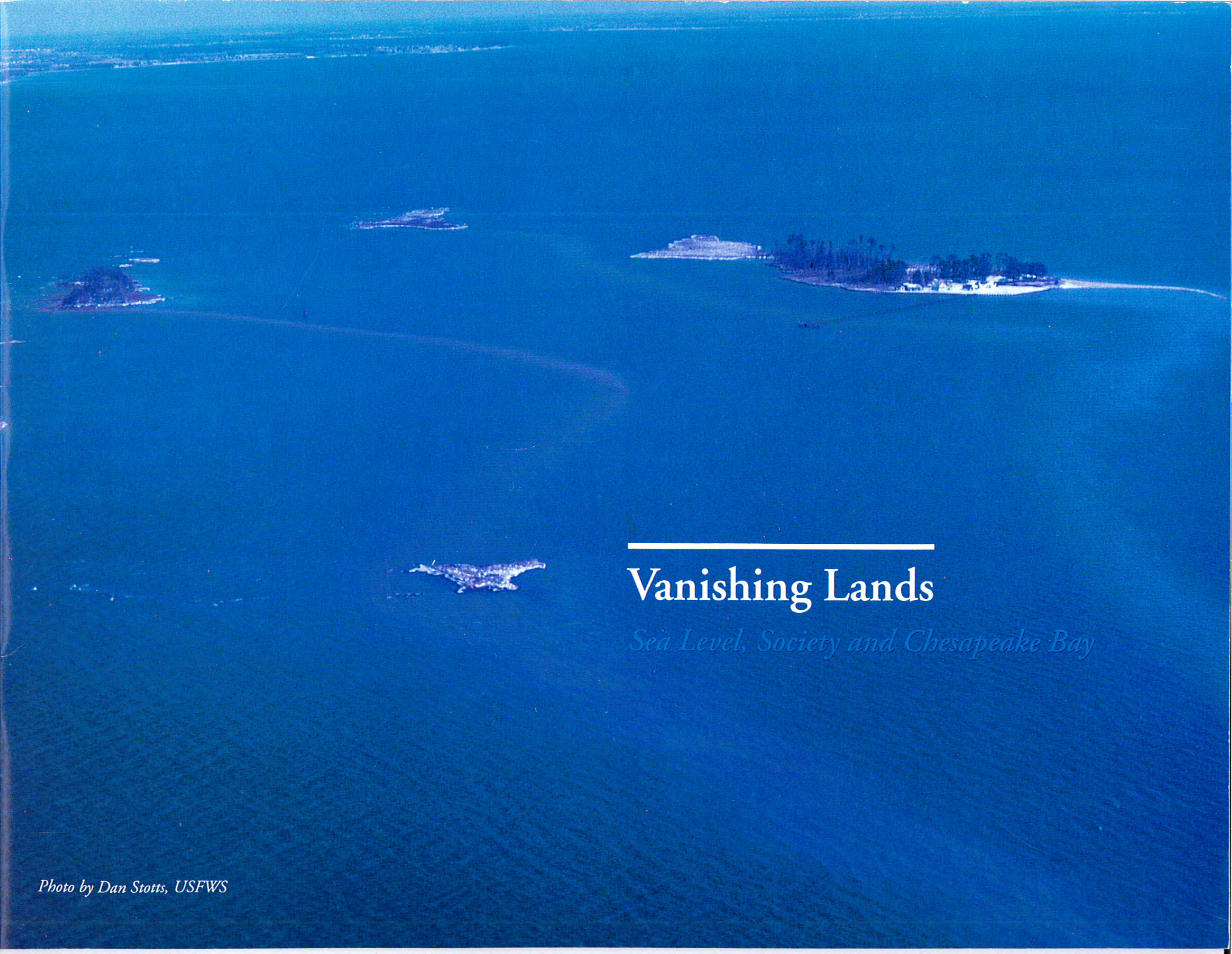


Vanishing Lands

Sea Level, Society and Chesapeake Bay

Photo by Dan Stotts, USFWS

Vanishing Lands

Sea Level, Society and Chesapeake Bay

- Stephen P. Leatherman[1]
- Ruth Chalfont[1]
- Edward C. Pendleton[2]
- Tamara L. McCandless[2]
- Steve Funderburk[2]

[1] *Laboratory for Coastal Research*
University of Maryland
College Park, Maryland

[2] *Chesapeake Bay Field Office*
U.S. Fish and Wildlife Service
Annapolis, Maryland

1995

Contents

Acknowledgments iv

Introduction 1
- Evolution of the Chesapeake Estuary 2
- Greenhouse Effect and Global Warming 6
- Sea-Level Rise 8

Estuary Dynamics and Sea-Level Rise 10
- Coastal Dynamics 11
- The Bay's Ecology 14
- Edge Ecosystems 16

The Human Influence: Ecosystem Impacts 19
- Land Use 20
- Influence of European Settlement 20
- Population Growth and Urbanization 21
- Loss of Habitat 23

Impacts of Sea-Level Rise: Coastal Land Loss 25
- Western Shore 27
- Eastern Shore 29
- Bay Island Communities 31

Society's Response to Sea-Level Rise 38
- Retreat 39
- Structural Erosion Control 39
- Retreat vs. Stabilization 41
- Restoration and Sediment Recycling 42
- State Response 43

At the Crossroads: A Cooperative Vision 44

Bibliography 47

Acknowledgements

The following organizations supported this work:

- W. Alton Jones Foundation
- Chesapeake Bay Field Office
  U.S. Fish and Wildlife Service
- Chesapeake Division
  Naval Facilities Engineering Command
- National Fish and Wildlife Foundation
- William Bingham Foundation
- Marpat Foundation

Front cover photo of Poplar Island complex by:

Dan Stotts

Back cover photo of Randle Beach by:

Stephen P. Leatherman, Ph.D.

Graphics by:

Guinn Cooper

We appreciate the assistance of:

Glenn Kinser, Ph.D., U.S. Fish and Wildlife Service; and Joe Hautzenroder, Natural Resources Manager, Chesapeake Division, Naval Facilities Engineering Command.

Reviews by the following professionals are appreciated:

Victor Kennedy, Ph.D.; Robert Nicholls, Ph.D.; Vincent Pito; David Parker; and Ian Eliot, Ph.D.

Introduction

- *Evolution of the Chesapeake Estuary*
- *Greenhouse Effect and Global Warming*
- *Sea-Level Rise*

Chesapeake Bay is an immense body of water that helps define the American landscape, just as do the mighty Mississippi, the Rio Grande, Lake Superior, and Puget Sound. The Bay, with all its rich history and resource abundance, is at a crossroad of change. Described by Native Americans as *Tschiswapeki*—the great shellfish bay—the Bay in the past experienced predominately seasonal changes. Spring ushered in new life with rivers nearly choked with spawning shad, river herring, and striped bass. Summers meant warm weather, bothersome insects, and plentiful blue crabs. Fall signaled the striped bass and bluefish migrations. And, just as today, wave after wave of migrating waterfowl were the harbinger of winter. The Native Americans in the Bay region lived with change, expected change, and adapted to change.

Today's civilization is no less affected by a changing Chesapeake. We too conjure an array of images as the seasons change, and we take profit and solace from this immense ribbon of tidal water. Unlike the situations facing early Native Americans, however, today's changes signify ominous signs for tomorrow's Chesapeake. These are changes born from a burgeoning population reliant on water for subsistence and pleasure. Today's changes often make the headlines—diseased oysters, toxic pollution, excessive nutrients, overharvesting, uncontrolled development, sewage overflow, loss of Bay grasses, and destruction of wetlands.

Chesapeake Bay is experiencing yet a different kind of change, one that is not easily discernible or controlled. This change, in concert with continued coastal urbanization, potentially overshadows all other harmful changes affecting this dynamic ecosystem. This change is known as *sea-level rise,* a force that over millennia has given birth to the Chesapeake and continues to shape it. Moreover, it is a force that will likely cause significant changes in Chesapeake ecosystems and human settlements.

This handbook describes the formation of the Chesapeake ecosystem, its characteristics, how it is being changed by sea-level rise, and how modern civilization may alter the rate of sea-level rise. Most important, however, this handbook offers choices—those actions we can take as individuals and as a society to protect this treasured estuary.

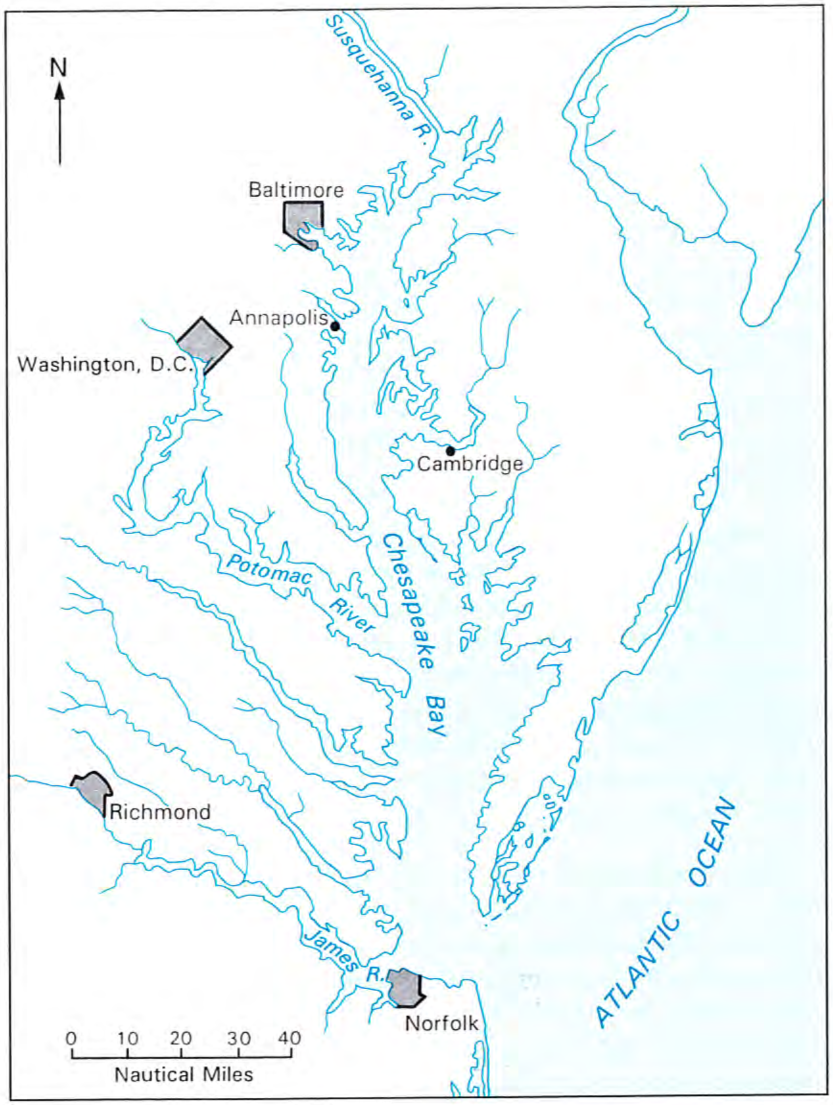


Figure 1. The Chesapeake Bay.

♦ Evolution of the Chesapeake Estuary

Chesapeake Bay is a permanent fixture in almost everyone's mind (Figure 1). Defined on maps and described in geography classes, the Bay takes center stage along the mid-Atlantic coast. The rivers that drain into Chesapeake Bay are almost as famous as the Bay itself—Potomac, Susquehanna, York, and James. The Bay served indigenous populations for thousands of years. Colonists established small scattered villages along its rich shoreline, and today's metropolitan cities rise along the banks. Even with its apparent permanence, this unique body of water has been changing for thousands of years, and that change continues.

Chesapeake Bay is the nation's largest estuary. An estuary is a semi-enclosed basin with fresh water flowing in at one end and salt water coming in at the other, creating a nutrient-rich zone of turbidity. The geology and hydrology of Chesapeake Bay greatly influence the types of habitats and living resources found in the estuary. During the last 10,000 years, a riverine ecosystem was converted into the estuary of today (Figure 2). As the sea level rose, the basin was flooded and became a shallow embayment, presenting a new set of physical conditions that would significantly change the character of its habitats and use by living resources.

The Bay's ever-changing character or evolution illustrates a lesson taught in elementary school about liquids—they assume the shape of their container. The container of the Bay is the valley cut by the Susquehanna River through the flat coastal plain of Maryland and Virginia many thousands of years ago. The ocean and rivers have taken considerable time in filling that container—almost 15,000 years. The evolution of the Chesapeake is a reflection of the container (geology), sources of water (hydrology), living resources and habitats (biology), and temperature patterns (climatology) expressed over millennia. In this evolutionary change, the Bay becomes more than a form; it becomes a process similar to viewing one still frame of a full-length movie. The rate of filling—sea-level rise—causes profound changes in the estuary's character.

During the last several million years, sea levels have risen and fallen as massive glaciers advanced and retreated across North America (Figure 3). So much of the Earth's water was locked up in these massive ice sheets that sea level rose and dropped by over 300 feet (Figure 4). Each time sea levels rose, another 'Chesapeake Bay' was pushed landward across the

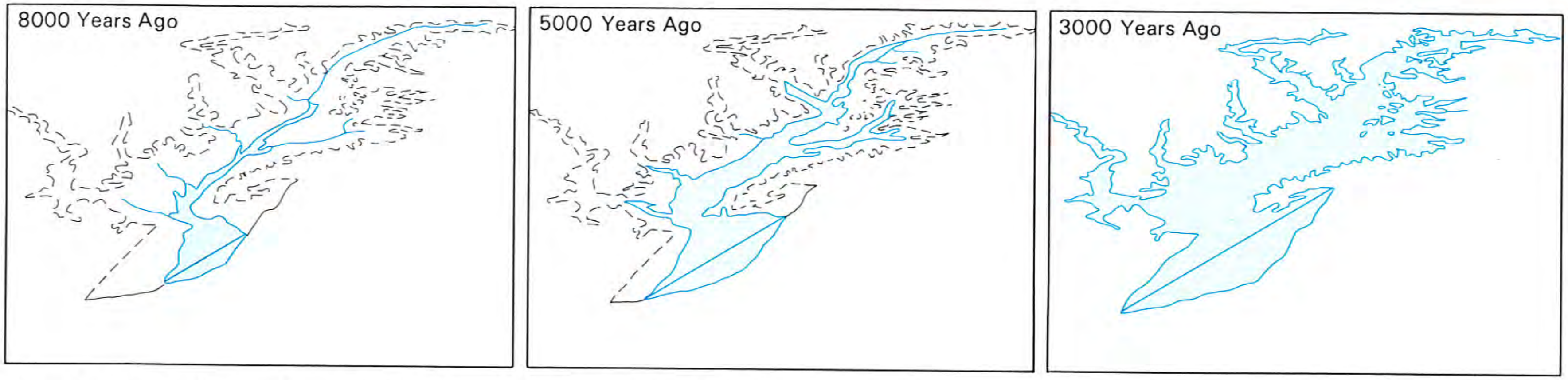


Figure 2. Rising sea level transformed the Susquehanna and other rivers into the Chesapeake Bay.

continental shelf and up the Susquehanna River valley that we know. This emergence, and re-emergence of the Bay is a geological phenomenon driven by sea-level rise. This, in turn, is controlled by climate change. This process continues as today's Bay evolves and grows at the expense of the land due to present-day sea-level rise.

Geology

Chesapeake Bay has long since drowned the river bed and valley of the Susquehanna, which 15,000 years ago emptied into the Atlantic Ocean about 200 miles farther offshore than at present (Figure 2). As glaciers melted after the last Ice Age, the constantly rising sea submerged the low-lying coastal plain, converting it into the continental shelf.

The Atlantic coastal plain, which extends more than 100 miles inland, was submerged 10 million years ago. It is characterized by a gently sloping surface. In some areas, the change in elevation is only 1 foot per 1,500 feet. On the Eastern Shore, the slope may be as gradual as 1 foot per mile. The coastal plain is composed of loose sediments, mostly clay, silt, and sand. The coastal plain covers an area from the Atlantic shoreline, inland, to the *fall line*—a point where river falls and rapids appear. This fall line, a much earlier coastline, marks the boundary where the coastal plain meets the higher Piedmont plateau, and the farthest point inland that rivers are navigable. For this reason, cities such as Baltimore, Richmond, and Washington, D. C., sprang up as trading ports in Colonial times along this geological boundary.

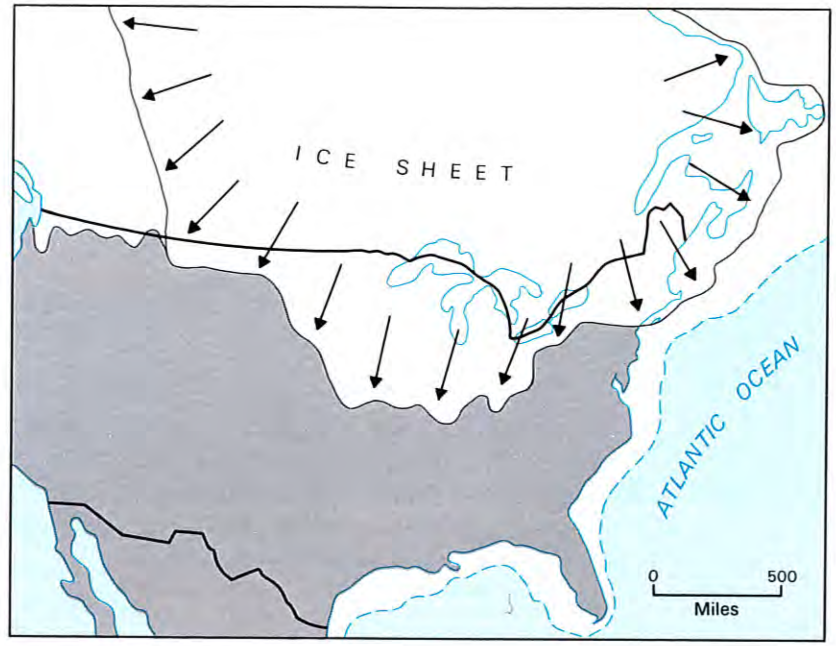


Figure 3. Maximum extent of ice 18,000 years ago during the last glaciation. Sea level was over 300 feet below its present level, and the shoreline at that time was hundreds of miles offshore (see dashed line).

