Shore Erosion as a Sediment Source to the Tidal Potomac River, Maryland and Virginia

A Water-Quality Study of the Tidal Potomac River and Estuary

United States Geological Survey Water-Supply Paper 2234–E

ERRATA SHEET

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pg. E14 fig. 12B	change scale	2" = 7.29 miles
pg. E16 fig. 13B	change scale	2" = 7.29 miles
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By Andrew J. Miller

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2234–E

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FOREWORD

Tidal rivers and estuaries are very important features of the Coastal Zone because of their immense biological productivity and their proximity to centers of commerce and population. Most of the shellfish and much of the local finfish consumed by man are harvested from estuaries and tidal rivers. Many of the world's largest shipping ports are located within estuaries.

Many estuaries originate as river valleys drowned by rising sea level and are geologically ephemeral features, destined eventually to fill with sediments. Nutrients, heavy metals, and organic chemicals are often associated with the sediments trapped in estuaries. Part of the trapped nutrients may be recycled to the water column, exacerbating nutrient-enrichment problems caused by local sewage treatment plants, and promoting undesirable algae growth. The metals and organics may be concentrated in the food chain, further upsetting the ecology and threatening the shell and finfish harvests. Our knowledge of the processes governing these phenomena is limited and the measurements needed to improve our understanding are scarce.

In response to an increasing awareness of the importance and delicate ecological balance of tidal rivers and estuaries, the U.S. Geological Survey began a 5-year interdisciplinary study of the tidal Potomac River and Estuary in October of 1977. The study encompassed elements of both the Water Resources Division's ongoing Research and River Quality Assessment Programs. The Division has been conducting research on various elements of the hydrologic cycle since 1894 and began intense investigation of estuarine processes in San Francisco Bay in 1968. The River Quality Assessment program began in 1973 at the suggestion of the Advisory Committee on Water Data for Public Use which saw a special need to develop suitable information for river-basin planning and water-quality management. The Potomac assessment was the first to focus on a tidal river and estuary. In addition to conducting research into the processes governing water-quality conditions in tidal rivers and estuaries, the ultimate goals of the Potomac Estuary Study were to aid water-quality management decision-making for the Potomac, and to provide other groups with a rational and well-documented general approach for the study of tidal rivers and estuaries.

This interdisciplinary effort emphasized studies of the transport of the major nutrient species and of suspended sediment. The movement of these substances through five major reaches or control volumes of the tidal Potomac River and Estuary was determined during 1980 and 1981. This effort provided a framework on which to assemble a variety of investigations:

(1) The generation and deposition of sediments, nutrients, and trace metals from the Holocene to the present was determined by sampling surficial bottom sediments and analyzing their characteristics and distributions.

(2) Bottom-sediment geochemistry was studied and the effects of benthic exchange processes on water-column nutrient concentrations ascertained.

(3) Current-velocity and water-surface-elevation data were collected to calibrate and verify a series of one- and two-dimensional hydrodynamic flow and transport models.

(4) Measurements from typical urban and rural watersheds were extrapolated to provide estimates of the nonpoint sources of sediments, nutrients, and biochemical oxygen demand during 1980 and 1981.

(5) Intensive summertime studies were conducted to determine the effects of local sewage-treatment-plant effluents on dissolved-oxygen levels in the tidal Potomac River.

(6) Species, numbers, and net productivity of phytoplankton were determined to evaluate their effect on nutrients and dissolved oxygen.

(7) Wetland studies were conducted to determine the present-day distribution and abundance of submersed aquatic vegetation, and to ascertain the important water-quality and sediment parameters influencing this distribution.

(8) Repetitive samples were collected to document the distribution and abundance of the macrobenthic infaunal species of the tidal river and estuary and to determine the effects of changes in environmental conditions on this distribution and abundance.

The reports in this Water-Supply Paper series document the technical aspects of the above investigations. The series also contains an overall introduction to the study, an integrated technical summary of the results, and an executive summary which links the results with aspects of concern to water-quality managers.

Philip Cohen
Chief Hydrologist

James P. Bennett
Potomac Study Coordinator

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By Andrew J. Miller

Abstract

The shoreline of the tidal Potomac River attained its present form as a result of the Holocene episode of sea-level rise; the drowned margins of the system are modified by wave activity in the shore zone and by slope processes on banks steepened by basal-wave erosion. Shore erosion leaves residual sand and gravel in shallow water and transports silt and clay offshore to form a measurable component of the suspended-sediment load of the tidal Potomac River.

Erosion rates were measured by comparing digitized historical shoreline maps and modern maps, and by comparing stereopairs of aerial photographs taken at different points in time, with the aid of an interactive computer-graphics system and a digitizing stereoplotter. Cartographic comparisons encompassed 90 percent of the study reach and spanned periods of 38 to 109 years, with most measurements spanning at least 84 years. Photogrammetric comparisons encompassed 49 percent of the study reach and spanned 16 to 40 years. Field monitoring of erosion rates and processes at two sites, Swan Point Neck, Maryland, and Mason Neck, Virginia, spanned periods of 10 to 18 months.

Estimated average recession rates of shoreline in the estuary, based on cartographic and photogrammetric measurements, were 0.42 to 0.52 meter per annum (Virginia shore) and 0.31 to 0.41 meter per annum (Maryland shore). Average recession rates of shoreline in the tidal river and transition zone were close to 0.15 meter per annum. Estimated average volume-erosion rates along the estuary were 1.20 to 1.87 cubic meters per meter of shoreline per annum (Virginia shore) and 0.56 to 0.73 cubic meter per meter of shoreline per annum (Maryland shore); estimated average volume-erosion rates along the shores of the tidal river and transition zone were 0.55 to 0.74 cubic meter per meter of shoreline per annum.

Estimated total sediment contributed to the tidal Potomac River by shore erosion was 0.375×10^6 to 0.565×10^6 metric tons per annum; of this, the estimated amount of silt and clay ranged from 0.153×10^6 to 0.226×10^6 metric tons per annum. Between 49 and 60 percent of the sediment was derived from the Virginia shore of the estuary; 14 to 18 percent was derived from the Maryland shore of the estuary; and 23 to 36 percent was derived from the shores of the tidal river and transition zone. The adjusted modern estimate of sediment eroded from the shoreline of the estuary is about 55 percent of the historical estimate.

Sediment eroded from the shoreline accounted for about 6 to 9 percent of the estimated total suspended load for the tidal Potomac River during water years 1979 through 1981 and for about 11 to 18 percent of the suspended load delivered to the estuary during the same period. Annual suspended-sediment loads derived from upland source areas fluctuated by about an order of magnitude during the 3 years of record (1979–81); shore erosion may have been a more important component of the sediment budget during periods of low flow than during periods of higher discharges. Prior to massive land clearance during the historical period of intensive agriculture in the 18th and 19th centuries, annual sediment loads from upland sources probably were smaller than they are at present; under these circumstances shore erosion would have been an important component of the sediment budget.

At current rates of sediment supply, relative sea-level rise, and shoreline recession, the landward parts of the tidal Potomac River are rapidly being filled by sediment. If these rates were to remain constant over time, and no sediment were to escape into Chesapeake Bay, the tidal river and transition zone would be filled within 600 years, and the total system would be filled in less than 4,000 years. Given a slower rate of sediment supply, comparable to the measured rate during the low-flow 1981 water year, the volume of the tidal Potomac River might remain relatively stable or even increase over time. Changes in rates of shore erosion probably are less significant for the future of the estuary than changes in rates of sediment supply from upland sources.

INTRODUCTION

Coastal Plain estuaries provide vital resources for major population centers along the Atlantic seaboard of the United States; the Chesapeake Bay is the largest and most productive of these estuarine systems. Estuaries are natural sinks for sediments, nutrients, metals, and organic pollutants, and the circulation of saltwater and freshwater under the influence of tides, winds, and river discharges creates a complex hydrodynamic, chemical, and biological environment. Important environmental changes throughout the Chesapeake Bay system in recent decades, combined with the results of previous research efforts, have increased awareness that estuaries are fragile and, on a geological time scale, ephemeral environments.

The Potomac River is the largest tributary to Chesapeake Bay; with respect to annual discharge of water and sediment, the Potomac River is second only to the Susquehanna River among the rivers that drain into the Bay. The Potomac River has had a number of sediment and water-quality problems in recent decades, including accelerated siltation in the vicinity of Washington, DC, pollution by municipal and industrial wastes, and noxious phytoplankton blooms.

A Potomac Estuary Study was initiated by the U.S. Geological Survey in October 1977. The study included research efforts to understand: (1) Modern geological processes and Holocene development of the system; (2) geochemistry of bottom sediments and nutrient cycling; (3) hydrodynamics of the tidal river and estuary; (4) patterns of sediment transport and loads of sediments and nutrients from various sources; (5) distribution and abundance of submersed aquatic vegetation; and (6) benthic ecology of the macro infauna of the tidal river and estuary.

Purpose and Scope

The shoreline study was undertaken to investigate the distribution of erosion rates along, and the load of sediments from the shoreline source to the tidal Potomac River. The contribution of shore erosion to the sediment budget of the tidal Potomac River is important in modeling movement of sediments into and through the system, in understanding rates of sediment accumulation on the floor of the tidal river and estuary, and in determining concentrations of nutrients and sediment-borne trace metals. Shore erosion also is of interest to the public, because the fate of most unprotected waterfront property exposed to broad fetches of open water in the Potomac Estuary and Chesapeake Bay is eventual destruction by waves and tides.

Specific objectives of the study were:

1. Identify the major processes causing shore erosion and monitor erosion rates at selected sites along the shoreline.
2. Measure shoreline changes that have occurred in recent decades and during the past century, and characterize the distribution of shore-erosion rates in terms of both the rate of lateral recession and the rate of volume erosion per unit length of shoreline.
3. Provide estimates of the amount of sediment contributed annually to the tidal Potomac River by shore erosion.
4. Evaluate the relative importance of shore erosion compared with other sources providing suspended sediment to the system.
5. Estimate the rate of filling or volume expansion of the estuary under present conditions and under alternative assumptions.

Acknowledgments

Peter Gibson of the Coastal Hazards Branch at the National Ocean Survey provided mylar photocopies of original shoreline maps for use in cartographic shoreline comparison and also gave helpful advice on use of the historical maps. Copies of several of the historical maps were borrowed from the Virginia Institute of Marine Sciences with the permission of Robert Byrne. Daily wave observations were made consistently and carefully by Richard Jameson and by Louis Galeano. Permission for access to the monitoring sites was granted by Dennis McCartney of the U.S. Steel Development Corp. and Marion Johnson of the U.S. Fish and Wildlife Service. Particular thanks for field assistance are due to Charles Richman and Robert O'Brien, in addition to many other fellow graduate students at the Johns Hopkins University. Assistance in cartographic and photogrammetric shoreline comparison was provided by members of the National Mapping Division of the U.S. Geological Survey, including: Joseph Beaulieu, Michael Domaratz, Joseph Fehrenbach, Angel Gonzalez, Robert Gwynn, Thomas Hampton, Robert Krivosucky, David Newman, Robert Neale, George Rosenfield, Richard Theis, Michael Troup, and Robin Worcester. Members of the Potomac Estuary Study group assisted in providing information, technical support, and field equipment.

STUDY AREA

The study area includes the shoreline of the main trunk of the tidal Potomac River (the Potomac Estuary and all parts of the Potomac River that are under tidal influence) in the reach extending from Gunston Cove on the Virginia side and Marshall Hall on the Maryland side down to the mouth at the confluence with Chesapeake Bay (fig. 1). The study reach includes about 350 km of shoreline along a midchannel length of about 145 km. Marginal embayments and tidal creeks were not included in this study.

The Chesapeake Bay system, a classic example of the drowned river-valley type of estuary (Pritchard, 1967), attained its present form as a result of the Holocene episode of sea-level rise that is still in progress. The Potomac River is the largest of several major tributaries that flow southeastward across the Coastal Plain of Maryland and Virginia to enter the west side of Chesapeake Bay. The Potomac River reaches the head of tide just below Little Falls, Maryland, and the tidal Potomac River extends another 182 km from the head of tide to the confluence with Chesapeake Bay (Lippson and others, 1979).

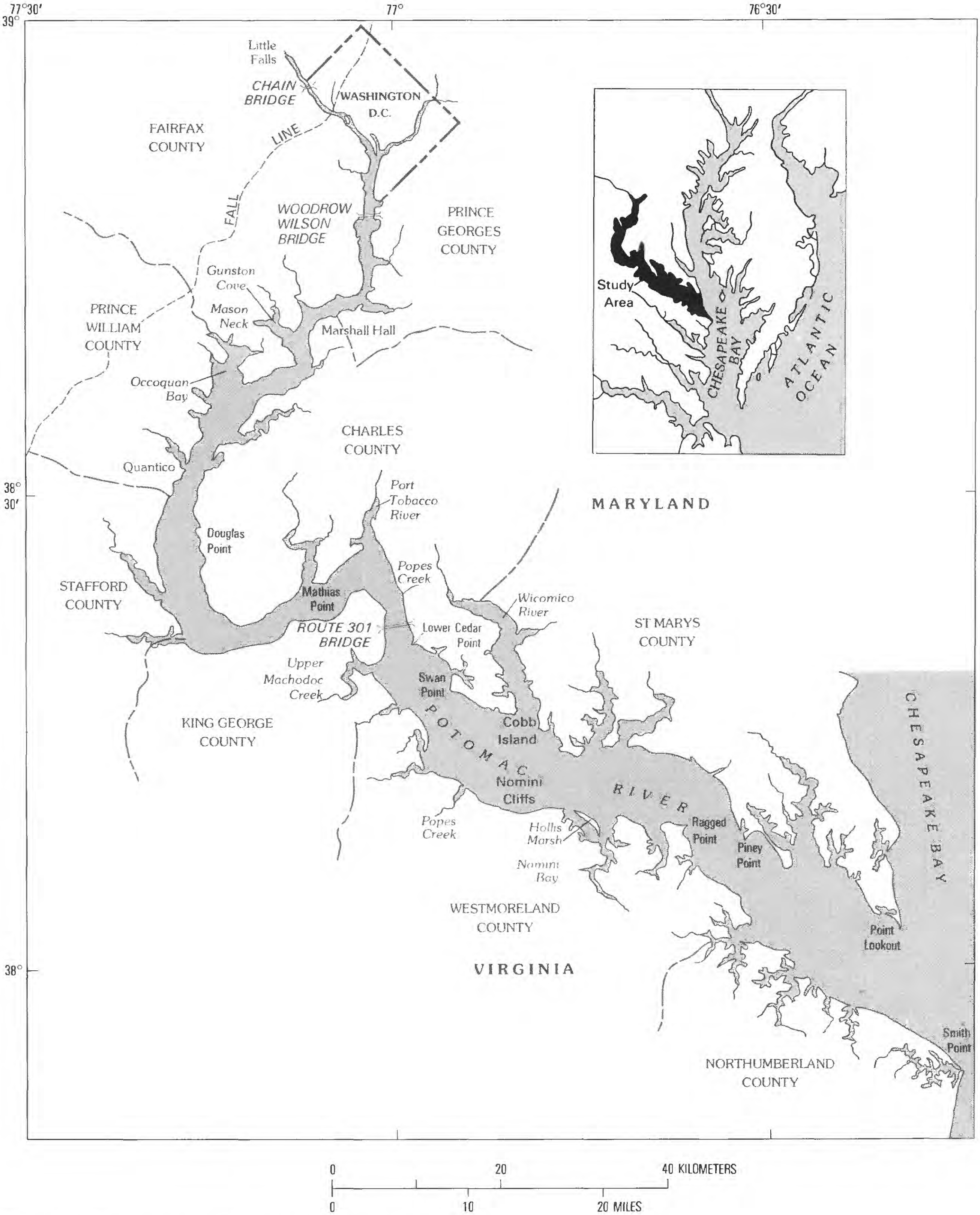


Figure 1. Place names and locations in the study area.

