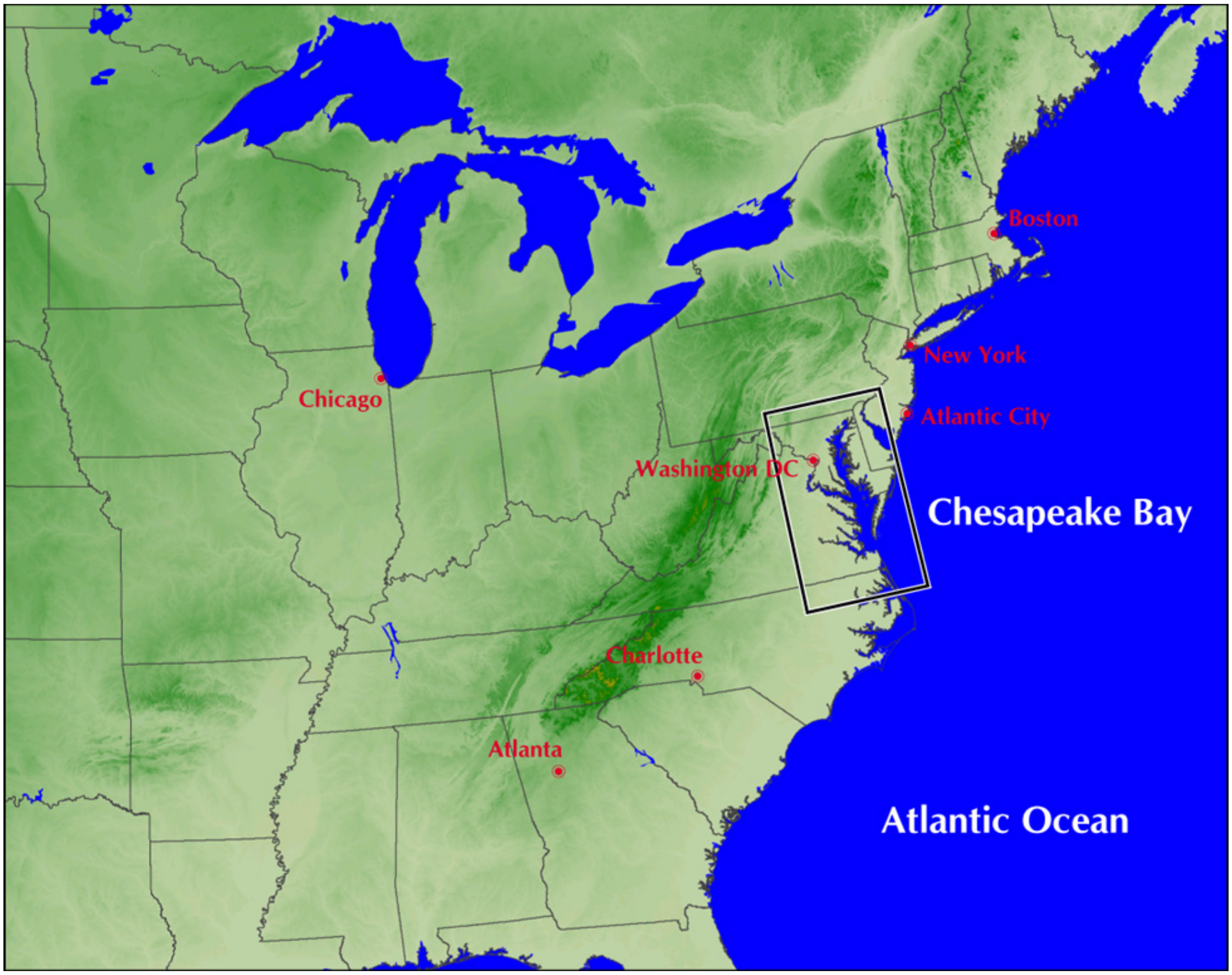


Figure 1. Eastern United States and Chesapeake Bay.

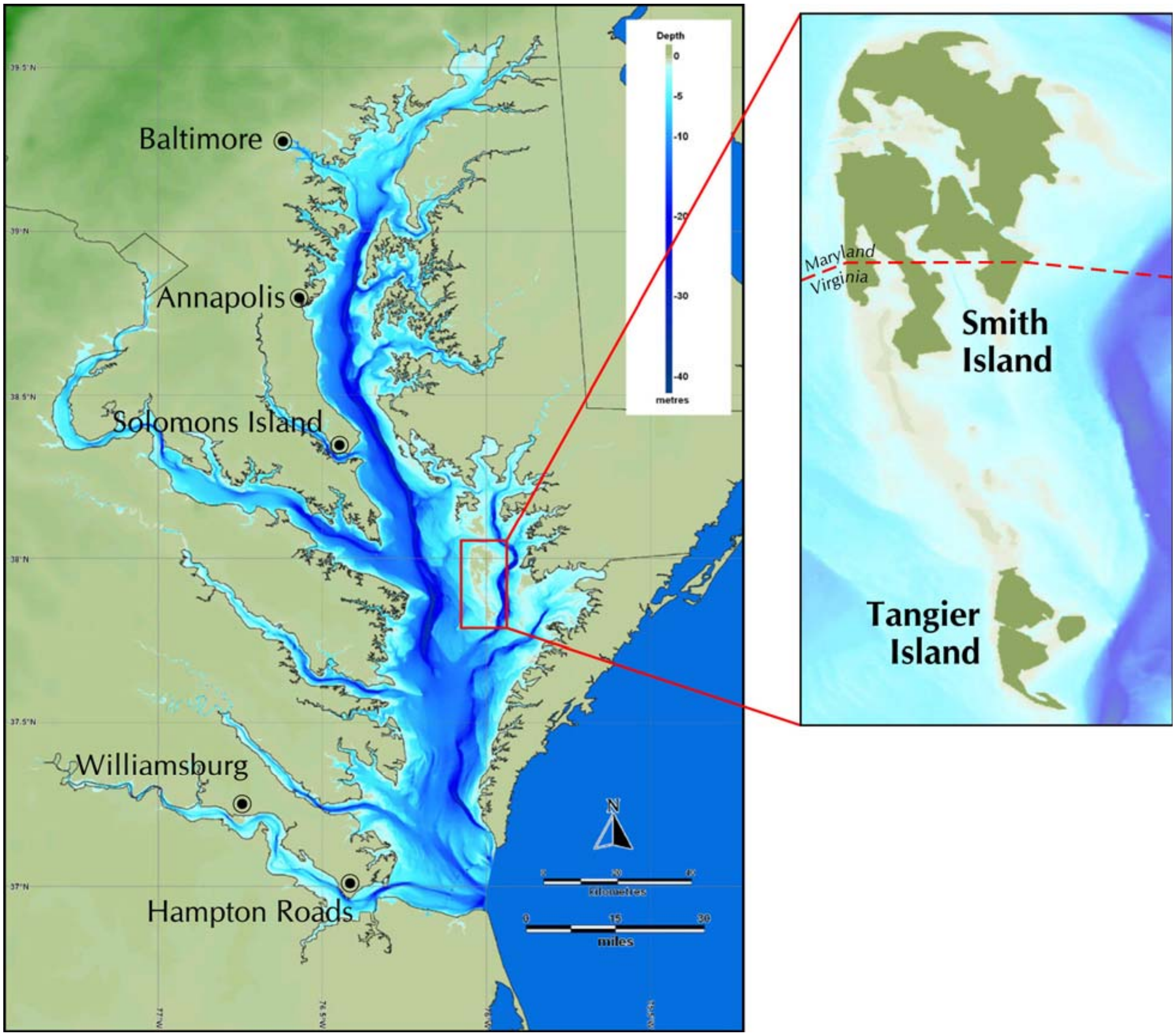


Figure 2. Bathymetric map of Chesapeake Bay showing Tangier Island.

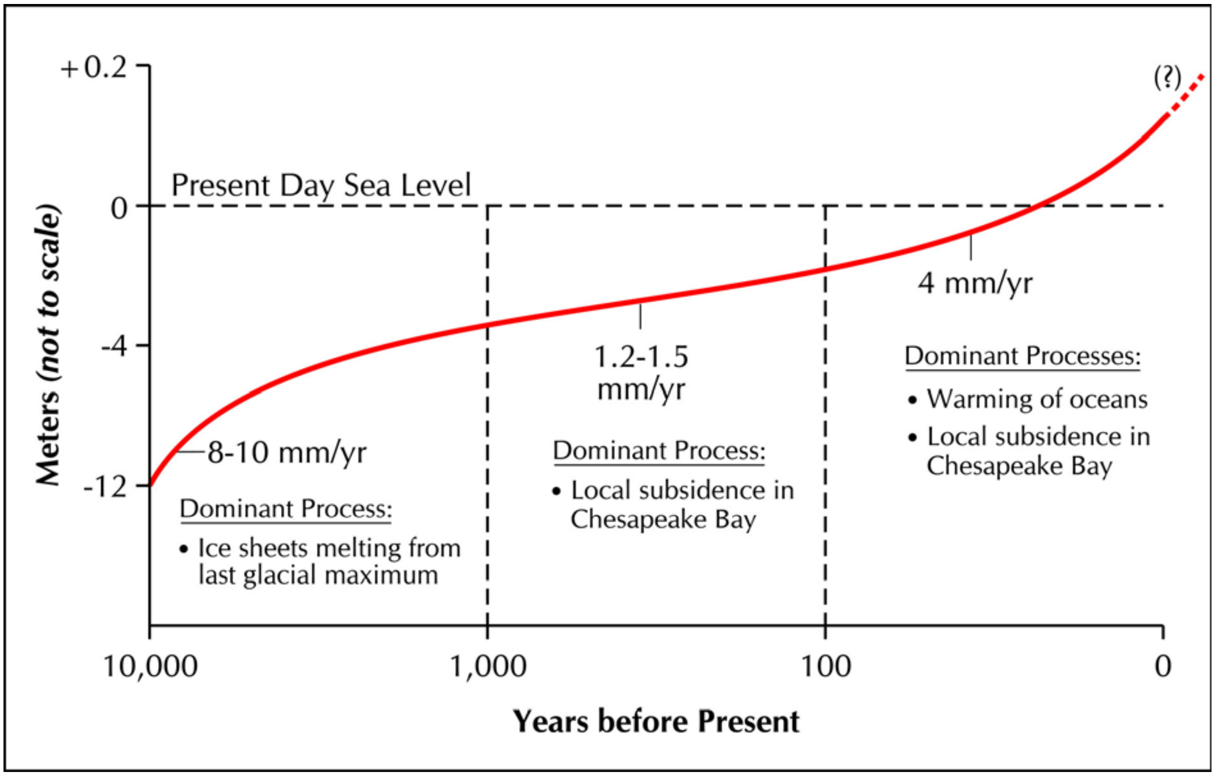


Figure 3. Qualitative relative sea level trend in Chesapeake Bay over the past 10,000 years.

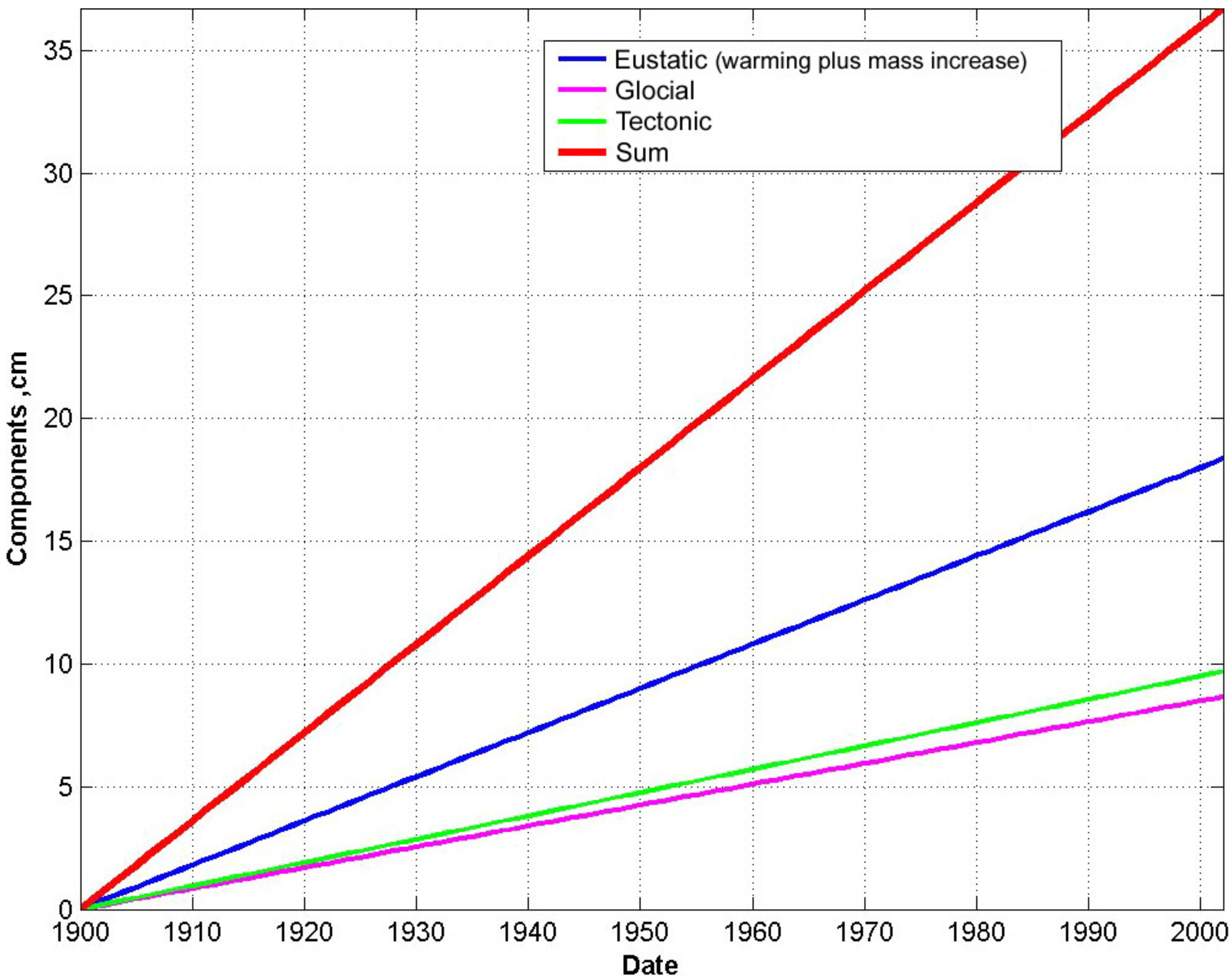
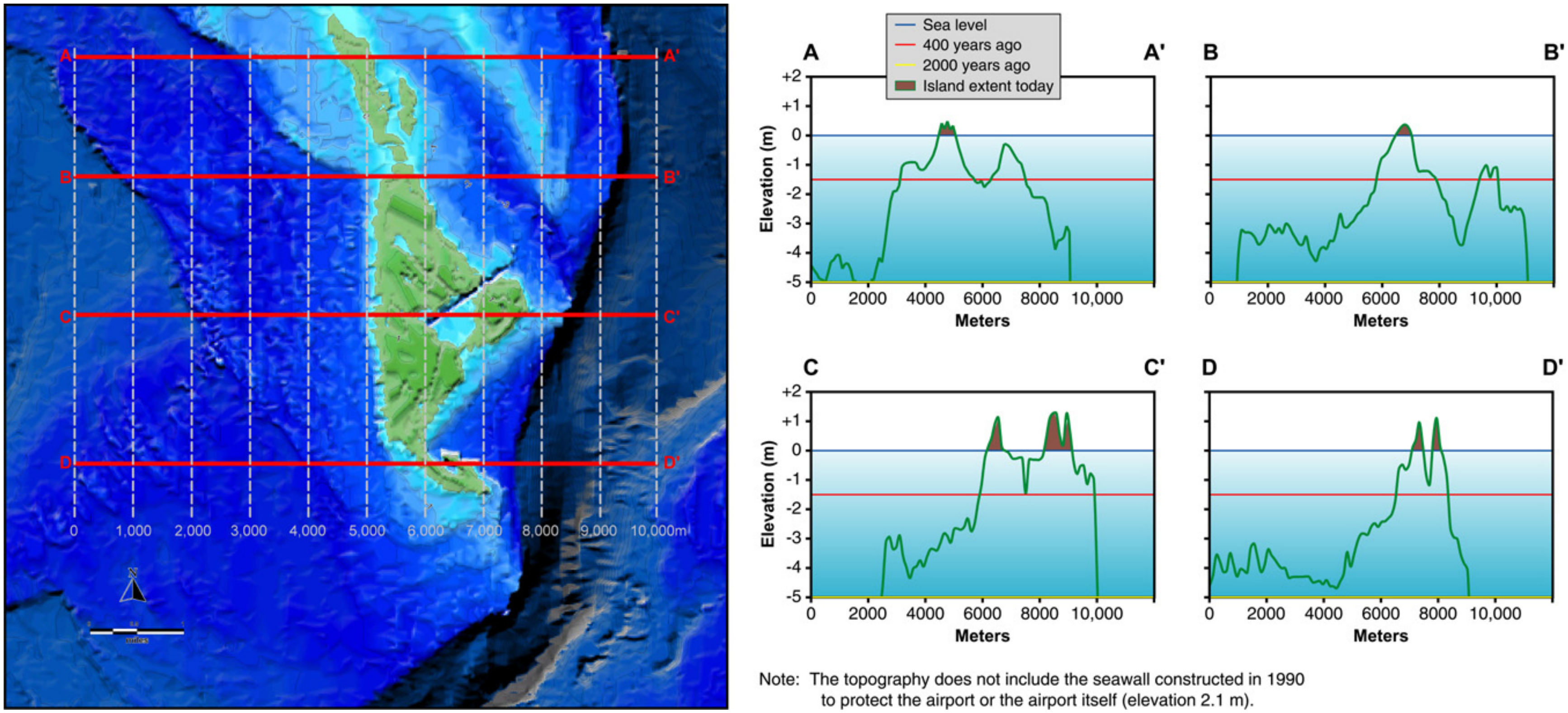


Figure 4. Components of relative sea level rise in the Chesapeake Bay over the past century.



Note: The topography does not include the seawall constructed in 1990 to protect the airport or the airport itself (elevation 2.1 m).

Figure 5. Bathymetry surrounding Tangier Island and topographic relief of the island.