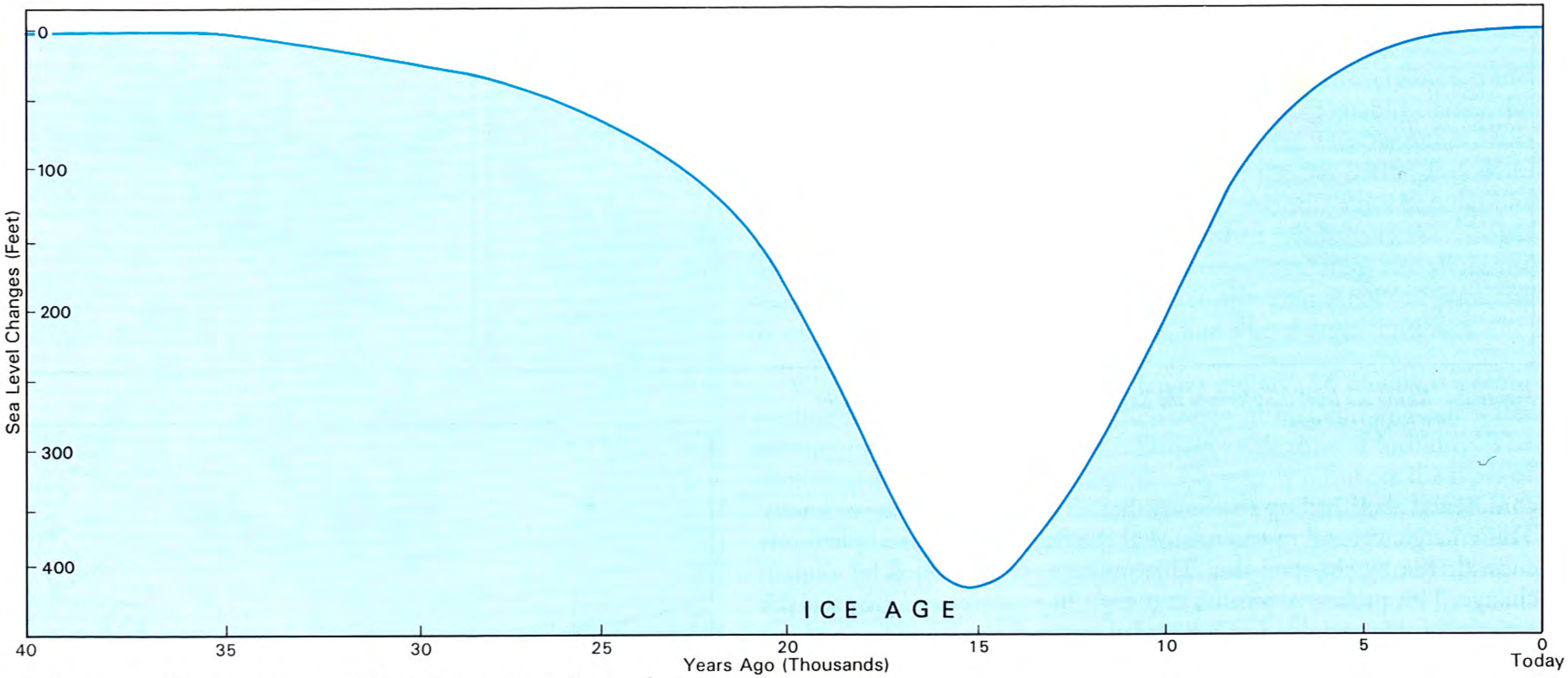


Figure 4. Sea-level rise curve for past 40,000 years, responding to advance and retreat of great ice sheets.

Hydrology

The Bay is best defined by water. Fresh water draining into the Bay originates from a number of large rivers and thousands of streams and creeks. The fresh water comes from a 64,000-square-mile watershed covering six states. The mixing of fresh and salt water within this semi-enclosed basin defines Chesapeake Bay as an estuary. It is the three-dimensional form of the basin that makes the Chesapeake unique. The Bay is very shallow, averaging less than 21 feet, and that shallowness greatly influences this ecosystem. The container named the Chesapeake has a unique shape or physiography, comprising 8,100 miles of shoreline, spanning 200 miles from north to south, and ranging in width from about 4 miles at Annapolis to 30 miles near the mouth of the Potomac River (Figure 1).

Biology

One of the most significant results of rising sea level was the development of salt marshes. About 5,000 years ago, the incoming sea waterw flooded the prehistoric Susquehanna River and its tributaries, but slowed dramatically as the average rate of sea-level rise declined to only 3 feet per thousand years (Figure 4). This rate was slow enough to allow proliferation of *Spartina* grass, which began to form vast salt marsh prairies on the Eastern Shore of Chesapeake Bay. Prior to this time, marshes lining the prehistoric estuary could not keep up with the faster rate of sea-level rise so they became inundated, reverting to open water. Only a narrow fringe marsh existed at the ever-changing interface between land and water. Once the rate of sea-level rise slowed, marshes maintained themselves by growing upward as well as advancing landward with rising water levels (Figure 5). The wide marshy plains that exist today developed during the past 5,000 years.

A marsh survives by building upon itself. As tidal waters flow over the marsh, suspended sediments as well as decaying roots and stems accumulate to form an organic peat layer, thereby raising the level of the marsh. The marsh grasses also creep landward with rising sea level. This process, known as *upland conversion*, changes the higher lands into wetlands.

Marshes maintain themselves through their ability to trap sediments from the water column and to accumulate their own organic material. However, the marsh must produce enough vegetation or trap enough sediment to keep pace with rising sea level. If an imbalance exists, the marsh will be jeopardized. Excessive sedimentation from uplands converts marshes to shrub habitat; diminished water flow can cause the marsh to dry out and decay; and inadequate sedimentation and prolonged flooding causes marshes to die and wash away.

Climatology

Geologic and hydrologic features define Chesapeake Bay at any point in time, but *climate* defines the size of the estuary. Climate drives the advance and retreat of glaciers, which alternately store and release vast amounts of water. While weather describes atmospheric conditions of a particular day and place, climate defines the nature of weather in specific regions, as characterized by temperature, precipitation, and prevailing winds.

Of these three characteristics, temperature is the most influential in the birth and death of estuaries. Climatic changes have punctuated geologic time with a series of *ice ages and interglacial (warm)* periods. The last great ice age peaked about 18,000 years ago when massive glaciers covered much of North America (Figure 3); sea level was more than 300 feet below its present position (Figure 4). The coastline of this time now lies underwater about 200 miles off the Atlantic coast (Figure 3). Rising

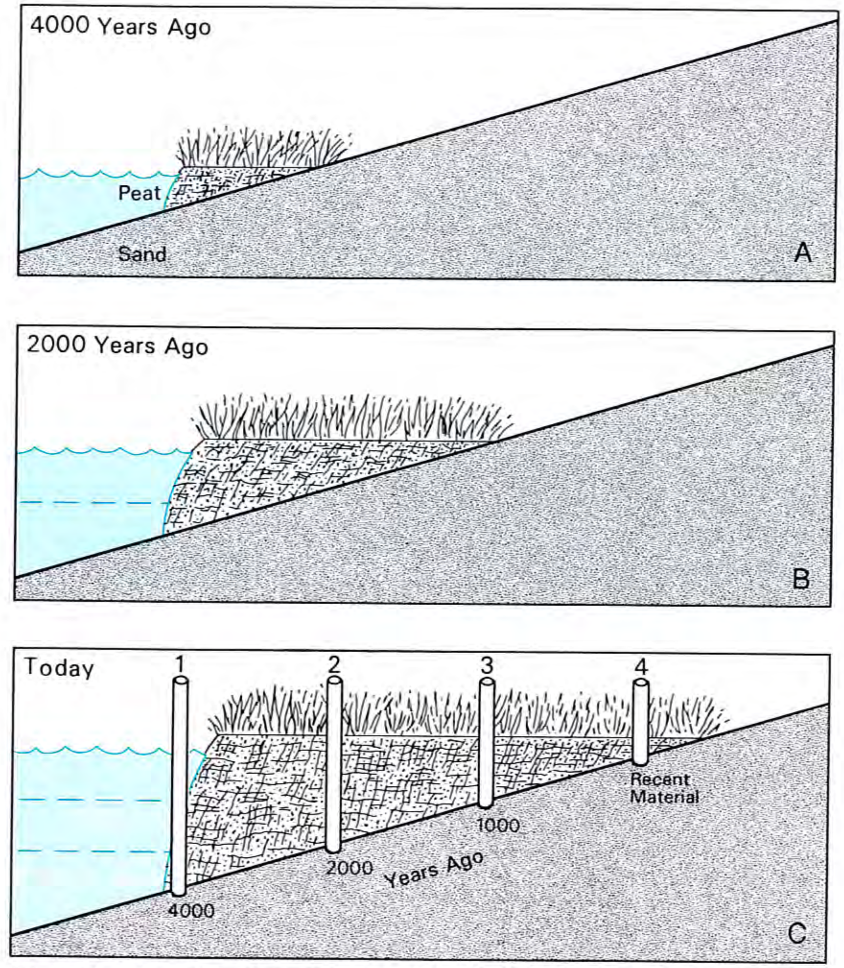


Figure 5. Growth and development of the Bay's wide marshy plains in response to slowly rising sea level. Core samples taken at the marsh peat base are used to age-date marsh development.

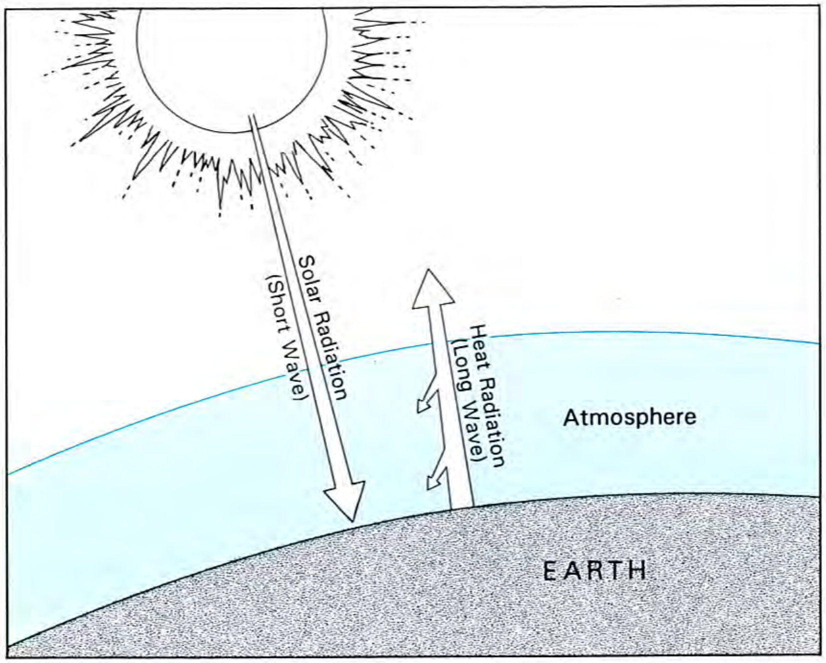


Figure 6. Schematic of the greenhouse effect. Small arrows indicate heat radiation directed back to Earth because of greenhouse gases.

waters from melting glaciers drove the coast inland, filling the Chesapeake basin (Figure 2). The warming temperature also expanded water molecules on the surface of the ocean in a process called *thermal expansion,* which contributed to the higher water levels.

Today we live in a *climatic optimum,* meaning the Earth is the warmest it has been within the current interglacial period (i.e., 35,000 years). The Earth should be moving imperceptibly toward the next ice age. Many climatologists, however, now believe that changes in the atmosphere's composition, caused by industrial activities, will significantly increase the global temperature and accelerate the rate of sea-level rise.

• Greenhouse Effect and Global Warming

The atmosphere largely defines a planet's potential for life by providing a balance of life-supporting gases and maintaining favorable temperatures. In contrast to the freezing atmosphere of Mars and the intolerably hot atmosphere of Venus, the Earth maintains ambient temperatures that sustain myriad life forms.

Two phenomena contribute to long-term temperature conditions, which greatly influence climate and hence variations in sea level. First, is the distance of the Earth from the Sun which determines the amount of solar energy the earth receives. Slight variations in the Earth's orbit around the Sun influence the amount of solar radiation reaching the planet, and have resulted in the waxing and waning of the great ice sheets on a time scale of about 100,000 years. Second, is the trapping of heat at the Earth's surface, known as the *greenhouse effect,* which regulates long-term temperatures. Incoming solar radiation is absorbed by and warms the Earth's surface (Figure 6). Some solar radiation is reflected back into space by the oceans and polar regions. A large proportion reradiates as heat that is absorbed by certain atmospheric gases and dust. In this way, the atmosphere blankets the Earth and behaves as a greenhouse, allowing heat to build up inside much like closed car windows do on a sunny day. Without the greenhouse effect, the Earth's average temperature would be about 0°F instead of 60°F.

Our atmosphere is 78% nitrogen, 21% oxygen, and 1% trace gases, including CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide), water vapor (H_2O), ozone (O_3), and man-made CFCs (chlorofluorocarbons). While trace gases constitute less than 1% of the atmosphere, they determine the Earth's temperature and hence climate. Increases of greenhouse gases from human activities can increase the atmosphere's ability to trap heat, promoting higher global temperatures. This phenomenon is commonly referred to as *global warming*.

A relative increase in greenhouse gases has occurred within the last century from a variety of human activities (Figure 8). These include increased releases of CO_2 from combustion of fossil fuels (oil, coal, and natural gas) for production of electricity, burning of gasoline by automobiles, and cutting down and burning forests, especially tropical forests (*deforestation*). Because trees consume CO_2 during photosynthesis, their destruction decreases our ability to reduce CO_2 levels. Pre-industrial levels of CH_4 have already doubled due to increases in cattle ranching following deforestation, gas venting, landfill decomposition, rice farming, and coal mining. Automotive emissions are the primary source of N_2O, which has increased by 19% over pre-industrial levels. Chlorofluorocarbons, also responsible for ozone depletion in the upper atmosphere, have dramatically increased in recent decades. These artificial chemicals

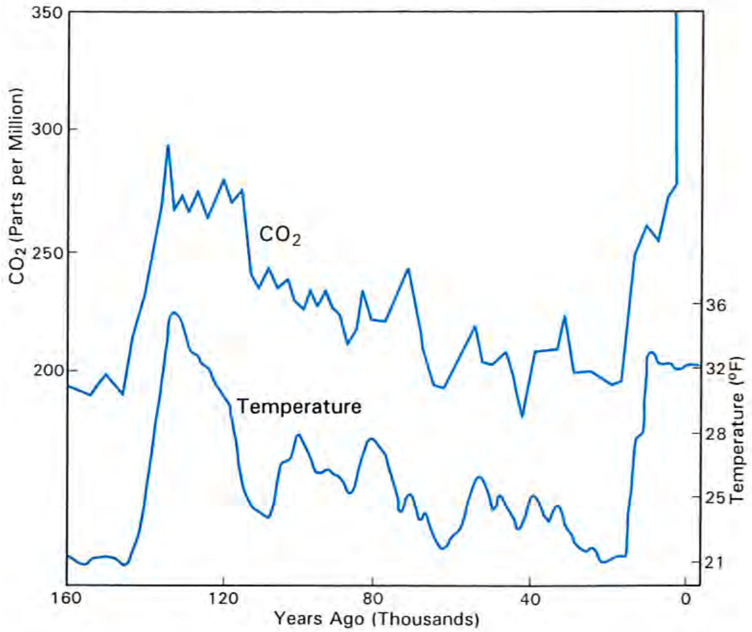


Figure 7. Correlation between temperature change and an increase of atmospheric CO_2 (Intergovernmental Panel on Climate Change, 1990).

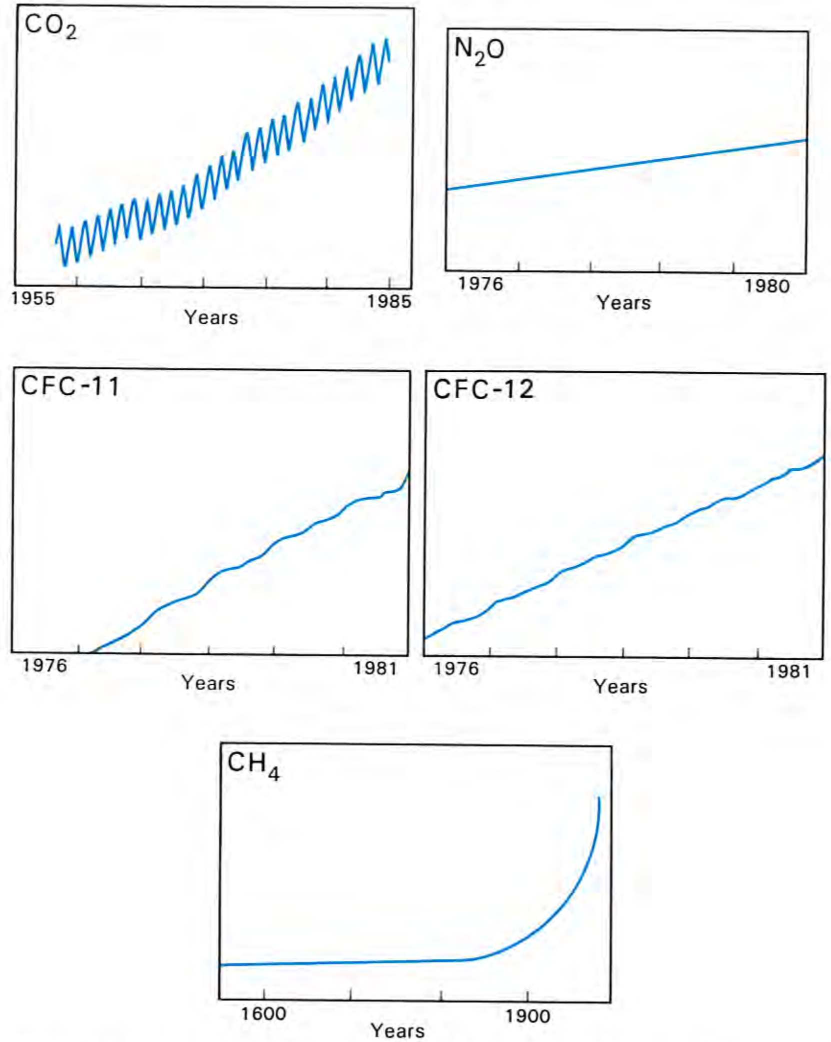


Figure 8. Increasing concentrations of greenhouse gases in the atmosphere (Intergovernmental Panel on Climate Change, 1990).