Hydrography

The boundary between freshwater and brackish water shifts landward and seaward within the reach between Quantico, Virginia, and the Route 301 Bridge (fig. 1) under the influence of varying freshwater discharges, tides, and winds. Because of this shifting locale, and because of variations in hydrography and channel geometry, this section of the tidal Potomac River is designated the transition zone. The tidal river section extends from the head of tide to Quantico, Virginia, but only the part of the tidal river below Marshall Hall, Maryland, and Gunston Cove, Virginia, is included in the present study. The estuary extends from the Route 301 Bridge to the mouth of the Potomac River at Chesapeake Bay (fig. 2). Channel width averages 2.5 km in the tidal river below Marshall Hall, 3.7 km in the transition zone, and 8.4 km in the estuary. Corresponding values of average depth are 5.2 m in the tidal river, 5.0 m in the transition zone, and 8.5 m in the estuary; average cross-sectional areas are 12,800 m^2 in the tidal river, 18,800 m^2 in the transition zone, and 67,000 m^2 in the estuary (table 1). Length of fetch for most sites along the shores of the estuary is greater than for most sites along the shores of the tidal river and transition zone.

Tides on the Potomac River are semidiurnal with an average period of 12.4 hours and a tide range between 0.3 and 0.6 m (Lippson and others, 1979). The rise and fall of water level may promote or prevent erosion of the shoreline by wind-driven waves, and the direction of the tidal current may affect local sediment transport in the nearshore zone. Dominant winds in the study area come from the north and northwest and from the south and southwest (U.S. Naval Weather Service Detachment, 1978; U.S. National Oceanographic and Atmospheric Administration, 1977). The northwest winds are more likely than the south and southwest winds to attain speeds of more than 5 m/s. North and northwest winds are dominant between October and April; south and southwest winds are dominant between April or May and September. Although northeast winds are relatively infrequent, severe storms accompanied by strong, sustained northeast winds (such as the Ash Wednesday storm of 1962) may do a large amount of damage in a short period of time.

Elliott (1978) observed that strong northwest winds drive water out of the Potomac Estuary and cause water levels to drop in the estuary. Periods of sustained northwest winds may allow large waves to build up in the estuary, but the waves may not be able to attack the shoreline if there is a substantial drop in the water level at the same time. South and southeast winds can have the opposite effect, causing a substantial rise in water levels. Wind also may cause local changes in water level by piling up water on the downwind side and lowering the level of the water surface on the windward side of a closed basin; this effect is known as wind setup. The effects of wind setup in a basin with a complex shape and free exchange with another body of water are difficult to predict (U.S. Army Coastal Engineering Research Center, 1977). The effect of cross-stream winds on water levels and on shore erosion in the tidal Potomac River is not presently known, but several authors have stated that setup of the water surface by winds blowing across Chesapeake Bay promotes erosion along the shores of the Bay (Schubel, 1968; Palmer, 1973; Byrne and Anderson, 1977).

Storm surge and wind setup during severe tropical storms and northeasters probably are major causes of shore erosion in the tidal Potomac River, particularly in the estuarine zone, where fetches are much broader than in the tidal river and transition zones. However, some tropical storms (such as Tropical Storm Agnes in June 1972) produce heavy rainfall without strong winds. Field measurements by the Maryland Geological Survey (McMullen, 1974) indicated that this storm, which caused record high freshwater discharges into Chesapeake Bay, brought modest increases in seasonal summer erosion rates along the shores of the Bay. Beach-profile changes indicated only modest loss of sediment due to Tropical Storm Agnes (Kerhin, 1974). No data are available to document the effects of any other major storm, but some residents of shore-front property along the lower Potomac Estuary claim to have lost as much as 5 m of land in a single night.

Published information on wave climate in the tidal Potomac River is not available. During the period from January 24, 1980, to August 25, 1981, visual observations of wave height and direction and of windspeed and direction were made daily by an observer on the north shore of the estuary at Potomac View (fig. 2). The maximum observed wave height was 0.5 m (1.7 ft); observed wave height equaled or exceeded 0.3 m (1.0 ft) on 21 occasions (table 2). Wind speed for these 21 observations ranged from 5 to 11 m/s, and the average speed was 6.7 m/s. Speeds of more than 13 m/s were measured on three occasions and other meteorological events brought strong winds and waves during the night, but as no wave-height measurements were made during these events, they are not included in table 2. Wave heights of 1 m or more have been observed by the author in the open waters of the estuary on moderately windy days.

Geology and Physiography

Variations in shoreline composition may affect resistance of the shoreline to erosive forces; these variations influence recession rates. The volume of sediment contributed by bank erosion along an arbitrary shoreline reach is the product of recession rate and bank relief; therefore, the distribution of shoreline relief also is of some importance to this study. Shoreline composition and relief are determined by the underlying geology of the region and by distributions of the various terraces bordering the tidal Potomac River.

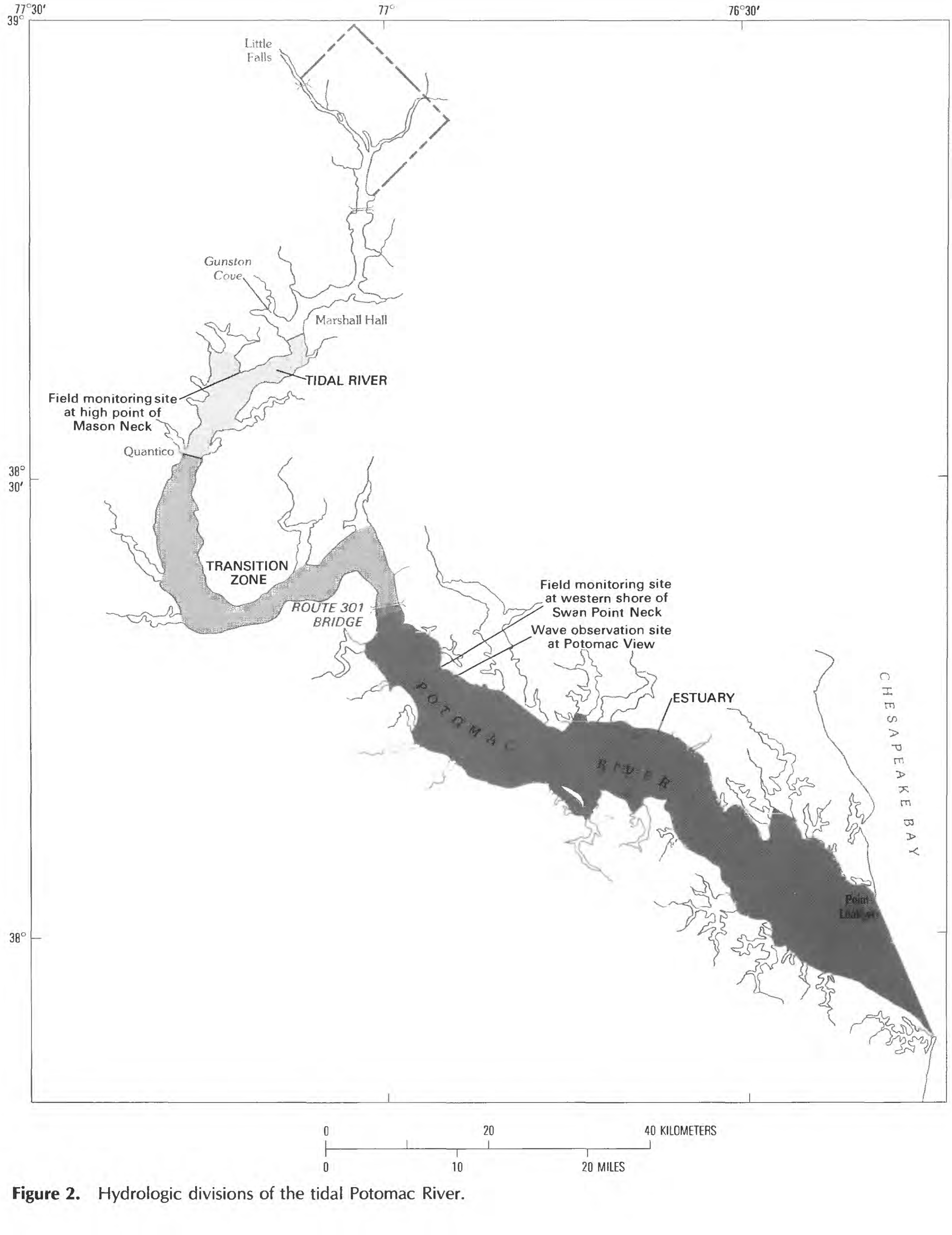


Figure 2. Hydrologic divisions of the tidal Potomac River.

Table 1. Average dimensions of the tidal Potomac River

Zone	Mean width (meters)	Mean depth (meters)	Mean cross-sectional area (square meters)	Total surface area (square meters)	Total volume (cubic meters)
Upper tidal river[2]---	1.13×10^3	3.21	0.36×10^4	0.38×10^8	0.12×10^9
Lower tidal river[3]---	2.49×10^3	5.19	1.29×10^4	$.60\times10^8$	$.31\times10^9$
Transition zone------	3.73×10^3	4.99	1.86×10^4	1.79×10^8	$.90\times10^9$
Estuary--------------	8.90×10^3	8.48	7.55×10^4	6.76×10^8	5.73×10^9

[1]Based on data from Lippson and others, 1979.
[2]Head of tide to Marshall Hall; not covered in this study.
[3]Marshall Hall to Quantico.

The tidal Potomac River is cut into the surface of a wedge of Coastal Plain sedimentary formations that overlap the crystalline rocks of the Piedmont at the Fall Line (fig. 1) and thicken to the southeast. These formations range in age from Cretaceous to Pleistocene, and they contain a record of ancient fluvial, estuarine, and shallow marine environments (Glaser, 1971). Because of regional dip, younger formations crop out at sea level as one moves seaward from northwest to southeast. Eocene greensands crop out at sea level along part of the transition zone shoreline, and Miocene sands, silts, and clays crop out at sea level along much of the Virginia shoreline of the estuary northwest of Nomini Bay. The most common deposits cropping out in the banks of the tidal Potomac River are Pleistocene terrace deposits that truncate the older formations. The Tertiary deposits are mostly semiconsolidated sediments that tend to be more cohesive and tougher than the Pleistocene deposits.

Dissected uplands of the Coastal Plain in the Chesapeake Bay area are capped by a blanket of deeply weathered gravels (Glaser, 1971). The upland surface intersects the Potomac River shoreline in a series of

Table 2. Maximum observed wave heights at Potomac View compared with windspeed and wind direction: 576 observations, January 24, 1980, to August 25, 1981

Exceedance frequency and range of windspeeds				
Wave height (meters)	Number of observations	Range of windspeed (meters per second)	Wave height equaled or exceeded: Number of observations	Wave height equaled or exceeded: Frequency (percent)
0.18	24	2.2 to 6.3	84	14.9
.21	18	2.2 to 8.0	60	10.4
.24	12	2.2 to 8.0	42	7.3
.27	9	4.0 to 6.3	30	5.2
.30	6	4.9 to 11.2	21	3.7
.34	5	5.4 to 8.0	15	2.6
.37 to .43	7	4.9 to 7.2	10	1.7
.46 to .52	3	5.4 to 8.9	3	.5

Distribution of wind directions for maximum wave heights

Range of wave heights (meters)	Number of observations (Cumulative percent of observations in given wave-height range that fall in each direction class is shown in parentheses): Southeast	South	Southwest	West	Northwest	North	Total
≥0.18	7	24	27	6	15	5	84
	(8.3)	(28.6)	(32.1)	(7.1)	(17.9)	(6.0)	(100)
≥.30	1	3	9	3	4	1	21
	(4.8)	(114.3)	(42.9)	(14.3)	(19.1)	(4.8)	(100)
Water too low for wave measurement.				1	6	2	9
				(11.1)	(66.7)	(22.2)	(100)

bluffs, ranging in elevation from 30 to 45 m, at several locations along the tidal river and transition zone, and along an 8-km reach on the Virginia side of the estuary just west of Nomini Bay. A fluvial terrace with an upper surface at about 24 to 27 m above present sea level (Mixon and others, 1972) crops out in bluffs at scattered locations bordering the tidal river and transition zone, and bluffs with elevations of 15 to 21 m are found at several locations along the transition zone and the estuary. A lower terrace bordering the tidal river has an upper surface at an elevation of 12 m (Mixon and others, 1972; Seiders and Mixon, 1981); banks along much of the shoreline of the transition zone and part of the Virginia shore of the estuary have elevations of 6 to 9 m above sea level. The lowest and youngest terrace surface bordering the tidal Potomac River generally is less than 4.5 m above sea level, and the distal ends of several peninsulas reach elevations of no more than 1 to 3 m. This terrace surface is present at several locations in the transition zone and also is present in the estuary along all of the Maryland shoreline and most of the Virginia shoreline. Marsh and swamp deposits at or near mean sea level occur along the shoreline and also fill the valleys of small tributary streams. These deposits are particularly common near the mouths of tidal creeks where rapid accumulation of sediment is occurring. As sea level rises, these deposits may be submerged or eroded by waves; at the same time, the environments in which the deposits form may transgress inland where the land-surface slope is gentle enough.

Along most of the shoreline, terrace surfaces at elevations lower than 15 m are separated from the uplands by a distinct scarp, marked by the location of the 15.2-m (50-ft) elevation contour on the topographic maps. The scarp outlines several old meander scars of the ancestral Potomac River. The lower terrace areas bordering the estuary are much wider than those along the tidal river and transition zone, and relief along most of the shoreline of the estuary is generally lower and less variable.

PROCESSES OF SHORE EROSION

Shore erosion in the tidal Potomac River is caused primarily by wind-driven waves and slope processes. Steeply cut banks are present along most of the shoreline. These banks are interrupted by low-lying areas of marsh and swamp that occupy small stream valleys flooded by rising sea level; the banks also are interrupted by spits and bars that form at the mouths of tidal creeks. Beaches at eroding bank sites generally are 2 to 6 m wide at local mean sea level, with slopes of 4 to 7 degrees, and they have a limited supply of sand that forms a veneer over an erosional bench of older material. The sand is derived mostly from bank erosion updrift of the site or at the site (Byrne and Anderson, 1977).

Evidence for erosion of low-lying areas includes vertical cut faces or undercut sections of marsh (fig. 3) and dead trees standing on the beach or in the water with their roots exposed. Erosion of marsh and swamp deposits probably is controlled by wave activity and by cohesive and tensile strength of the deposits. Ice along the shoreline may play a role by preventing wave erosion; however, abrasion and shearing of sediments can occur during breakup of the ice sheet.

Wave activity removes sand and accumulated debris at the base of the bank and attacks the bank directly. Steepening caused by basal erosion promotes increased activity by slope processes. As the rate of basal erosion increases, the dominant slope processes may change. Surficial weathering and rill erosion are dominant on slopes subject to little or no basal erosion (fig. 4), and slides and block falls are most common on banks that are unstable as a result of steepening by basal erosion (fig. 5).

The height of the beach is important in buffering wave energy and in determining whether waves are able to reach the base of the bank. Protective structures built along the shoreline are designed either to withstand the force of wave impact or to trap sand moving along the shoreline; these structures have become very common along the tidal Potomac River in recent decades as more and more

Figure 3. Eroding marsh at Swan Point Neck, Maryland.

Figure 4. Low bank (about 2 meters high) with rills from surface runoff, Virginia shore of Potomac Estuary.

waterfront property has been converted to residential use. A seawall built to protect an eroding bank may withstand wave impact, but the beach at such a site will be lost unless groins or jetties are present to trap sand. An unprotected seawall eventually will be undermined by wave scour at the base. In order to be effective, structures like the groins shown in figure 6 require an adequate supply of sand moving along the shoreline. Along much of the shoreline, sand is not available in large quantities. Much of the sediment travelling along shore tends to concentrate near the mouths of tidal creeks. In addition, prevention of bank erosion by construction of seawalls and jetties reduces the supply of sediment available and may promote erosion of unprotected sites. This effect has been observed in the field but has not been studied in detail in the Potomac. In 1977, approximately 18 to 20 km of seawalls, bulkheads, or riprap were present on each side of the estuary, and groins or jetties were present along even more of the shoreline. Protective structures were present along approximately 20 percent of the

Figure 5. Debris at base of bank (about 6 meters high) undermined by wave erosion, near Douglas Point, Maryland.

shoreline encompassed by photogrammetric measurements in the estuary.