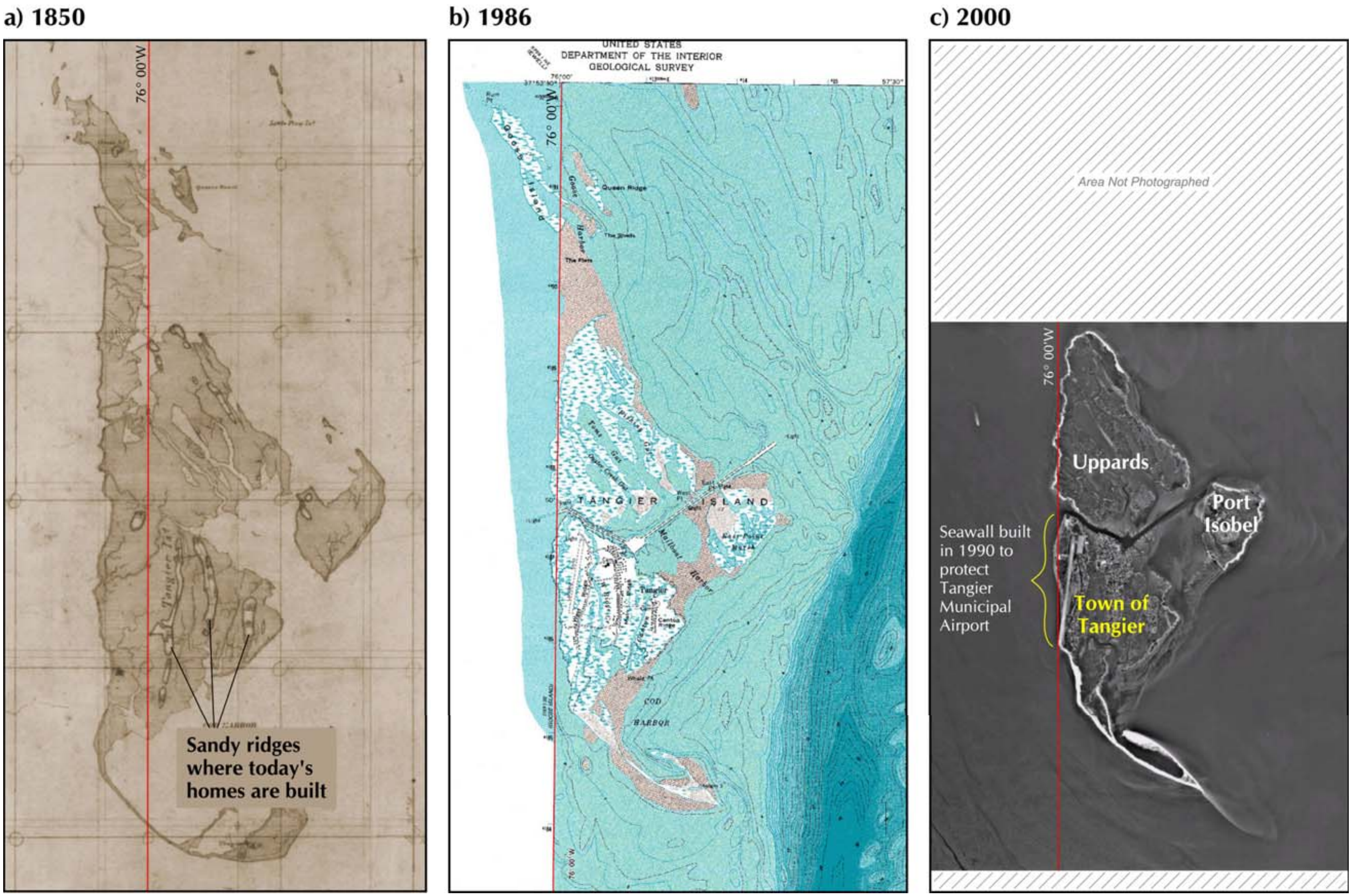


Figure 6. Extent of Tangier Island in 1850, 1986, and 2000.

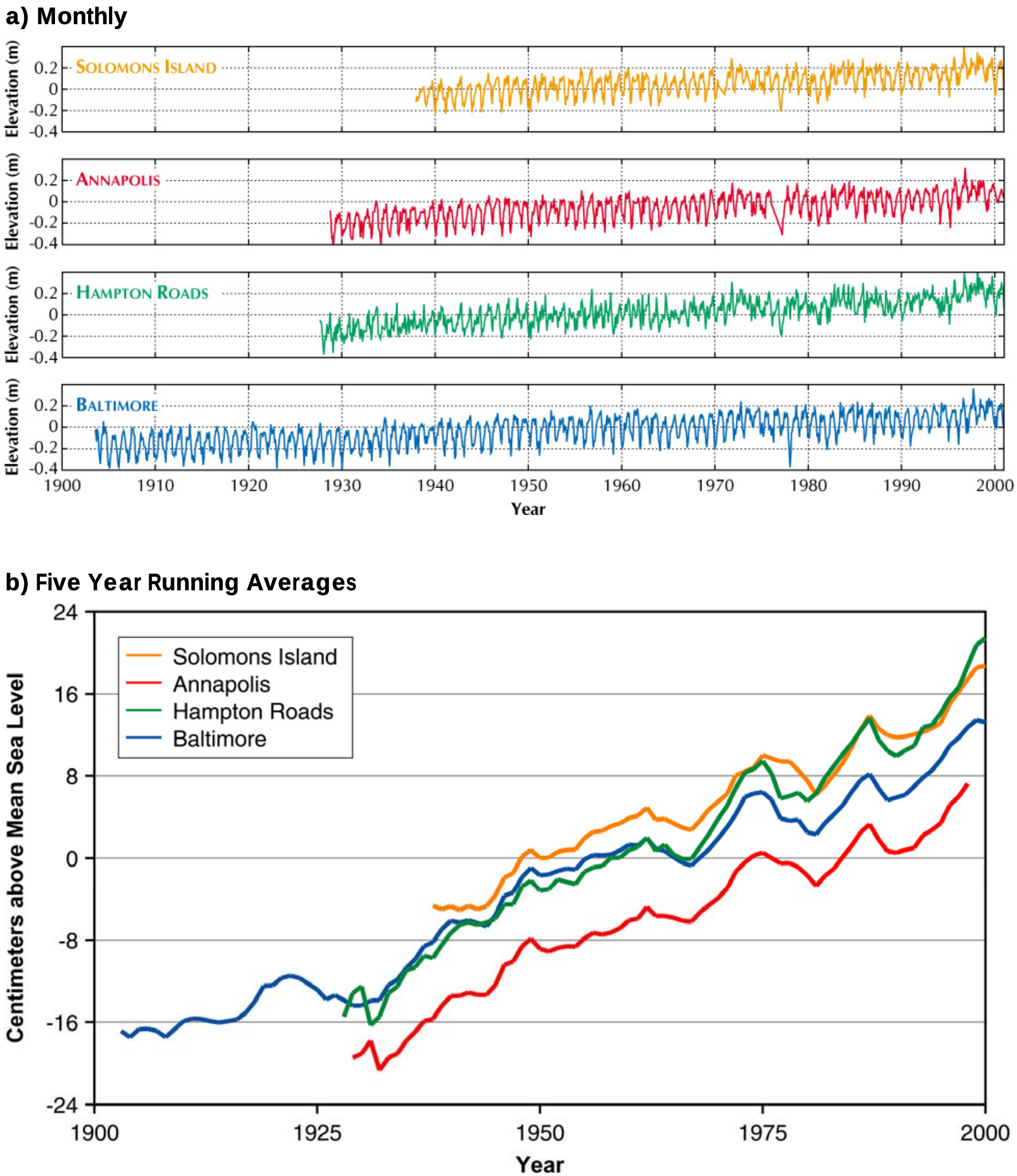


Figure 7. 20th century sea level changes in Chesapeake Bay.

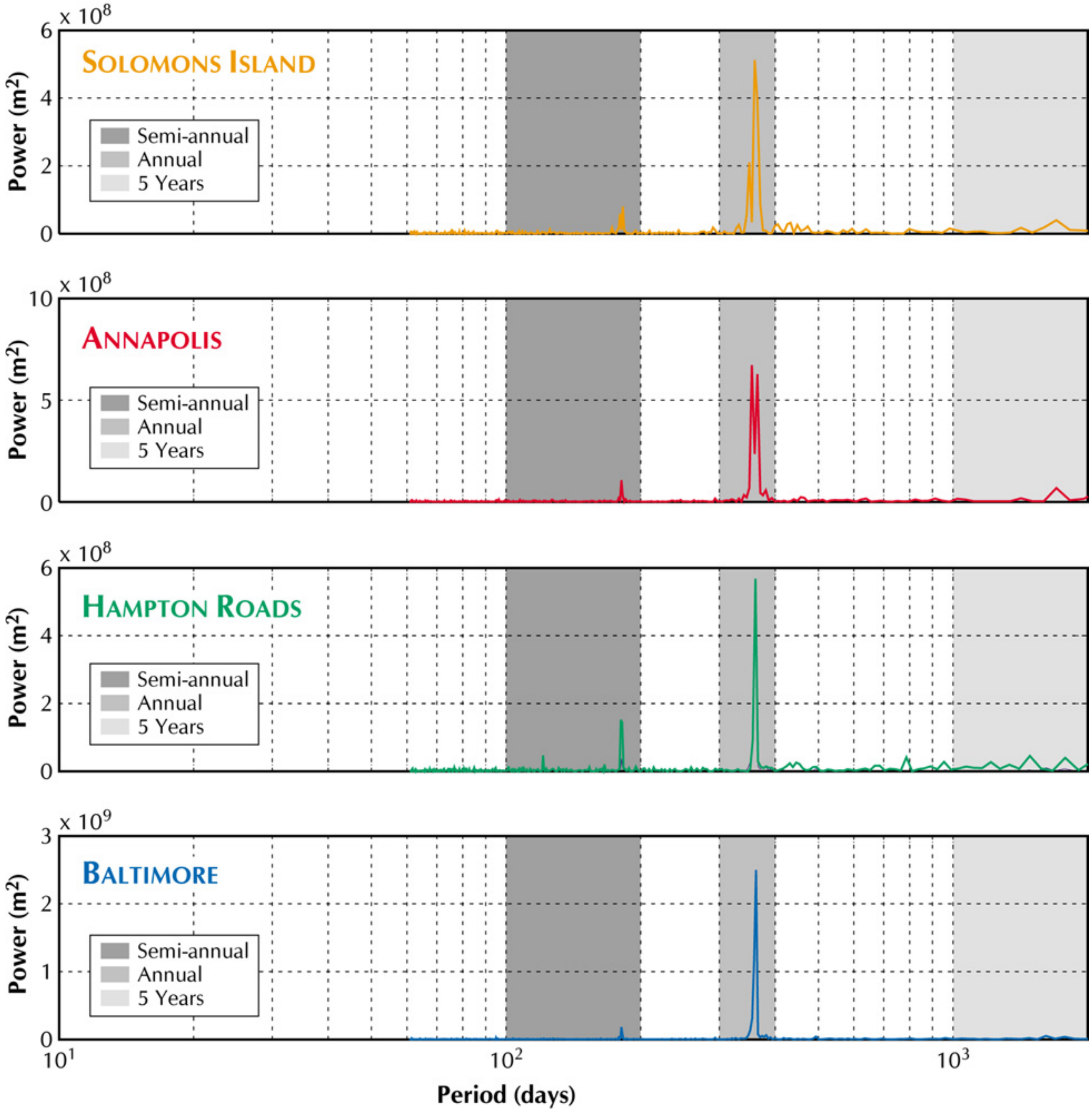


Figure 8. Major periodicities associated with sea level changes in Chesapeake Bay.

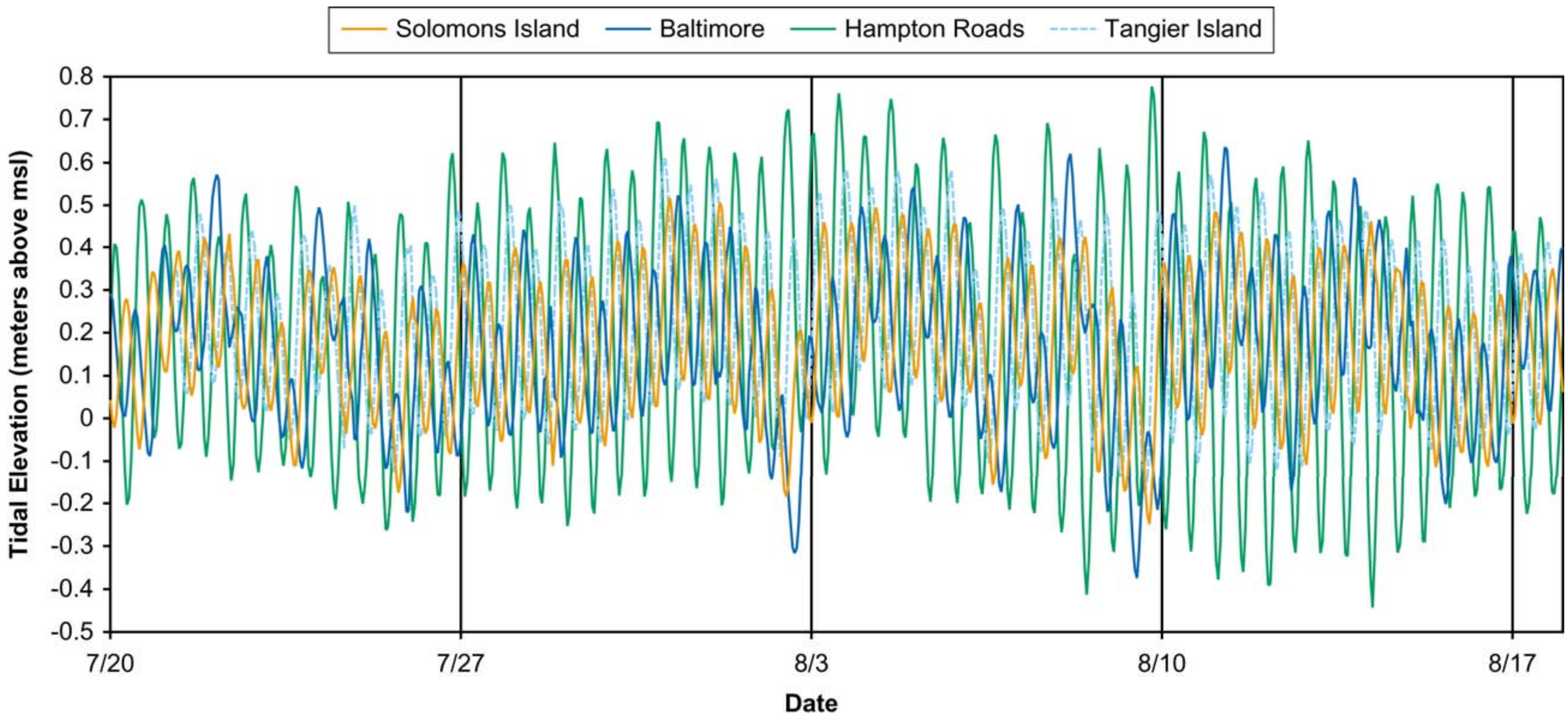


Figure 9. Tidal elevations in the Chesapeake Bay during July - August 1999.

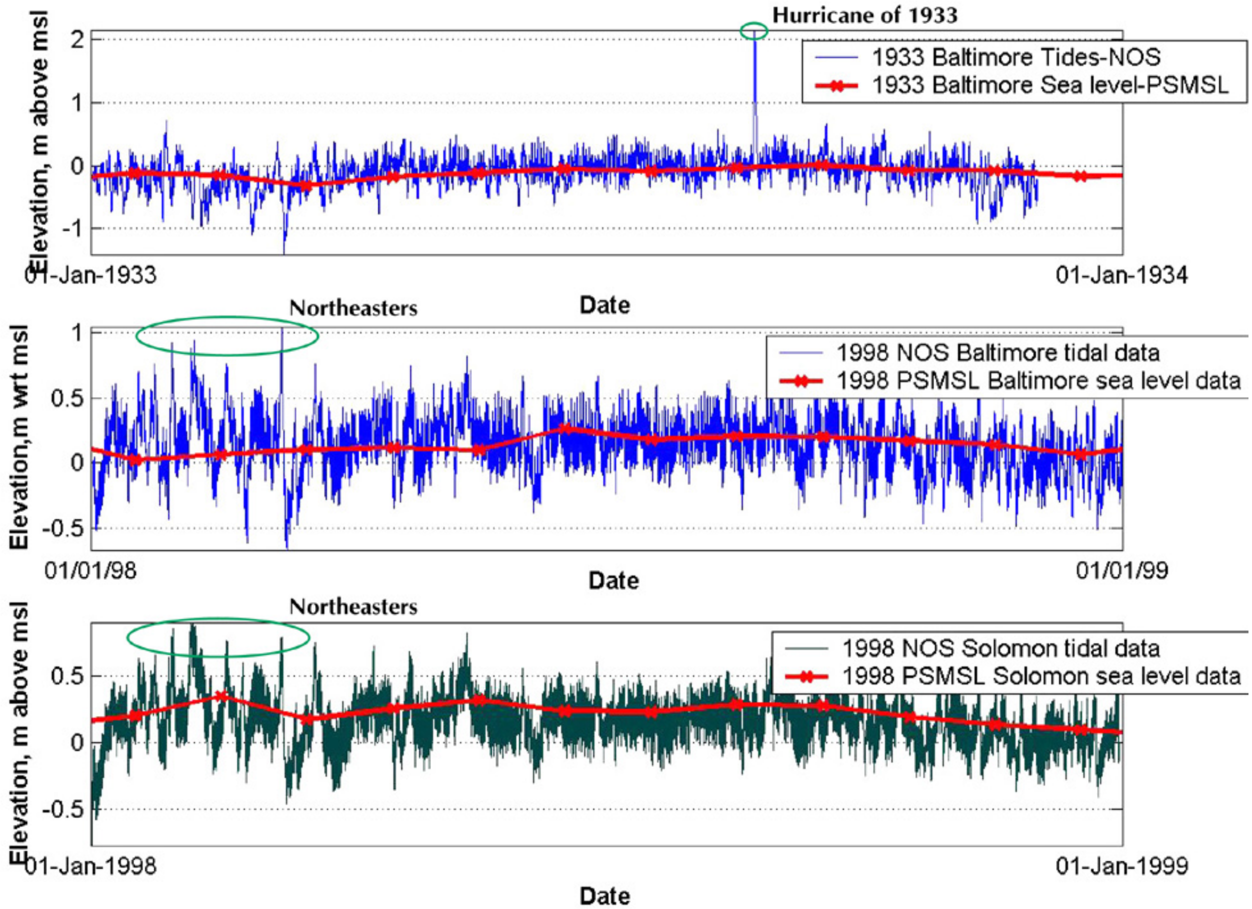


Figure 10. Sea level and tidal time series at locations in Chesapeake Bay.