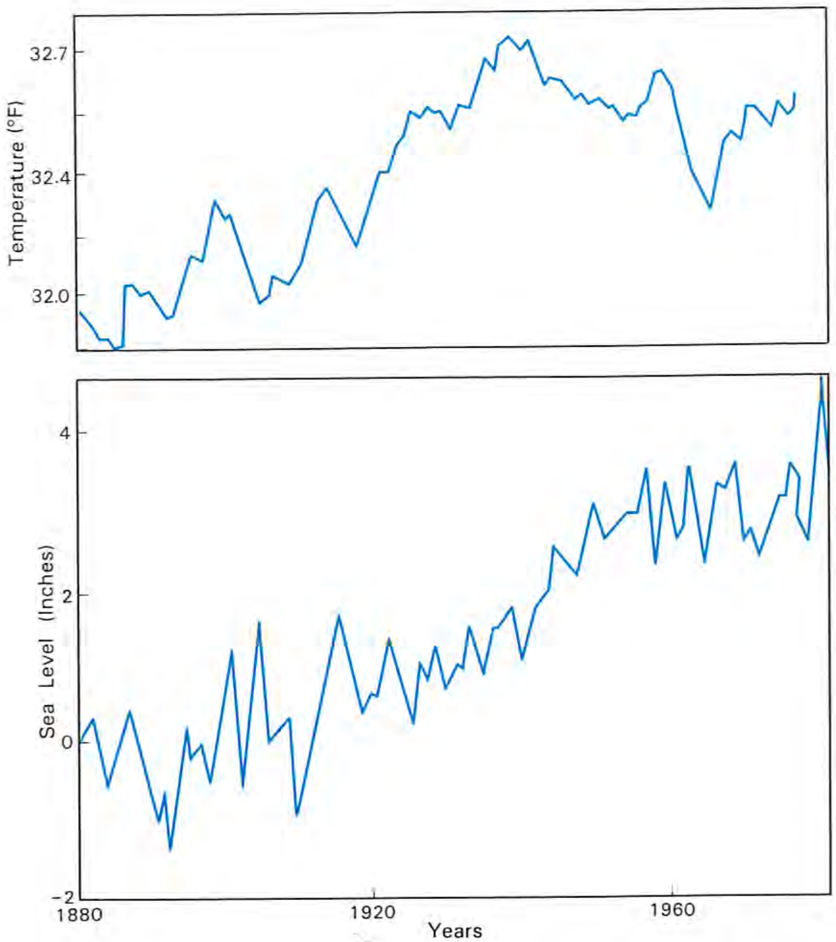


Figure 9. Correlation between global temperature and sea-level rise (Intergovernmental Panel on Climate Change, 1990).

have long lifetimes and several thousand times the capacity to trap heat in the atmosphere and reradiate it back to the Earth's surface of CO_2.

There is a strong correlation between past temperature change and atmospheric CO_2 (Figure 7) as determined from CO_2 trapped in glacial ice. Examination of deep ice cores reveals that CO_2 levels during the last Ice Age were 180 ppm (parts per million). By the 1880s the level had increased to 280 ppm and to 354 ppm in 1989. Half of that increase occurred since 1960. Ice cores show that present concentrations of CO_2 are higher than at any time in the last 160,000 years. Because scientists cannot explain all the factors controlling the Earth's climate, the exact amount or rate of temperature change and how much is human-induced is still debated. There is, however, a scientific consensus that increased concentrations of greenhouse gases will result in global warming. The National Academy of Sciences in 1983 estimated that the Earth's average temperature would increase by 2° to 7° F with a doubling of atmospheric CO_2 within the next 50 to 100 years.

There is a strong correlation between global temperature and sea level (Figure 9). The Earth's average temperature has increased 1° F during the past century, and sea level has risen about 6 inches worldwide. Effects always come later than causes because there is climate lag. Existing concentrations of greenhouse gases, specifically CO_2, commit the planet to further global warming, even if emissions ceased immediately worldwide. We therefore have a commitment to an accelerated rate of sea-level rise based on current greenhouse gas emissions.

♦ Sea-Level Rise

Of all potential impacts of human-induced climate change, a global rise in sea level appears to be the most certain and the most dramatic. For the last 5,000 years the rate was only 3 feet per 1,000 years. In the Chesapeake Bay region, the relative rise in sea level has been about 1 foot during the last 100 years (Figure 10). While this rapid rate is possibly a temporary acceleration, many scientists believe that it signals a new trend in response to global warming. If the rate of rise accelerates in the near future as projected, it could have serious repercussions for Chesapeake Bay.

Because water levels are measured relative to the land, relative sea-level rise in the Chesapeake Bay region has two components: global

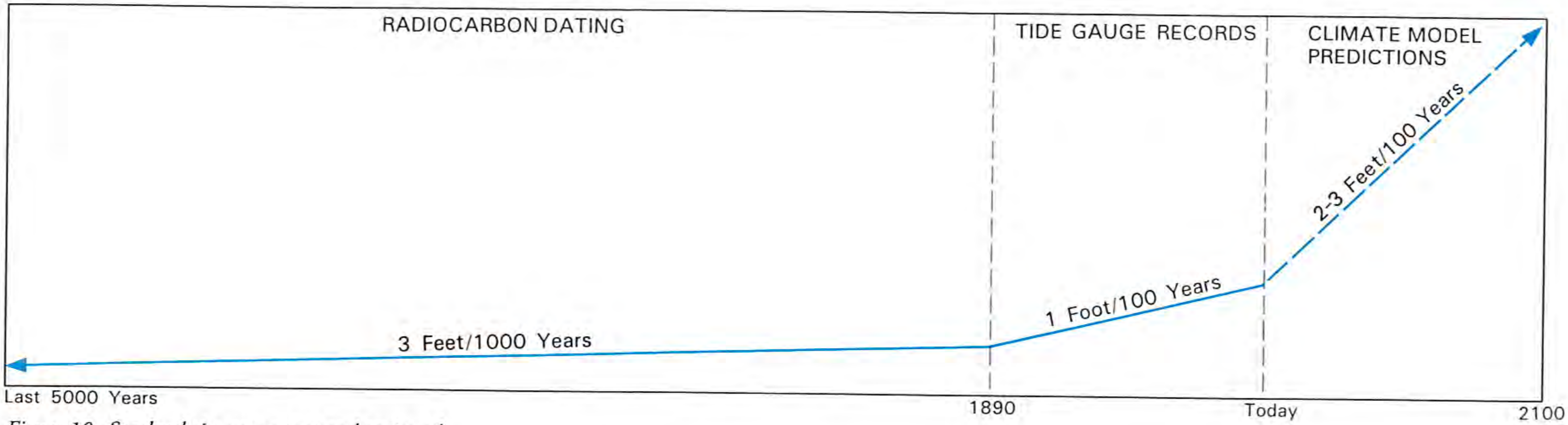


Figure 10. Sea-level rise curve: past and projected.

water level and land subsidence. Worldwide or *eustatic* sea-level rise is caused by water released from melting glaciers and thermal expansion of seawater. Both are related to global warming and have amounted to a 6-inch rise in the last century. Local or *isostatic* factors contribute to *relative* sea-level rise through *subsidence* or sinking of the land. In the Chesapeake Bay area, subsidence of land due to geologic factors and possibly excessive withdrawal of groundwater has amounted to 6 inches in the last 100 years. Consequently, there has been a relative increase of sea level in the Chesapeake Bay area of 1 foot in the last century (Figure 10).

Estuarine Dynamics & Sea-Level Rise

- *Coastal Dynamics*
- *The Bay's Ecology*
- *Edge Ecosystems*

The coastal dynamics of storms, waves, and tides provide much of the energy and water flux to maintain and sustain the Bay's highly productive ecosystems at the interface between land and water. The rise and fall of tides, mixture of fresh and salt water, and life cycles of plant and animal populations interact to create an estuary that is intricate and resilient. Sea-level rise over thousands of years greatly influenced this diverse ecosystem, but accelerated sea-level rise will cause changes to occur too rapidly. We are only beginning to understand and predict these changes.

♦ Coastal Dynamics

Sea-level rise is a pervasive and long-term force shaping the Bay. However, on a daily or yearly basis, other forces that ultimately interact with sea-level rise are far more noticeable. Specifically, coastal storms, waves, and tides greatly affect the Chesapeake estuary.

Storms

Two kinds of major coastal storms occur in the Bay region—*extratropical* winter storms (northeasters) and *tropical* storms (especially hurricanes). One or more northeasters usually occur between October and April, with the greatest frequency occurring in February and March each year. They migrate across the middle latitudes of the continent, obtaining energy from the interaction of warm and cold air. These large low pressure cells may have sustained winds of 40 to 50 mph. They often travel hundreds of miles a day, or, in some cases, can be held in place by blocking high pressure systems. The Ash Wednesday storm of March 5 through 8, 1962, the largest winter storm to affect Chesapeake Bay in the last 100 years, generated storm waves and a high surge for five successive high tides. This winter storm caused massive erosion, particularly along the cliffs of the Western Shore (Figure 11).

Hurricanes and other tropical storms develop in the tropics as a planetary self-regulatory mechanism to disperse heat away from the tropics and carry it to the poles. Unlike northeasters, hurricanes move slowly with a forward speed of 10 to 20 mph and occur with greatest frequency during August and September.

Some meteorologists feel that hurricane cycles are linked to the amount of rain in the western Sahel region of Africa. During a rainy period from 1947 to 1969 in the Sahel, 13 major hurricanes with winds over 110 mph struck the Atlantic coast. During a dry period from 1970 to 1987 only one such storm hit. This extended dry spell in Africa has ended, and recent hurricanes may represent the return of the great Atlantic hurricanes.

Hurricanes that make landfall are among the most destructive natural forces on Earth. The most dangerous part of a hurricane is the *storm surge*, which often is accompanied by high winds and heavy rains. The increased water elevation of a storm surge, more than 7 feet above normal tides, (Table 1) enables larger waves to break closer to shore, greatly increasing erosion and devastation to property. Simply by raising base

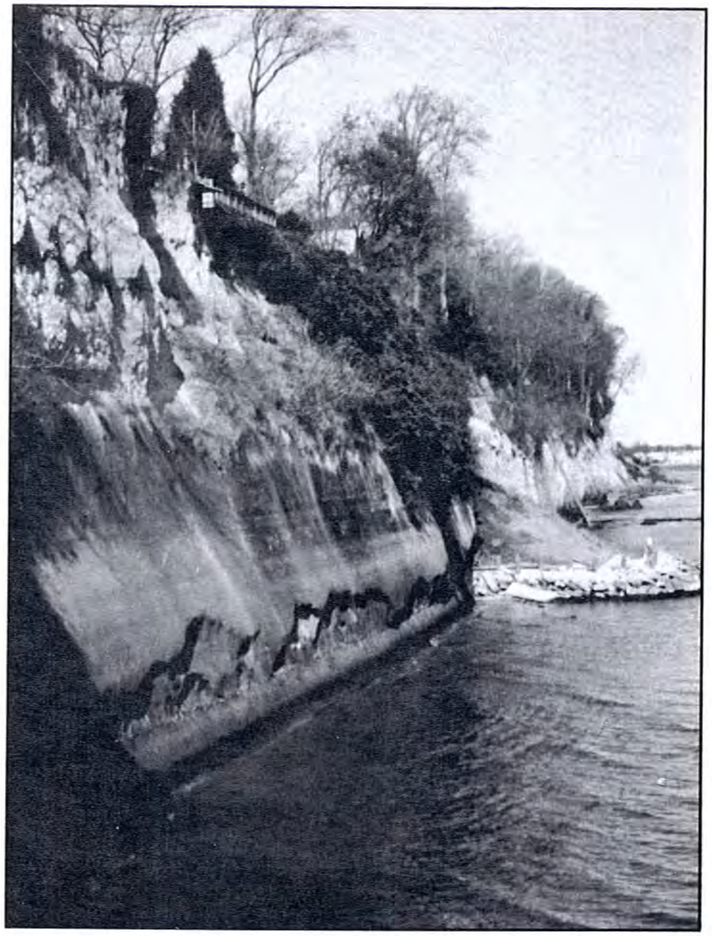


Figure 11. Much of the Western Shore of Chesapeake Bay is characterized by erosional cliffs (photo by Stephen Leatherman).

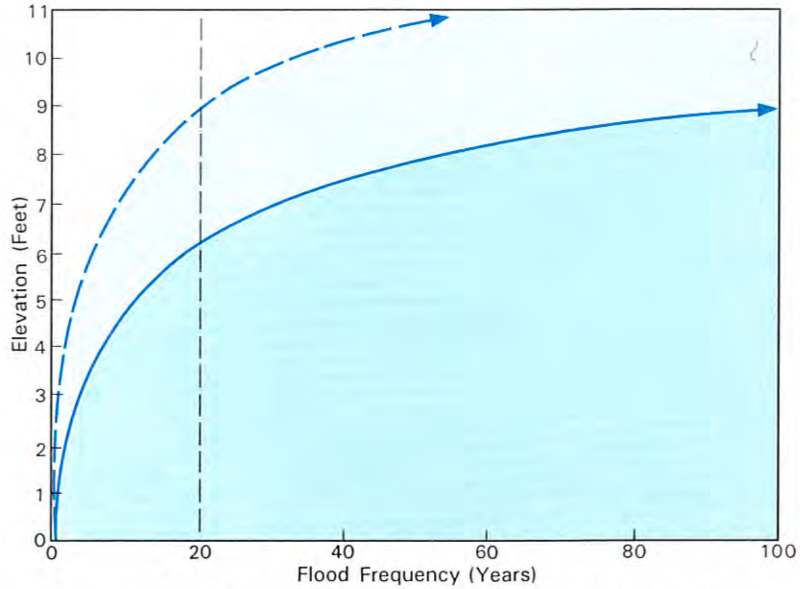


Figure 12. Flood frequency curve (solid curve from U.S. Army Corps of Engineers, Baltimore, Md.). A 3-foot rise in sea level (dashed curve) turns a 20-year storm into a 100-year flood.

water levels, sea-level rise increases the frequency of what we currently think of as 100-year floods, that is, a storm that has a 1% probability of occurring in any year. For instance, a 3-foot rise in sea level could turn a 20-year storm into a 100-year flood (Figure 12).

The power of storms to quickly and dramatically change the Bay was illustrated by the impact of Tropical Storm Agnes in June 1972. This storm dropped up to 18 inches of rain over the region, producing an abrupt increase in the normal flow of the Bay's tributaries. Huge volumes of fresh water entering the Bay briefly flushed most of the salt water from the estuary. Freshening of the Bay caused massive oyster mortalities; an estimated 2 million bushels of market-sized oysters died and young oyster spat were almost entirely wiped out over much of the Bay.

Waves

Waves in the Bay result from wind and locally from boat wakes. Wind waves range from ripples to seas over 3 feet high during storms. The size of a wave is limited by four factors—*fetch* (the distance across water that the wind blows), *water depth*, *wind duration*, and *wind speed*. The greater the fetch, the larger the waves that can be generated. The Bay's width averages only 20 miles, which limits wave heights. The prevailing wind direction is from the west-northwest, so most waves hit the Eastern Shore.

The height of a wave influences its destructive force. The energy of a wave, and therefore its erosive potential, is proportional to its height squared. For example, a 2-foot wave has four units of energy, whereas a 3-foot wave has nine units. This relationship shows why only slight increases in wave size can cause considerable increase in damage.

Predominant northwest winds plus the accompanying fetch down the Bay contribute to very high erosion rates for the Bay islands. For instance, Poplar Island in the upper Bay has an erosion rate of over 13 feet per year on its western shore. Although some sand accreted on the southwestern tip of this island as a sand spit, the amount of buildup was minimal compared to erosional losses. Today, even the sand spit is gone.

Tides

Tides are the principal means by which water and nutrients circulate in the Bay. They are of primary importance to estuarine plants and

Figure 13. Spartina salt marshes are a critical habitat in Chesapeake Bay (USFWS photo).

animals. Chesapeake Bay experiences semi-diurnal tides: two high tides and two low tides of about equal height occur during a lunar day of 24 hours and 50 minutes. The Bay's shallowness and irregular shoreline cause the timing and heights of high and low tides to be quite different, depending on location. Tide gauges throughout the Bay enable accurate calculations of time and height of high and low tides at measurement locations. These long-term records show that sea level has risen 1 foot in the last century.

Mean sea level is an averaged measurement of the surface of the sea for all stages of the tide as determined by hourly height readings of tide gauges. Mean high water, important to developers, and mean low water,

Date	Event	Location	Storm Surge (ft.)
1915, Aug 4	Hurricane	Baltimore	4.5
1923, Oct 24	Hurricane	Baltimore	3.0
1924, Sept 29	Hurricane	Baltimore	2.4
1928, Sept 19	Hurricane	Baltimore	4.2
1933, Aug 23	Hurricane	Baltimore	7.3
1954, Oct 16	Hurricane Hazel	Baltimore	4.8
1955, Aug 13	Hurricane Connie	Baltimore	6.0
1955, Aug 18	Hurricane Diane	Baltimore	3.1
1956, Apr 13	Hurricane	Hampton Roads	4.1
1960, Jul 30	Tropical Storm Brenda	Solomons Island	2.2
1962, Mar 8	Ash Wednesday Storm (Extratropical)	Annapolis	3.6
1972, Jun 23	Tropical Storm Agnes	Baltimore	2.1
1991, Oct 31	Halloween Extratropical	Hampton Roads	2.9
1992, Dec 10	Extratropical	Baltimore	2.6

Table 1. Major storm surges in Chesapeake Bay during the 20th century (from NOAA).

important to mariners for navigation, are the long-term averaged heights at the highest and lowest levels of the tide. Tidal range, or the difference between mean high and mean low water, varies from 1 foot or less (as in Baltimore Harbor) to over 3 feet at Norfolk and the mouth of the Bay. Coastal marshes exist in the intertidal zone between these two tidal extremes. *Spartina patens* salt marsh is a biological indicator of mean high water (Figure 13). This is the level that geologists compare through time to determine if sea level is rising and at what rate.