Some examples of bank heights and stratigraphic patterns occurring in eroding outcrops on the tidal Potomac River shoreline are shown schematically in figure 7. Erosion on low banks with simple stratigraphy (Swan Point Neck, profile on left side of fig. 7) consists of only a few steps: (1) Undercut, (2) collapse, (3) removal of debris; (1) undercut; and so on. Physical weathering by freeze and thaw and by wetting and drying may loosen materials and cause some surficial erosion; however, it is much less effective than wave attack in causing bank retreat. Trees on the bank may retard collapse but also may pull away a large section of the bank when they fall. Fallen trees on the beach absorb wave impact, trap sand, and may build up the local level of the beach.

Higher banks (5 to 12 m) with more complex stratigraphy (Mason Neck, middle profile in fig. 7) generally

Figure 6. Accumulation of beach sand trapped by groin field, Virginia shore of Potomac Estuary near Chesapeake Bay.

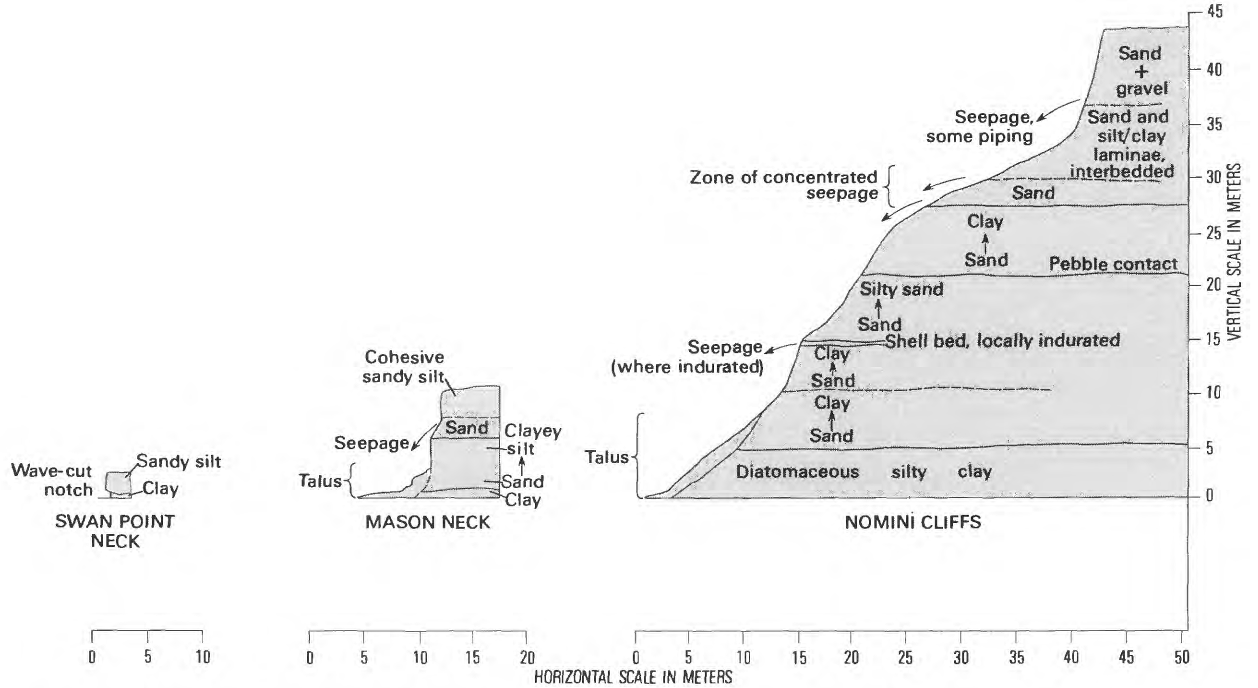


Figure 7. Comparative bank profiles from three sites along the shores of the tidal Potomac River.

do not collapse as a direct result of undermining by wave erosion. Steepening at the base produces a series of shallow translational failures or block falls that gradually work their way upslope. Seepage at contacts between relatively permeable and impermeable layers provides runoff for incision of rills below the seepage zone and promotes sapping and undermining of overlying layers. Seepage at the base may help undermine the bank, even where relatively little wave erosion occurs; this was noted by Palmer (1973) along the shores of the Chester River on the east side of Chesapeake Bay. High pore pressures caused by elevated ground-water levels during spring thaw favor the occurrence of solifluction and mudflows on the debris slope (fig. 8) and slab failures or rotational failures on the slope above the seepage zone. Rill erosion is important primarily when mass movement processes are inactive, but rill and gully channels on the slope face may act as chutes for mobilization of saturated debris in late winter and early spring. Large trees with extensive root systems can affect the pattern of erosion by stabilizing the upper part of a slope until the entire root mat has been undermined. Collapse of a tree may pull away as much as 5 to 10 m^3 of bank material, but, as was true for the previous example, the fallen tree also may protect the bank from further erosion as long as it remains in place at the bottom of the bank.

Sites with lithologies differing from the example from Mason Neck may not be affected by all these processes. A bank composed entirely of cohesionless thin-bedded sands and silts generally does not have zones of concentrated ground-water flow, but may undergo a series of shallow slides in response to steepening by wave erosion. Tertiary exposures of dense, cohesive glauconitic greensand with variable amounts of silt and clay are not as easily undercut as Pleistocene exposures of unconsolidated sand, silt, and clay, but may be abraded at the base by waves carrying sand grains or quarried by water forced into fractures and joints on wave impact (fig. 9). These exposures often are saturated, but seepage from the bank surface is slow. Exfoliation along sheet joints in overconsolidated material and weathering along joint planes of tectonic origin can reduce the ability of Tertiary materials to resist erosive forces. Where Tertiary material is capped by Pleistocene sands and gravels, seepage along the contact may undermine the upper layer.

The most complicated set of processes occurs on high bluffs with complex stratigraphy (Nomini Cliffs profile, right side of fig. 7). Other high bluffs in the study area are stratigraphically less complex and are subject to less intense wave erosion at the base; they do not display the full range of erosional features. Processes occurring on the Nomini Cliffs are affected by the presence of multiple seepage zones, discontinuous ironstone ledges, sheet joints, and tectonic joints. Channels incised in the face of the slope form permanent drainage systems for downslope transportation of water and sediment; broad scallops at the top of the slope are collecting areas for mudflows and debris slides. Along some sections of these bluffs, badland-like pinnacles have been carved in the upper part of the slope by rill and gully erosion. Loosening of surficial material by expansion and exfoliation along sheet joints, together with shallow slides of loosened

Figure 8. Mudflow on debris slope at the base of a 10-meter-high bank, Mason Neck, Virginia.

Figure 9. Eroding bank (about 6 meters high) composed of cohesive Miocene sediment, near Popes Creek, Virginia.

Figure 10. Debris fan derived from rotational landslide on the upper section of a high (40-meter) bluff, Nomini Cliffs, Virginia.

material, probably account for a substantial volume of erosion. Tectonic joints may guide the orientation of drainage channels and small stream valleys (Jacobson and Newell, 1982).

Large rotational landslips occur on the upper 10 to 20 m of the Nomini Cliffs above seepage zones marking perched water tables. The resulting debris fan at the toe of the bluff may extend 10 to 20 m into the water (fig. 10); several years may be required to remove this debris before the process of wave erosion at the base of the bluff can begin again. Recurrence intervals of large slope failures are unknown; several basins at the top of the slope, with steep headwalls and gently sloping floors, appear to be relict features formed by rotational landslips but are now inactive and covered by forest vegetation.

Volume-erosion rates along the shoreline depend both on the rate of shoreline recession and on the height of the bank. High bluffs are present along a relatively small part of the shoreline in the study area; however, if the high bluffs recede at rates comparable to those measured at shoreline sites with lower relief, they will produce a much larger volume of sediment per unit length of shoreline than low banks do. Thus the high bluffs are potentially important contributors of sediment to the tidal Potomac River.

METHODS OF INVESTIGATION

This study included a program of field investigations as well as a study of erosion rates based on cartographic and photogrammetric measurements. Field investigations were undertaken to identify major erosion processes, to monitor short-term erosion rates at two sites, and to study temporal and spatial variability of erosion. A sampling program for determination of the silt-clay and sand-gravel content of eroding banks was intended to provide information useful in assessing the amount of suspended sediment derived from shore erosion. The cartographic and photogrammetric measurements were the main sources of information on shore-erosion rates and contributions to the sediment budget of the tidal Potomac River.

Field reconnaissance of the shoreline was conducted from a small boat and from a car, and access to bank-sediment sampling sites was mostly by boat. Erosion-monitoring sites were established at locations not readily accessible to the general public and were reached by walking in from the nearest road. Methods used in field investigations included visual observations of shoreline morphology and shoreline features related to erosion processes, channel sampling of sediments from bank exposures, and repeated surveying of monumented cross sections, in addition to photographic and written records of change at monitoring sites along the shoreline.

Measurements of long-term shoreline change were based on comparison of historical shoreline maps with modern maps along 90 percent of the study reach and on comparison of aerial photographs from different dates along 49 percent of the study reach. Methods of measuring shoreline change from maps and photographs were developed for this project and involved the use of an interactive computer-graphics system and a topographic stereoplotter equipped with digital encoders. These methodswere developed because of uncertainties inherent in the methods described in other literature and because of the specific requirements of this project for accurate measurements of relatively slow erosion rates over large areas. The photogrammetric method is subject to revision and refinement; it is potentially applicable to other fields of geologic and hydrologic research.

Field Investigations

Because one major goal of this study was to estimate the contribution of suspended sediment from shore erosion to the tidal Potomac River, a field sampling program was conducted in the summer of 1980 to determine how much of the sediment exposed in the banks might be expected to behave as suspended sediment when eroded. Previous investigators (Schubel, 1968; Biggs, 1970) have assumed that the silt-clay component of sediment eroded from the Chesapeake Bay shoreline is the same as the suspended-sediment contribution from the shoreline. Examination of bottom sediments in both the tidal Potomac River and in Chesapeake Bay indicates that silt and clay from shore erosion is carried offshore from the shallow shoreline flats into deeper water, leaving behind a lag deposit of sand (Ryan, 1953; Knebel and others, 1981). In accordance with this published evidence, it is assumed here that the silt-clay fraction of the bank material sampled can be used to estimate the mass of suspended sediment derived from shore erosion.

Samples of bank sediment were collected and lithologic descriptions were recorded at 76 outcrops along the tidal Potomac River shoreline (fig. 11). Sediment samples taken at each outcrop consisted of a set of subsamples of uniform size collected at vertical intervals of 0.6 m throughout the height of the bank and placed in a single sample bag. Outcrops varied in height from less than 1 to 45 m. Sediment samples were brought back to the laboratory and wet-sieved to separate the silt-clay component (<0.062 mm) from the sand-gravel component. Dry weights of the sample before sieving, and of the residue after sieving, were compared to calculate the percentages of silt-clay and of sand-gravel components.

Field monitoring of short-term bank-erosion rates and processes included transit surveys of monumented cross sections as well as maintenance of a photographic and written record. Monitoring was conducted at two locations, one along the shoreline of the tidal river and one along the shoreline of the estuary (fig. 2). Banks at both sites were composed of erodible Pleistocene sediments. The Swan Point Neck site, on the Maryland shore of the estuary, was on a west-facing exposure with about 3 m of relief. Severe erosion was occurring at the site when it was first visited. Monitoring began during January 1980 and continued biweekly until June 1980; it continued monthly after that until the end of October 1980, when a continuous bulkhead was erected along a 1.3-km length of shoreline. The Mason Neck site was located at High Point, on the southwestern tip of the Mason Neck peninsula in the Mason Neck National Wildlife Refuge. Bank relief at this site was about 12 m, and field evidence indicated continuing severe erosion; monitoring began during December 1979 and continued biweekly until June 1980, continued monthly until August 1980, and continued bimonthly until July 1981.

Cartographic and Photogrammetric Methods

Measured erosion rates and calculated sediment contributions are based on two independent sets of shoreline comparisons. First, comparisons were made between historical shoreline maps and modern shoreline maps; second, comparisons were made between aerial photographs of two different dates.

The oldest maps used in cartographic comparisons included the oldest available U.S. Coast and Geodetic Survey historical shoreline maps, compiled at a scale of 1:20,000 by planetable survey during the 1860's. These were compared with modern U.S. Coast and Geodetic Survey—now National Ocean Survey (NOS)—shoreline surveys and planimetric maps, compiled at a scale of 1:10,000 from aerial photographs dating between 1951 and 1971. The 1860's maps were unavailable for several parts of the shoreline and, in one instance, a shoreline map dating from 1905 was used. U.S. Geological Survey topographic quadrangle maps dating from 1942 and from 1967 were substituted for the modern maps in several

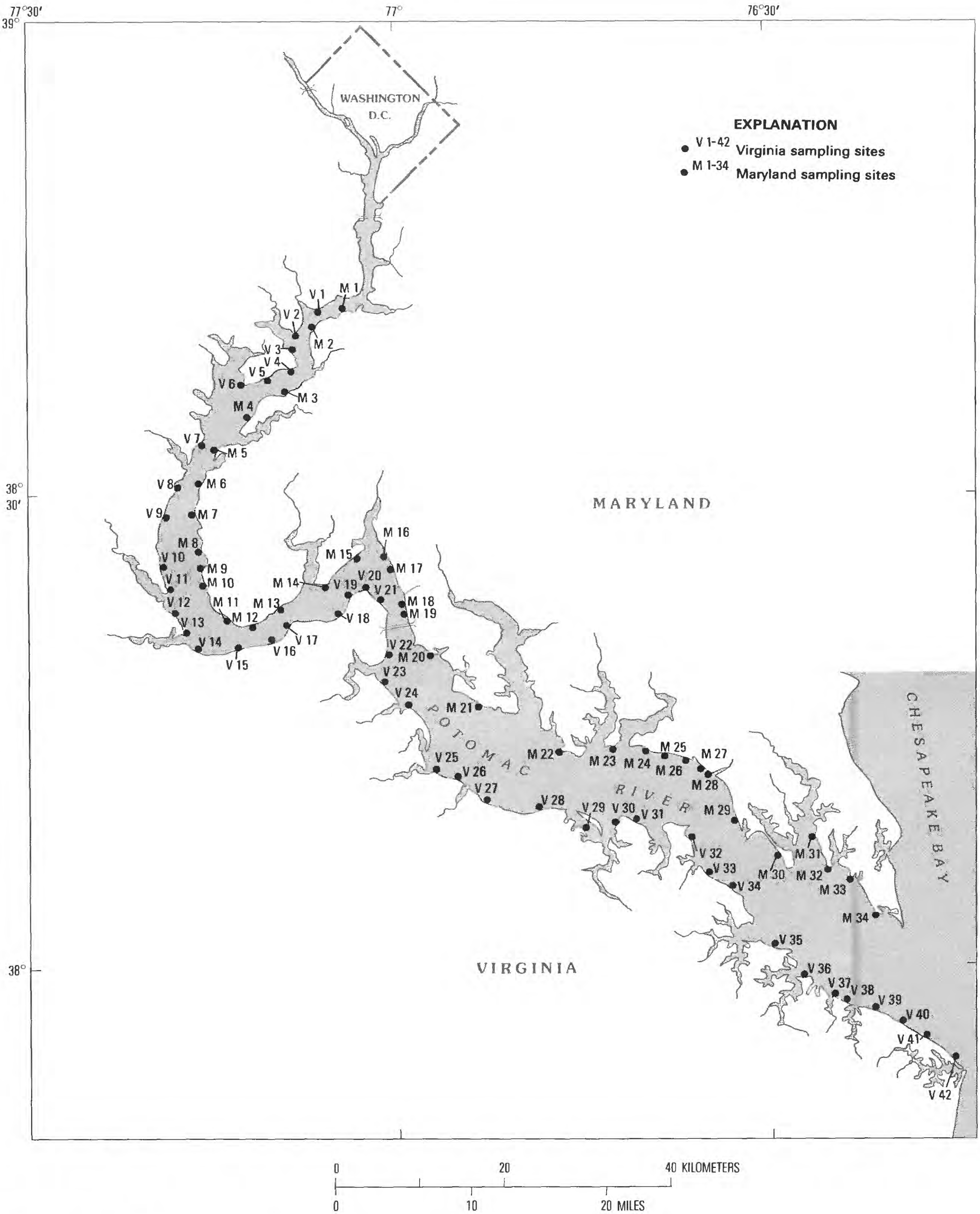


Figure 11. Bank-sediment sampling sites.