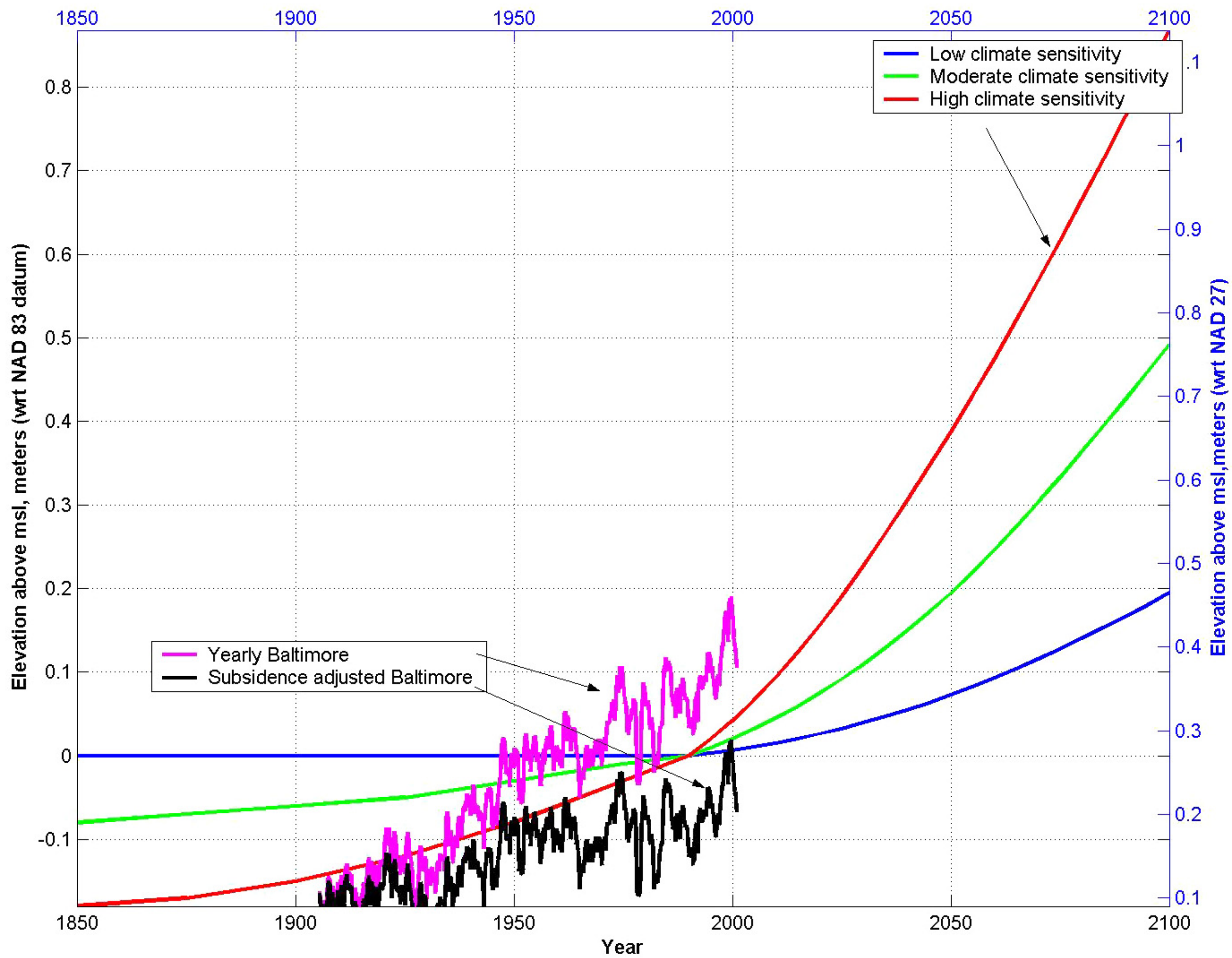


Figure 11. Range of estimated sea level changes over the 21st century and observed values over the 20th century.

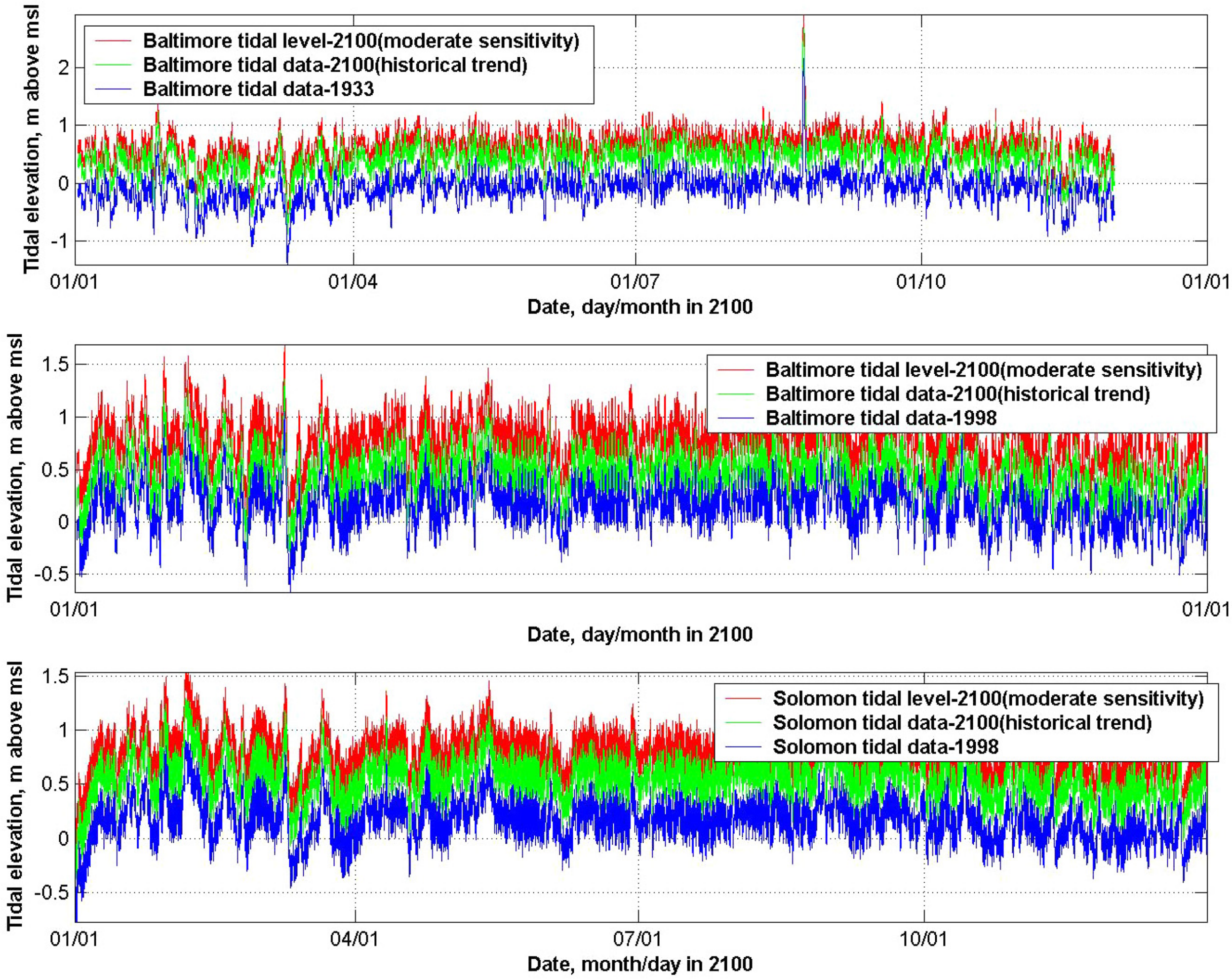
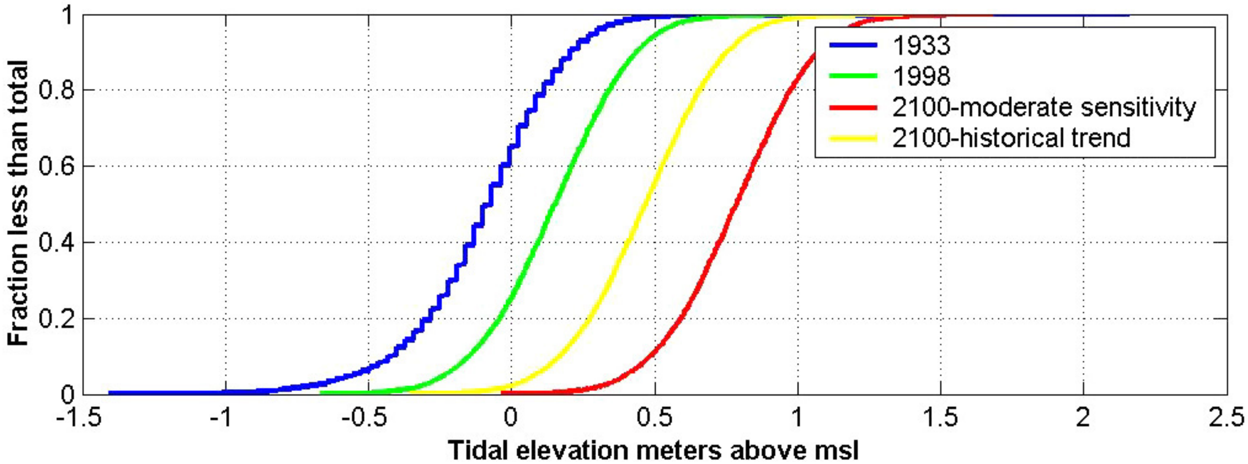


Figure 12. Projected tides in the year 2100 from historical tides in 1933 and 1998.

a) Baltimore



b) Solomons Island

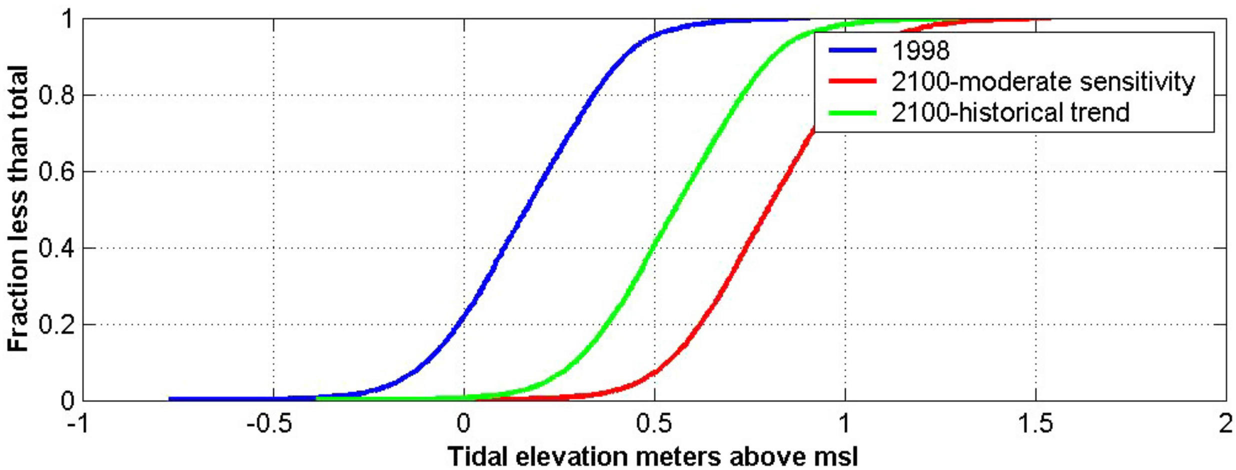
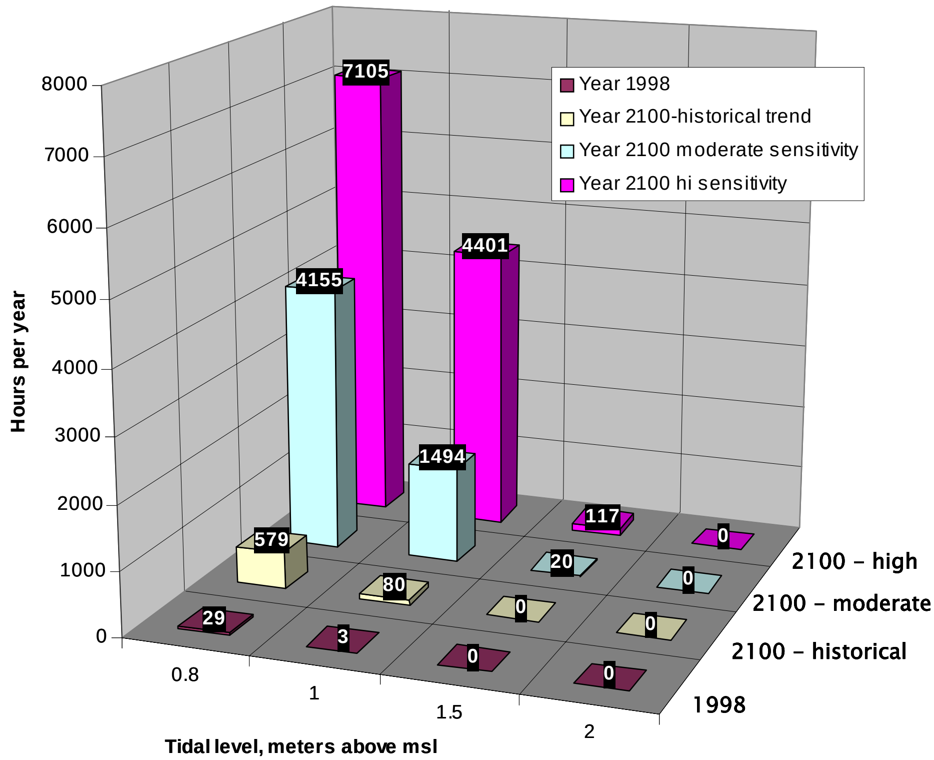
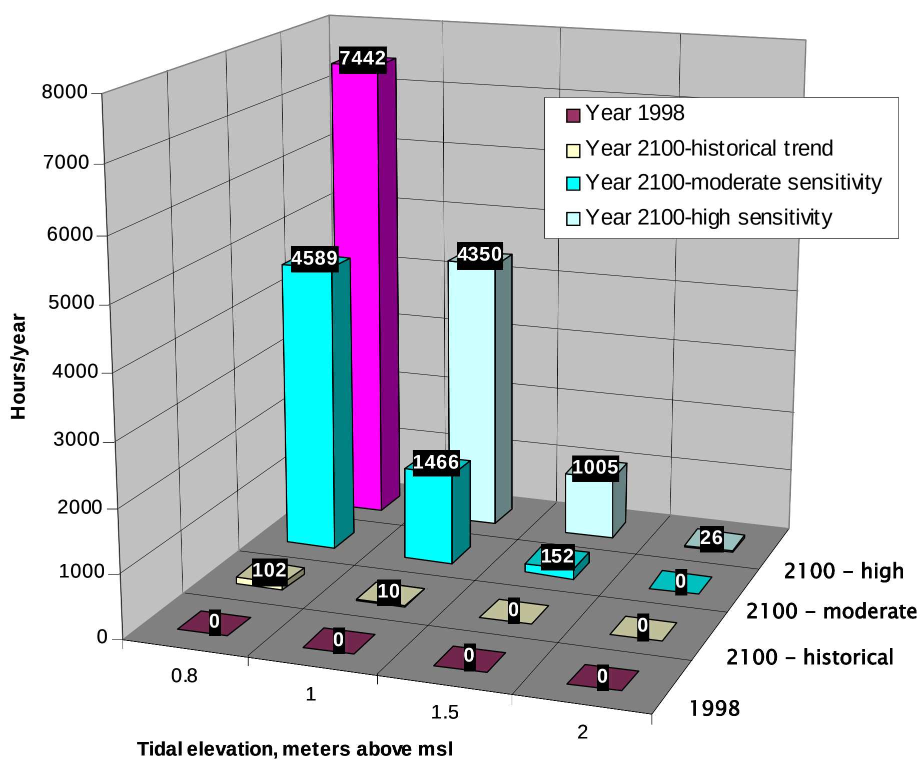


Figure 13. Cumulative distribution of tides: 1933-2100.