Meteorological factors can influence tides, especially in broad, shallow estuaries like Chesapeake Bay. For instance, if the barometric pressure is low or a strong wind is blowing onshore, the water can rise much higher than it would by tidal influences alone. In extreme events, high tides, low pressures, and strong onshore winds can create abnormally high storm surges (Table 1).

Sea-level rise, accompanied by other factors of global climate change, will have profound effects on the way the Bay operates. Circulation patterns will change as saline waters intrude farther up the Bay and as regional rainfall patterns change. Warmer ocean temperatures may boost hurricane intensity and perhaps frequency, increasing erosion, flooding, and damage to coastal areas hit by tropical storms.

♦ The Bay's Ecology

Chesapeake Bay waters are by no means homogeneous. Gradations of temperature, salinity, suspended sediment, and oxygen richness appear routinely both horizontally and vertically. The constantly changing physical and chemical environment demands that Bay organisms be flexible and resilient to enable them to survive through time periods as short as a tidal cycle or as long as geologic eons.

It is not possible to know precisely how the Bay ecosystem will respond to the combined influences of sea-level rise, global warming, and continued impacts from human activities. However, concern is warranted based on what we know about present-day conditions and the processes that maintain them. Because of fresh water inputs from rivers, salinities change from fresh or almost fresh in the upper Bay to near ocean strength at the mouth of the Bay (Figure 14). If rainfall and fresh water inputs to the Bay diminish, fresher areas of the Bay could approach the salinity levels of the ocean through the process of saltwater intrusion. This is a long-term process with major impacts on the ecosystem.

Twice each day, high salinity waters from the ocean move into the Bay on flood tides. Where the saltier, denser water meets fresher, less dense waters, a salinity wedge is created with freshwater flowing out to sea on top and salty water moving inland underneath. During the spring runoff, or at times of regionally heavy rainfall, water salinities decrease throughout the Bay, and the salt wedge is driven seaward. Droughts cause this salt water wedge to encroach farther up the Bay. Long-term sea-level rise has the same effect as a drought, except the water becomes permanently more saline. An increase in salinity can shift entire biological communities in the Bay, most notably freshwater marshes. Oyster bars, which thrive in brackish water conditions, could be harmed by invasion of marine oyster drills and starfish. In addition, the oyster diseases MSX and *dermo* thrive in saltier water. Warmer waters could have direct impacts on plant and animal species because feeding, growth, and especially reproduction are temperature-sensitive. For instance, the soft-shelled clam is already at the southernmost point of its range. Warming water temperatures would subject populations to greater heat stress in summer, perhaps eliminating this species from the Bay. On the other hand, the introduction of new species adapted to warmer climates in more southerly estuaries may gradually occur naturally.

Dissolved oxygen, already at alarmingly low levels in deeper portions of the Bay, might decline even further because warmer water holds less oxygen. Oxygen depletion causes mobile species to abandon formerly suitable habitat, and immobile species, like the oyster and other benthic bivalves, to die of anoxia (i.e., lack of oxygen). Even mobile species like the striped bass and blue crab require well-oxygenated waters and may suffer in parts of their range. Temperature shifts over the course of a year turn over the Bay's water, recycling nutrients and contributing to estuarine productivity. If global warming were to narrow the seasonal temperature difference, there could be a decline in nutrient recycling and productivity.

Shore erosion, responsible for more than half the sediment in the Bay's water, will dramatically increase in response to accelerated sea-level rise. As erosion proceeds, new sediments will be continually resuspended. Sediment particles with associated bacteria and organic matter take oxygen from the water column, especially as temperatures become

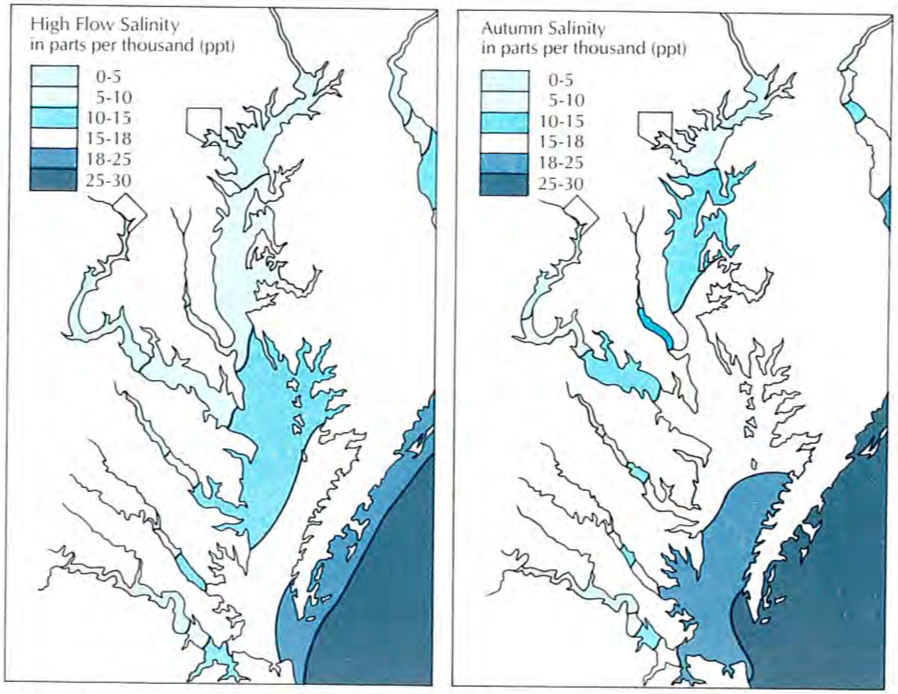


Figure 14. Sea-level rise will force saline waters further upstream, altering the Bay ecosystem (adapted from EPA).

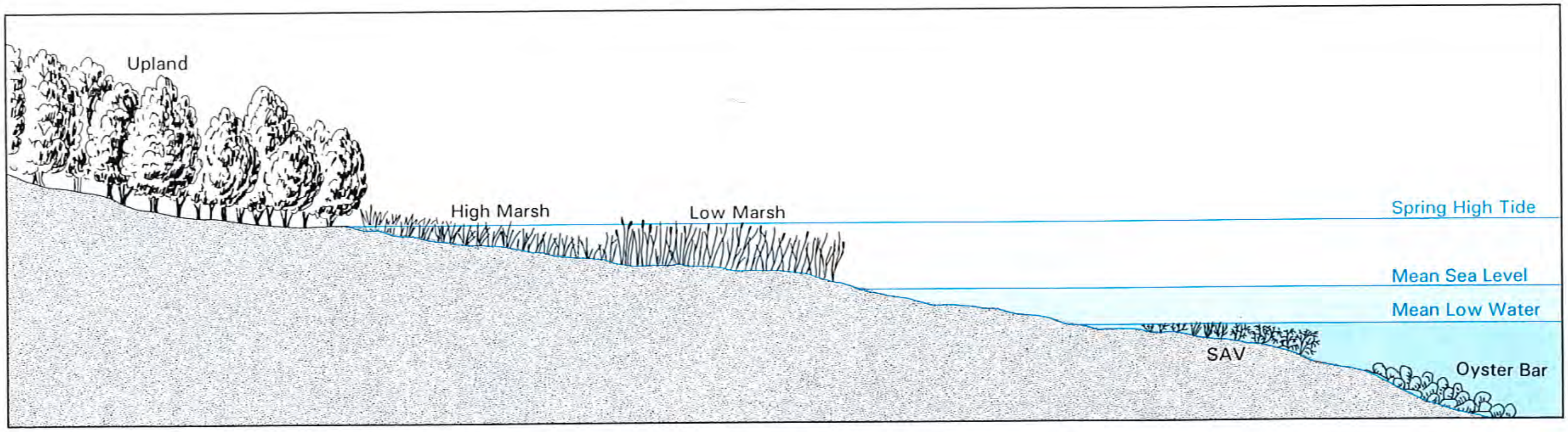


Figure 15. Edge ecosystems, consisting of shallow water areas and adjacent wetlands, are the most productive areas in the Bay, as well as the area's most vulnerable to accelerated sea-level rise.

warmer and salinities increase. These particles also block light penetration through the water. Therefore, as sea level rises, areas around the fringes of the Bay will become warmer, more turbid and hold less oxygen. The result is less hospitable environments for plants and animals that live there.

♦ Edge Ecosystems

The biologically rich and important edges of the Bay are likely to be the sites of greatest ecological change (Figure 15). Although no portion of the Bay is devoid of life, shallows from the shoreline to depths of 5 feet or less contain the vast majority of living organisms. It is in this zone that oysters grow and Bay grasses thrive (Figure 15). The latter provide protection and food for juvenile fish and crustaceans (most notably the blue crab), as do the Bay's fringing tidal wetlands. Both grass beds and marshes are "nurseries" for young fish, crabs and other organisms, providing food and protection from predators. Wetlands are also vital to the maintenance of water quality and as a buffer against shore erosion and storm damage.

Bay grasses, called submersed aquatic vegetation (SAV), are significantly influenced by the light and physical energy conditions at any particular site. Sea-level rise will increase water depths and turbidity, ultimately resulting in SAV demise due to decreased light penetration. Climate change may exacerbate these conditions with more frequent and intense hurricanes, thus accelerating shore erosion, stirring up the shallow bottoms, and uprooting grasses.

Coastal wetlands are frequently inundated, often on a daily basis by tides (Figure 15). It may seem odd, therefore, to consider sea-level rise as a threat. Most coastal wetlands can compensate for slowly rising water levels by trapping sediments from the water column and/or accumulating their own plant leaves and stems on the marsh surface. The large expanse of marshes on the Eastern Shore has kept pace with slowly rising sea levels over the past 5,000 years principally by accumulation of their own dead organic matter. However, a slight increase in the rate of sea-level rise can tip the balance, resulting in large-scale plant die-off as is already occurring at Blackwater National Wildlife Refuge, Dorchester County, Maryland.

When marshes depend on organic matter as their primary source of sediment, the rate of sea-level rise has a direct effect on the survival of marsh vegetation. In coastal Louisiana, for example, wetlands undergoing high subsidence rates of almost a half inch per year, coupled with insufficient sediment input, are behaving in the way we would expect marshes to respond to accelerated sea-level rise—they are experiencing rapid land loss. Louisiana is presently losing more than 20 square miles per year in response to a very high relative rate of sea-level rise.

Like Louisiana, large areas of marsh on the Eastern Shore of Maryland have exhibited increasing rates of breakup and conversion to open water during the past several decades. Losses occur largely in marsh interiors, where relative sea-level rise overwhelms the slow accumulation of new sediments from plants and tidal inputs from marsh creeks. Small shallow ponds form as marsh plants die from chronic waterlogging and as marsh peats become susceptible to erosion. Winds and storms enlarge the ponds as banks erode, and the peats themselves decompose into a slurry.

Muskrats and nutria feeding on plant roots and tender shoots may hasten the process of pond formation and enlargement. Non-stressed or healthy marshes recover from occasional intense feeding by these rodents (a consequence of local overpopulation). In Louisiana and Chesapeake Bay, marshes on the threshold of deterioration because of rapid relative sea-level rise no longer show this remarkable ecological resilience.

As water levels rise, low-lying uplands adjacent to the shore will be converted to wetlands over time (Figure 16). This conversion unfortunately is not a viable process for replacing the valuable wetlands being submerged by rising sea levels. First, the process of wetland encroachment onto uplands is much slower than the rate at which existing

Figure 16. Slowly rising sea level causes trees to die as the marsh invades a forested area on the Eastern Shore (photo by Stephen Leatherman).

Figure 17. Structurally stabilized shores in the Bay provide no place for marshes to form or migrate (USFWS photo).

wetlands are converting to shallow open water. Second, human development has constrained the landward advancement of wetlands. Extensive stabilization of the Bay shoreline (Figure 17) as well as conversion of coastal woodlands and farms to urban and residential development have removed buffer areas that would become wetlands in response to sea-level rise. Furthermore, there is a continuing trend of waterfront development.

Submergence of coastal wetlands by sea-level rise will affect the entire Bay ecosystem. With their demise will come the loss of animals that live there, as well as other organisms that indirectly depend on marshes as part of the Bay's expansive food web. For instance, young fish and crustaceans move onto the marsh surface to feed during high tides. Wading birds, hawks, eagles, and other birds frequently forage in wetlands. Several species, including rails, herons, egrets, marsh wrens, and red-winged blackbirds, nest in marshes. Coastal marshes are important habitats for muskrats, otter, deer, and raccoons.

The Bay's marshes perform a number of important functions. These grassy habitats process, remove, and add nutrients to nearby waters, exporting some and retaining others in a complicated process that changes seasonally. Marshes export decomposed plant material or detritus that becomes a basis for the Bay's food web. Sea-level rise jeopardizes and may permanently alter these valuable functions.

Accelerated sea-level rise is significant when considering the survival, adaptability and biodiversity of wildlife. Slow, steady sea-level rise over geologic time gave species time to migrate, adapt or otherwise evolve to accommodate these rising waters. When wetlands or open-water shallows slowly migrated landward, birds and other animals relocated their foraging grounds and territories farther inland. If sea level rises rapidly, there may not be enough time for species to adapt to environmental change. Even if adaptations were possible, suitable habitat is less available now due to human disturbance and development. No longer as healthy and resilient, the Chesapeake's edge habitats now face these additional stresses associated with accelerated sea-level rise.

The Human Influence: Ecosystem Impacts

- *Land Use*
- *Influence of European Settlement*
- *Population Growth and Urbanization*
- *Loss of Habitat*

Ever since people first inhabited the Chesapeake watershed, there have been impacts on the Bay. Important questions involve the degree of historical impacts on the Bay ecosystem and the problems facing the Bay today. It is well known that a number of Bay species are now depleted because of overharvesting or poor water quality from pollution. Understanding the Bay's ecological response to accelerated sea-level rise is critical for preventing large-scale losses of the Chesapeake's attributes that we rely on and value.

There is much we do not know about the response of the Bay ecosystem to sea-level rise. We do know that the seas are rising. We know the seas have risen at least three times faster during the last century than during the last 5,000 years. Climate models predict a 2- to 3-foot rise over the next hundred years, a rate that poses immediate consequences for low-lying coastal lands, particularly island habitats and marshes (see Figure 10). Much of the land area that comprises the Chesapeake Bay islands has already been lost in response to a sea-level rise of only 1 foot during the last century.

Figure 18. Sediment runoff from agricultural fields results in siltation problems in the Bay (USFWS photo).

♦ Land Use

The relationship a culture establishes between itself and nature, whether cooperative or adversarial, is of primary importance to the health and vitality of the land and its people. As the eroding edge of the prehistoric Bay threatened a campsite, native tribes moved their tents farther inland. It may be argued that Colonists knew nothing of coastal geomorphology or sea-level rise and unwittingly made choices at odds with nature. Settlers created artificial boundaries called property lines and imported the concept of permanence and ownership. So began a cultural behavior in conflict with the dynamic landscape of coastal areas. Today we continue to develop along the coast, a movable boundary, making sea-level rise an even greater problem.

♦ Influence of European Settlement

Until the 1600s, the Chesapeake Bay watershed was covered with lush vegetation. Roots bound the soil and canopies of dense leaves tempered the effects of wind and rain on the land. Analysis of sedimentary layers shows that during the first stage of European colonization, people cleared about 20% of the land; by the mid-19th century thousands of acres of oak-dominated forest were cleared for corn and tobacco. After fields were depleted and abandoned, the soil had no protective ground covering. This allowed wind and rain to move millions of tons of precious topsoil into the Bay each year (Figure 18).

By the 1800s, siltation became such a problem that the county seat at Joppatown on the Gunpowder River was moved to Baltimore. Today the stone mooring posts which tethered ocean-going ships to the dock are more than two miles inland (Figure 20).

Sediment from agricultural erosion created mud flat areas on formerly sandy shorelines around the Eastern Shore. Marsh grasses colonized these mud flats, creating new wetlands. Today soil conservation practices and dam construction (causing sediment to accumulate in reservoirs rather than shallows) in concert with sea-level rise are tipping the scales the other way.

♦ Population Growth and Urbanization

Chesapeake Bay suffers from overwhelming and dynamic human impacts; too many people are creating too much waste and exceeding the limits of the natural system. In this uniquely interdependent estuarine ecosystem, the watershed is a funnel and the Bay is the recipient of whatever falls or washes in. Each individual's action is multiplied exponentially by the other 13 million people living in the watershed.

Between 1940 and 1986, the population in the Chesapeake Bay watershed increased 87%, with concentrations in the Richmond, Norfolk-Virginia Beach, and Baltimore-Washington areas (Figure 19). The watershed has degraded from a lack of planned development and increased pollution and congestion. Nearly a third of the land development presently stressing Chesapeake Bay occurred since 1970, only a few decades compared to the 350 years since European settlement. It is projected that by the year 2020, there will be over 16 million people living in the Chesapeake Bay region, twice the 1950 population figure.

Fresh water needs of the population, largely satisfied through groundwater pumping, are adding another dimension to the stresses and demands upon the Bay. Groundwater is fresh water that has seeped in over millennia and filled the sandy layers, called *aquifers*, beneath the land surface (Figure 21). Many miles inland these layers reach the surface in what are termed recharge areas. It is here that rainwater can seep into the sand layers and recharge the groundwater.