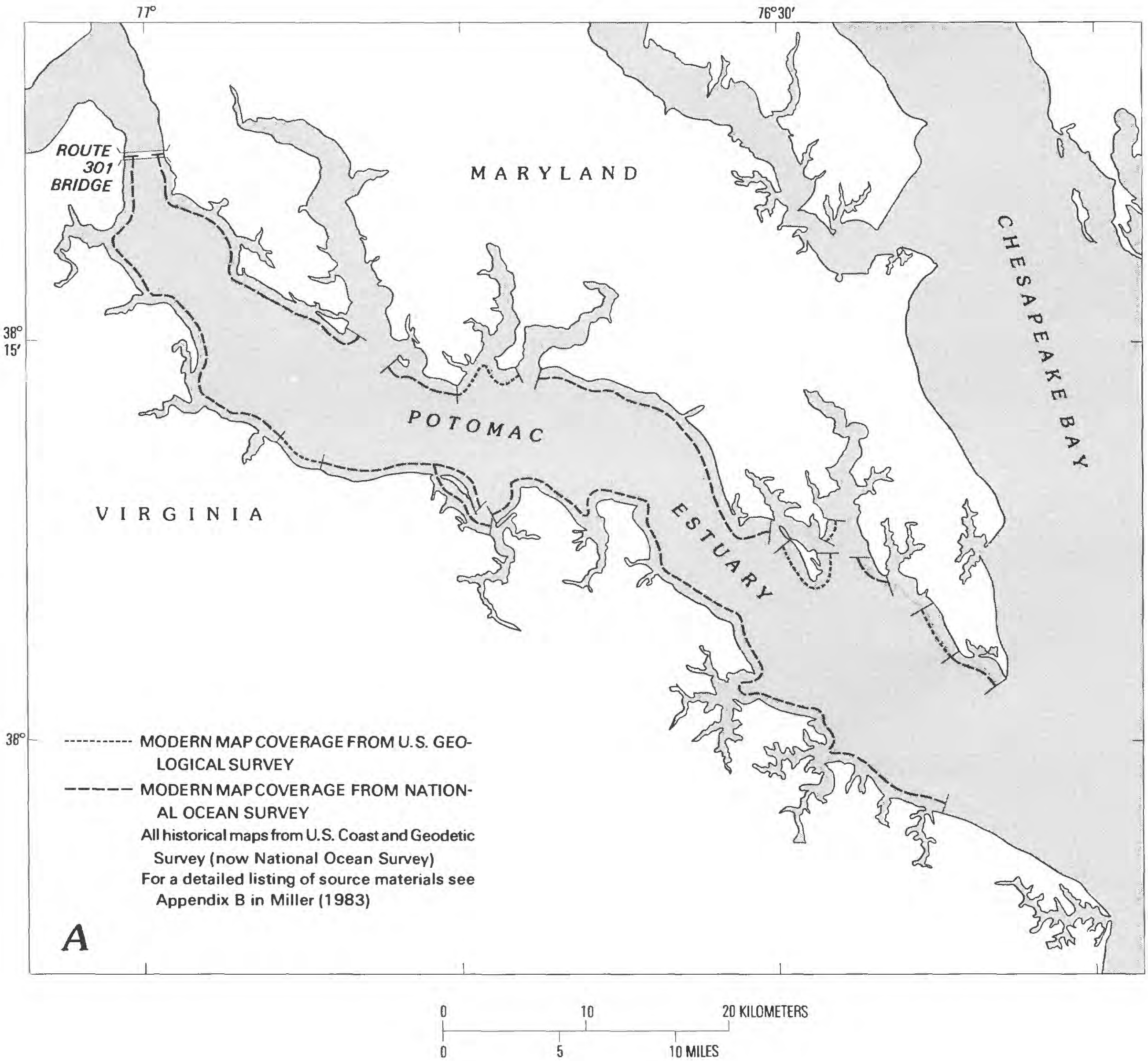
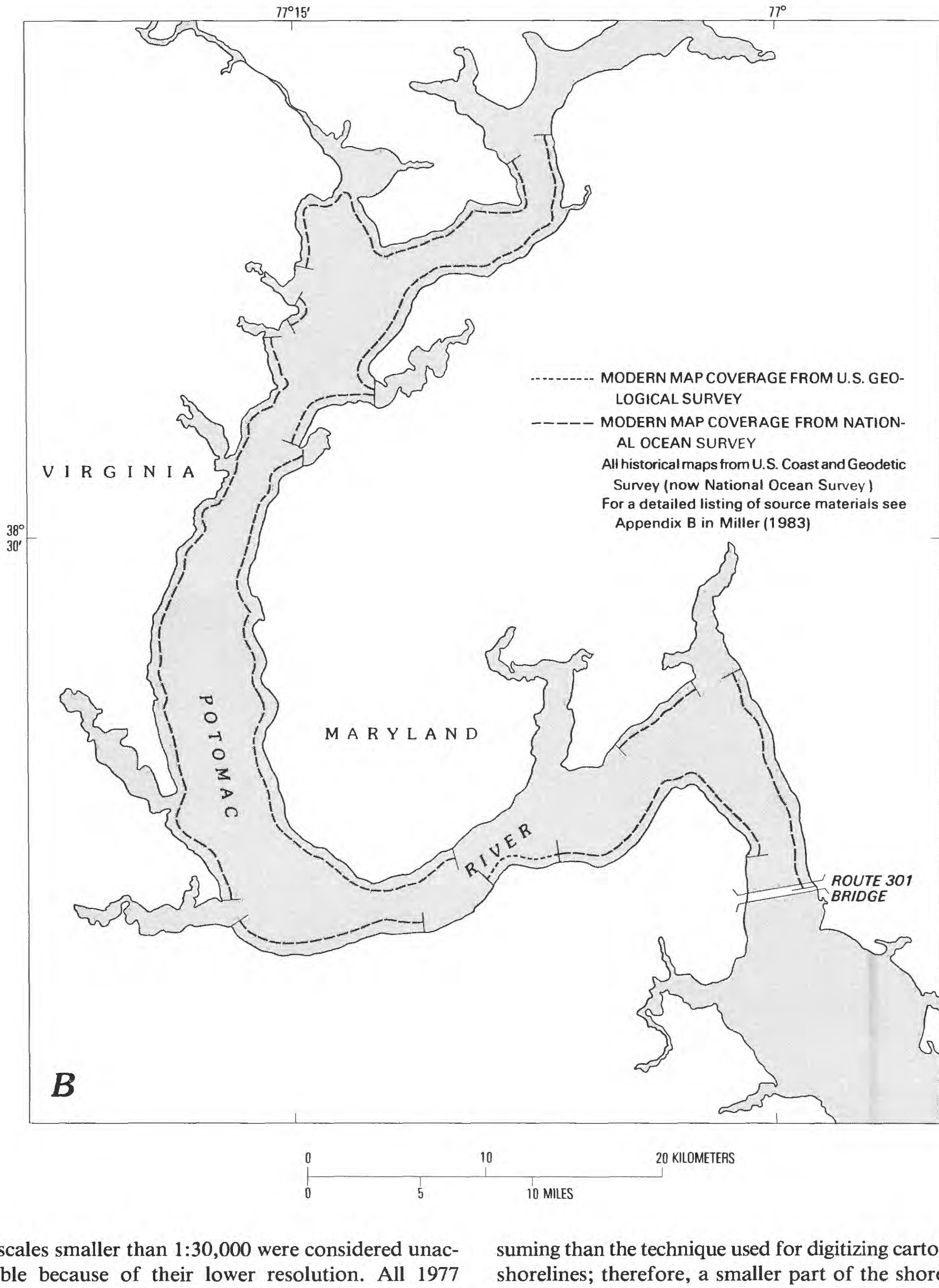


Figure 12 (above and following page). Shoreline locations included in cartographic comparisons. *A*, along the estuary; and *B*, along the tidal river and transition zone.

instances. The time period in the cartographic comparisons ranges from 37 to 109 years; most measurements span a period of 84 years or more. Stable-base mylar photocopies of the NOS maps and original plastic peelcoat templates of the U.S. Geological Survey maps were used to avoid shrinkage distortion inherent in paper prints. The part of the shoreline used in the cartographic comparisons is shown in figure 12*a* and *b*; for a detailed listing of source materials by origin, date, and scale, see Appendix B in Miller (1983).

The earliest series of aerial photographs available for the study area was made during 1937 and 1938 for the U.S. Agricultural Stabilization and Conservation Service. Because of problems with image quality, radial lens distortion, and focal length of the aerial camera, and because of insufficient stable reference points for comparison with modern photographs, this series (with one exception) was not used in photogrammetric measurements of shoreline change. Stable-base film-positive contact prints of aerial photographs made for the U.S. Coast and Geodetic Survey between 1951 and 1961, or made for the U.S. Geological Survey in 1952, were compared with a set of film-positive contact prints of aerial photographs made in 1977 for the U.S. Army Corps of Engineers, Baltimore District. Scales of the earlier photographs range from 1:15,000 to 1:30,000; photographs



with scales smaller than 1:30,000 were considered unacceptable because of their lower resolution. All 1977 photographs have a nominal scale of 1:24,000. The part of the tidal Potomac River shoreline used in photogrammetric comparisons is shown in figure 13*a* and *b*.

The technique developed for collecting data from aerial photographs was more complicated and time consuming than the technique used for digitizing cartographic shorelines; therefore, a smaller part of the shoreline of the study area was measured using photogrammetric data. Data representing every part of the study area were obtained, but emphasis was on sites that appeared (on the basis of field inspection) to be undergoing significant erosion.

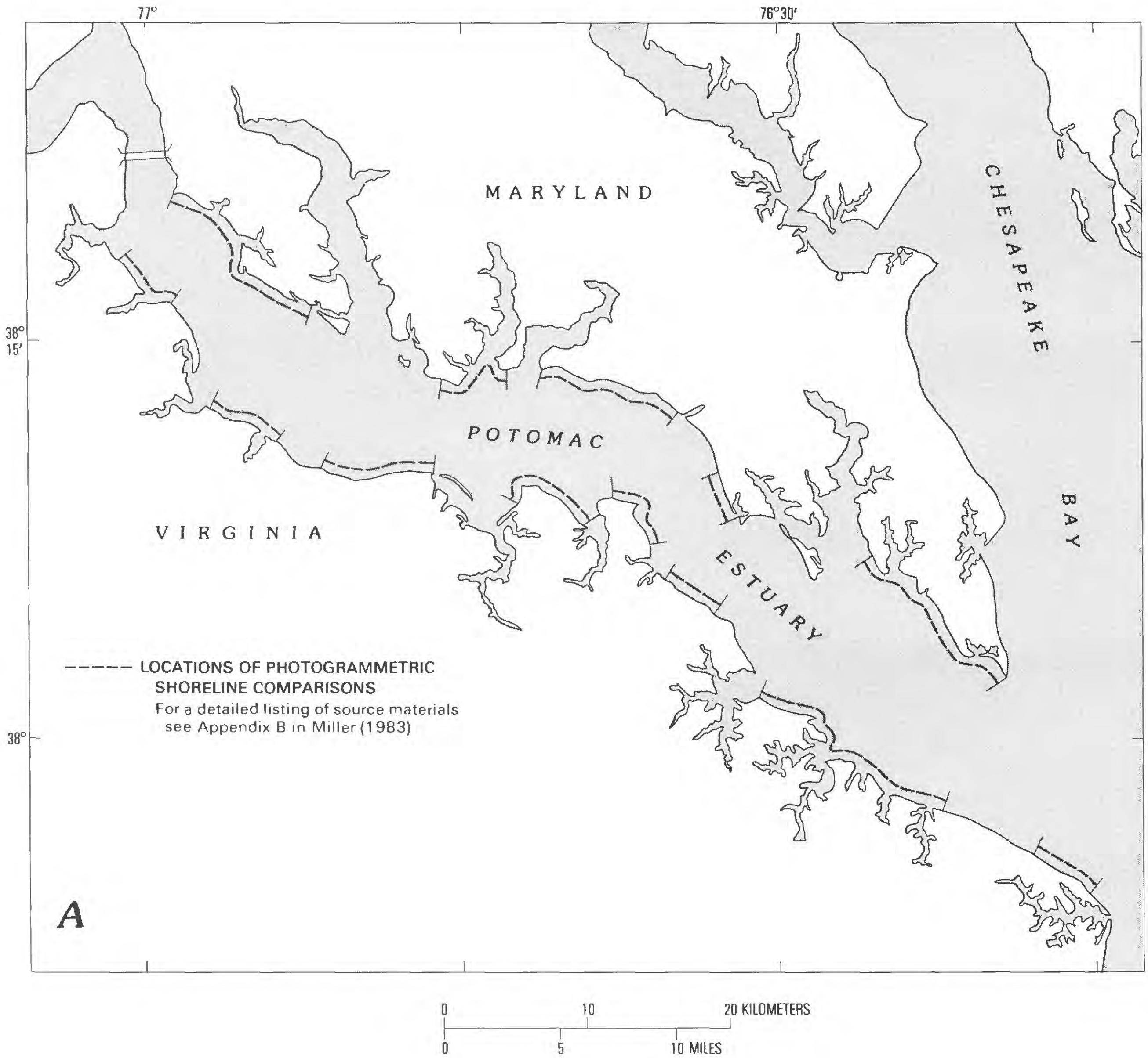
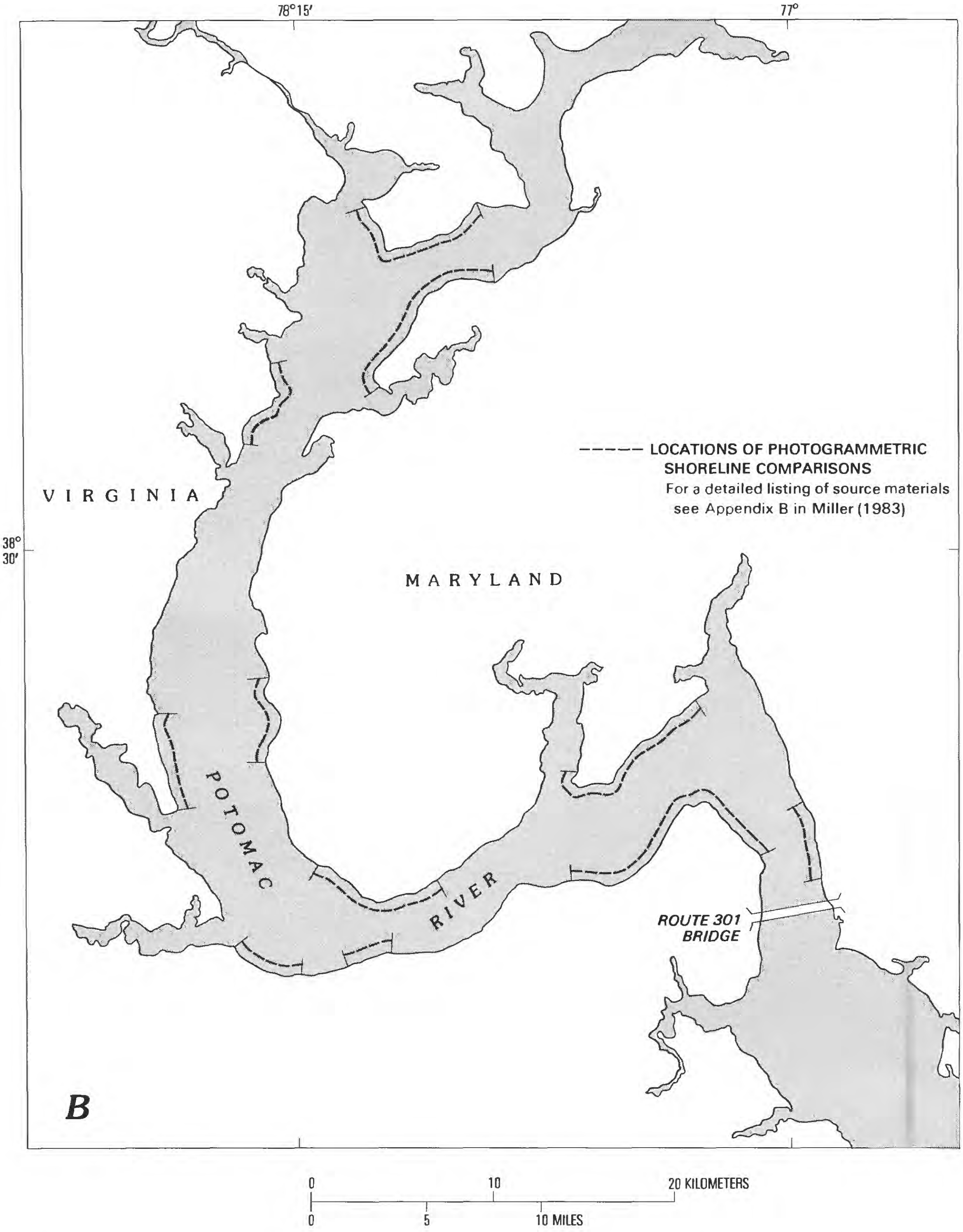


Figure 13 (above and following page). Shoreline locations included in photogrammetric comparisons. *A*, along the estuary; and *B*, along the tidal river and transition zone.