a) Based on Baltimore Data for 1998



b) Based on Solomons Island Data for 1998



c) Based on Baltimore Data for 1933

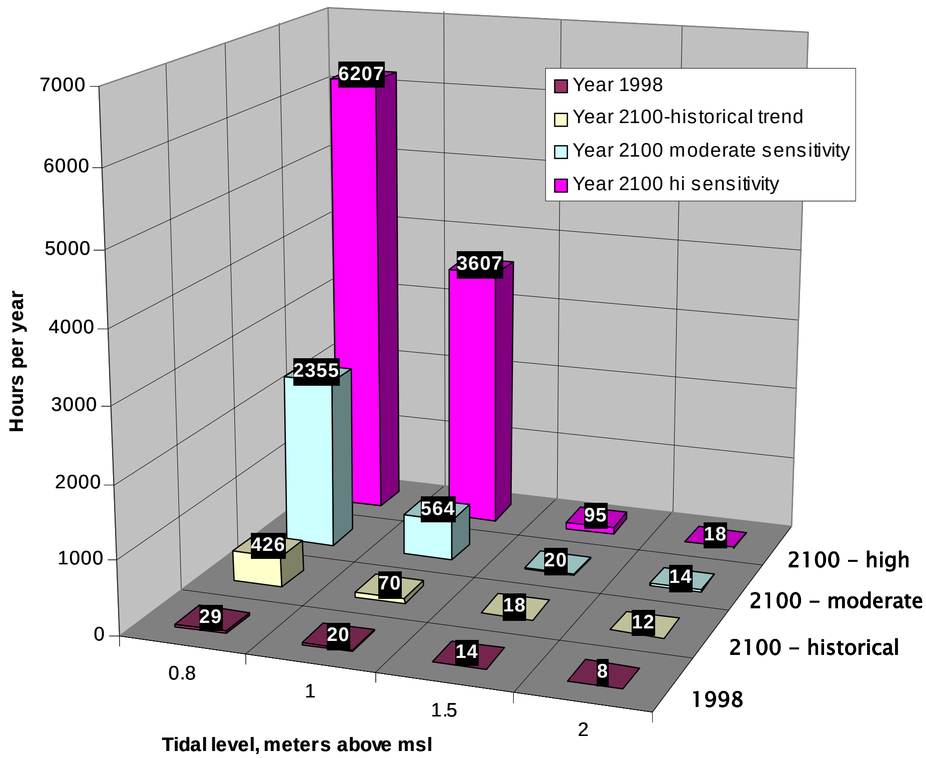
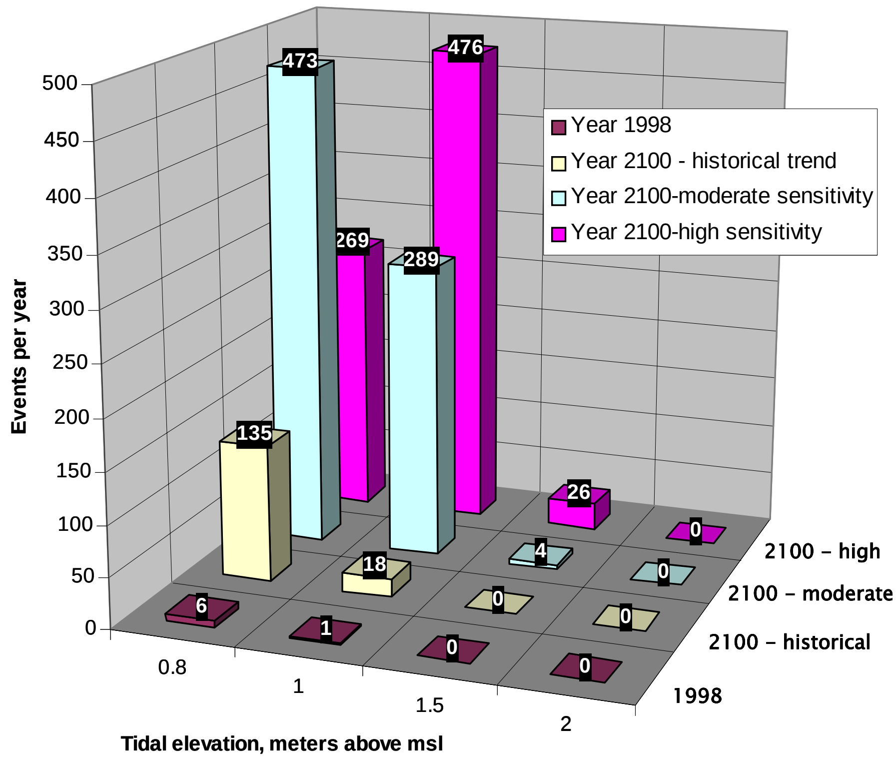
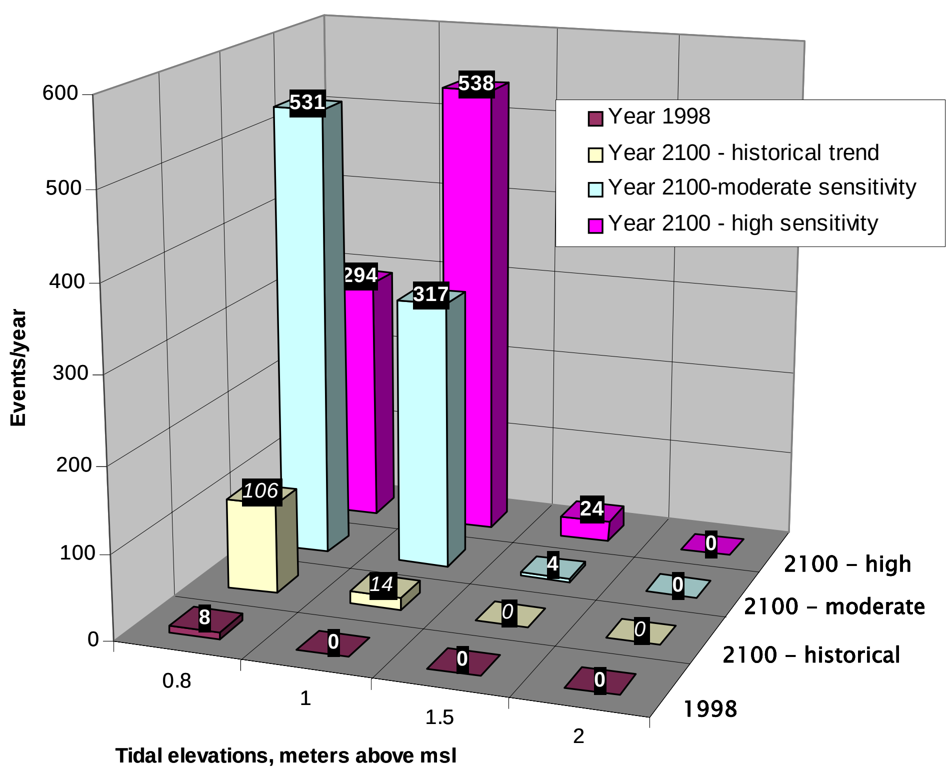


Figure 14. The number of hours per year when tidal elevations exceed specified levels.

a) Based on Extrapolation from Baltimore Data for 1998



b) Based on Extrapolation from Solomons Island Data for 1998



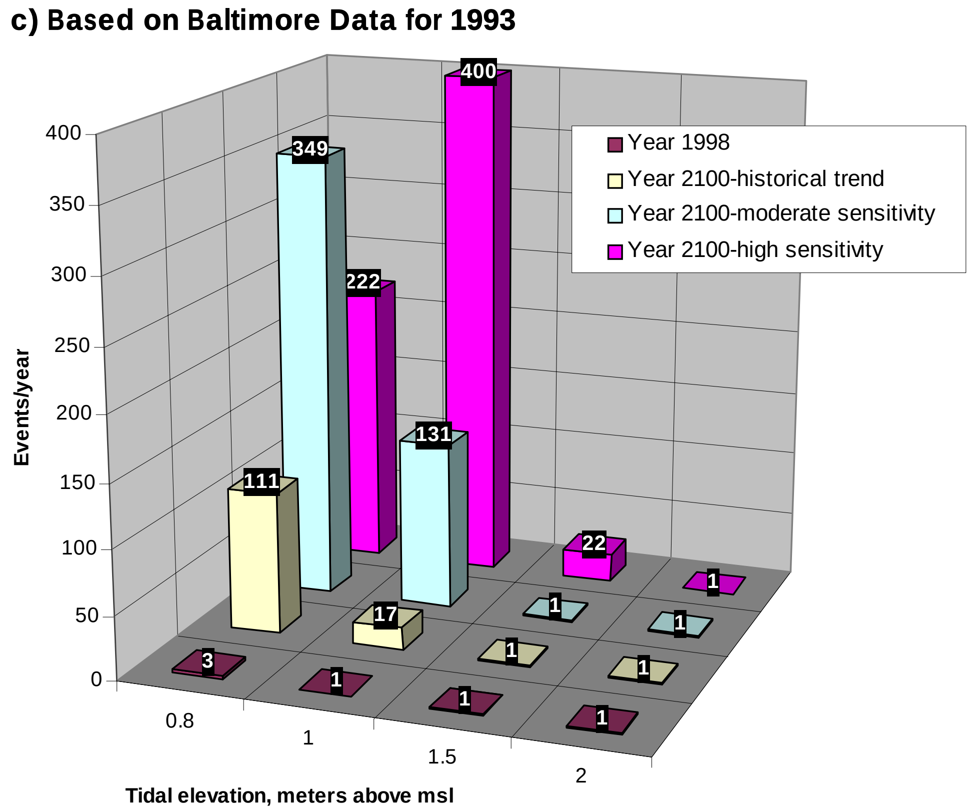


Figure 15. Events per year at Tangier Island when tidal elevations exceed the levels shown.

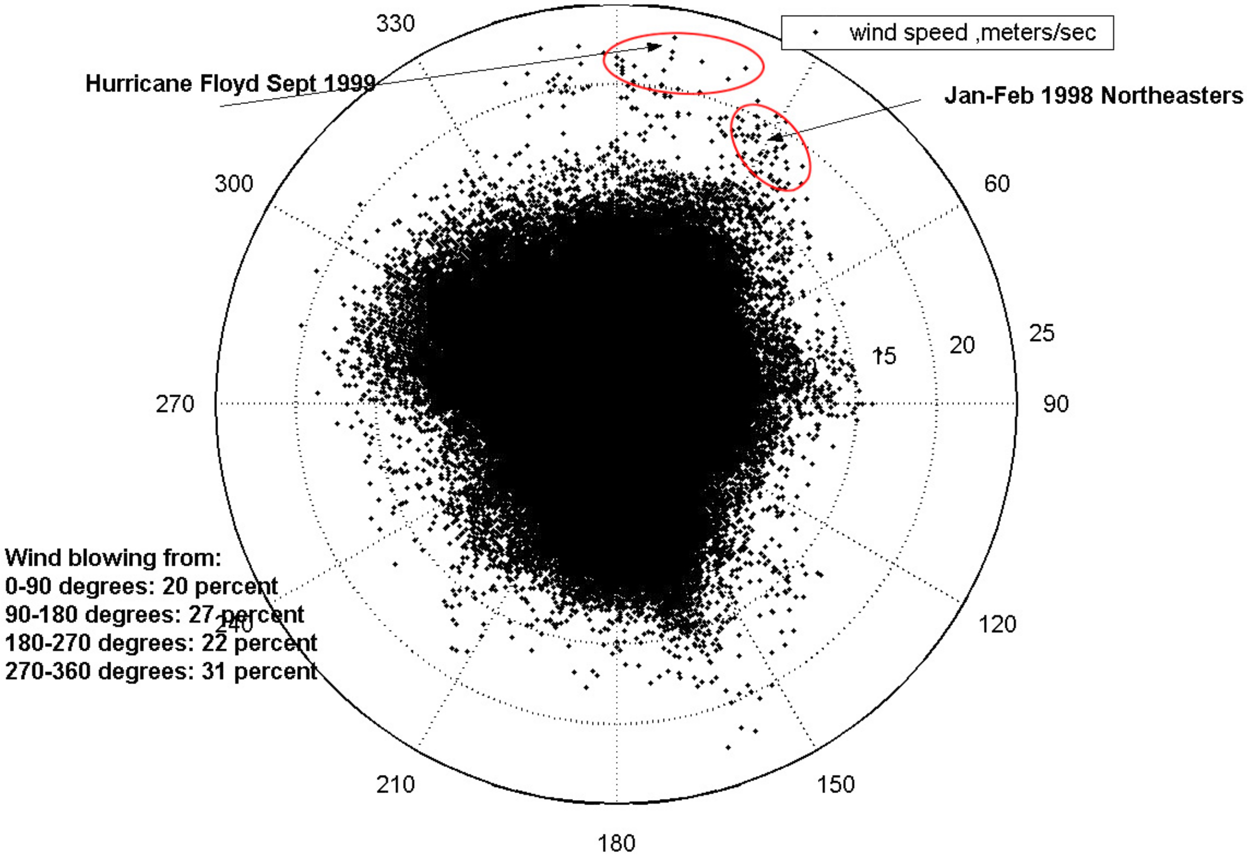


Figure 16. Wind speed and direction (degrees from) for 1997-2001 data at TPLM2, 60 km north of Tangier Island.

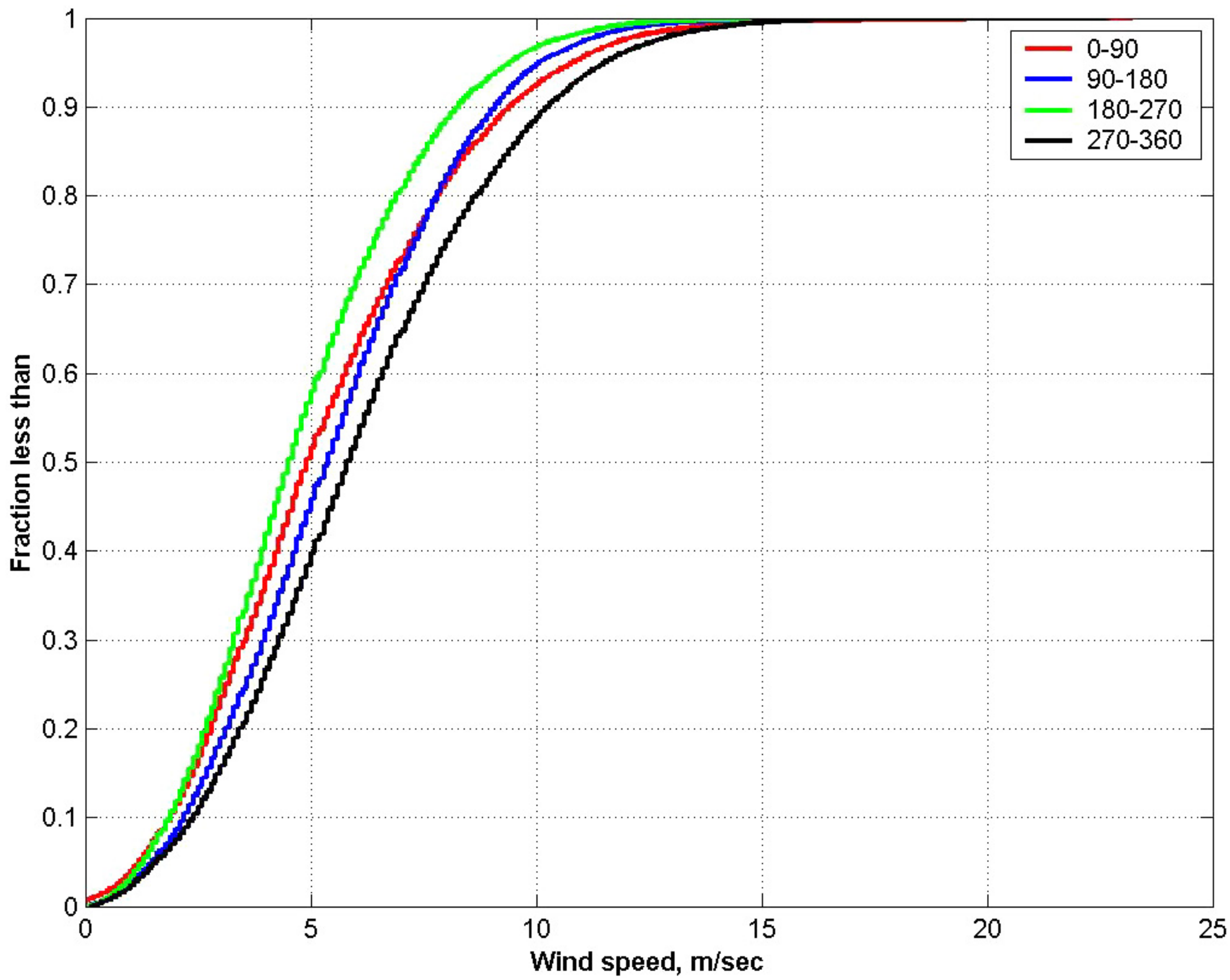


Figure 17. Wind speeds by quadrant for 1997-2001.

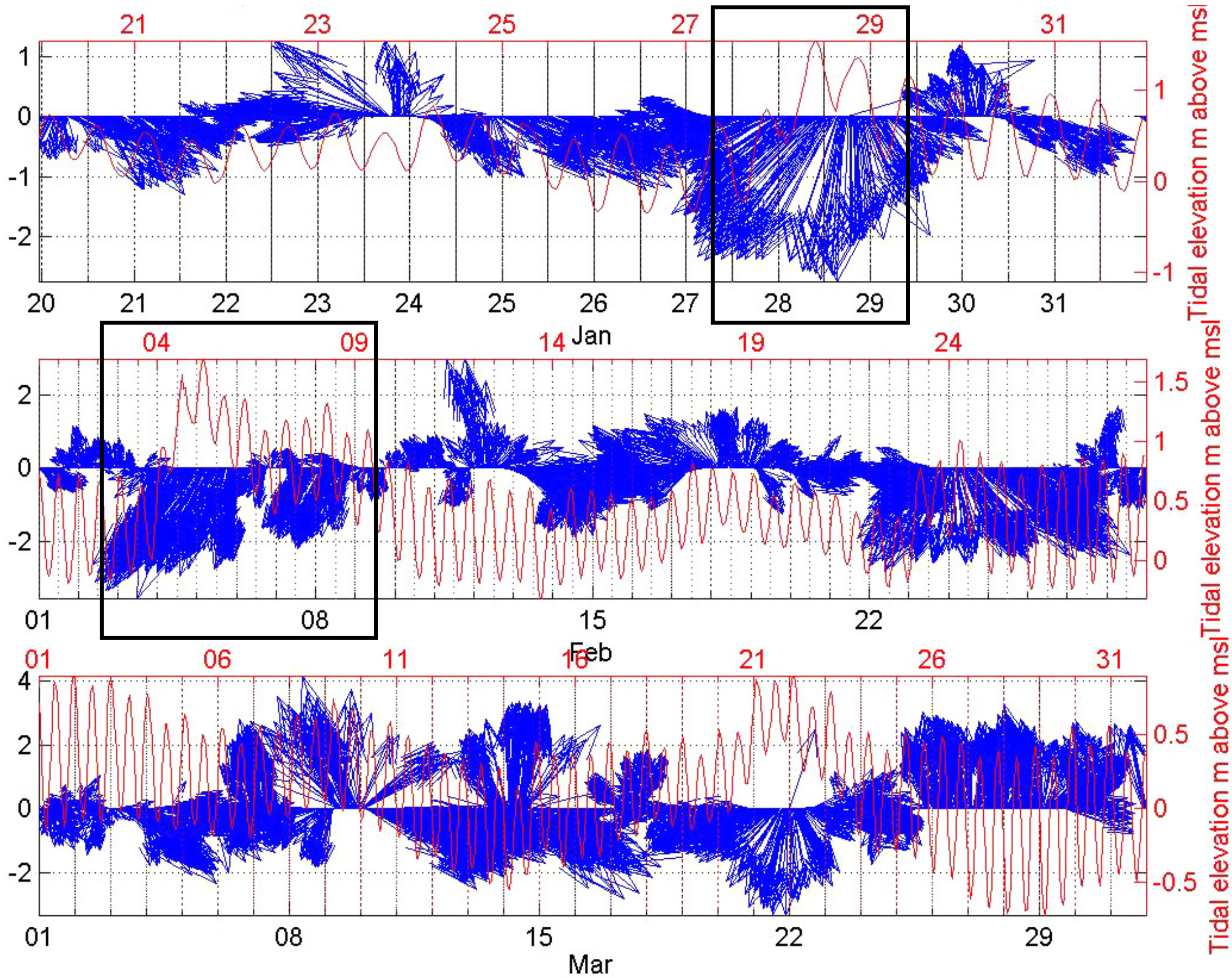


Figure 18. Response of tidal elevations in Chesapeake Bay to wind speed and direction, January - March 1998.