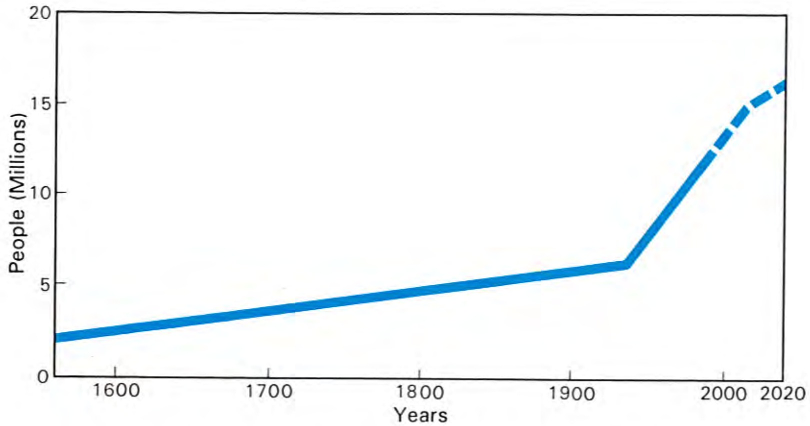


Figure 19. Population growth in the Chesapeake watershed.

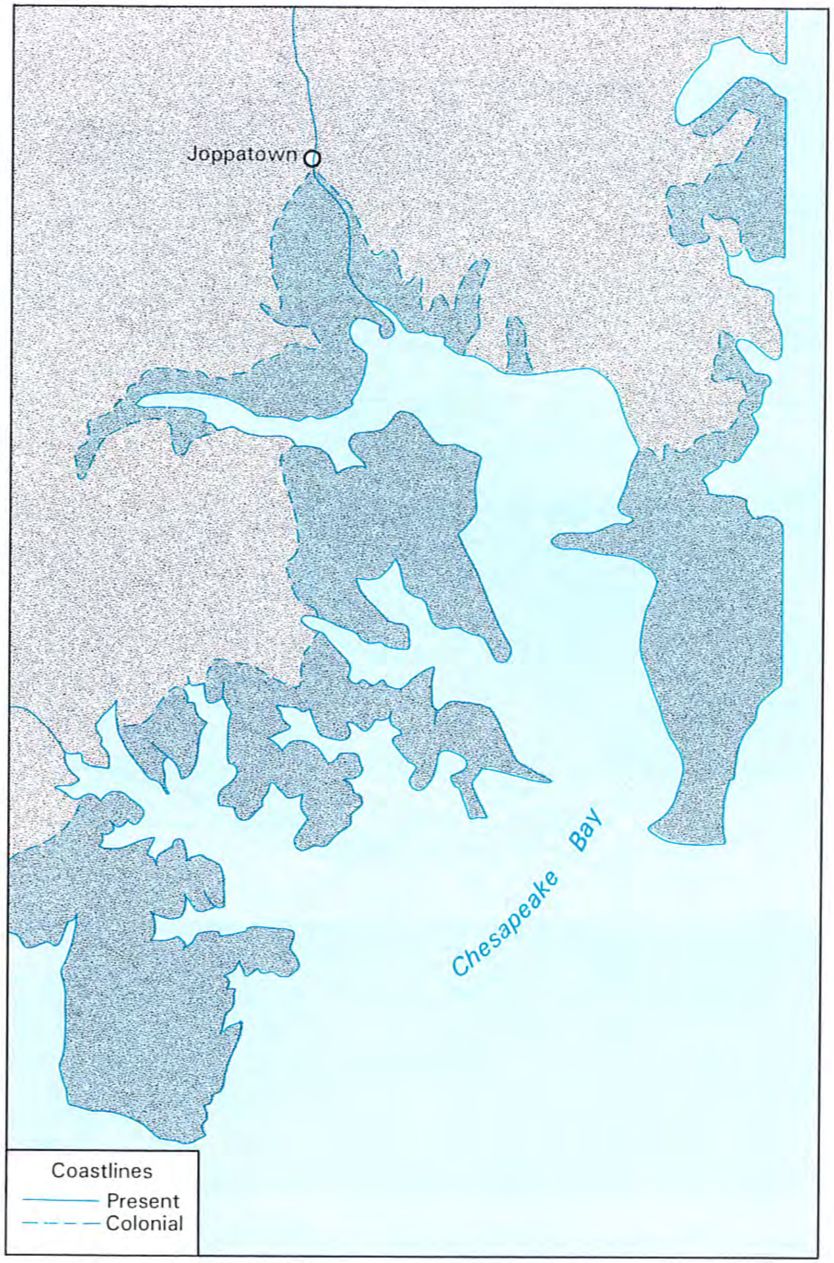


Figure 20. Poor land practices during Colonial times resulted in massive quantities of soil washing into nearby waterways, causing excessive sedimentation and fouling of navigable waters such as Joppatown harbor (EPA, 1989).

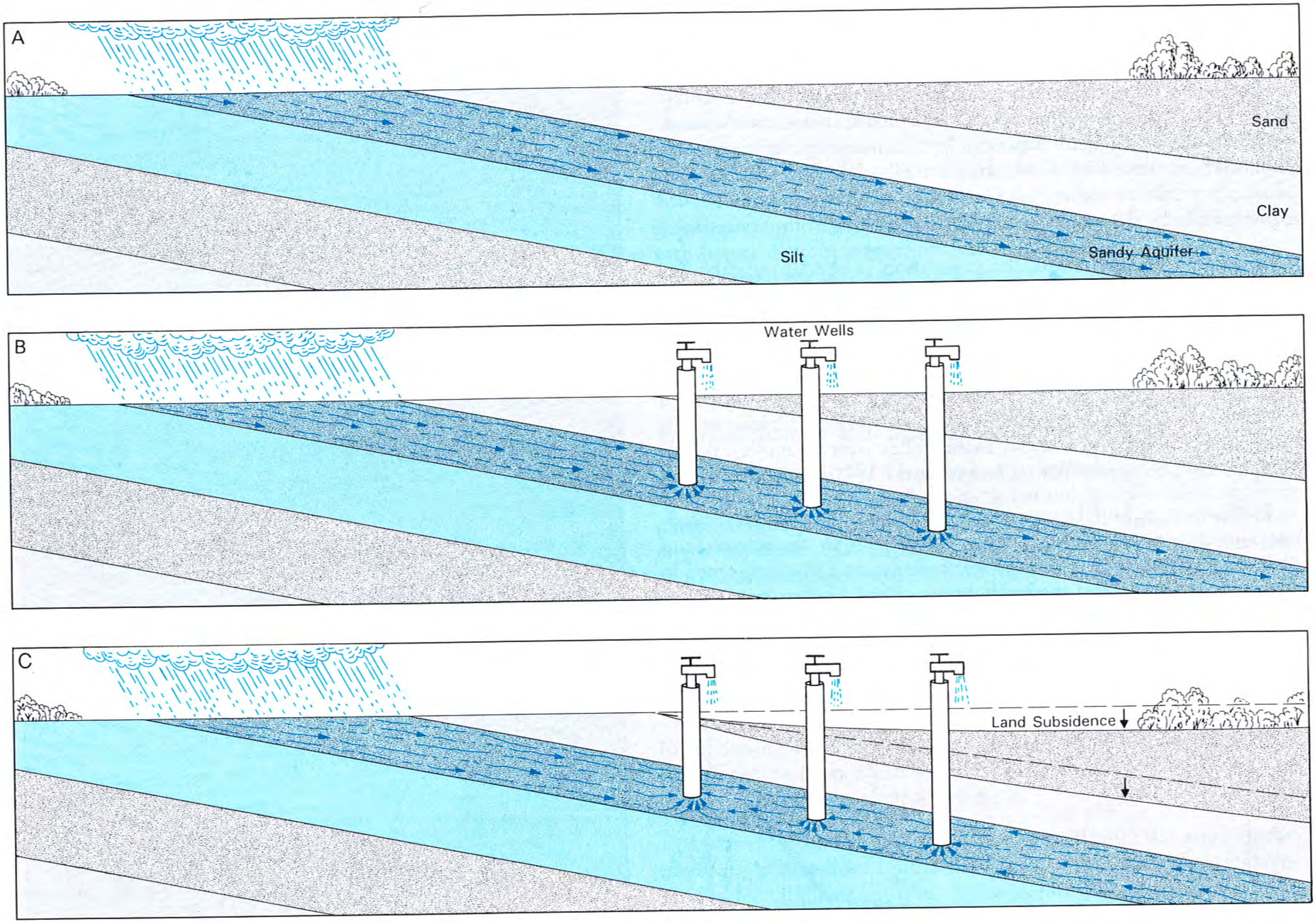


Figure 21. Groundwater withdrawal removes water from clay layers, resulting in layer compaction and land subsidence.

Population growth increases the demand for groundwater, which can be extracted many times faster than it can be recharged. Excessive demand leads to drilling of deeper wells and eventual failure (running dry) of near-surface aquifers. Buildings, pavements, and roads prevent water from seeping into the ground and recharging the aquifer. Perhaps most damaging and irreversible in the long run is subsidence or land-level drop, accounting for about half of the relative sea-level rise in the Chesapeake Bay region. While this generally is a geologic trend, it may be in part influenced by human activities.

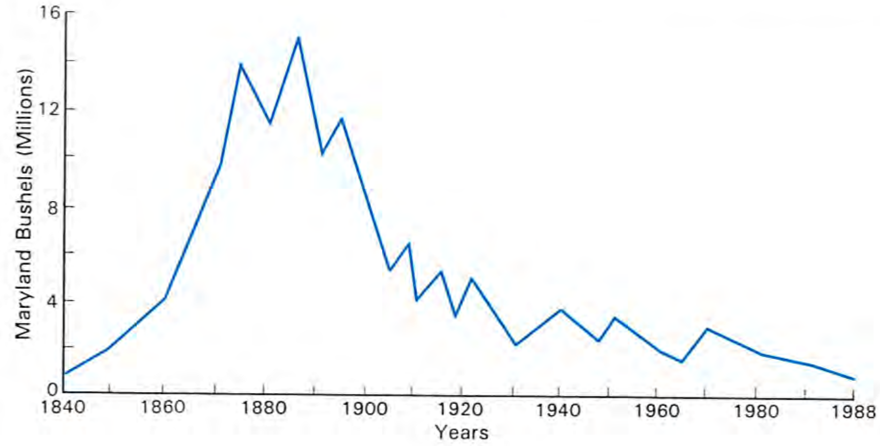
Clays, especially the marine clays in coastal regions, have a high water capacity. As water is extracted from sandy aquifers, moisture is drawn out of the surrounding clay layers, causing them to shrink. The land surface sinks in response to groundwater extraction (Figure 21).

Enhanced rates of subsidence in the Chesapeake Bay region during the last 100 years may be related to excessive groundwater extraction. Increased use of groundwater from subsurface aquifers in southern Delmarva began with seafood canning operations in the late 19th century and expanded with development of the poultry industry and truck farming. This timing coincides with increases in shore erosion of Bay islands as well as marsh loss.

♦ Loss of Habitat

Another result of urbanization has been the loss of habitats upon which animals feed and reproduce. Of the major habitat types in the Chesapeake Bay watershed, the brackish and tidal freshwater marshes, SAV beds, and oyster bars (see Figure 15) are of crucial importance to this estuarine ecosystem. Three kinds of wetlands—salt marsh, brackish marsh, and tidal freshwater marsh—develop natural zonations. In these three habitats, sea-level rise is a controlling factor of plant zonation. Therefore, accelerated sea-level rise causes serious alterations in these estuarine habitats.

Declining water quality from pollution has seriously impaired aquatic habitats throughout Chesapeake Bay. The principal sources of pollution are fertilizers, herbicides, pesticides, and organics from agricultural and urban landscapes, toxic chemicals from industrial sites, and nutrients and certain toxins from public sewage treatment plants. Controlling these sources of pollution has been the focus of a major regional effort to restore



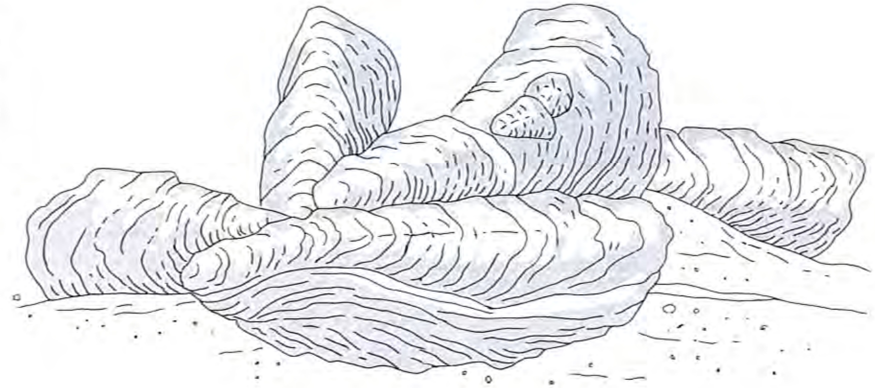


Figure 22. The number of oysters landed in the Bay has declined significantly during the last century.

Chesapeake Bay habitats. That effort recognizes the role of living resources in maintaining a healthy ecosystem. This biological filtering greatly reduces high turbidity which is a major stress to SAV and oysters. At the turn of the century, the oyster population was capable of filtering all the Bay water in only four days, according to estimates. Currently, the oyster population is so small that it takes more than a year to filter the Bay's water.

There are few self-sustaining natural oyster beds today (Figure 22). Decline of these natural beds has been linked to overharvesting, increased siltation, loss of the shell substrate on which the oyster spat set, declining water quality, and disease. Oysters and water quality are symbiotic. Water quality declines when there are fewer oysters to remove excess nutrients, and there are fewer oysters when water quality declines.

One impact of rising sea level is increased erosion, resulting in an influx of suspended sediment into the water column. Whether the shore responds by erosion or upland conversion depends on elevation, sediment type and supply, wave energy, tidal range, and rate of sea-level rise. Property owners, viewing erosion and upland conversion as a net loss of usable land, use various engineering techniques to temporarily stem the rising waters.

The use of shoreline engineering to halt upland conversion blocks the migration of marshes and dooms the habitat to inundation or drowning in place. Marshes at the bayward foot of bulkheads or revetments are not able to encroach upon the uplands and are gradually overwhelmed by a rapidly rising sea. The draining, dredging and filling of wetlands along Bay shores for commercial and residential development, agricultural land, and highways have also resulted in a net loss of habitat (Figure 23).

Figure 23. Subdivisions and condominiums, such as at Chesapeake Beach, Md., have been built on dredged and filled wetlands (photo by Stephen Leatherman).

Bay habitats are presently under much stress, and many are no longer healthy and resilient. Dwindling habitat is further compounded by a rising sea. Development along a dynamic and constantly changing coast creates a human-induced shortage of estuarine habitat by denying marshes the ability to migrate landward, and in so doing, makes sea-level rise an even greater problem.

Impacts of Sea-Level Rise: Coastal Land Loss

- *Western Shore*
- *Eastern Shore*
- *Bay Island Communities*

Chesapeake Bay serves as an ideal laboratory to investigate the physical effects of accelerated sea-level rise and to explore the range of impact and response strategies. The region is characterized by diverse coastal environments, from the high cliffs of the Western Shore to the low-lying coastal plain on the Eastern Shore (Figure 24). The Bay's shoreline, more than 8,100 miles long, is subject to all sea-level rise impacts: erosion, inundation of low-lying lands, wetland loss, salt-water intrusion into aquifers and surface waters, and increased flooding and storm damage. Bay islands that supported entire villages are disappearing, and vast expanses of salt marsh are drowning. With such a diversity of landforms and ecosystems responding to sea-level rise impacts, Chesapeake Bay serves as a microcosm of threatened coastal areas worldwide.

Coastal land loss in the Chesapeake Bay region is a major issue today because more and more people are moving closer to the water's edge. At the same time, sea level has been rising at a rapid rate—about 1 foot during the last century.

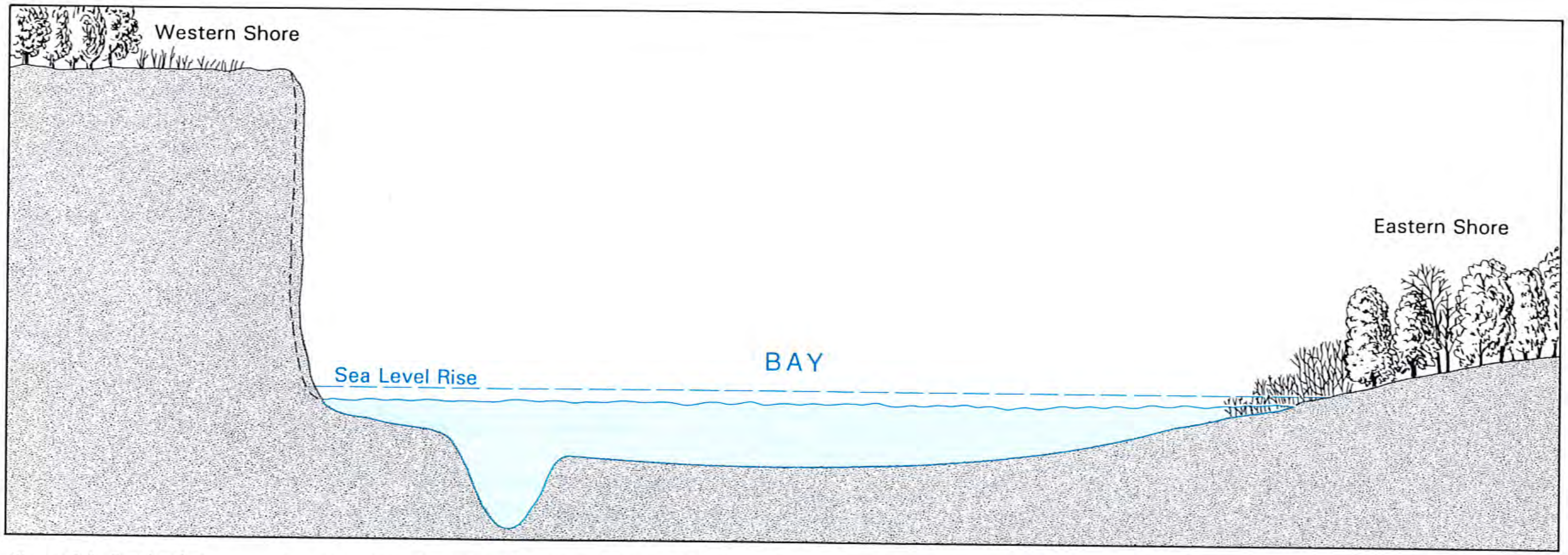


Figure 24. Sea-level rise causes land loss through erosion of Western Shore cliffs (note dashed line) and submergence of Eastern Shore wetlands (not to scale).