All cartographic and photogrammetric shoreline comparisons were accomplished with the aid of an interactive computer-graphics system belonging to the U.S. Geological Survey. The system consists of a minicomputer, peripheral disk drives and tape drives, and a series of user terminals with command menus, alphanumeric keyboards, digitizing tables with freely moving cursors, and video-display screens (fig. 14). The user creates a graphic design file based on a rectangular cartesian-coordinate system; design elements consist of strings of coordinate pairs stored in digital form in disk files. The digital data are translated by electronic scanners into graphic format and displayed as lines on the screens. Map shorelines were recorded by using a high-resolution (0.075-mm) digitizing light table; shoreline features from aerial photographs were digitized by using a stereoplotter connected to the interactive computer-graphics system. The stereoplotter recorded elevations as well as locations in the horizontal plane. Scaling, coordinate matching, and measurement of shoreline change were accomplished with the aid of coordinate-transformation programs and distance- and area-measurement functions built into the system. Methods are discussed in Miller (1983).

Determination of Recession and Accretion Rates

Change along a shoreline reach between any two dates was measured by (1) dividing the digitized shorelines



into short segments, (2) constructing closed polygons bounded by line segments perpendicular to the more recent shoreline at each end, and (3) measuring the area (A_i) between the shorelines within each polygon (fig. 15). The length (l_i) of shoreline along each segment also was measured; when significant changes in shoreline length occurred over time as a result of recession or accretion, the longer value was used in order to provide a conservative estimate of the average recession or accretion distance. The average recession or accretion distance along the segment, X_i, was calculated as the quotient:

$$X_i = A_i / l_i \,. \quad (1)$$

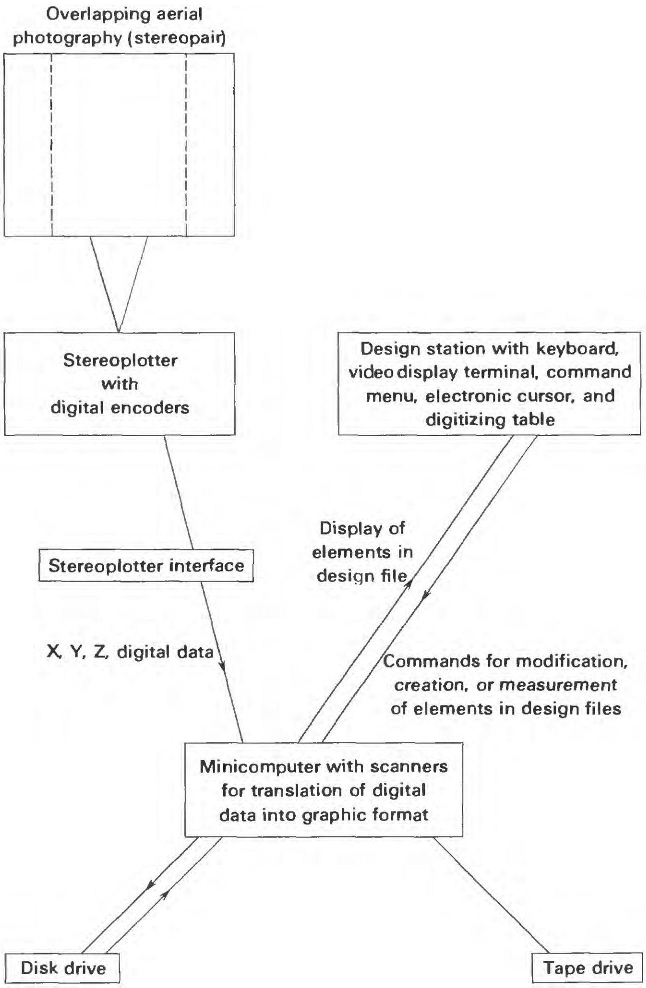


Figure 14. Elements of interactive computer-graphics system with digitizing stereoplotter.

The average rate of erosion or accretion along each segment was calculated as the quotient:

$$a_i = \frac{A_i}{(t_2 - t_1)} \tag{2}$$

for average change in area per unit time (square meters per annum), and:

$$x_i = \frac{X_i}{(t_2 - t_1)} \tag{3}$$

for the average linear rate of change (square meters per meter of shoreline per annum, or meters per annum of recession or accretion) where $t_2 - t_1$ is the time span, in years, between the dates of the two maps or stereomodels. Along an individual shoreline segment, it also is true that:

$$x_i = a_i / l_i \tag{4}$$

Even if individual measurements do not span exactly the same period of time, an average recession rate for a set of measurements can be calculated by first converting each measurement to an annual rate. Erosion rates may fluctuate on a time scale of years to decades; average annual rates presented here are not meant to imply constant rates during the time span used.

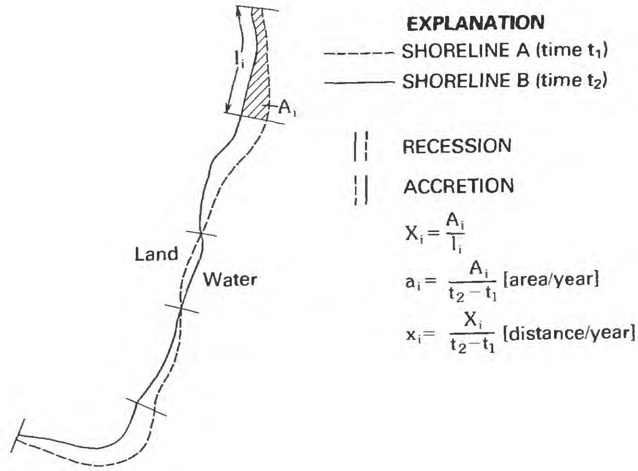


Figure 15. Basis for calculation of rates of shoreline recession and accretion.

Although neither the cartographic measurements nor the photogrammetric measurements span a uniform time period, comparisons of the two sets of measurements are based on the assumption that they can be considered as two separate, internally consistent data sets. The photogrammetric measurements are regarded as indicators of modern (about 1951–77) erosion rates, and the cartographic measurements are regarded as indicators of historical (about 1860–1970) erosion rates.

A set of contiguous square cells was superimposed on the digitized shorelines in each file (fig. 16). Each cell had sides that were 610 m (2,000 ft) long. The cell size chosen was large enough that the average recession or accretion rate calculated for each cell tended to smooth out some of the local variability that would occur in a set of measurements made at discrete points. The cells also were small enough that patterns in the distribution of erosion rates along the shoreline were not masked by the smoothing process. The total length of digitized shoreline in the study area was divided into 489 cells; average rates for shoreline reaches were based on the set of measurements collected for individual cells along each reach (Miller, 1983). The length of shoreline contained within each cell was not constant, because of the irregular shape of the shoreline. Most cells included about 550 to 750 m (1,900 to 2,500 ft) of shoreline.

Multiple shoreline features are visible on aerial photographs; more than one of these features can be digitized and used in analysis of shoreline change. The features chosen for use in this study included the mean high-water line, the base of the bank, the top edge of the bank, and the edge of the marsh. A generalized illustration of these features is shown in figure 17. On banks

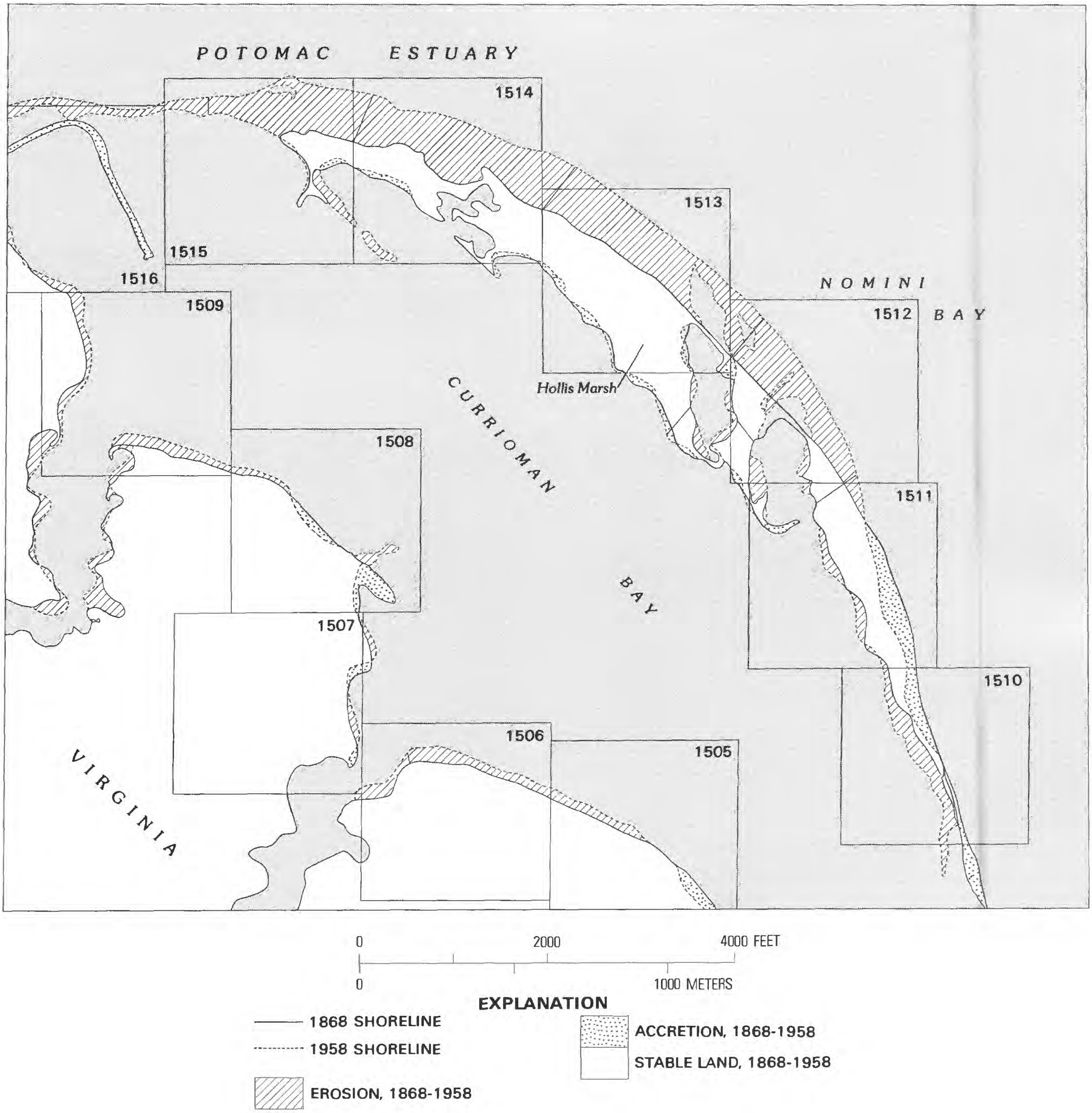


Figure 16. Set of contiguous square cells along the shoreline. Example shows comparison of digitized map shorelines at Hollis Marsh on the Virginia shore of the estuary. Areas of recession, accretion, and stable land are indicated as described in the explanation.

with high relief and complex geometry, contours and cross-section profiles were sometimes recorded. Artificial protective structures such as bulkheads, groins, and breakwaters also were digitized.

Photogrammetric measurements of bank recession were based on changes in the location of the base of the bank and of the top edge of the bank, where both were recorded; if one of these two features was obscured by shadows or vegetation or not recorded because of poor image quality, the other feature was used. The mean high-water line was used if nothing else was clearly visible on the photographs. This line usually is marked by a color or tone change on the beach and has been used by previous authors in measuring shoreline change (Stafford and Langfelder, 1971; Dolan and others, 1979). In areas where beaches are broad, transient changes in beach

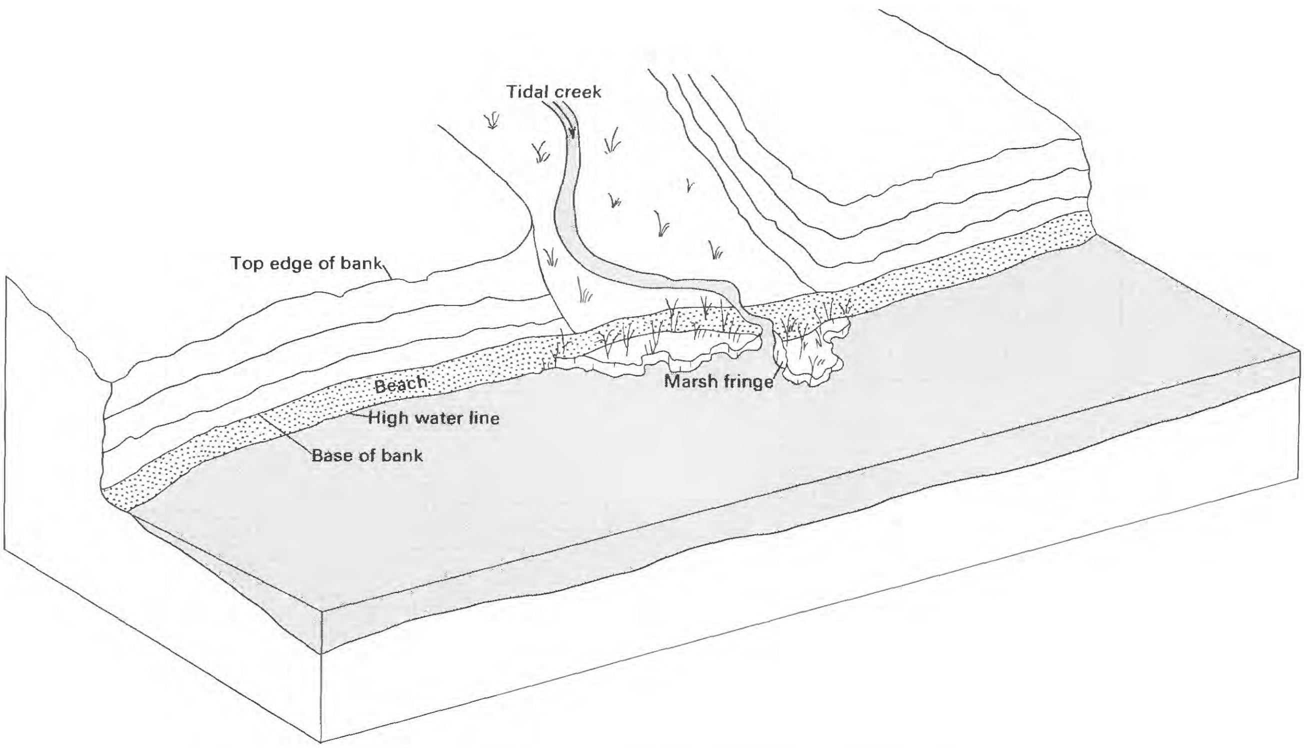


Figure 17. Generalized illustration of shoreline features digitized from aerial photographs.

profile from storms, tides, or changes in local sediment supply can cause landward or seaward migration of the high-water line, while the bank remains unchanged. Therefore, the high-water line was used as an indicator only of changes on the beach, when other evidence indicated that the bank had remained stable during the time period in question. The only shoreline feature actually shown on the maps is the mean high-water line (Shalowitz, 1964; Ellis, 1978); all cartographic measurements were based on changes in the location of this line.