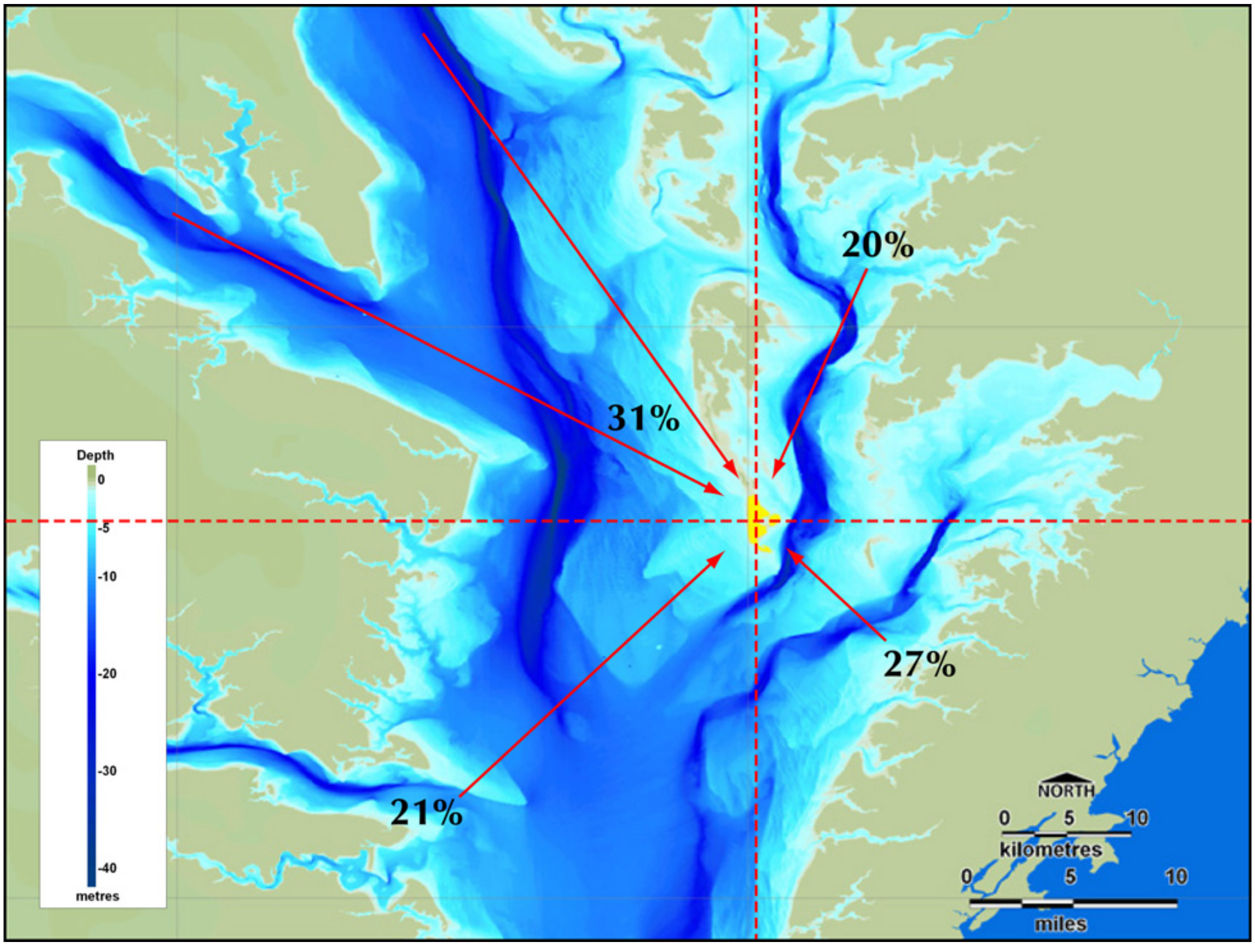


Figure 19. Illustration of percent of time winds blow from each quadrant and approximate fetch denoted by lengths of arrows with respect to Tangier Island.

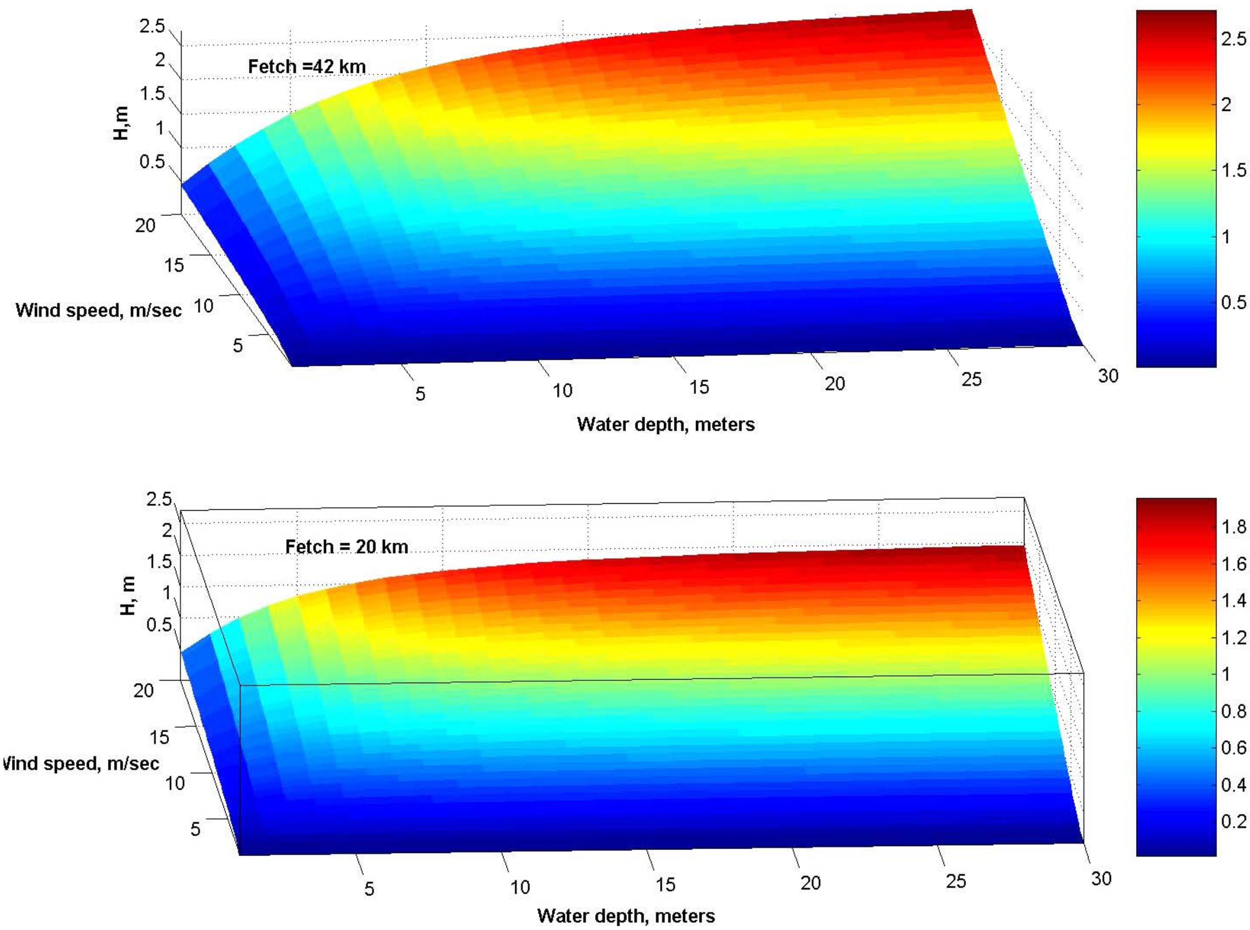


Figure 20. Wave height distributions for two different fetches.

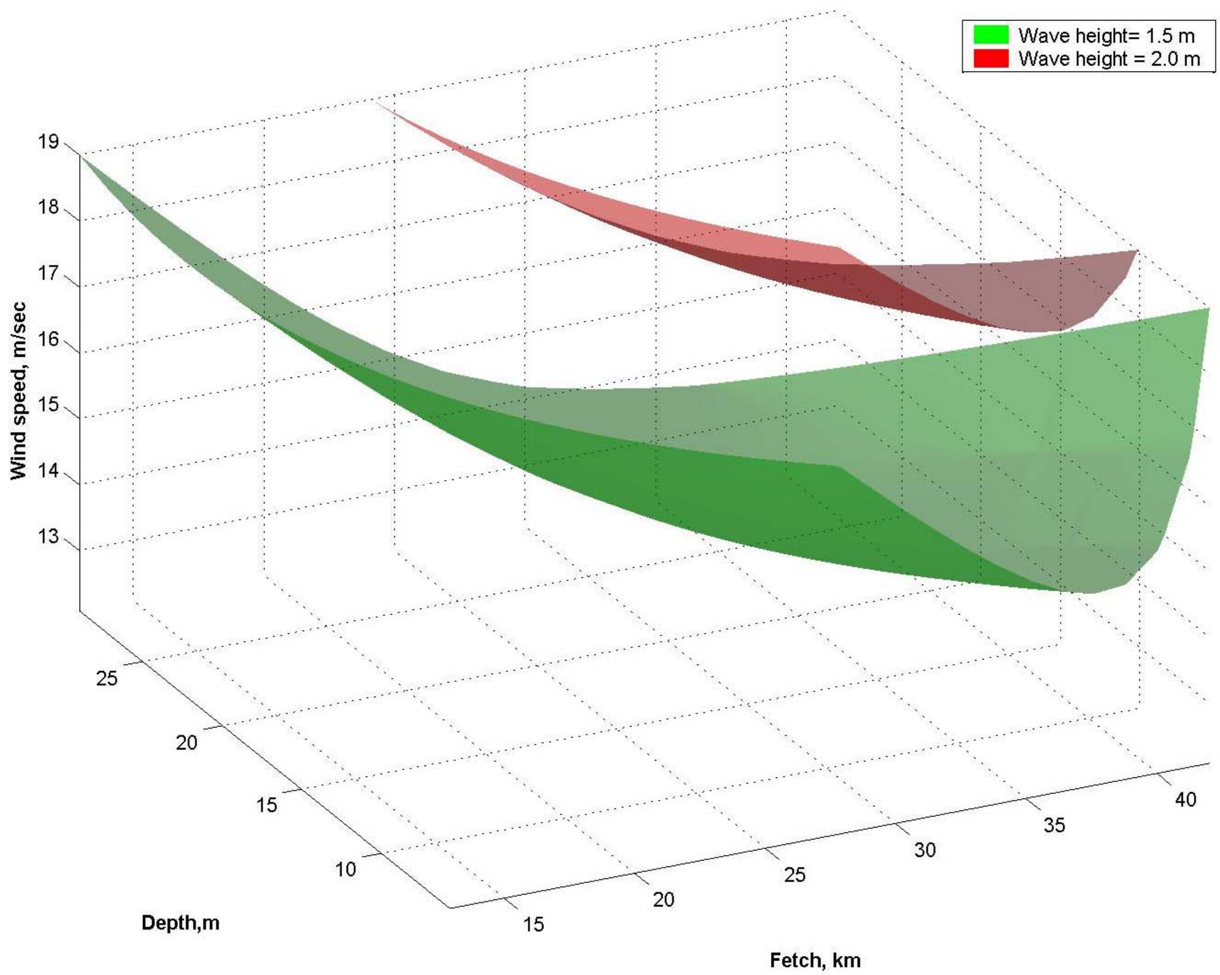


Figure 21. Isosurfaces of two wave heights generated in Chesapeake Bay.

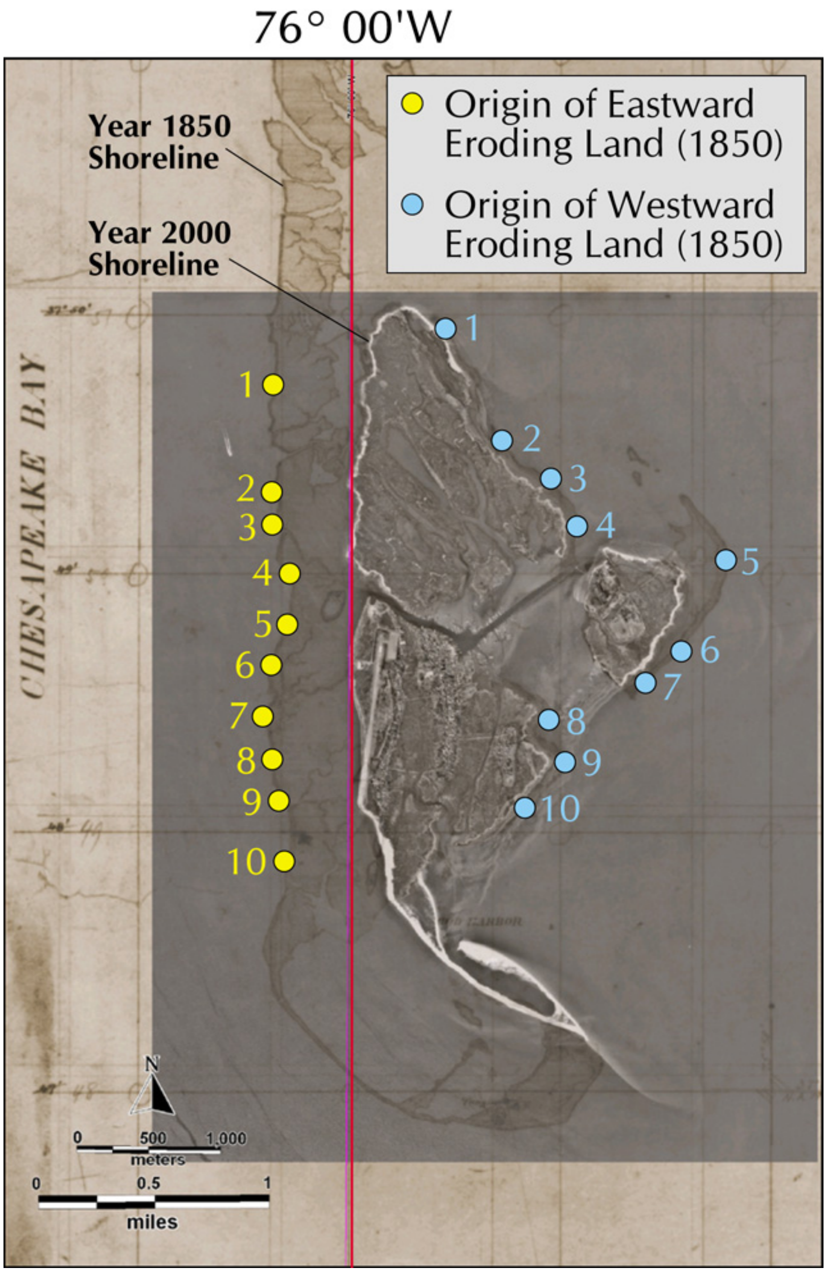
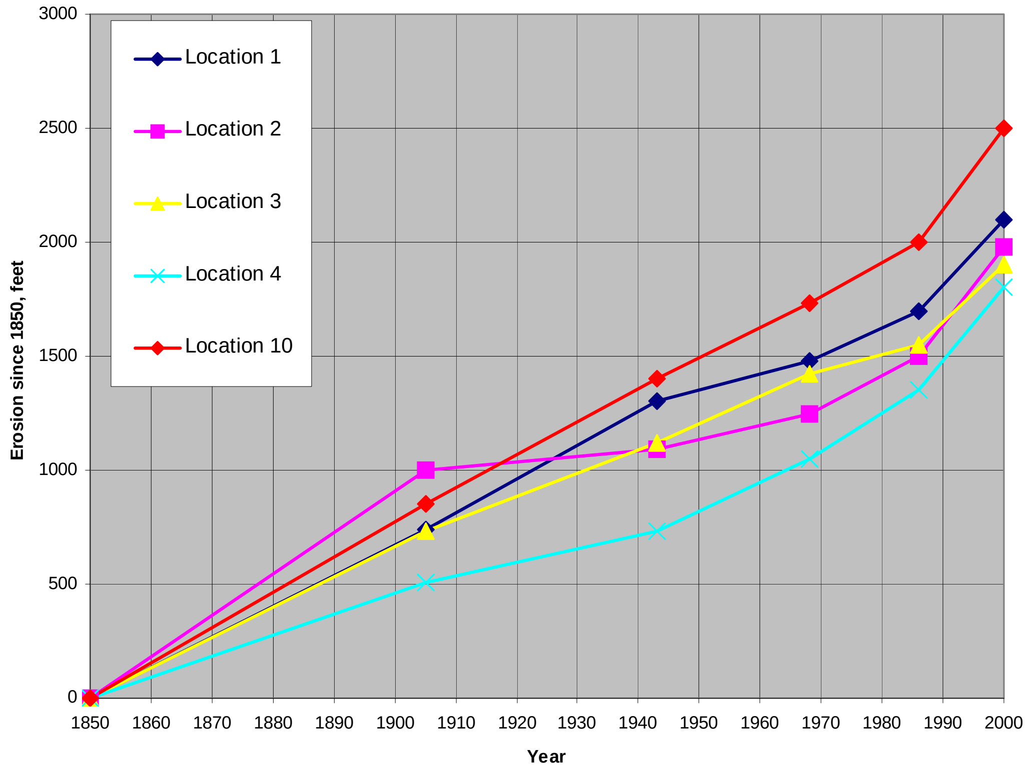
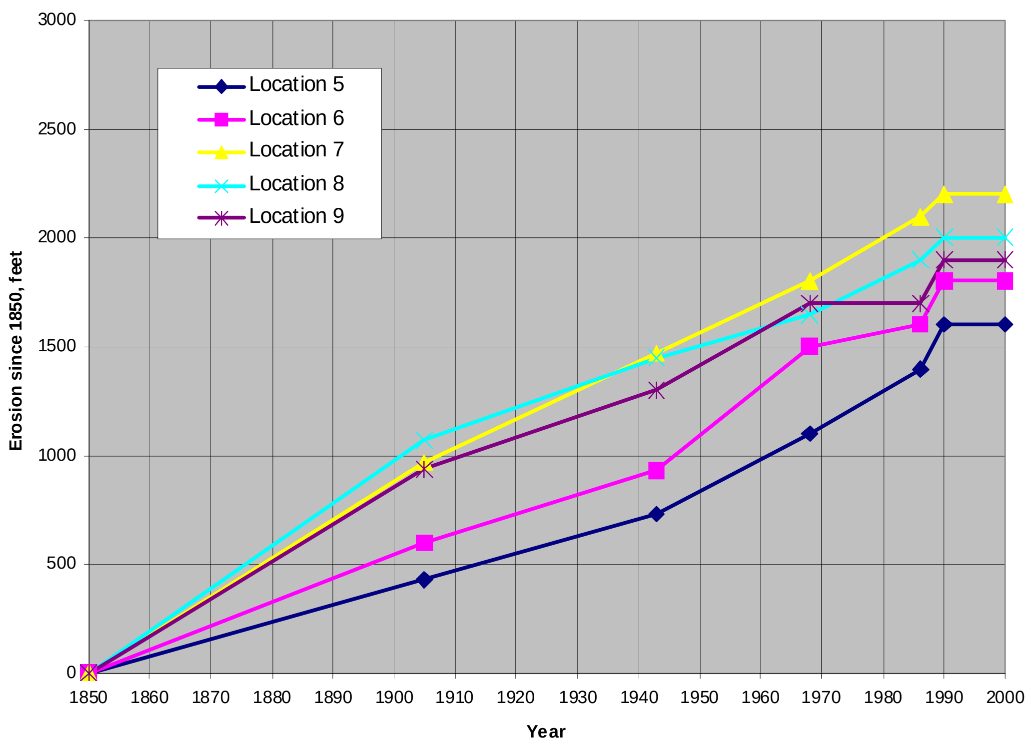