Over the next few decades we can anticipate that sea-level rise will be of a magnitude at least comparable to or slightly exceeding the rate of rise today, and *we must prepare for a 3-foot overall rise during the next 100 years* (see Figure 10). This amount of change could prove devastating to existing island communities, such as those on Smith and Tangier islands in Chesapeake Bay. In addition to increased flooding problems, erosion would be greatly accelerated by higher water levels.

The Chesapeake Bay coastline responds to sea-level rise in two different ways—submergence and erosion. Submergence is the total inundation of the land by the rising water, and erosion is the physical removal of sediment, resulting in land loss. Submergence and erosion are evident on the Bay's Eastern Shore, while cliff retreat through erosion is dominant on the Western Shore.

Land loss is not a recent phenomenon; it has occurred gradually at least since European settlement in response to slowly rising sea level, but map evidence indicates increased rates of loss in the last century. Because of the early exploration and settlement of the Chesapeake Bay region, excellent historical data are available. For instance, Kent Island was settled in 1631, and original Royal land charters and tax records of the Chesapeake Bay islands have been kept since that time. Maps, charts, and photos obtained from historical societies, museums, and the National Archives, document the changes over the centuries. Land loss information can also be obtained from newspaper accounts of storm events or the demise of an island (Tables 2 and 3).

Cockey's	Herring	Sharps
Cows	Long	Sherwood
Great Marsh	Powell	Swan
Hambleton	Punch	Turtle Egg
	Royston	

Table 2. Islands lost in Chesapeake Bay.

Island	Historic Acreage (date)	Recent Acreage (date)	% Lost	Comments
Poplar	1400 (1670)	125 (1990)	91	Abandoned in 1930
Sharps	890 (1660)	0	100	Drowned in 1962
St. Clements	400 (1634)	40 (1990)	90	Abandoned in 1920s
Barren	700 (1664)	250 (1990)	64	Abandoned in 1916
Hoopers	3928 (1848)	3085 (1942)	21	Submerging
Bloodsworth	5683 (1849)	4700* (1973)	17	Submerging
Holland	217 (1668)	140* (1990)	35	Abandoned in 1922
Smith	11033 (1849)	7825* (1987)	29	Submerging

**mostly marshy land*

Table 3. Historic size comparison of Chesapeake Bay islands.

♦ Western Shore

The Western Shore, the cliffed shoreline of Maryland, is composed of sediments ranging from loose sand to blue marine clays that tower up to 100 feet above the Bay water level (Figure 25). These impressive cliffs, almost vertical in places, are maintained by wave undercutting at their toe. Retreat rates average 1 to 2 feet per year based on a comparison of historical maps and charts.

Waves, particularly during storms, are literally eating away part of Maryland's history, as bits and chunks of sediment fall along the retreating cliff face. St. Clement's Island on the Potomac River, where the Colonists first landed in 1634, is considered the Plymouth Rock of the state of Maryland. When first settled, it covered over 400 acres and, as described in Captain John Smith's log, was "thickly wooded with cedars, sassafras and nut trees, with herbs and flowers everywhere"; today it has shrunk through cliff erosion to about 40 acres with few remaining trees. While the land area was dwindling, the U.S. government built a lighthouse on the southern tip of the island in 1853. The lighthouse remained active until the 1920s; eventually, erosion caused its collapse into the Potomac River.

Little of the pre-Colonial development was truly static in nature. As the eroding edge threatened a campsite, the people moved their tents and belongings farther inland. The European colonists, however, built more substantial housing, urbanized development, and lighthouses to mark the navigable channels. Unfortunately, not enough attention was given to the soft, erodible sediments upon which these structures and sentinels to the sea were built, and no one realized at that time that sea level was rising, mandating continued shore retreat.

Jutting out into the sea where the Potomac River empties into the Chesapeake Bay lies Point Lookout, one of the most scenic spots on the Bay. The original land grant of 2,964 acres originated from Lord Baltimore in 1634. As much as 50% of Point Lookout has eroded away in the past 100 years based on map comparisons (Figure 26).

Point Lookout has historically been a place of conflict dating back to disputes between the local Native Americans and settlers over land use. As early as the 1850s this neck of land was covered with wooden cottages and was used as a vacation resort area. The onset of the Civil War in 1862 brought on financial troubles, and the military took over the land. First

Figure 25. Erosion of the Western Shore cliffs has resulted in loss of houses (Randle Cliffs area) (photo by Stephen Leatherman).

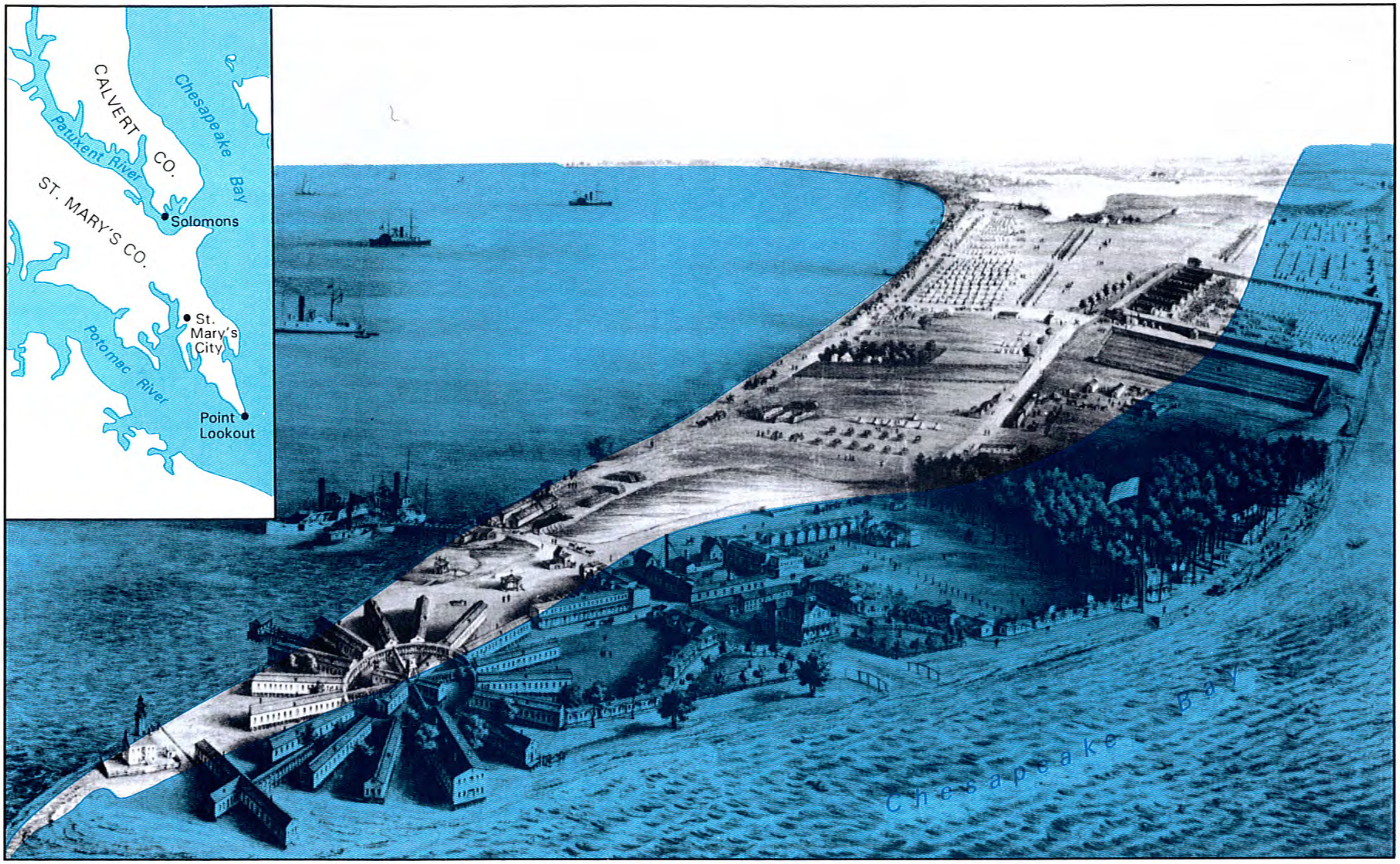


Figure 26. Map comparisons of Point Lookout, showing the pre-stabilized shoreline (in blue) superimposed on a Civil War-era map (National Archives).

it served as a hospital, but after the Battle of Gettysburg, the hospital was converted to a prisoner-of-war camp. Over 10,000 Confederate soldiers were confined here, and Point Lookout gained a brutal reputation at the time. Nearly all the remnants of this Civil War-age encampment have succumbed to the sea. While erosion has not been rapid by Baywide standards, a loss of several feet per year along the eroding edge can eventually claim considerable real estate. The still-functioning Point Lookout Lighthouse, once perilously perched on a sand shoal, has now been fortified by barged-in rock boulders (Figure 27).

Coastal land loss can be prevented, but the price can be high, depending on the wave energy and currents. The historic towns and present-day ports of Annapolis and Baltimore have been effectively fortified against sea-level rise impacts. These harbors are naturally protected from the larger waves along the main stem of the Bay by their location. Such urban areas receive protection through the construction and maintenance of bulkheads and revetments.

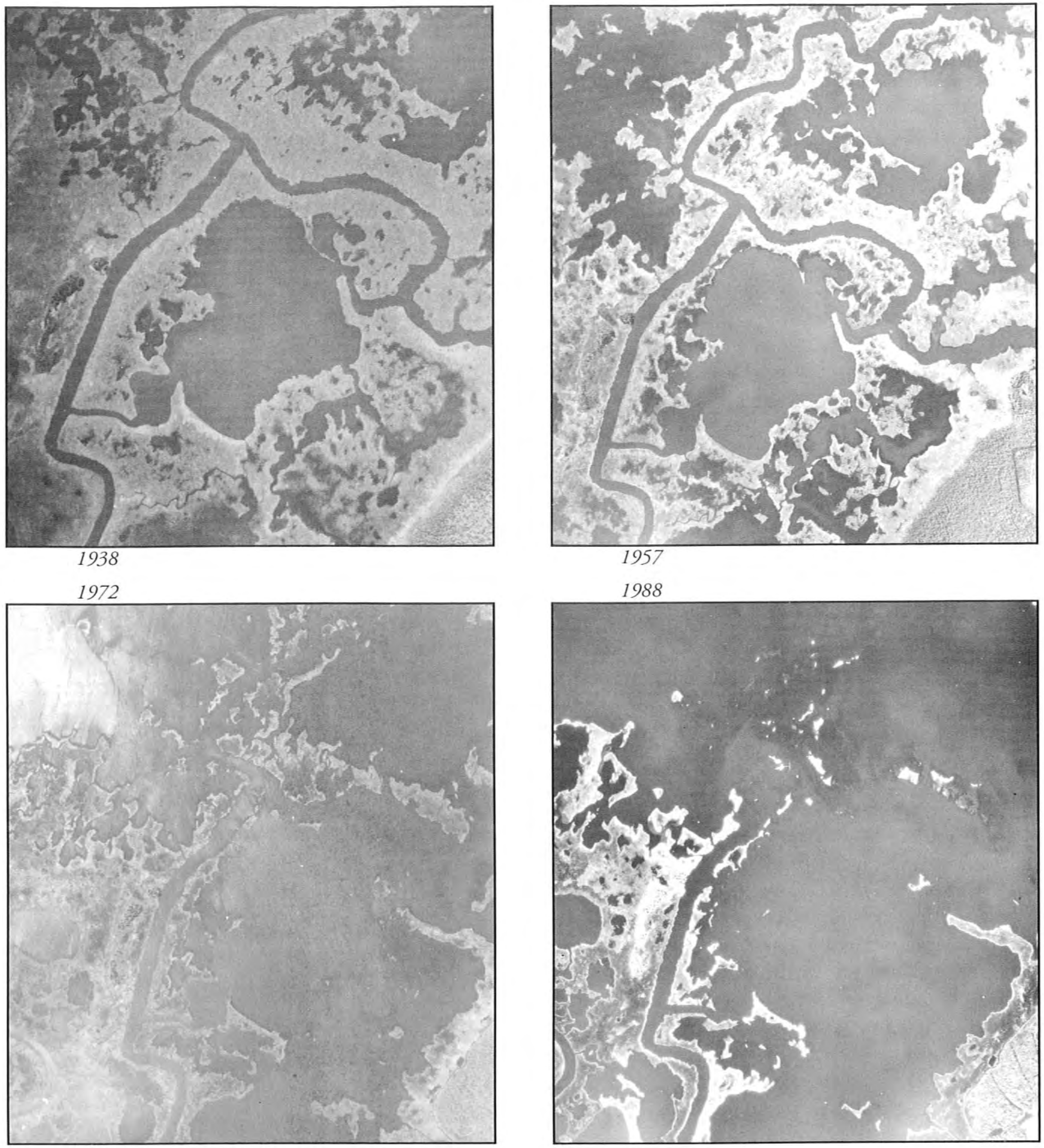
Figure 27. The Point Lookout Lighthouse area has been restored and stabilized but at the expense of the "point" (see Figure 26) (photo by Steven Leatherman).

♦ Eastern Shore

The flat and low-lying Eastern Shore contrasts sharply with the high eroding bluffs of the Western Shore (Figure 24). While there is erosion along the Bay edge, the primary response to rising sea levels on the Eastern Shore is submergence of upland areas and drowning of marshes.

The Eastern Shore is the site of one of the largest and most important expanses of coastal wetlands along the U.S. Mid-Atlantic coast. Blackwater National Wildlife Refuge near Cambridge, Maryland, is heavily used by Canada and snow geese and numerous species of ducks. Unfortunately, over one-third of the total marsh area, about 5,000 acres, was lost between 1938 and 1988, and the trend is continuing (Figure 28). Marsh losses have also been documented at other wildlife management areas in the Chesapeake and Delaware bays. During the past 50 years an imbalance has developed so that relative sea-level rise is occurring significantly faster than deposition on the marsh surface, eventually resulting in salt-water intrusion, waterlogging and plant demise. Intertidal salt marshes can only adapt to relatively moderate rates of sea-level rise; rapid increases in sea level (>0.2 inches per year) can literally drown most of the Bay's wetlands, converting them to shallow water areas. As sea levels continue to outpace the ability of the marsh to maintain elevation, the magnitude of the total loss will increase.

Figure 28. Historical air photos show rapid marsh breakup and loss at Blackwater National Wildlife Refuge in Dorchester County on the Eastern Shore of Maryland.



While existing salt marshes are sustaining heavy losses, which will only accelerate through time, the real hope for the future is the new marshes developing at the shore edge. However, the landward penetration of brackish water plants is viewed by Eastern Shore residents as a loss of good agricultural land (Figure 29). While the shrinking of the arable lands will undoubtedly reduce the farmer's yield of corn and other crops, the loss is not significant in the larger sense of the region; ample space is available elsewhere for agricultural activities, and defensive measures such as bulkheads are not justified because of the high cost of protecting this low-lying land.

The real fate of new marshes is determined by increased development. As the Bay's shore continues to urbanize, the perceived benefits of development may justify the costs. Bulkheads will then be built to line the high ground, and marshes will literally be squeezed out of existence with sea-level rise (Figure 30).

In summary, the Western Shore suffers the least by comparison from this interaction between land and sea. Here, older sediments interlaced with hard clay are more resistant to erosion, and the prevailing northwest winds generate wave action against the Eastern Shore. The rising water levels in the Bay continue to drown the low-lying coastal plain supporting an essential base of the Chesapeake's food chain—the living salt marsh. The islands of Chesapeake Bay suffer greatly from waves and tides as sea level slowly rises.

♦ Bay Island Communities

The human dimension of sea-level rise impacts is best exemplified by an examination of land loss on the Chesapeake Bay islands. Sizeable islands have been substantially reduced in size or even drowned as shown on successive 19th and 20th century maps and charts. Sharp decreases in island area led to the widespread abandonment of settlements on many of the islands in the first decades of this century (Tables 2 & 3). Depopulation of islands has occurred as rising sea levels have caused progressive erosion, submergence, or both, eventually eliminating habitation, especially in the wake of a hurricane.

The Bay islands, composed of fine-grained clay deposits, are artifacts of the changing course of the Susquehanna River. They lie generally north-south, parallel to the main stem of the Bay, a few miles from the Eastern Shore (Figure 31). Although their exact origin is still unknown,

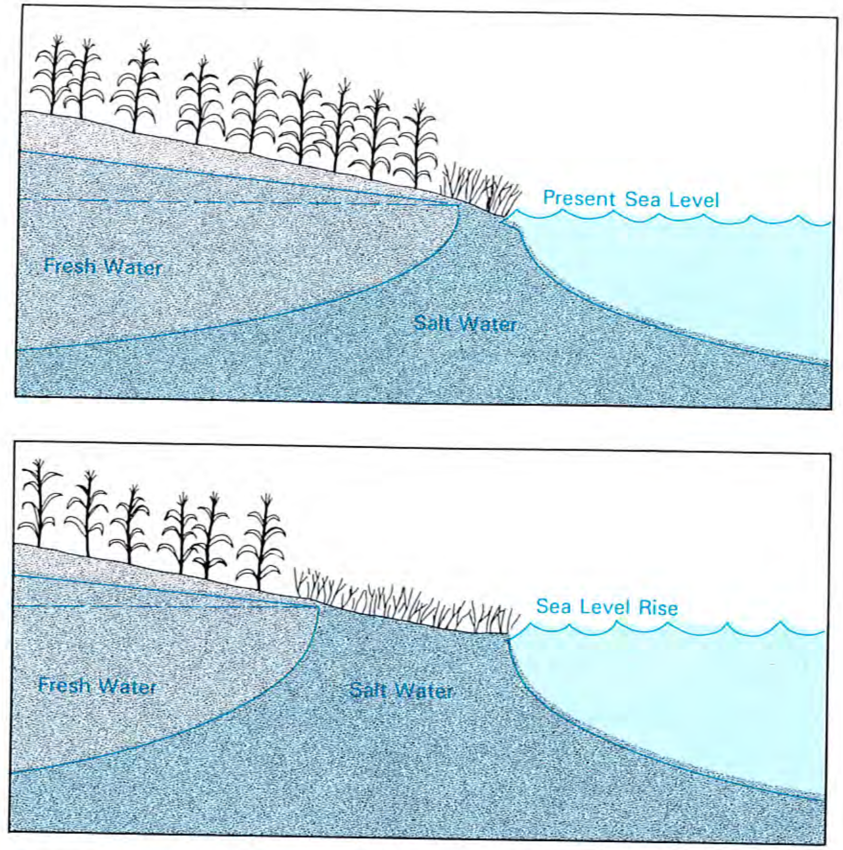


Figure 29. Saltwater intrusion and upland conversion occur on low-lying areas in response to rising sea level.