Where the shore zone was occupied by a beach with no bank, or where accretion occurred at the base of the bank, the mean high-water line was the reference feature for photogrammetric measurements of erosion or accretion. In marshy areas, changes in the location of the edge of the marsh were measured. At some locations along the shores of the estuary, marsh was visible at the base of the bank in the earlier set of photographs but had been removed completely in the later set of photographs. Average recession rates for these locations were based on the sum of the total area of marsh in the earlier photographs and the area of bank eroded between the earlier and later dates; volumes of sediment derived from marsh erosion and from bank erosion at the same location were calculated independently and then added together.

Shoreline Relief

The volume of sediment derived from shore erosion is calculated by multiplying the area of change along some specified segment of shoreline by the average height of that segment. Average bank heights were determined for each bank segment within each cell, as follows. For shorelines where photogrammetric data were collected, every digitized point had an elevation, and these elevations were sampled at intervals of 15 to 30 m (50 to 100 ft) along the shoreline. Along beaches and along low shorelines where no bank was present, shoreline elevation could not be measured directly. For beaches associated with banks, field observations indicated an average height of 0.6 m above mean sea level; for spits and bars with higher berms, an average height of 0.9 m above mean sea level was estimated (Miller, 1983). The eroding part of the narrow fringe of marsh often seen interfingered with beach sediments was observed to be about 0.6 m thick; more extensive eroding marshes were assumed to be 0.9 m thick. Byrne and Anderson (1977) assumed a thickness of 0.9 m for eroding or accreting marsh in tidewater Virginia.

Where photogrammetric measurements were not available, shoreline elevation was estimated from the contours on U.S. Geological Survey topographic quadrangle maps. The contour interval for most maps is 3.1 m (10 ft), but intermediate heights can be interpolated. The lowest contour shown on these maps is a 1.5-m (5-ft) contour in areas of low relief. In these areas, the values cited previously were used for average height of beach and marsh; estimates based on field reconnaissance and on spot measurements were used for average height of banks with elevations of less than 1.5 m (5 ft).

The rate of relative sea-level rise between 1940 and 1975 in the Chesapeake Bay region varied from 3.1 mm/a (Baltimore station) to 4.2 mm/a (Portsmouth station) (Hicks, 1978). An earlier report (Hicks, 1972) quoted rates for the period from 1940 to 1970 of 2.6 and 3.4 mm/a at the same stations. Subsidence rates mapped by Holdahl and Morrison (1974) from releveling of geodetic benchmarks in the Chesapeake Bay area are based on an assumed rate of eustatic sea-level rise of 1.0 mm/a and indicate subsidence of about 1.2 to 2.0 mm/a in the Potomac Estuary. If these rates are correct, a relative sea-level change in the range 0.22 to 0.42 m has occurred during the past 100 years in the study area. However, the height correction due to sea-level change is within the range of uncertainty of height measurements; sea-level rise, therefore, has not been considered in estimating volumes of sediment eroded from the shoreline during the past century.

Volume Calculations and Volume-Erosion Rates

Most eroding banks along the tidal Potomac River were treated as simple slopes that undergo parallel retreat over time periods of decades. Calculations of the volume of eroded sediment, V_i, along an arbitrary segment of shoreline were based on the formula:

$$V_i=(A_i)\ (h_i) \tag{5}$$

where

A_i is the calculated area of bank erosion, and

h_i is the average bank height along shoreline segment, i.

The average annual volume of sediment eroded from the bank along a single segment, v_i, is:

$$v_i=(a_i)\ (h_i) \tag{6}$$

where a_i is the average annual area of bank erosion (equation (2), p. 16).

Along shoreline segments where no bank is present, the annual volume of sediment erosion or accretion is calculated using equation 6, but in this instance, a_i is defined as the average annual area of change of the high-water line or edge of marsh, and h_i is the estimated or assumed elevation of the feature above mean sea level. The average volume of sediment eroded per unit length of shoreline during time period (t_2-t_1), E_i, is defined as:

$$E_i=V_i/l_i \tag{7}$$

and the average annual volume-erosion rate is:

$$e_i=v_i/l_i \tag{8}$$

Accuracy

Several sources of error may affect the accuracy of measurements of shoreline change (Miller, 1983). Individual components of error for photogrammetric measurements in this study were estimated by experiment. Cartographic measurements were subject both to measurement error and to error inherent in the source maps; experimental results were combined with assumptions based on published accuracy standards or other historical information. Conservative estimates of measurement errors were made to avoid unjustified optimism concerning reliability of the results (Miller, 1983).

The estimated standard deviation of average measured distances between digitized map shorelines for single cells was about 9.2 m. Measured distances of shoreline change at different locations ranged from less than 10 to more than 100 m. Errors for adjacent cells were assumed to be mutually independent. An additional error component, attributed to errors in measurement of the shift of the geographic reference datum (Shalowitz, 1964) on the historical maps, was estimated to have a standard deviation of about 4 m; this error component was assumed to be propagated uniformly across the map (see Miller, 1983, for details). For a single cell, the root mean square error of X_i is 10.0 m; if the measurement spans a period of 90 years, the root mean square error for the average annual recession rate, x_i, is 0.11 m/a.

Three values of standard deviation for photogrammetric measurements, based on interpretation of empirical tests, were chosen to represent different levels of photointerpretation error for any digitized feature within a single cell (Miller, 1983):

Good visibility	$\sigma=1.1$ m
Moderate visibility	$\sigma=2.3$ m
Poor visibility	$\sigma=3.7$ m .

Errors associated with tilt, relief displacement, and scale distortion of the photographic print are eliminated by the procedure used in this study; otherwise, these sources of error can be serious impediments to accurate analysis of shoreline change. Photointerpretation errors described here are attributable primarily to problems with image quality or to obstructions (that is, shadows and vegetation) blocking a clear view of the feature being digitized. An additional error term is attributed to error in matching coordinates of control points on the photographs. The pooled root mean square error for a set of 41 coordinate transformations was 1.0 m along either axis in the cartesian plane. Photointerpretation errors for each digitized shoreline feature and coordinate-matching errors along either axis in the cartesian plane are all assumed to be mutually independent; therefore, $\sigma^2_{X_i}$, the variance of the measured distance between two features, is the sum of the squares of the standard deviations assigned to these error components. If a distance is measured between a shoreline feature digitized from a stereopair with good visibility and a corresponding shoreline feature digitized from a stereopair with moderate visibility, the calculated value of σ_{x_i} is 2.9 m. If the measurement spans a period of 20 years, the standard deviation of the bank recession rate for the cell in question is 0.15 m/a. The standard deviation of an average recession distance based on separate measurements at the top edge of the bank and at the base of the bank can be calculated using a weighting formula (Miller, 1983).

Another error component affecting both photogrammetric and cartographic measurements is associated with height measurements. The standard deviation of measurements of h_i from photogrammetric data is assumed to have a value of 0.6 m, and standard deviations of measurements of h_i based on interpolation from topographic maps are assumed to be mostly in the range between 0.6 and 1.6 m (Miller, 1983).

The variance of an average annual volume estimate, $\sigma^2_{v_i}$, depends on the variance of the recession rate, $\sigma^2_{x_i}$, on the variance of the height, $\sigma^2_{h_i}$, and on the measured values of recession rate and height (Miller, 1983). Average volume-erosion rates and standard deviations of average volume-erosion rates for a sample reach along the Virginia shore of the Potomac Estuary were calculated by Miller (1983). Cartographic comparisons along the reach included 21 cells with a combined shoreline length of about 14,300 m; average volume-erosion rate was 0.92 m^3/m of shoreline per annum, with a standard deviation of 0.14 $(m^3/m)/a$. Photogrammetric data for the same reach included 15 cells with a combined shoreline length of about 9,400 m; the average volume-erosion rate was 0.67 m^3/m of shoreline per annum, with a standard deviation of 0.13 $(m^3/m)/a$. These calculated standard deviations apply only to measurement accuracy; they are not meant to describe either variability within the population of cells or temporal variability of erosion processes.

SHORE-EROSION RATES

Major findings of this study are based on cartographic and photogrammetric measurements. Field investigations provide information on erosion processes and on short-term local rates of erosion, which may be highly variable. Information on silt-clay content of bank-sediment samples is combined with the results of cartographic and photogrammetric measurements in estimating contributions of suspended sediment to the tidal Potomac River from shore erosion.

Silt-Clay Content in the Banks of the Tidal Potomac River

Sites where samples of bank sediment were taken are identified in figure 11; the percentage of silt and clay measured in each sample, height of the bank exposure, and the stratigraphic type are listed in table 3. Measured values of silt-clay content range from 1.0 to 81.5 percent; 59 of 76 measurments are in the range between 25 and 66 percent.

Average values of silt-clay content were calculated for groups of bank-sediment samples for use in estimating the silt-clay component of sediment eroded from the shoreline. Because bank relief and stratigraphy varied locally and because widespread Pleistocene terrace sediments included a broad range of silt-clay content, samples were not grouped by geologic formation. Samples were grouped (sections A–K of fig. 18) on the basis of similarities in sediment type, clustering of measured values of silt-clay content, or proximity along the shoreline. A simple average value was calculated for all bank samples from each of the shoreline sections shown in figure 18; these values were assumed to represent average silt-clay content for all sediment eroded from each section. The results were used later in estimating suspended-sediment contributions to the tidal Potomac River from shore erosion.

Field Measurements of Erosion Rates

Field measurements of shore erosion were made at six bank profiles on the west shore of Swan Point Neck and at five bank profiles on the west shore of Mason Neck (fig. 2). The profiles at Swan Point Neck included two groups of three profiles each; the groups were located about 500 m apart, and profiles in each group were 5 to 15 m apart. Recession rates in the northern group were extremely rapid, with an average rate during the 10-month period of 3.0 m/a (table 4). In the southern group, the average recession rate was 0.4 m/a. The main difference between the two sites was a broader, higher beach at the southern site, with a greater density of fallen trees along the shoreline. Measured erosion rates for these six profiles encompass almost the entire range of values measured along the tidal Potomac River shoreline by cartographic and photogrammetric methods, as will be shown below. The rates demonstrate the enormous variability in short-term erosion that may be induced by local factors.

At High Point (Mason Neck), a set of three profiles within a 10-m reach was established at a site, HP–1, facing south-southwest toward the direction of maximum fetch (19 to 22 km). A pair of profiles about 15 m apart was located about 250 m north of the first set, at HP–4, facing almost due west across Occoquan Bay. At HP–1, average recession rate was 0.5 m/a and average volume-erosion rate was 4.6 $(m^3/m)/a$; at HP–4, average recession rate was 0.4 m/a and average volume-erosion rate was 3.6 $(m^3/m)/a$ (table 5). Maximum and minimum rates were measured at two profiles that happened to

Table 3. Bank-sediment samples

[P, Pleistocene terrace sediments; Mu, upper Miocene sediments of Chesapeake Group (possibly includes upland deposits of Glaser, 1971, and other authors); Ml, lower part of Chesapeake Group, Choptank and Calvert Formations at base; E, Eocene Nanjemoy Formation; Pa, Paleocene Aquia Formation; K, Cretaceous sediments of the Potomac Group. Where more than one formation is listed, the uppermost part of the column is listed last; for example, E,P indicates Nanjemoy Formation truncated by Pleistocene terrace sediments]

Sample[1]	Silt + clay (percent)	Height of section (meters)	Stratigraphic type
M1	65.8	5.5	P
M2	29.5	4.3	P
M3	65.6	13.0	P
M4	43.7	12.0	P
M5	57.6	7.8	P
M6	23.2	5.0	P
M7	14.2	9.1	Pa,P
M8	61.3	8.5	P
M9	16.4	8.5	Pa,P
M10	41.0	7.0	P
M11	34.8	7.0	P
M12	45.6	4.5	P
M13	75.8	5.7	P
M14	60.9	6.6	P
M15	70.0	3.2	P
M16	31.0	7.0	E
M17	26.7	30.0	E,Ml
M18	32.0	30.0	E,Ml,Mu
M19	18.0	6.4	E
M20	43.2	3.5	P
M21	63.8	3.2	P
M22	21.8	3.1	P
M23	65.6	3.0	P
M24	61.9	2.8	P
M25	69.2	2.8	P
M26	36.1	3.5	P
M27	1.0	4.2	P
M28	14.8	3.0	P
M29	33.0	2.0	P
M30	40.0	1.7	P
M31	38.6	1.8	P
M32	54.7	1.2	P
M33	37.4	4.0	P
M34	24.6	1.5	P
V1	49.8	5.9	K
V2	31.6	18.0	K
V3	42.5	13.3	P
V4	48.1	7.6	P
V5	42.5	7.0	P
V6	56.1	11.3	P
V7	16.5	7.0	K(?)
V8	20.9	5.0	P
V9	35.2	9.0	P
V10	45.1	3.8	P
V11	41.2	6.5	P
V12	21.2	21.3	Pa
V13	33.5	5.2	Pa,P
V14	26.4	5.7	E
V15	38.0	12.1	E/P
V16	20.9	13.5	E/P
V17	78.4	4.3	P
V18	29.8	15.0	E,Mu
V19	48.0	16.5	E,Ml(?),Mu(?)
V20	38.2	7.0	P
V21	66.6	4.0	P
V22	39.0	6.1	P
V23	37.8	6.0	Ml,P
V24	52.9	6.7	Ml,P
V25	29.7	5.1	Ml
V26	34.4	4.9	Ml,P
V27	30.2	6.0	Ml,P
V28	33.2	40.0	Ml,Mu
V29	40.2	8.5	Ml
V30	24.3	4.1	P
V31	65.7	2.5	P
V32	43.1	2.5	P
V33	25.8	3.0	P
V34	81.5	3.2	P
V35	48.5	1.5	P
V36	38.4	2.0	P
V37	52.0	2.3	P
V38	40.6	2.4	P
V39	13.0	3.8	P
V40	33.4	2.6	P
V41	45.9	2.0	P
V42	37.1	2.3	P

[1]See figure 11 for sample locations.

be located 10 m from each other; the difference in rates resulted partly from the presence of a large tree at the top of the bank that affected the plan geometry of the bank and partly from the configuration of fallen trees on the beach that affected patterns of sediment transport and wave activity. Slope processes and bank stability were strongly affected by stratigraphy of the bank and by the amount of groundwater seepage occurring during late winter and early spring.

Local variability of short-term erosion rates at both erosion sites is large. Field observations indicate that some of the factors causing variability of rates along the shoreline (such as the configuration of fallen trees on the beach) may have only transient effects that would be smoothed out if a longer period of record were available. Spatial variability of rates also may be present over longer time scales; local variation in lithology, nearshore bathymetry, and other unspecified factors can contribute to persistent variations of erosion rates. Field monitoring is necessary in order to identify these factors and to distinguish short-term and local variations of erosion rate from the average values derived from cartographic and photogrammetric measurements.

Cartographic and Photogrammetric Measurements of Erosion Rates

The tidal Potomac River shoreline was divided into 19 numbered reaches (fig. 19), and average recession and volume-erosion rates for these reaches (table 6) were calculated from the tabulated rates for individual cells. The number of cells in each reach ranged from 7 to more than 50. Reaches along the estuary were divided at major changes in shoreline orientation and geometry or at major changes in shoreline relief. Shores of the tidal river and transition zone were simply broken into three main parts, each consisting of a pair of reaches on opposite sides of the tidal Potomac River.