Figure 22. Tangier Island: 1850 vs. 2000.

a) On Western Shore at Locations Not Influenced by Seawall



b) On Western Shore at Locations Influenced by Seawall After 1990



c) On Eastern Side of Island

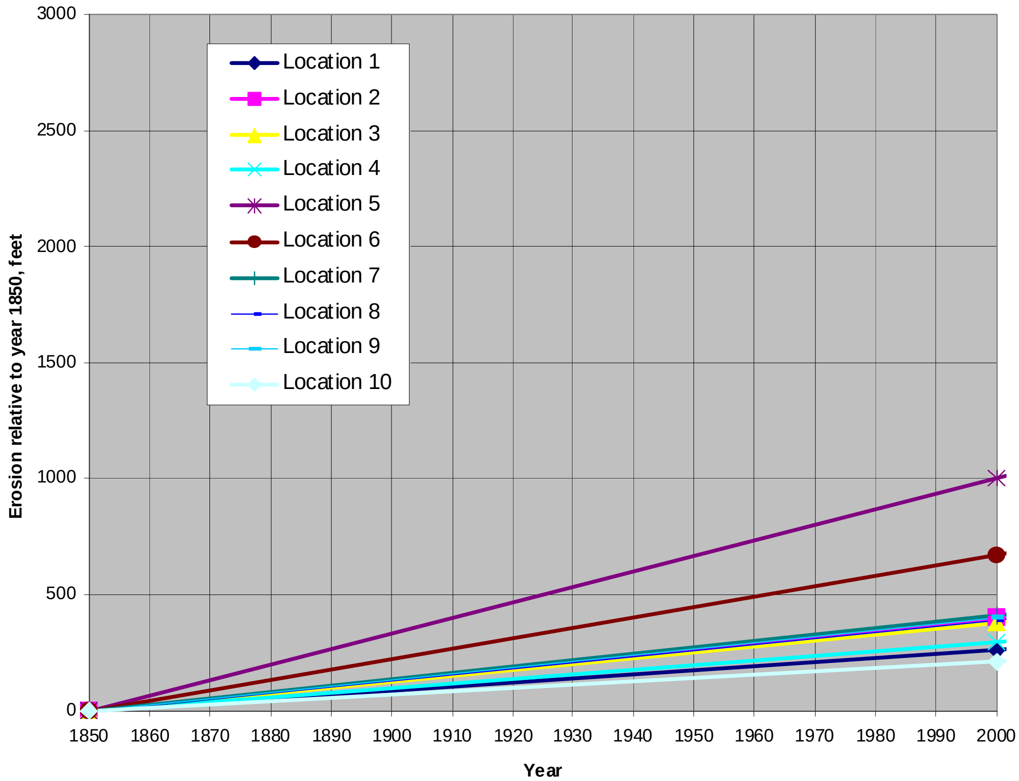


Figure 23. Erosion of shoreline of Tangier Island 1850-2000.

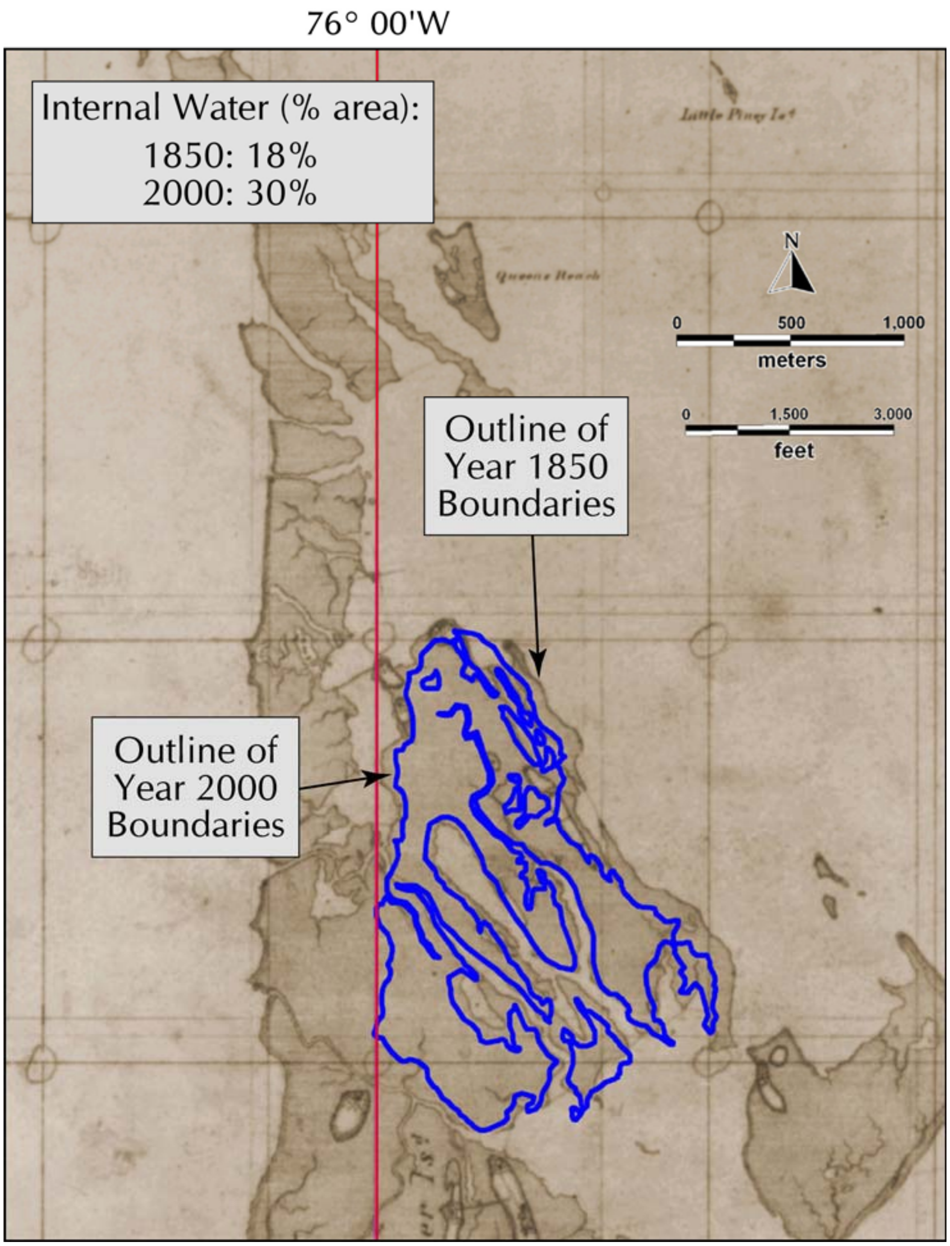


Figure 24. Comparison of internal water on part of Tangier Island: 1850 vs. 2000.

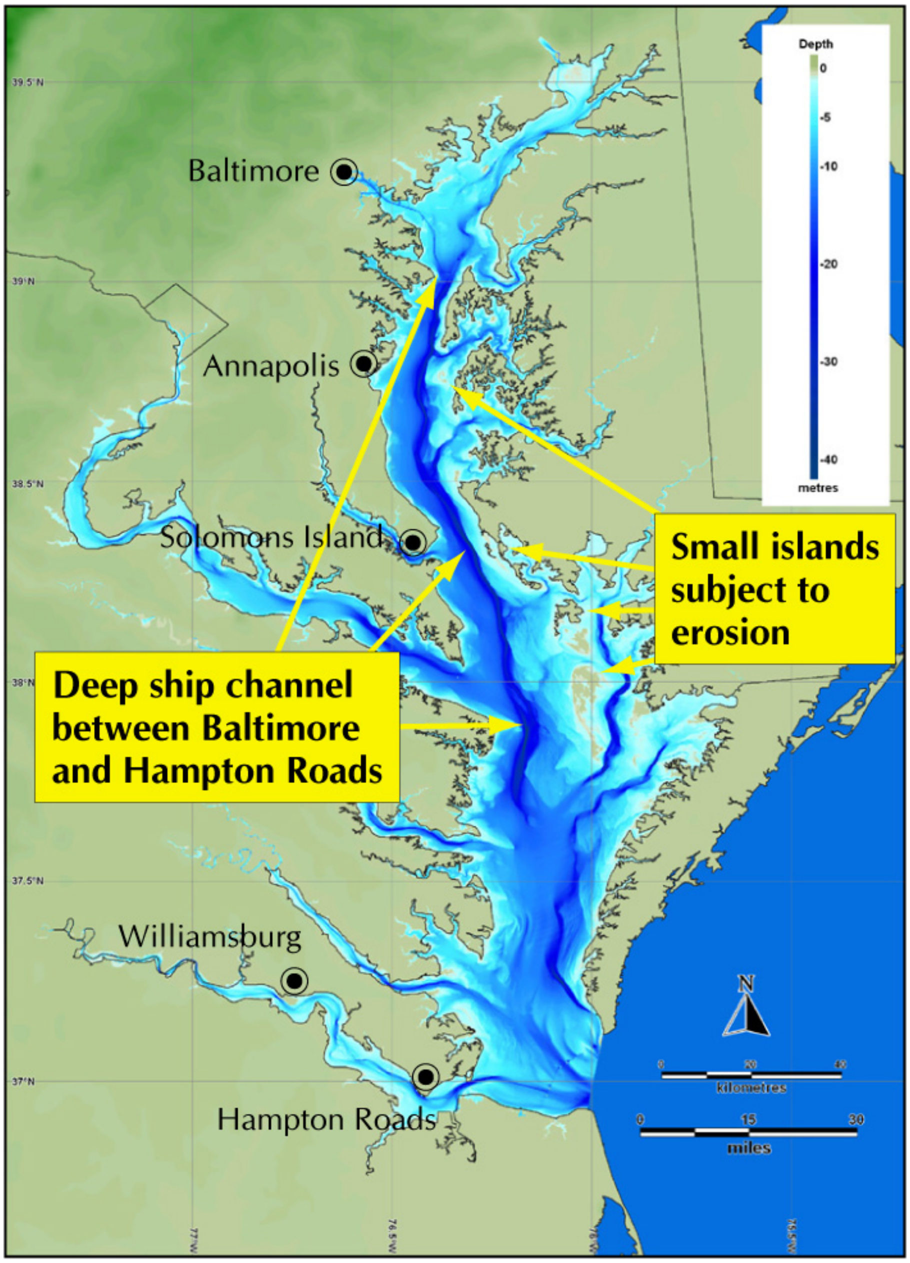


Figure 25. Chesapeake Bay ship channel in relation to small islands within the bay.

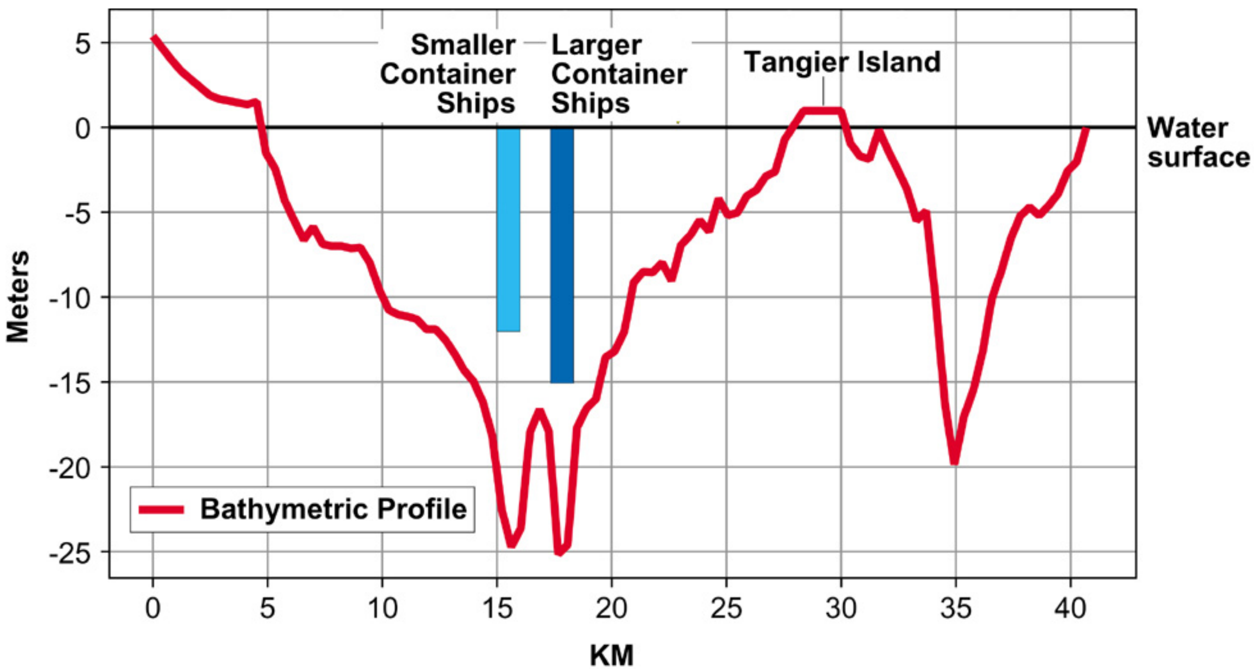


Figure 26. Cross-section of Chesapeake Bay through Tangier Island and depths of container ships.

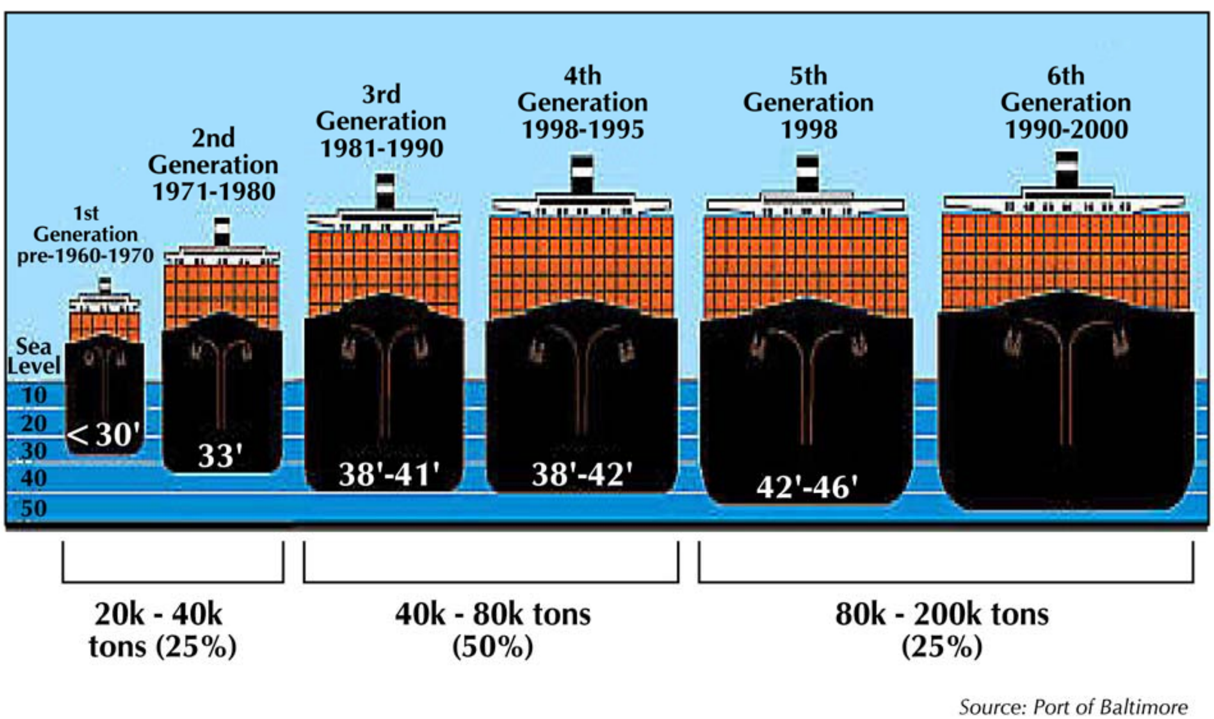


Figure 27. Evolution of container ships in Chesapeake Bay over past 50 years.

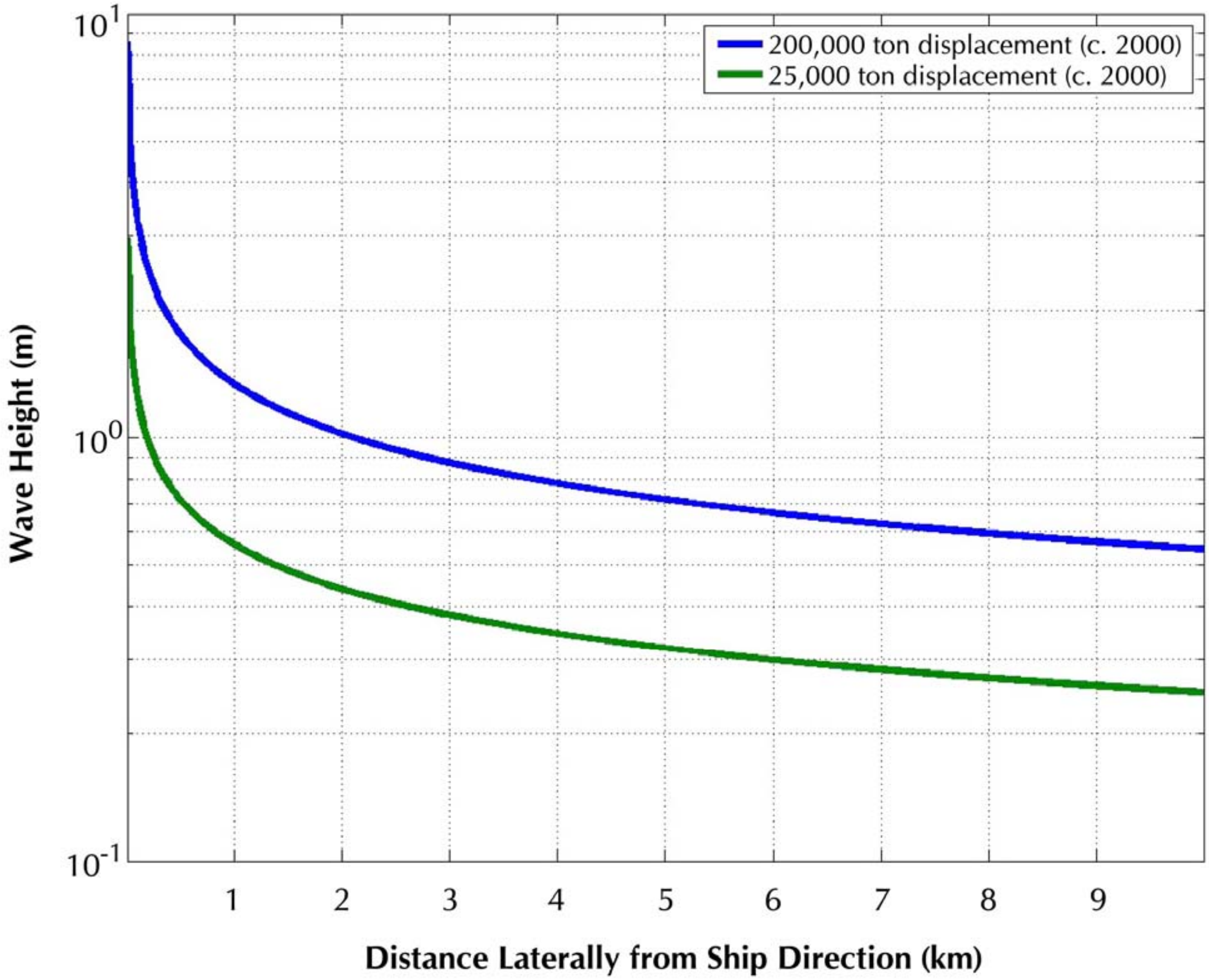


Figure 28. Predicted ship generated wave heights (depth Froude number = 0.8).