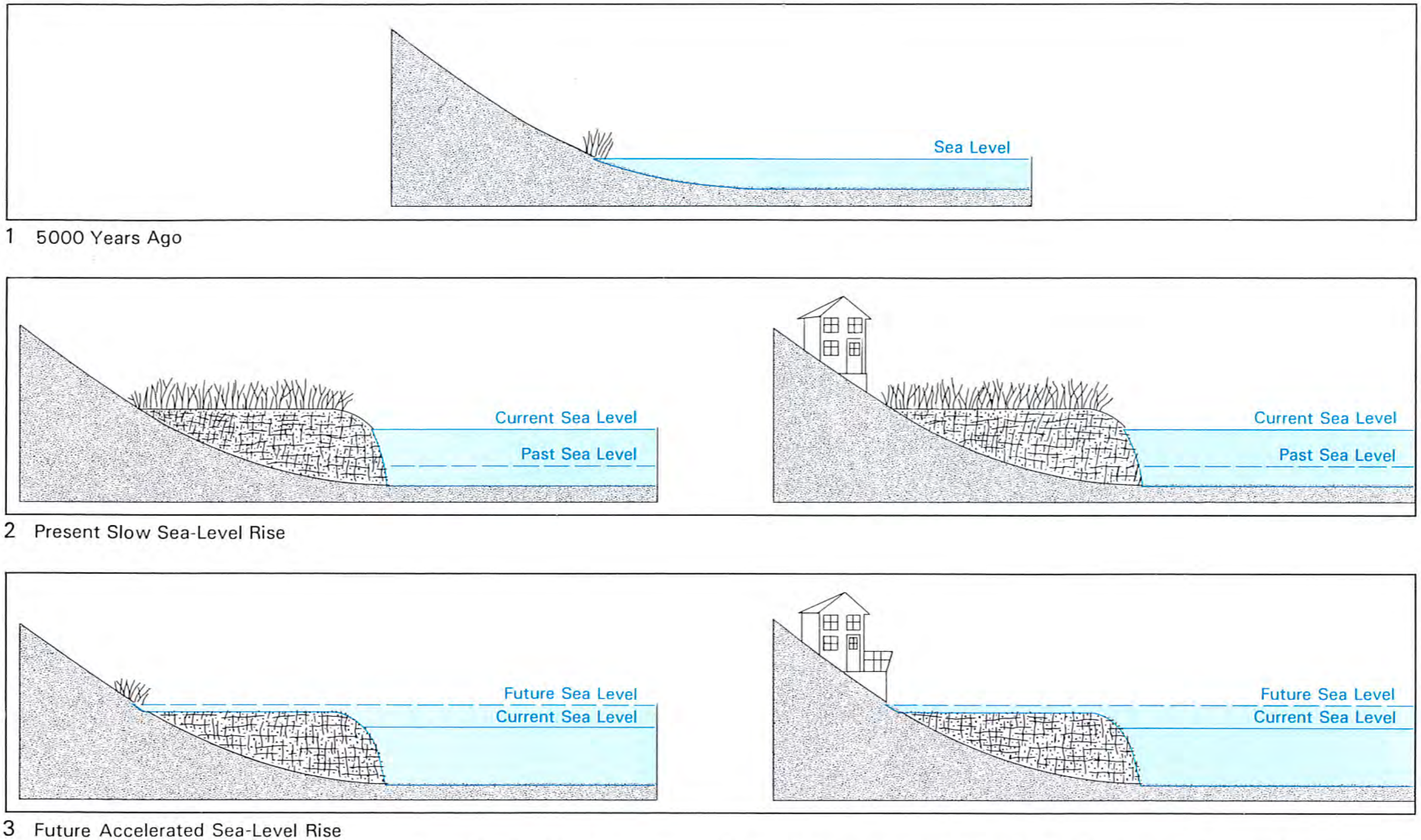


Figure 30. Evolution of coastal wetlands as sea level rises. Note that future protection of existing houses with bulkheads can result in a total loss of wetlands.

the islands were obviously land of higher elevation, probably connected to the mainland. Their erosion and submergence are a natural geomorphic phenomena driven by rising sea level.

The highest points on the Bay islands are ridges, but even here elevations of 10 feet are not reached. Most of the land area exists from near sea level to less than 5 feet above the present water level. The smallest islands of less than 1,000 acres, which also tended to be the lowest, have fared worse as sea levels rose and much dry land was lost. While the much larger islands of Smith and Tangier still support towns, the last permanent residents have left Holland and Poplar islands, and Sharps Island has totally vanished (Table 2).

Poplar Island

The original size of Poplar Island is estimated at 2,000 acres based on the outline of the existing sand shoal now surrounding the island. When first encountered by Captain John Smith in 1608, it was somewhat smaller. The first recorded sale transaction in the late 1670s reported 1,400 acres.

During the War of 1812, the British fleet occupied Poplar, as they had during the American Revolution. In 1848 the first truly accurate map of this island was produced by the U.S. Coastal Survey (Figure 32). The island was greatly reduced in size from the 1600s, but it still measured roughly 790 acres. Erosion and submergence continued to take their toll, and this single island split into a main island and several smaller islands, now known as the Poplar Island Complex.

Around 1900 at the height of settlement, about 15 families totalling 70 to 100 people lived on the Poplar Islands Complex. The main island was still large enough to support the small town of Valliant. This town included a general store, post office, school, church, and a sawmill. The community flourished until the 1920s when serious erosion became evident, and most islanders abandoned their homes. By 1930 Poplar was completely deserted.

The following year, a group of politicians purchased the Poplar Islands. They founded the exclusive Jefferson Islands Club in 1931. Many famous politicians, including Presidents Franklin D. Roosevelt and Harry S. Truman, came here for business as well as pleasure.

Fire destroyed the wooden clubhouse in 1946, marking the end of this era. This event, coupled with the island's continuing erosion and submergence, forced the group to relocate their Jefferson Islands Club to St. Catherine's Island in the Potomac River. (Unfortunately, they chose another eroding island on the Western Shore of Maryland; at one point this clubhouse was threatened and almost fell into the Potomac until fortified by a substantial and expensive seawall.)

Relative sea-level rise and the resulting erosion caused Poplar's demise. The island is slipping away at the rapid rate of more than 13 feet a year and will probably disappear by the turn of the century at present rates of land loss unless drastic action is taken (Figure 33).

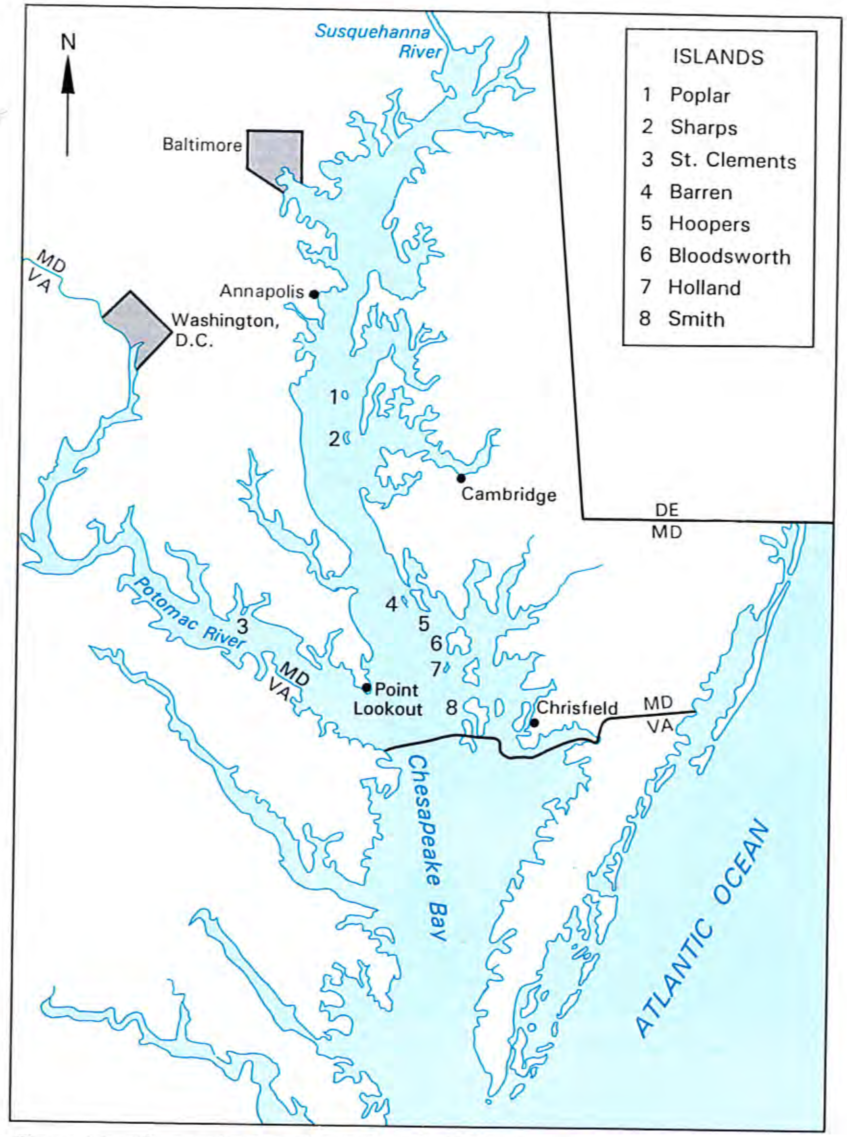


Figure 31. Chesapeake Bay islands (see also Table 3).

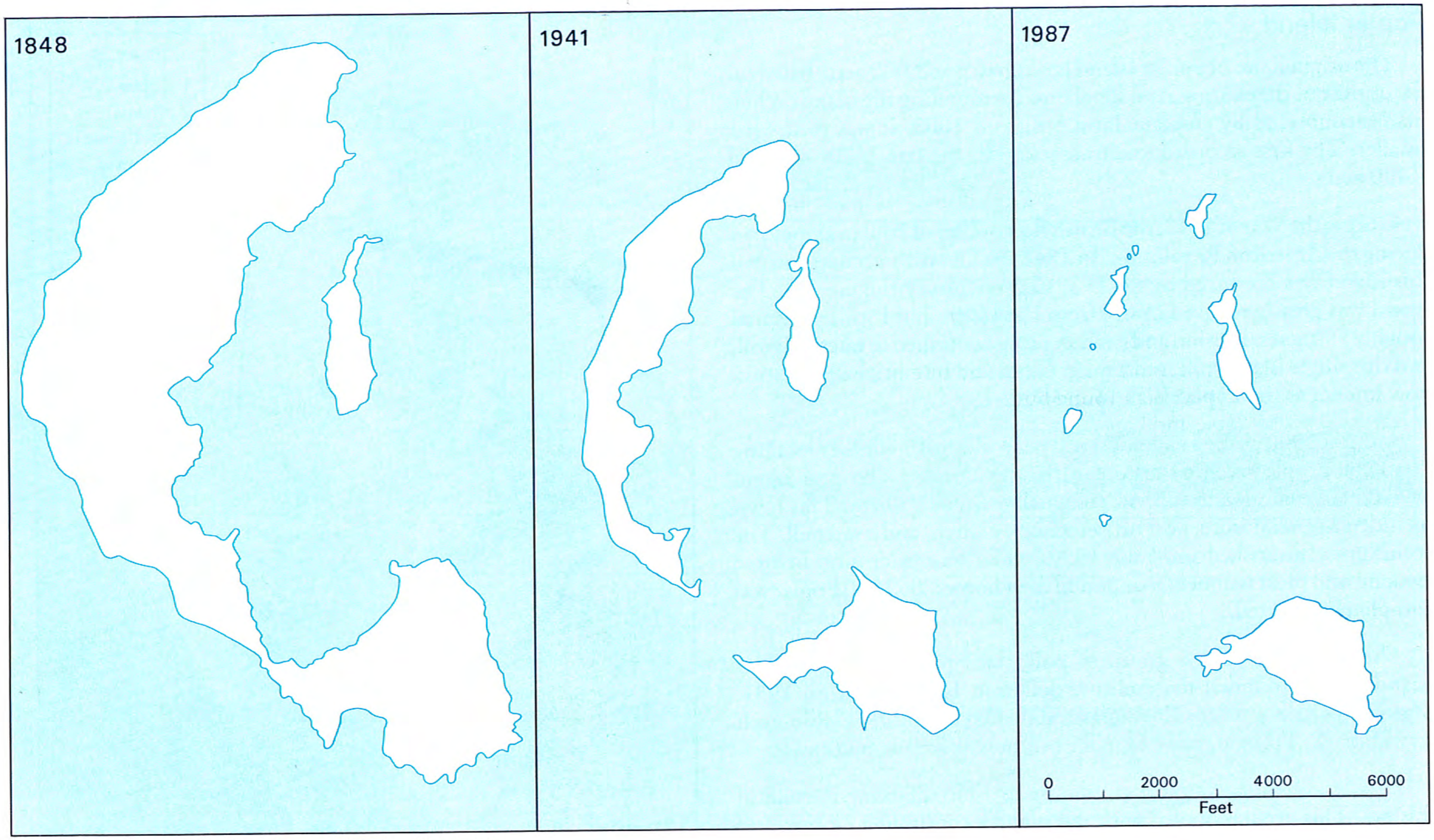


Figure 32. Historical shoreline changes of Poplar Island, Md.

The Maryland House of Delegates passed a resolution in 1968 to stop the erosion at Poplar Island. Federal and state governments completed a study calling for placement of structure around the islands to prevent erosion. High construction cost prevented the government from taking action. Poplar Island was fast on its way to becoming another sand shoal in Chesapeake Bay. However, recent efforts to stabilize the island and create habitat using deposited dredged material and sunken barges as breakwaters, may reestablish this one-time playground of presidents into a haven for wildlife.

Bloodsworth Island

Known locally as the "sinking island," Bloodsworth Island's arable land has given way to brackish water over the centuries, with corn fields reverting to salt marshes. The recorded history of Bloodsworth Island indicates the changing uses of the land over time in response to slowly rising sea level. The earliest map of the area by Augustine Hermann in 1673 shows the area as a series of small islets surrounded by a fringe marsh. At least 50 acres were under cultivation with a few small houses and fruit trees also present.

The first accurate map of the area, produced in 1849 by the U.S. Coastal Survey, shows seven structures on small upland tracts. By this time the island was dominated by wetlands, but brick rubble and building foundations have been found buried a half foot down. Because of the rising water table and higher salinity of the soil, the land became less suitable for permanent occupancy. By the 1920s the island was abandoned as tidal flooding caused the land to be too wet and salty for cultivation. The land area became covered with needle rushes and salt marsh grasses. Because of its somewhat protected position, shallow offshore water, and marshy, erosion-resistant substrate, the total land area has changed little by comparison to the more northerly islands in the Bay (Figure 31).

Bloodsworth Island now serves as a refuge for migrating waterfowl during the winter months; a nesting area for herons in the spring on the last remaining upland area (Fin Creek Ridge); and a bombing range and testing area for its present owner, the U.S. Navy. Despite the regular bombing of a portion of the island, Bloodsworth remains an important overwintering and stopover area for many waterfowl, including geese, ducks, herons, egrets, songbirds, osprey, and bald eagles (Figure 34).

The large expanse of marshes at Bloodsworth can maintain itself to some extent under slowly rising sea-level conditions, but an accelerated rate of rise will drown the salt marsh with no chance for migration. Therefore, without mitigating measures, this island group has a limited future under the present scenario of sea-level rise.

Smith Island

Smith is one of the largest islands in Chesapeake Bay; it is situated in the states of Maryland and Virginia (Figure 31). Three small towns are located here—Ewell, the largest and unofficial capital of the island;

Figure 33. Rapid shore erosion is undermining a forest on Poplar Island, Md. (photo by Ruth Chalfont).

Figure 34. Wildlife depends upon marshlands for feeding, resting and reproduction (USFWS photo).

Figure 35. The towns on Smith Island exhibit low relief and therefore much vulnerability to even small increases in sea level (USFWS photo).

Rhodes Point, the most fearful for its survival; and Tylerton, separated from the other two towns by water (Figure 35). The people of Smith Island remained almost isolated from the rest of the world for more than 200 years, and only since the beginning of the 20th century has their Elizabethan English become diluted with American English.

Smith Island is quite low, and several great storm tides have flooded the island in the past. Almost the entire island is low marsh, but this was not always the case, as Smith Island was first called "woodlands" by the Colonists. The perceived threat by local inhabitants is erosion, but in actuality, submergence due to rising sea levels is responsible for converting the dry woodlands to wetlands.

Smith Islanders have repeatedly tried to interest state and federal officials in constructing a bulkhead to prevent further erosion of the community's Bay side. Erosion is certainly a problem, but bulkheads alone will do nothing to stop submergence with rising sea levels. The only alternatives would be to raise the entire island land surface by jacking up the houses and pumping sand onshore from the adjacent shoals, or surrounding the developed areas with large ring dikes, making them like Medieval castles with natural moats. Neither option is being considered, although the U.S. Army Corps of Engineers has decided to explore the use of riprap and dredge material to reinforce rapidly eroding areas.

Smith Islanders are the "last of a dying breed," referring both to their Elizabethan heritage and dwindling population, a population that is also threatened by socioeconomic pressures in addition to environmental pressures. The 1910 census showed that there were more than 800 people living on the island. This number today is reported to be fewer than 400.