In each reach some cells are included in both cartographic and photogrammetric measurements and some cells are included in only one set of measurements; in some reaches, parts of the shoreline are not included in either set of measurements. Average recession and volume-erosion rates tabulated in the first part of table 6 and graphed in figure 20 are based on all measured cell data within each reach. Average rates based only on cells with overlapping measurements, as well as percentages of shoreline length covered by overlapping measurements, are tabulated by reach in the second part of table 6. Graphed recession rates and volume-erosion rates for reaches on each side of the estuary are arranged (fig. 20) with the upstream reach to the left and the downstream reach to the right; the three pairs of reaches from the tidal river and transition zone also are arranged with the upstream direction to the left and the downstream

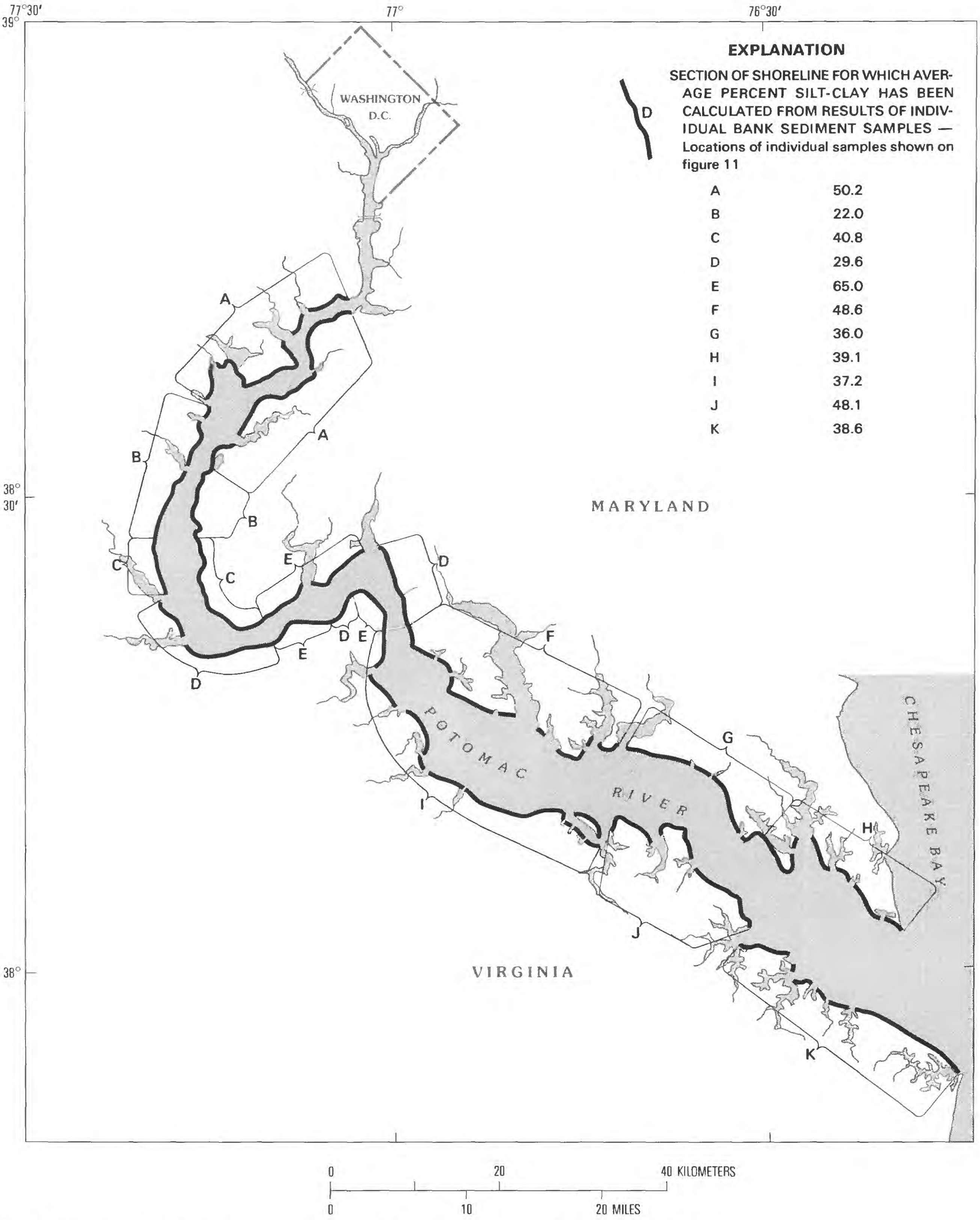


Figure 18. Average silt-clay content of grouped bank-sediment samples along the shoreline.

Table 4. Field-measured changes, western shore of Swan Point Neck, January 8 to October 31, 1980
[-- indicates no measured change]

Profile	Change in bank cross section (square meters)	Bank height (meters)	Mean recession distance (meters)	Mean recession rate (meters per annum)	Mean volume-erosion rate (cubic meters per meter per annum)
North group					
SP-W1	10.7	2.9	3.7	4.6	13.2
SP-W2	6.3	2.6	2.4	3.0	7.8
SP-W4	2.6	2.2	1.2	1.5	3.2
Average	6.5		2.4	3.0	8.1
South group					
SP-W5	--	1.3	--	--	--
SP-W6	.8	1.5	.5	.6	.9
SP-W7	.7	1.5	.5	.6	.9
Average	.5		.3	.4	.6
Average for both groups.	3.5		1.4	1.7	4.3

direction to the right. (Upstream and downstream are defined with respect to the net seaward tidally averaged flow of the Potomac below the head of tide.)

The most rapid recession rates in the estuary were greater than 1 m/a and were measured along reach 1, near the mouth on the Virginia shore. This reach is exposed to waves travelling across Chesapeake Bay from the northeast and is subject to elevated water levels caused by wind setup in the Bay. The trend of the shoreline along much of this reach has been smoothed out by erosion and deposition and is almost perpendicular to the direction of longest fetch, but north and northwest winds blowing across the Potomac Estuary also generate waves capable of attacking this part of the shoreline.

Cartographic recession rates also were quite rapid along Hollis Marsh (reach 5b), where the average rate was

Table 5. Field-measured changes, High Point, Mason Neck, February 1980 to July 1981
[-- indicates no measured change]

Profile	Top recession (meters)	Change in bank cross section (square meters)	Bank height (meters)	Mean recession (meters)	Mean recession rate (meters per annum)	Volume-erosion rate (cubic meters per meter per annum)
Site HP-1						
A[1]	1.4	14.0	10.0	1.4	0.9	8.9
B	1.0	5.6	10.0	.6	.4	3.9
C	--	1.8	10.0	.2	.1	1.2
Average	.8	7.1		.7	.5	4.6
Site HP-4						
A	--	6.1	10.2	.6	.4	4.2
B	.8	4.4	9.7	.5	.3	3.0
Average	.4	5.3		.5	.4	3.6
Average for both sites	0.6	6.2		0.6	0.4	4.1

[1]December 1979 to July 1981.

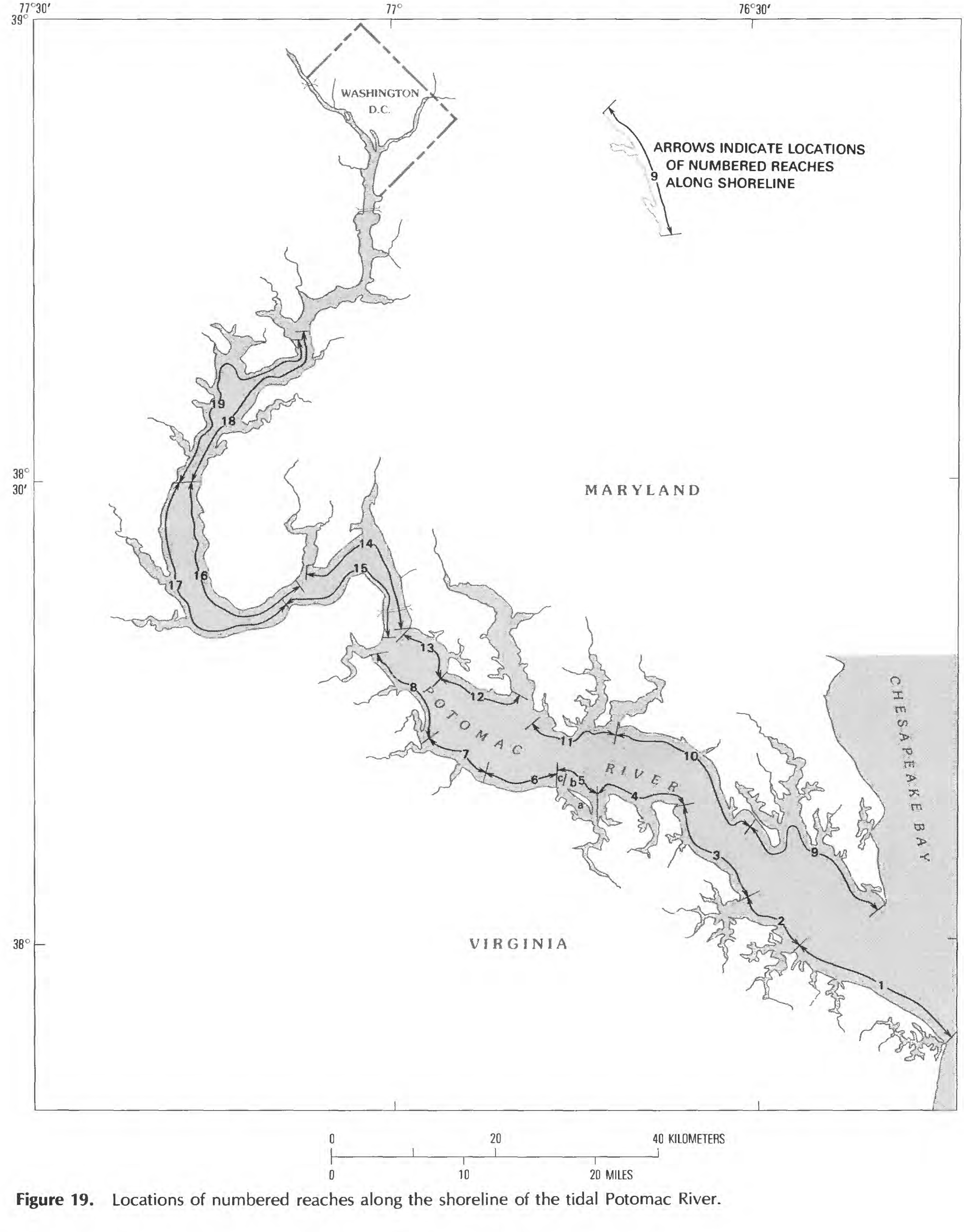


Figure 19. Locations of numbered reaches along the shoreline of the tidal Potomac River.

Table 6. Summary of erosion-rate measurements for numbered reaches

[Parentheses indicate net accretion; dashes indicate net erosion with average rate slower than 0.05 meter per annum; nd indicates no data; nom indicates no overlapping measurements]

Reach	Estimated reach length (meters)	Cartographic methods: Average recession rate (meters per annum)	Cartographic methods: Average volume-erosion rate (cubic meters per meter per annum)	Cartographic methods: Reach length measured (percent)	Photogrammetric methods: Average recession rate (meters per annum)	Photogrammetric methods: Average volume-erosion rate (cubic meters per meter per annum)	Photogrammetric methods: Reach length measured (percent)
			All measurements included in average for reach				
1	22,000	1.2	2.0	34	1.0	1.9	59
2	12,500	.5	.6	100	.6	.7	69
3	16,100	.6	1.6	100	.4	1.2	37
4	14,300	.3	.9	100	.2	.7	65
5A	7,500	.1	.8	100	nd	nd	nd
5B	4,200	.8	.8	100	nd	nd	nd
5C	1,200	.2	.4	100	(1.19)	(1.10)	100
6	9,200	.3	8.3	100	.2	3.2	85
7	8,600	.5	2.1	100	.3	1.5	65
8	15,500	.2	.7	87	.2	.7	23
9	25,800	.7	1.0	76	.4	.6	68
10	23,100	.3	.8	100	.4	.7	58
11	10,800	.3	.4	100	--	.2	59
12	10,800	.3	.6	100	.4	.5	47
13	7,900	.2	.3	100	.5	1.1	95
14	20,300	--	.9	80	.2	.6	59
15	19,600	.2	.6	100	.2	.9	54
16	29,000	.1	.3	80	.2	1.0	42
17	34,600	.2	.6	92	.2	.9	29
18	26,000	0.1	0.7	100	--	0.6	37
19	30,000	.1	.3	100	.1	.5	37
			Rates based on overlapping measurement within each reach				
1	22,000	1.2	1.9	32	1.3	1.9	31
2	12,500	.6	.7	73	.6	.7	69
3	16,100	.7	2.0	37	.4	.2	37
4	14,300	.4	1.2	68	.2	.7	65
5A	7,500	nom	nom	nom	nd	nd	nd
5B	4,200	nom	nom	nom	nd	nd	nd
5C	1,200	nom	nom	nom	nd	nd	nd
6	9,200	.5	9.3	84	.2	3.2	85
7	8,600	.5	2.2	61	.3	1.5	65
8	15,460	.3	1.1	24	.2	.7	23
9	25,800	.8	1.2	45	.5	.7	44
10	23,100	.4	1.0	57	.4	.7	58
11	10,800	.2	.3	60	--	.2	59
12	10,800	--	.2	48	.4	.5	46
13	7,900	.2	.3	96	.5	1.1	95
14	20,300	--	.9	39	.2	.6	39
15	19,600	.2	.8	54	.2	.9	54
16	29,000	0.1	0.5	43	0.2	1.0	42
17	34,600	.1	.8	30	.2	.9	29
18	26,000	.1	.9	36	--	.6	37
19	30,000	.2	.5	38	.1	.5	37

0.8 m/a, and along reach 9, near the mouth on the Maryland shore of the estuary, where the average rate was 0.7 m/a. Hollis Marsh is a long spit-like feature trending from northwest to southeast across Nomini Bay, with only about 1 m of relief. Although Hollis Marsh erodes rapidly (historical changes are shown in fig. 16), it is not a significant source of sediment because relief is so low. Shoreline relief along reach 9 is fairly low