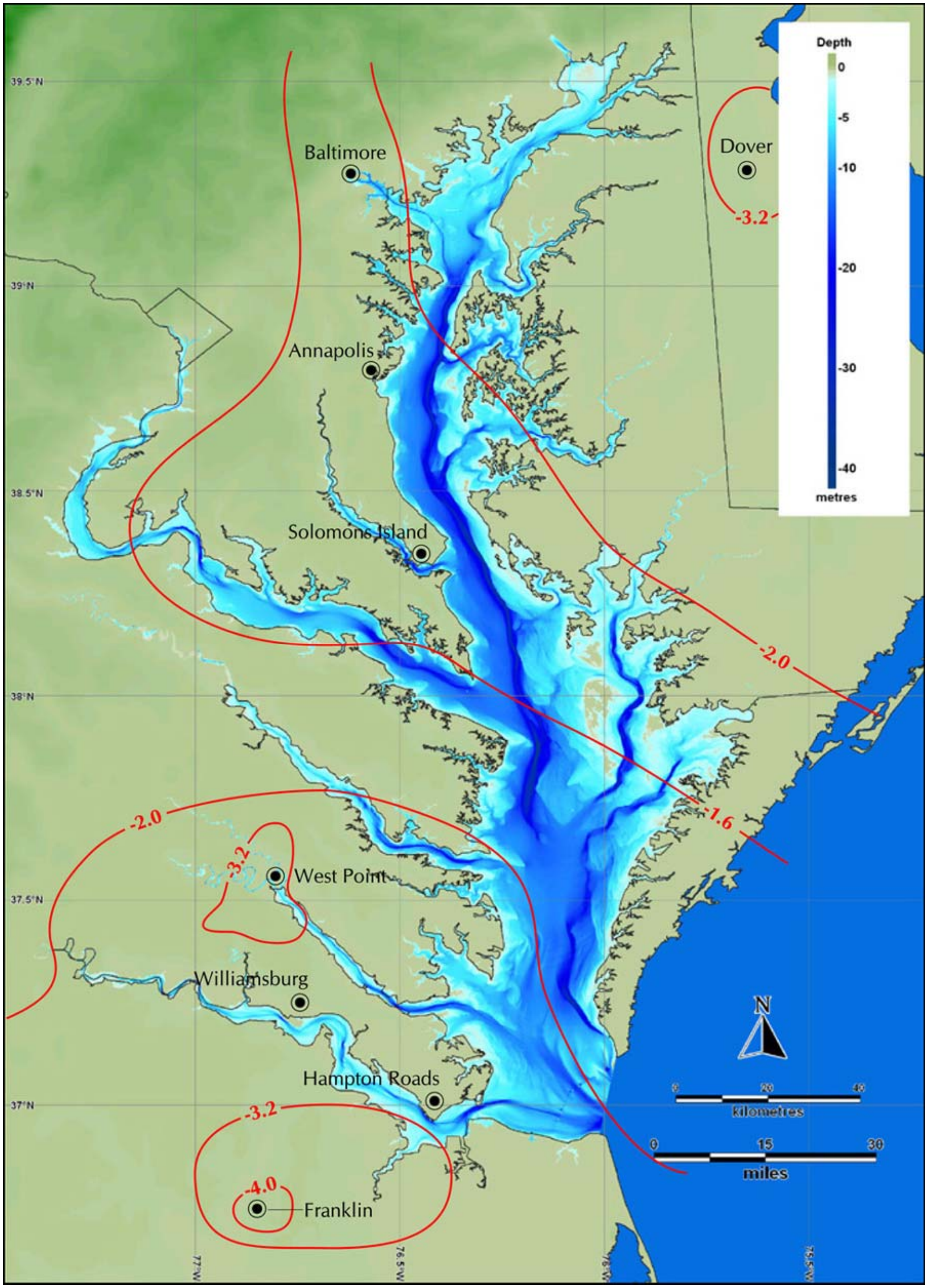


Figure 29. Estimated annual surface elevation changes (mm/yr) throughout Chesapeake Bay area (modified from Davis, 1987).

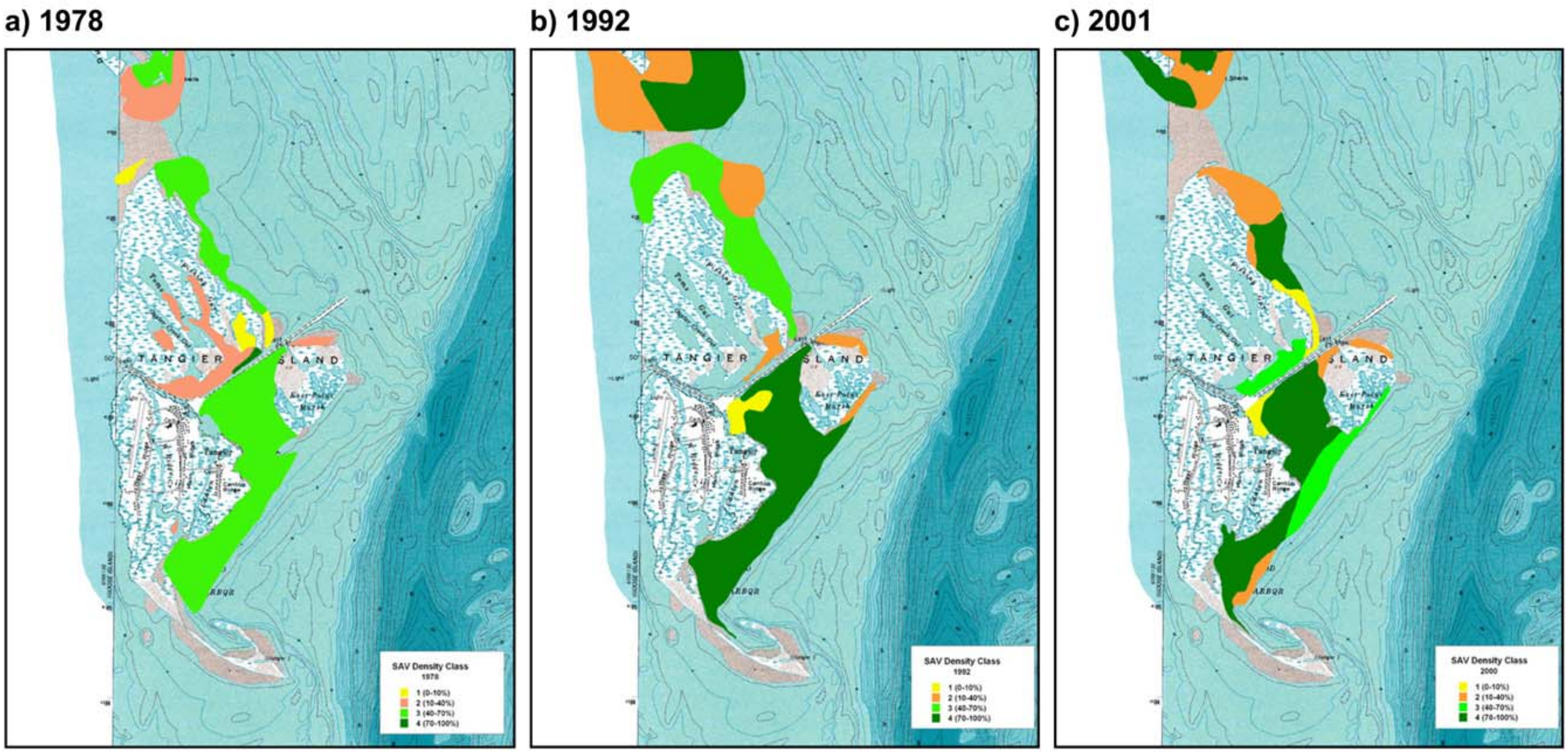


Figure 30. SAV densities around Tangier Island.

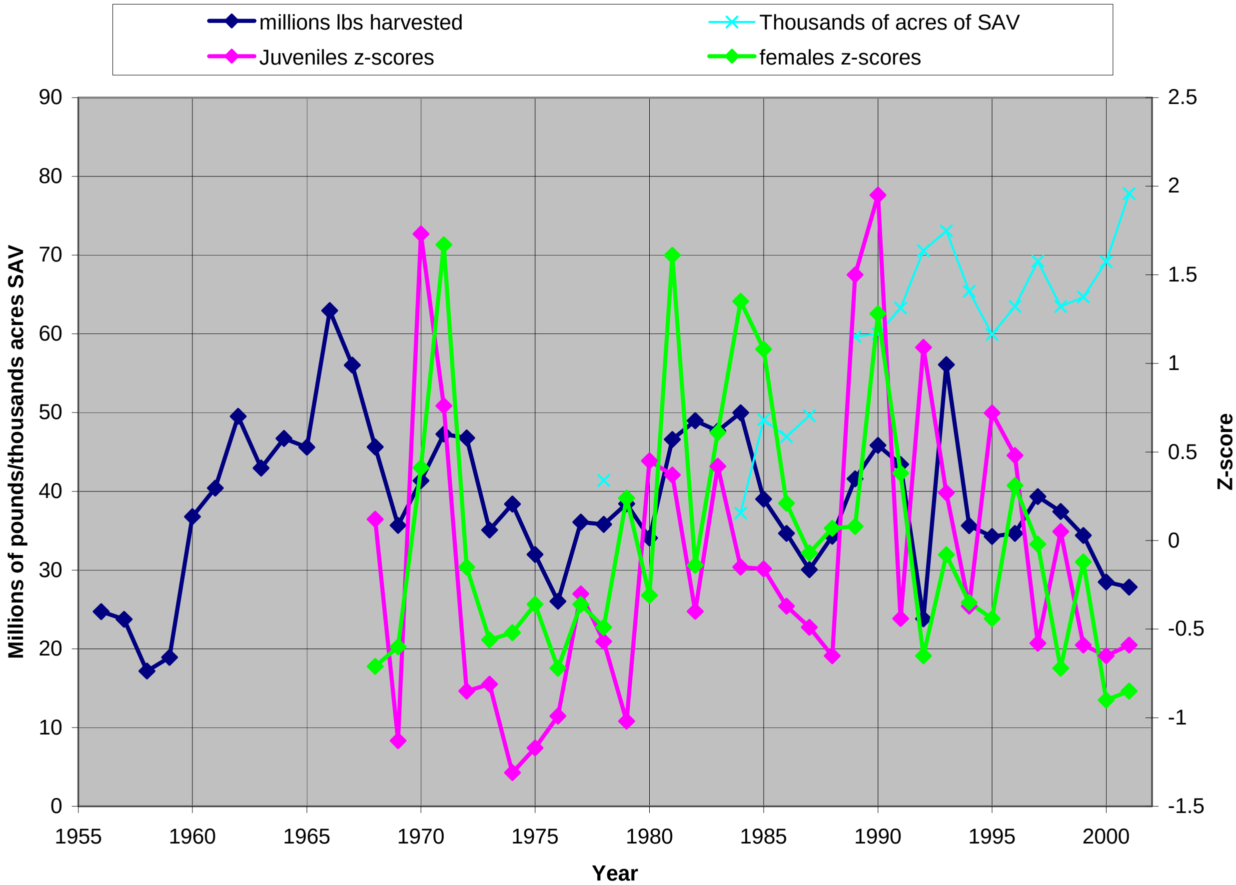


Figure 31. Indicators of Blue crab abundance in Chesapeake Bay and number of acres of bay covered with SAV.

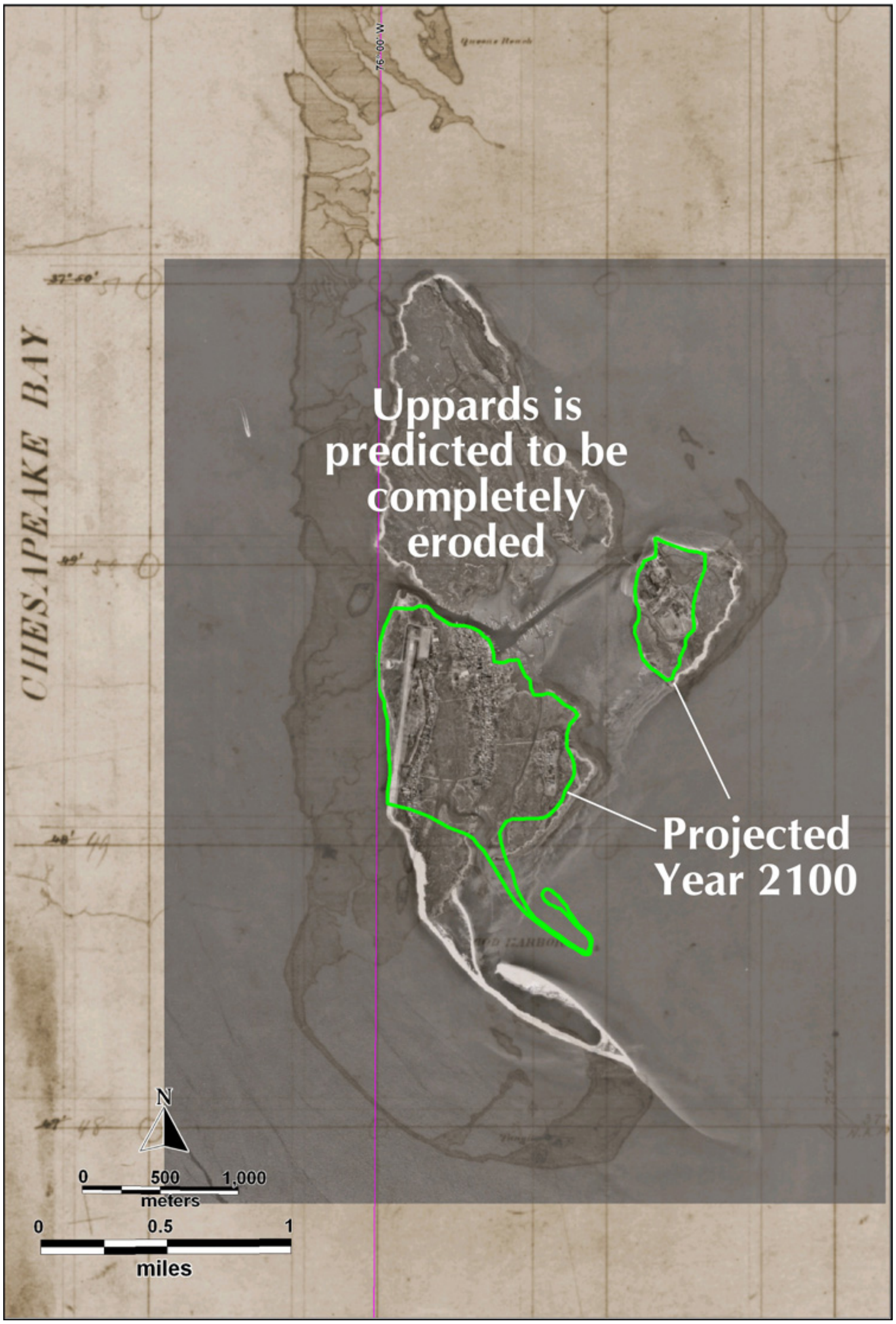


Figure 32. Comparison of Tangier Island: 1850, 2000, and projected to year 2100.