From the flatlands of the Eastern Shore to the steep cliffs on the Western Shore, shifting shorelines eternally place at risk seemingly secure civilizations. The eroded sediments find their way to other areas in the estuary, contributing to the irreversible process destined over time to fill in even as the water eats away at the land. Just as the primordial Susquehanna River flooded some eight millennia ago to form the Bay, so this estuary has a limited life span.

Society's Response to Sea-Level Rise

- *Retreat*
- *Structural Erosion Control*
- *Retreat vs. Stabilization*
- *Restoration and Sediment Recycling*
- *State Response*

As a society we have ignored sea-level rise and its impacts on Chesapeake Bay. The sea has always been the great leveler and as such, the Chesapeake is a microcosm of sea-level rise impacts worldwide. With increased greenhouse gases, higher global temperatures, sea-level rise, beach erosion, wetlands loss and increasing coastal populations, coastal ecosystems such as the Chesapeake are compromised (Figure 36). A 3-foot rise in sea level is predicted during the next century. Sandy beaches are expected to erode at 2 to 5 times their current rate. Eroding Bay islands could be lost in decades.

There are essentially three responses to rising sea level: *coastal retreat, beach maintenance,* and *shoreline fortification.* The latter option is the most expensive but has been successful in Chesapeake Bay due to relatively low wave energies. Planned retreat is often the best option for sparsely developed areas. Beach maintenance is the most attractive alternative when high value is placed on recreational beaches such as Sandy Point State Park in Maryland. Selection of the appropriate response will depend on site-specific conditions, costs, land values, and coastal infrastructure.

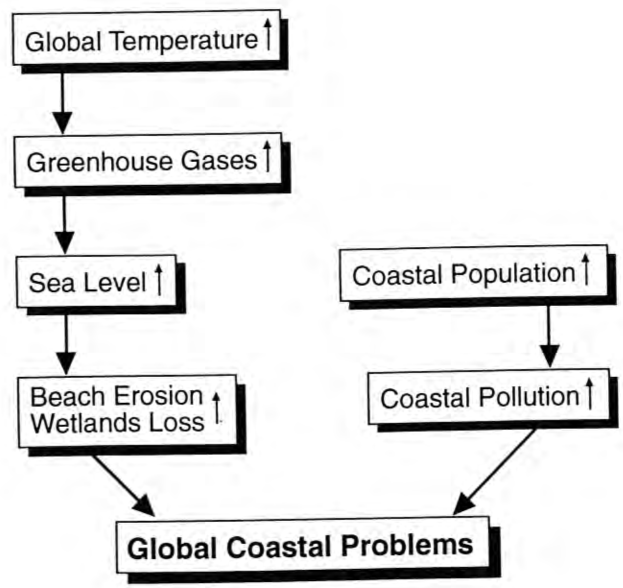


Figure 36. Global coastal problems: a collision course.

♦ Retreat

Retreat is the best response to sea-level rise when shoreline stabilization is environmentally unsound or economically unfeasible. The policy required to implement a gradual retreat from the shore includes zoning, building codes, setbacks, and land-use plans. Planning a strategy for retreat from the coast can take years to decades of lead time; therefore, community retreat should be planned well in advance and carried out in a logical, orderly manner.

Three mechanisms of retreat are recommended: first, removal of buildings that are threatened or interfere with beach access as shore retreat proceeds; second, prohibition on reconstruction of buildings that are destroyed or significantly damaged (>50%) by storms, and major renovations prohibited to buildings threatened by sea-level rise; and finally, new beachfront construction should not be permitted.

Some states have already made strides toward gradual retreat. Maine has adopted *presumed mobility* of the shoreline as a way to guide coastal development and to protect habitats, allowing the flow of sand or water within the coastal system. The idea of presumed mobility is to meld short-term development aims with long-term goals for maintenance of wetlands and other coastal ecosystems. Maryland has enacted *critical areas* regulations to provide a 1,000-foot wide shore buffer for all tidal waters.

♦ Structural Erosion Control

Coastal property is often protected by construction and maintenance of *bulkheads* or *revetments*. Bulkheads are vertical walls built parallel to the shoreline to hold back the sea and to "shore up" the land to prevent erosion (Figure 37). Revetments, made of stone or concrete rubble, cover the shore at a sloping angle (Figure 38). Coastal land loss can be prevented, but the price is often high, depending on wave energy and currents.

Bulkheads are the most commonly engineered structures along the Bay shoreline. However, because these structures are immovable, they prevent the landward migration of marshes and other wetlands. Fronting beaches eventually disappear as erosion proceeds. Wooden bulkheads, treated with toxic chemicals to prevent rotting and biological degrada-

Figure 37. Bulkheads have been used extensively throughout the Bay to stabilize upland areas, but at the expense of the beach (USFWS photo).

Figure 38. Riprap revetment is preferred over bulkheads for shore stabilization in the Bay (USFWS photo).

Figure 39. Offshore breakwaters with beach fill have been used at Bay Ridge, Annapolis to protect the cliff and provide a recreational beach (photo by Ed Fulford).

tion, also provide no habitat for plants and animals, and chemicals can leach out of the wood into Bay waters.

Revetments or riprap last longer than bulkheads because they are constructed of rocks and placed on an angle with the natural slope of the shore. Waves dissipate their energy over the stones and flow back without causing significant erosion. Rocks can provide habitat for plants and mollusks such as oysters and mussels, depending on wave energy, and they create a more natural interface.

Both bulkheads and revetments must be designed with wraparound ends so waves do not scour out the upland soil, undermining their stability. However, given the transient nature of a migrating coast driven by sea-level rise, all structures are subject to failure; maintenance and storm impact will determine when.

Offshore breakwaters are perhaps the best stabilizing option, but they are the most expensive. Breakwaters are designed to lower wave energy and hence to reduce the erosive potential along the shoreline. Rocky breakwaters provide a substrate for shellfish and plant life, and they sometimes protect an area for the establishment of a small salt marsh. With the construction of offshore breakwaters, several communities have rebuilt and stabilized their shorelines (Figure 39).

♦ Retreat vs. Stabilization

The costs and benefits of stabilization versus retreat must be carefully examined. Understanding shoreline behavior and planning accordingly is the most efficient approach to living near a dynamic coast. Setbacks should be defined so buildings are not constructed near a moving shore. South Carolina mandates a setback 40 times the average annual erosion rate for a single family home and 60 times for larger structures. North Carolina prohibits erosion control structures so that building close to an eroding shore will eventually result in a loss of property. The National Flood Insurance Program is already burdened with billions of dollars of insured properties constructed too close to the water's edge. Building setbacks basically represent a policy of gradual retreat from the shore.

Retreat can occur in a well-planned manner with long-term vision, or abandonments could be forced by catastrophic events (Figure 40). Unprotected and unwisely developed coastal areas appear increasingly vulnerable to catastrophic hurricanes and northeasters. By contrast, the Dutch have long constructed dikes and barriers to protect highly urbanized areas. These are, however, high-cost, high-maintenance responses to sea-level rise. For the Chesapeake Bay islands, often it is impractical and prohibitively expensive to prevent Baywide land loss in the face of rising sea levels. Historically, Bay islanders have retreated to the mainland when overcome by salinization, erosion, and submergence of their land.

Engineering and technological solutions to sea-level rise impacts are sometimes seen as economically feasible when viewed over the short term. Thus the construction of expensive erosion-control structures to protect shorefront buildings continues. With foreknowledge that sea-level rise is occurring, there is the opportunity for public education and long-term planning. Unfortunately, the gradual, ongoing retreat of the Bay shoreline through erosion and submergence is not yet a concern of most elected officials and the public. Therefore, long-term planning has not occurred.

Figure 40. A hunting lodge on Barren Island collapses as shore erosion continues unabated (USFWS photo).

Figure 41. Marsh establishment is a nonstructural way to stabilize low-energy shores and provide habitat for fish and wildlife (top is planted area and bottom is same area a year later) (USFWS photos).

♦ Restoration and Sediment Recycling

Vegetation can be established in low wave energy areas in the lee of offshore breakwaters or along the Bay's tributaries to restore marshlands, increase habitat, and trap sediment (Figure 41). Grading to appropriate slopes or sand filling may be necessary if a wave-cut bank has formed. Along the main body of the Bay, where storm waves can be more than 3 feet in height, simple initiation and maintenance of a vigorous stand of salt marsh vegetation is not practical.

Protection, enhancement, and restoration of Chesapeake Bay wetlands is an important non-structural erosion control option. Marsh formation should be encouraged wherever possible. Without wetlands we lose an important component of the food chain, a cleansing filtration system, and protection from storms and flooding. When marshes encroach onto agricultural land through the process of upland conversion, defensive measures are generally not economically justified. Even though marshes are protected by federal legislation, bulkheads built along the higher ground to protect houses will squeeze this vital habitat out of existence with sea-level rise (see Figure 30).

Chemically clean dredged material can be used for beach nourishment or habitat restoration. Dredging of harbors and channels, such as the outer Baltimore Harbor and the mouth of the South River, is an ongoing necessity for shipping and commerce. This dredged material is dumped in designated areas throughout the Bay. As these spoil areas fill, innovative solutions are necessary for future disposal of this material. For example, clean dredged material has been placed along the shoreline at Eastern Neck National Wildlife Refuge for marsh reestablishment. In other coastal areas, there has been success with spraying thin deposits of dredged sediment over marshes to aid in their upward growth and to counter the effects of sea-level rise. This concept of sediment recycling has many potential benefits. Like other resources, sediment remains useful and no longer is viewed as a burdensome waste.

Sediment recycling for habitat restoration is planned for some eroding Chesapeake Bay islands that serve as habitat for black ducks, mallards, great blue herons, egrets, ospreys, and bald eagles. State and federal agencies have initiated a cooperative effort to use dredged material for habitat restoration at Poplar Island (Figure 42). Construction of a riprap berm with dredge material along the historic "footprint" of the island will build up the land. The dredge material will be used to fill some areas to marsh elevation and convert other areas to uplands for nesting habitat. Tidal ponds also will be created and planted with SAV.

The U.S. Navy has started a significant restoration project in partnership with the Maryland Department of Natural Resources, University of Maryland's Laboratory for Coastal Research, Ducks Unlimited, and the U.S. Fish and Wildlife Service on Bloodsworth Island. At the turn of the century, healthy populations of waterfowl and other wildlife inhabited loblolly pine forests, agricultural fields, and a diverse wetland system. Saltwater intrusion caused by rising sea level has destroyed the fields and forests, leaving only black needle rush, a vegetation less attractive to wildlife.

In an effort to counteract this loss of habitat, the U.S. Navy has taken a pro-active approach. Artificial nesting structures have been erected to provide additional nesting sites for great blue herons and osprey (Figure 43). Over 1,000 acres have been set aside, free from military operations, to protect a large nesting colony of great blue herons. Potholes created by bombing activities now support SAV that is very attractive to waterfowl. In support of the Chesapeake Bay Agreement, the U.S. Navy on Bloodsworth Island is continuing to develop and implement creative solutions to habitat loss.

Figure 42. Sketch of a plan to restore Poplar Island.

Figure 43. The U.S. Navy placed artificial nesting structures on Bloodsworth Island to provide nesting sites for ospreys (U.S. Navy photo).

♦ State Response

It is important that the states of Maryland and Virginia begin the process of adapting to and planning for rising sea level to avoid future impacts. We are at a critical juncture of population increase and shore development in the watershed. Selection of the appropriate response will vary by site, but comprehensive Baywide planning is necessary. Future development should accommodate, not increase, vulnerability to future sea-level rise. Locations of coastal infrastructure (roads, bridges, utilities and sewers) and coastal defenses (bulkheads and revetments) should be planned based on the most reasonable estimates of sea-level rise (i.e., 2 to 3 feet in the next century). While coastal zone management plans should ensure that risks to human populations are minimized, these management plans should also protect and restore estuarine habitats to ensure the survival of this irreplaceable coastal environment.

At the Crossroads: A Cooperative Vision

Accelerated sea-level rise places Chesapeake Bay at the crossroads. Even more poignant, however, is that civilization is at the crossroads, for it is our reliance on the values of Chesapeake Bay that stands in jeopardy.

The lessons we have learned from science and from our own experience should move us to take a responsible course of action. Commitments have already been made to reverse the problems of toxic and nutrient pollution, overharvesting, wetland loss, and careless development. To create a vision of change for the elusive and almost insidious problem of sea-level rise, we must continue to collect information and apply it wisely. The more we know about sea-level rise and the estuarine environment in which we live, the better prepared we will be to identify and adopt alternative courses of action.

We have two basic mandates: *reduce greenhouse gases and prepare civilization for a continued and accelerated rise in sea level.* The way to reduce greenhouse gas emissions is to reverse those practices discussed earlier: prevent deforestation, promote reforestation, and maximize use of forest products; reduce automobile emissions, seek alternatives sources to fossil fuels (e.g., solar and wind), use less polluting fossil fuels; reduce energy consumption and seek energy-efficient technology and products; recycle products and design new products for comprehensive recycling; recover and market methane from landfills; recover and use waste heat (cogeneration); and, most important, curb population growth.

Preparing for sea-level rise will require a completely new way of designing and planning the land we occupy as a society. The essential response will be "fight" or "flight"—to protect uplands, if feasible, or to retreat from the eroding and submerging shores to allow for landward migration of marshes. Without a commitment to responsible long-term planning, society will forever be burdened with the slow destruction of shorefront homes and coastal infrastructure. This approach will be extremely difficult to implement because waterfront real estate is so valuable. However, without long-term planning that includes zoning, open space, and buffers, society at large will have to pay for the continuous losses along the shoreline. These costs will be driven home by the impact of a catastrophic coastal storm.

Commitments must also be made to enhance and restore lost or degraded habitats to offset development pressures. Governments, industry, and private citizens can contribute to these efforts. Beneficial use of clean dredged material to restore lost habitats should be investigated at every opportunity. Reestablishment of fringe marshes along shorelines and prudent use of riprap can also be appropriate solutions. New programs encouraging private citizens to restore natural habitats on their property must be expanded, such as the Wetlands Reserve Program, Partners for Wildlife Program, and Waterfowl Habitat Improvement Program.

In ***Turning the Tide***, Tom Horton and William Eichbaum discuss resilience as the Bay's ability to "buffer and stabilize itself against both natural and human environmental insult." Much of this resilience, which lies in coastal wetlands, submersed grasses, oyster bars and other natural features, has been lost. Our cooperative mandate is to move forward with pro-active plans to restore this resilience. Every decision must be backed with information, education, and research, and made in the ethics of sound conscience. Legislation must spell out limitations and provide proper incentives. Through this lens of a cooperative vision, all matters, including our response to sea-level rise, must be decided for the good of society and for the long-term health and vitality of Chesapeake Bay.

Bibliography

Downs, L.L. and S.P. Leatherman, 1993, Shoreline Trend Analysis: Calvert County, Maryland, *Journal of Coastal Research*, in press.

Douglas, B.C., 1991, Global Sea-Level Rise, *Journal of Geophysical Research*, V. 96, p. 6981-6992.

Gehrels, W.R. and S.P. Leatherman, 1989, *Sea-Level Rise: Animator and Terminator of Coastal Marshes: An Annotated Bibliography on U.S. Coastal Marshes and Sea Level Rise*, Vance Bibliographies, Monticello, Il., 39 pp.

Horton, Tom and William Eichbaum, 1991, *Turning the Tide: Saving the Chesapeake Bay*. Island Press, Washington, D.C., 324 pp.

Intergovernmental Panel on Climate Change, 1990, *Scientific Assessment of Climate Change*, Working Group I., WMO-UNEP, Geneva, Switzerland.

Kearney, M.S. and J.C. Stevenson, 1991, Island Land Loss and Marsh Vertical Accretion Rate: Evidence for Historical Sea Level Changes in Chesapeake Bay. *Journal of Coastal Research*, V.7, p. 403-415.

Kennedy, V.S., 1990, Anticipated Effects of Climate Change on Estuarine and Coastal Fisheries, *Fisheries*, V.15, p. 16-24.

Leatherman, S.P., 1986, *Effects of Sea-Level Rise on Coastal Ecosystems*, U.S. Senate Publication 99-723, Washington, D.C., p. 141-153.

Leatherman, S.P., 1992, *Coastal Land Loss in the Chesapeake Bay Region: An Historical Analog Approach to Global Change Analysis and Response, in the Regions and Global Warming: Impacts and Response Strategies*, J. Schmandt, ed., Oxford University Press, p. 17-27.

National Research Council, 1987, *Responding to Changes in Sea Level: Engineering Implications*, National Academy Press, Washington, D.C., 148 pp.

National Research Council, 1990, *Managing Coastal Erosion*, National Academy Press, Washington, D.C., 182 pp.

Orson, R., W. Panageotou and S.P. Leatherman, 1985, Response of Tidal Salt Marshes of the U.S. Atlantic and Gulf Coast to Rising Sea Levels. *Journal of Coastal Research*, V.7, p. 29-37.

Reid, Walter V. and Mark C. Trexler, 1991, *Drowning the National Heritage: Climate Change and U.S. Coastal Biodiversity*, World Resources Institute, Washington, D.C., 48 pp.

Stevenson, J.C., L.G. Ward, M.S. Kearney and T.E. Jordan, 1985, *Sedimentary Processes and Sea-Level Rise in Tidal Marsh Systems of Chesapeake Bay in Wetlands of the Chesapeake*. Washington, D.C.: The Environmental Law Institute, p. 37-62.

Schubel, J.R., 1986, *The Life and Death of the Chesapeake Bay*. Maryland Sea Grant, University of Maryland, College Park, Md., 45 pp.

Tennenbaum, M.S. and R. Costanza, 1990, The Plight of the Chesapeake, in *NPG Forum Paper*, Teaneck, N.J., 6 pp.

United States Environmental Protection Agency, 1989, *Chesapeake Bay: Introduction to an Ecosystem*. Washington, D.C., 32 pp.

Vellinga, P. and S.P. Leatherman, 1989, Sea-Level Rise, Consequences and Policies, *Climatic Change*, V.15, p.175-189.

White, Christopher, 1989, *Chesapeake Bay: Nature of the Estuary, A Field Guide*, Tidewater Publishers, Centreville, Md., 212 pp.

Wray, R., 1992, *Island Land Loss in the Chesapeake Bay, M.S. Thesis*, University of Maryland, College Park, Md., 178 pp.