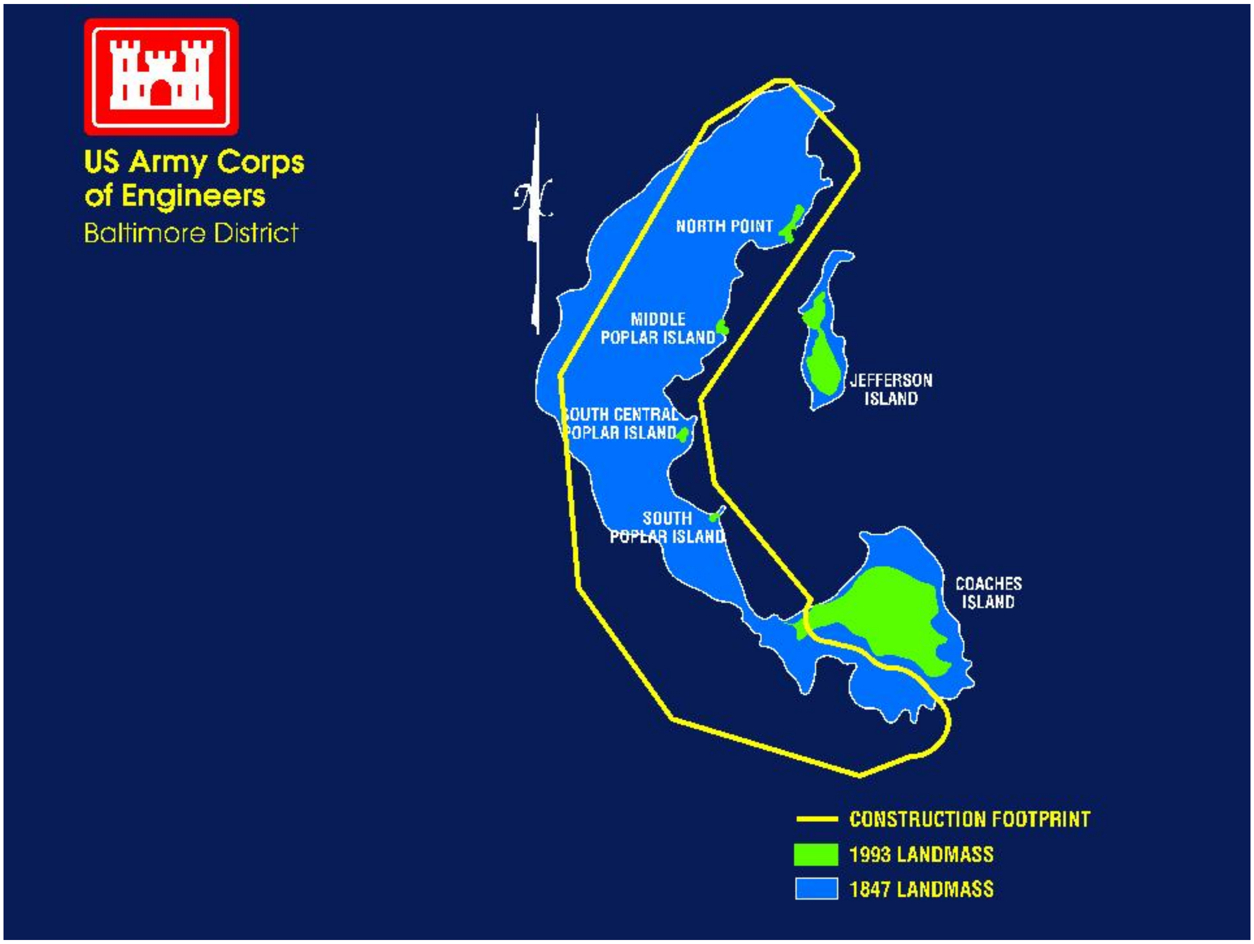


Figure 33. Outline of extent of proposed Poplar Island remediation
(url: http://www.nab.usace.army.mil/projects/Maryland/poplarisland.htm)

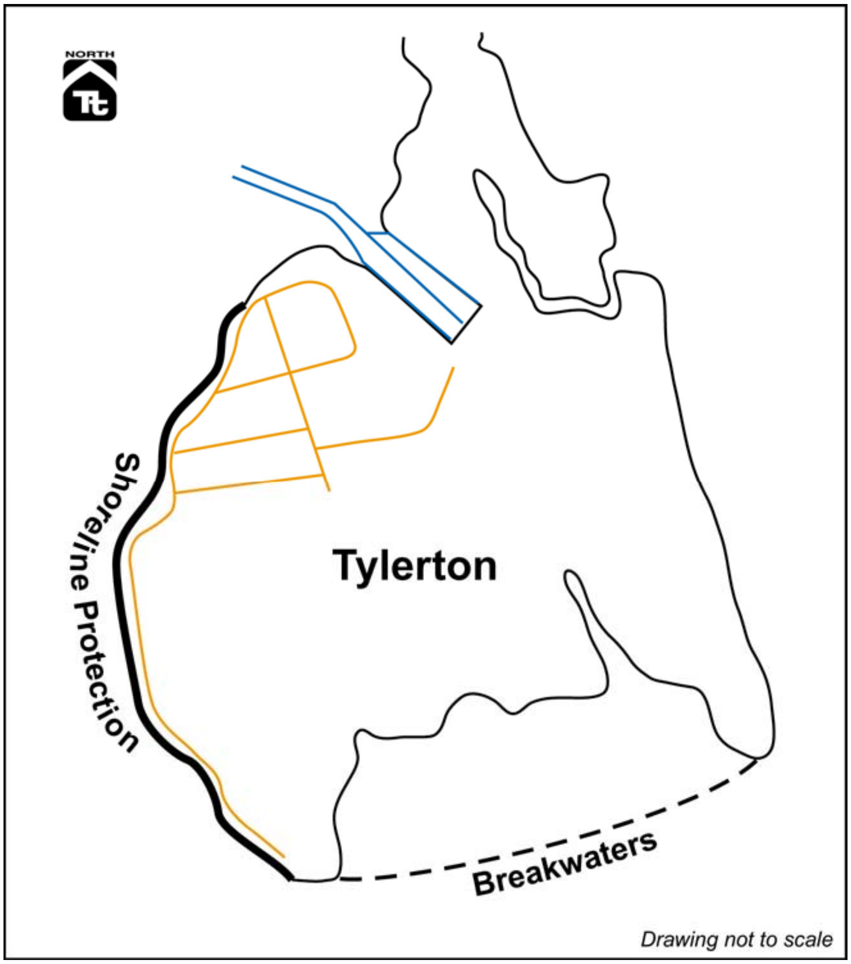


Figure 34. Shoreline erosion protection projects completed in Tylerton, Smith Island in 2001 (USACE, 2001).

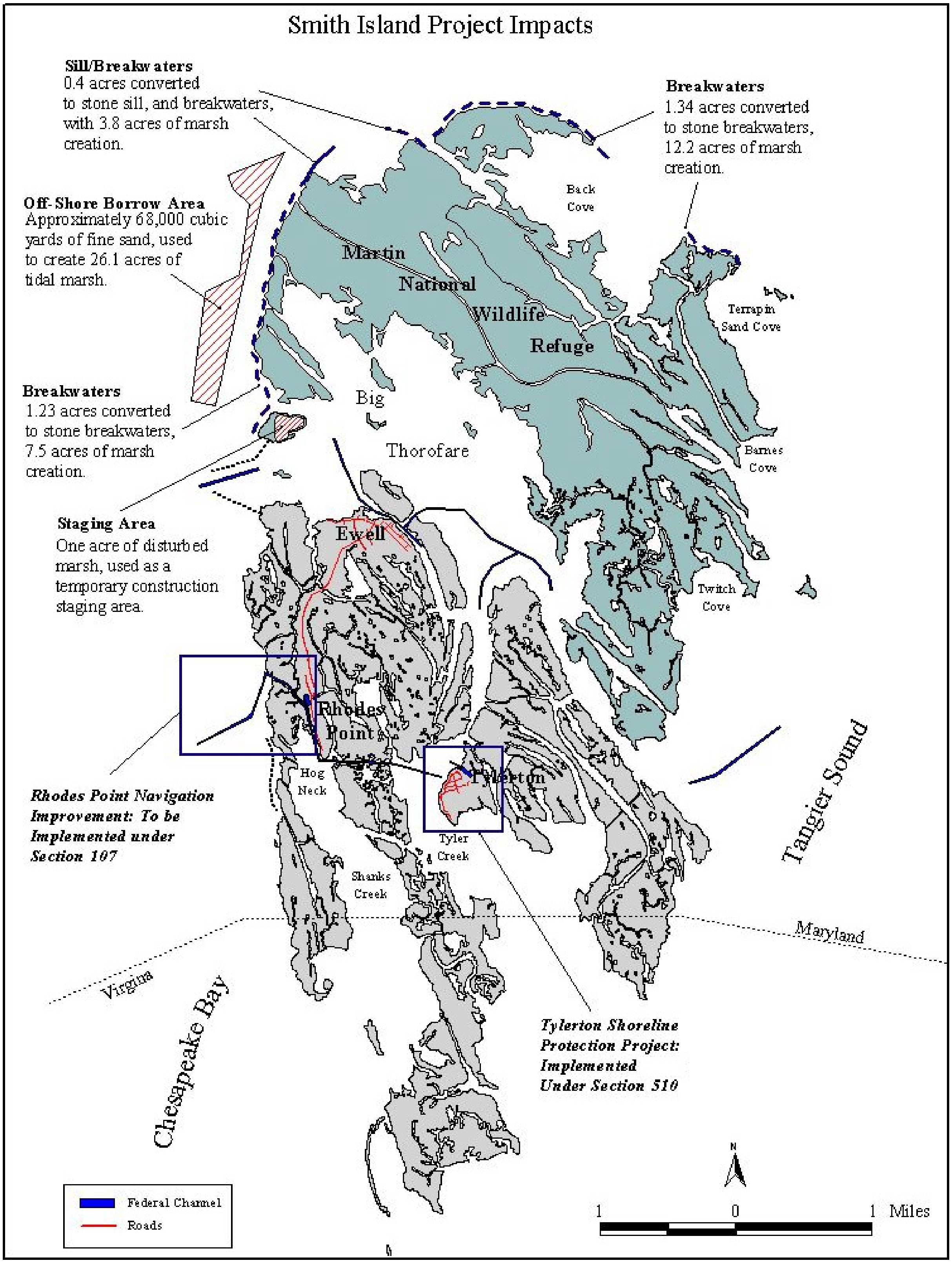


Figure 35. Proposed and recently completed remedial actions on Smith Island (USACE, 2001).

EXHIBIT:
PHOTOGRAPHS ON TANGIER ISLAND, VIRGINIA THAT RELATE TO ISLAND EROSION ISSUES

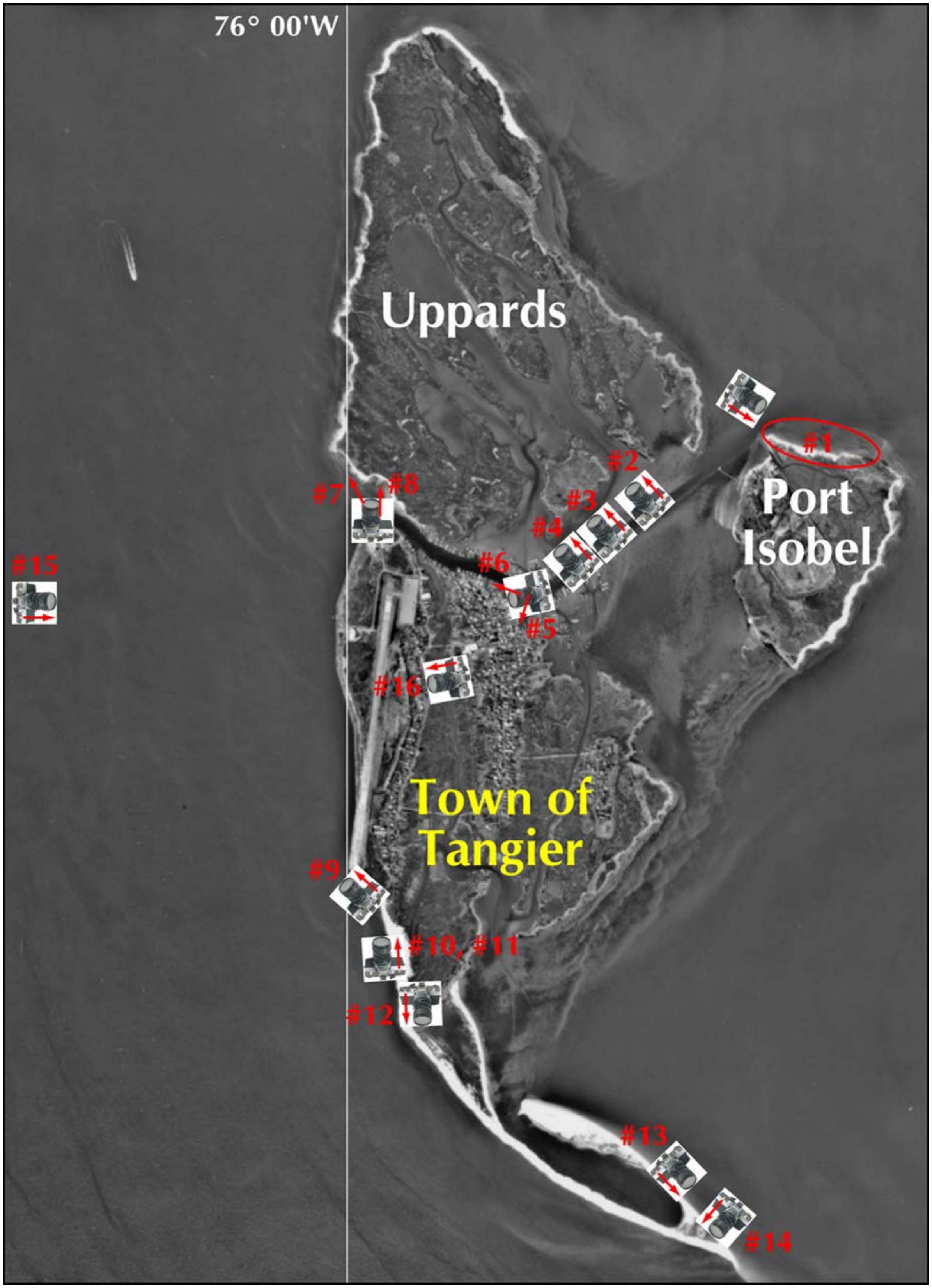
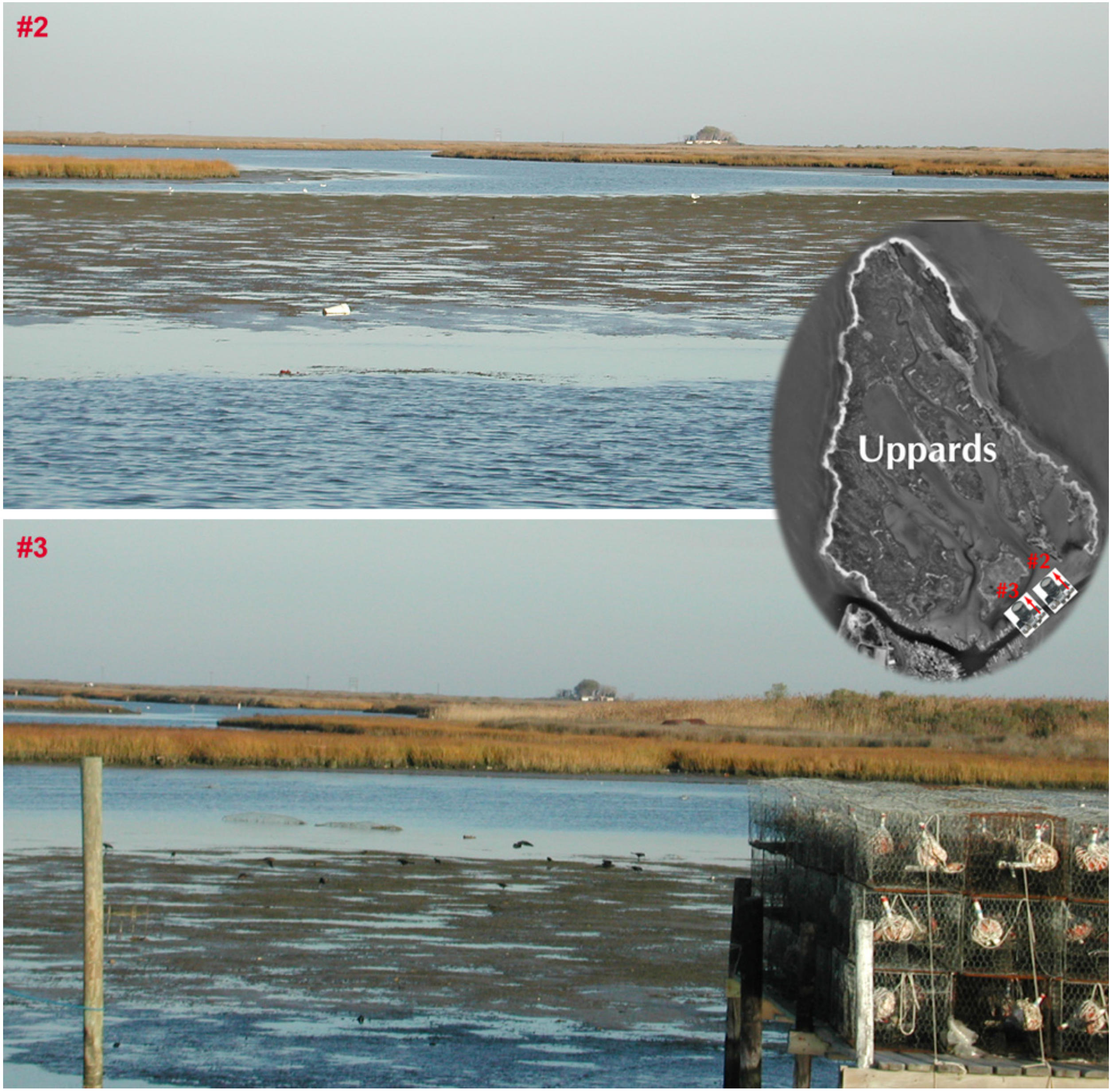


Exhibit: Photographs on Tangier Island, Virginia that relate to island erosion issues.

Photograph #1 (November 18, 2002): Erosion on Port Isobel. Shoreline erosion is more advanced at locations where pines trees, planted in the 1970's, are not present. This shoreline of Port Isobel is typically on the leeward side of the island, so the rate of shoreline erosion is less than on the western side of the island. On this day, winds were blowing from the northwest, and sizeable waves were impacting even the leeward side of the island.



Photographs #2 and #3 (November 19, 2002): Looking towards Uppards at a time of extreme low tide. Sea grass is evident on the exposed tidal flats. A hunting lodge is present in the extreme far distance. The channels on the far side of the mud flats run nearly the entire distance of Uppards, and are called "guts". Within a few years at least one of these guts (Tom's Gut) may be connected directly to the bay, assuming erosion continues at the present rate.

Photograph #4 (November 18, 2002): The Loretta Star in dock on the north side of the main channel and harbor that runs approximately east west through the island. The crab pots have been put in storage for the winter. Uppards can be seen on the far side.

Photograph #5 (November 18, 2002): In the main harbor area looking to the southeast. The Swain Memorial Church can be seen in the background. The large building in the left foreground is the power plant that supplies electricity to both Tangier Island and Smith Island to the north.

Photograph #6 (November 18, 2002): In the main channel looking all the way to the open bay to the west. Note the heavy development all along the channel on both sides. Typically on the right (adjacent to Uppards) crab houses are located. On this day a strong northwest wind was blowing and white caps can faintly be seen entering the harbor.

Photograph #7 and #8 (November 18, 2002): At the western entrance to the Tangier North Channel. A strong northwesterly wind was blowing large waves into the harbor. Evidence of shoreline erosion on the shoreline across the channel is evident. The power lines transmit electricity to Smith Island to the north.

Photograph #9 (November 18, 2002): At the southern end of the seawall that was constructed in 1990. The erosion that occurred from 1990 to 2002 is evident by comparing the marsh grass retreat on the protected and unprotected sides of the seawall.

Photographs #10 and #11 (November 18, 2002): At the shoreline (low tide conditions) deposits of peak can be seen and cause the waves to splash upon impacting the deposits. This is evidence of a past lower sea level, and illustrates that the shoreline is both eroding and migrating to the east in this area.

Photograph #12 (November 18, 2002): Active erosion of the marsh grass that anchors the sand dune. Near the end of November active photosynthesis has ceased in most of the grasses, and they have turned brown. As seen in the photograph, a few exceptions are evident.

Photograph #13 (November 18, 2002): The remnants of an old pier. Note the pilings that are barely sticking out of the sand. This is evidence of the eastward migration of the sand over the years.

Photograph #14 November 18, 2002): A fallen brick structure partially buried by the migrating sands.

Photograph #15 (June, c. 1978): A large ship in the main channel of the Chesapeake Bay, about 10 km west of the island.

Photograph #16 (November 18, 2002): Shirley's Bed and Breakfast. One of two B&B's that cater to the tourists on the island. Each year for the past twenty-five years, about 20,000 tourists have visited the island to observe its unique culture.