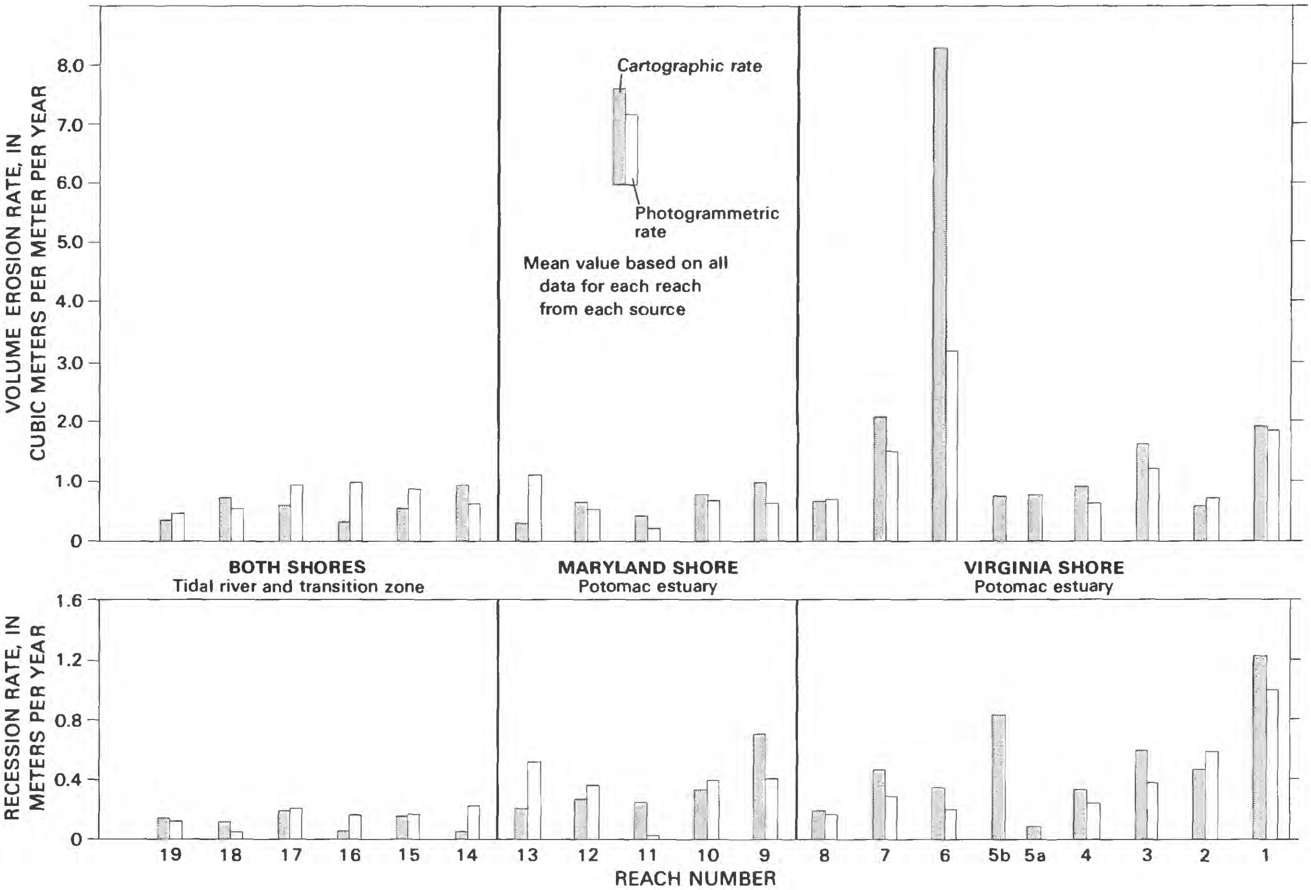


Figure 20. Erosion rates for numbered shoreline reaches along the tidal Potomac River. Within each section of the graph, the reach closest to Chesapeake Bay is shown at the right and the reach closest to the head of tide is shown at the left. Along the tidal river and transition zone, reaches 14 and 15, 16 and 17, and 18 and 19 form pairs that face each other from opposite shores. See figure 19 for locations.

but is comparable with relief near the mouth along the Virginia shore; eroding banks are between 1 and 4 m high. Measurements along reach 9 indicate that southeast exposures erode much more slowly than west- or southwest-facing exposures and may actually accrete or remain stable. The average photogrammetric recession rate for the reach (0.4 m/a) is slower than the average cartographic recession rate, partly because of construction within the past 25 years of protective structures along several sections of the shoreline that underwent severe erosion in the past.

Average recession rates along reaches elsewhere in the estuary are mostly between 0.1 and 0.6 m/a; average recession rates in the tidal river and transition zone are mostly less than or equal to 0.2 m/a. Average photogrammetric recession rates are slower than average cartographic recession rates along most reaches on the the Virginia shore of the estuary. Photogrammetric recession rates are more rapid than cartographic recession rates along part of the Maryland shore, particularly at reach 13 near the landward end of the estuary, where erosion appears to have accelerated in recent decades (fig. 20). Bulkheads were built along much of this shoreline during the 1970's to counteract the erosion trend. In the tidal river and transition zone, comparison of average cartographic and photogrammetric recession rates does not reveal any distinctive pattern (fig. 20).

Volume-erosion rates depend on shoreline relief as well as recession rate; the most rapid volume-erosion rates for any reach in the tidal Potomac River were measured along the Nomini Cliffs, reach 6 on the Virginia shore of the estuary. Although average recession rates of these cliffs are slower than rates measured for most other reaches on the Virginia shore, the cliffs are as much as 5 to 10 times higher than eroding banks elsewhere along the Virginia shore of the estuary. The average cartographic volume-erosion rate for reach 6 was 8.3 (m^3/m)/a; the average photogrammetric volume-erosion rate for reach 6 was 3.2 (m^3/m)/a. Three other reaches along the Virginia shore of the estuary had more rapid recession rates than reach 6 and had average volume-erosion rates between 1.2 and 2.1 $(m^3/m)/a$; average volume-erosion rates for all other reaches along the shoreline of the estuary and of the tidal river and transition zone were between 0.2 and 1.1 $(m^3/m)/a$. Relief along the Maryland shore of the estuary is low, and rapid recession rates generally occur where altitudes are no higher than 3 m, yielding volume-erosion rates comparable with the slower eroding reaches among those located along the Virginia shore. Relief along the shores of the tidal river and transition zone is much higher than along most of the Virginia shore of the estuary, but recession rates are slower; resulting volume-erosion rates are comparable to those along the Maryland shore of the estuary. High bluffs are present at several locations in the tidal river and transition zone, but, with the exception of isolated short sections, they erode much more slowly than the Nomini Cliffs do and are not important contributors of sediment.

Maximum recession and volume-erosion rates measured for individual cells along the shoreline of the estuary (fig. 21) were considerably higher than average recession rates for shoreline reaches. The fastest recession rates, 2.5 m/a (cartographic) and 4.3 m/a (photogrammetric), were measured at a site near the mouth of the estuary along the Virginia shore. The greatest volume-erosion rates, 21.3 $(m^3/m)/a$ (cartographic) and 7.0 $(m^3/m)/a$ (photogrammetric), were measured at sites along the Nomini Cliffs. Maximum recession rates in the tidal river and transition zone were measured along marshy shorelines and attained values in excess of 1.0 m/a, but almost all eroding banks in this part of the study area had slower recession rates. Maximum volume-erosion rates calculated for individual cells in the tidal river and transition zone were 5.0 $(m^3/m)/a$ (cartographic) along a set of 30-m-high bluffs near Popes Creek, Maryland, and 5.1 $(m^3/m)/a$ (photogrammetric) at High Point on Mason Neck (fig. 21).

Average Erosion Rates for Major Divisions of the Shoreline

The set of erosion-rate measurements made in this study does not include the entire shoreline of the study area. As a result it was necessary to extrapolate average volume-erosion rates and average annual total volumes of erosion from the available information. Photogrammetric measurements are not randomly distributed along the shoreline because of (1) the history of development of the measurement techniques, (2) limits on availability of source materials, and (3) choices made in planning the research. Available measurements are organized in contiguous blocks with broad gaps between them. Although an attempt was made to obtain a representative sample of shoreline locations, the importance of identifying and quantifying major sources of sediment from shore erosion dictated the inclusion of sites suspected of having rapid erosion rates.

Methods of estimating average volume-erosion rates and average annual total volumes of erosion, described below, were designed to overcome the problem posed by the nature of the sample. Because the photogrammetric and cartographic measurements overlap along much of the shoreline, it was possible to characterize the degree to which the set of photogrammetric measurements was biased by inclusion of sites with rapid erosion rates. Weighting methods and supplementary data from cartographic measurements were used to correct the average erosion rates and calculated erosion volumes.

For reaches where overlapping cartographic and photogrammetric measurements were available along part of the shoreline, and only one set of measurements was available along the remainder of the shoreline, it was assumed that the ratio of measured rates in the overlap area could be used to synthesize missing rates from available measurements in the non-overlap area. In other words, the ratio of average photogrammetric recession rate in the overlap area, x_{po}, to average cartographic recession rate in the overlap area, x_{co}, was assumed equal to the ratio of average photogrammetric and cartographic recession rates in the non-overlap area, x_{pn}/x_{cn}. This assumption is expressed in the equation:

$$\frac{x_{po}}{x_{co}} = \frac{x_{pn}}{x_{cn}} \quad . \qquad (9)$$

For an arbitrary reach where cartographic measurements are available along the entire shoreline and photogrammetric measurements are available only along part of the shoreline, x_{pn} is unknown. The unknown quantity can be estimated by rearranging equation (9) to give:

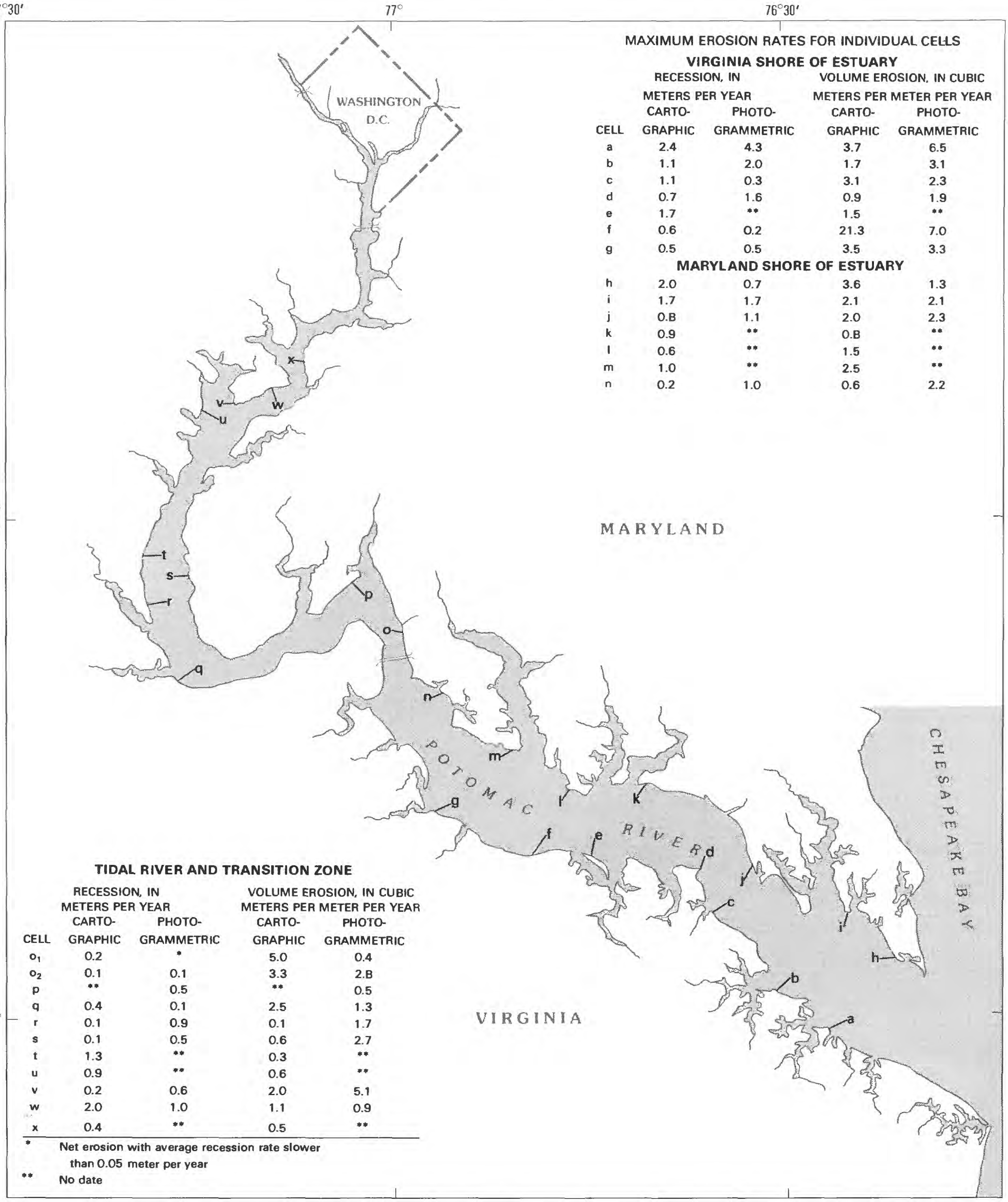
$$x_{pn} = (x_{po}/x_{co})x_{cn} \quad . \qquad (10)$$

The adjusted average photogrammetric recession rate for the entire reach, x_{pr}, was calculated in two steps. First, the annual area of erosion in the overlap area, $x_{po}l_o$, and the estimated annual area of erosion in the non-overlap area, $x_{pn}l_n$, were summed. Next, that sum was divided by $l_o + l_n$, where l_o is the length of shoreline in the overlap area and l_n is the length of shoreline in the non-overlap area. In equation form, the procedure was:

$$x_{pr} = \frac{x_{po}l_o + x_{pn}l_n}{l_o + l_n} \quad . \qquad (11)$$

The same procedure was used to calculate average volume-erosion rates, e_{cr} (cartographic) and e_{pr} (photogrammetric).

The length of shoreline included in cartographic measurements along the Virginia shore of the estuary is



MAXIMUM EROSION RATES FOR INDIVIDUAL CELLS

CELL	RECESSION, IN METERS PER YEAR: CARTO-GRAPHIC	RECESSION, IN METERS PER YEAR: PHOTO-GRAMMETRIC	VOLUME EROSION, IN CUBIC METERS PER METER PER YEAR: CARTO-GRAPHIC	VOLUME EROSION, IN CUBIC METERS PER METER PER YEAR: PHOTO-GRAMMETRIC
VIRGINIA SHORE OF ESTUARY				
a	2.4	4.3	3.7	6.5
b	1.1	2.0	1.7	3.1
c	1.1	0.3	3.1	2.3
d	0.7	1.6	0.9	1.9
e	1.7	**	1.5	**
f	0.6	0.2	21.3	7.0
g	0.5	0.5	3.5	3.3
MARYLAND SHORE OF ESTUARY				
h	2.0	0.7	3.6	1.3
i	1.7	1.7	2.1	2.1
j	0.8	1.1	2.0	2.3
k	0.9	**	0.8	**
l	0.6	**	1.5	**
m	1.0	**	2.5	**
n	0.2	1.0	0.6	2.2

TIDAL RIVER AND TRANSITION ZONE

CELL	RECESSION, IN METERS PER YEAR: CARTO-GRAPHIC	RECESSION, IN METERS PER YEAR: PHOTO-GRAMMETRIC	VOLUME EROSION, IN CUBIC METERS PER METER PER YEAR: CARTO-GRAPHIC	VOLUME EROSION, IN CUBIC METERS PER METER PER YEAR: PHOTO-GRAMMETRIC
o_1	0.2	*	5.0	0.4
o_2	0.1	0.1	3.3	2.8
p	**	0.5	**	0.5
q	0.4	0.1	2.5	1.3
r	0.1	0.9	0.1	1.7
s	0.1	0.5	0.6	2.7
t	1.3	**	0.3	**
u	0.9	**	0.6	**
v	0.2	0.6	2.0	5.1
w	2.0	1.0	1.1	0.9
x	0.4	**	0.5	**

* Net erosion with average recession rate slower than 0.05 meter per year

** No date

Figure 21. Maximum erosion rates measured for individual cells along the shoreline of the tidal Potomac River. The tables in this figure list recession and volume-erosion rates based on cartographic and photogrammetric measurements for cells at the locations indicated by the lowercase letters on the map.

about 94,000 m; the length of shoreline included in photogrammetric measurements is about 55,000 m; and the length of shoreline included in overlapping measurements is about 49,000 m. Average cartographic and average photogrammetric recession rates both are 0.46 m/a, based on all measurements from each data set (table 7); however, the average cartographic recession rate in the overlap area is 0.60 m/a, and the average cartographic recession rate in the non-overlap area is only 0.30 m/a. Clearly the set of locations chosen for photogrammetric measurements includes sites with faster recession rates than the set of locations not chosen for photogrammetric measurements. A similar pattern is visible on examination of the volume-erosion rate data. Average volume-erosion rates based on all available measurements are 1.84 $(m^3/m)/a$ (cartographic) and 1.44 $(m^3/m)/a$ (photogrammetric), but cartographic rates in the overlap area are nearly 3 times as great as cartographic rates in the non-overlap area (table 7).

Comparisons of average cartographic and photogrammetric rates, based only on measurements from locations where the two data sets overlap, indicate that the cartographic rates are substantially higher than the photogrammetric rates. This statement is true both for average recession rates in the overlap area and for average volume-erosion rates in the overlap area (table 7). The discrepancy does not appear as large when one compares average rates based on all available measurements because the set of photogrammetric measurements, covering 50 percent of the Virginia shore of the estuary, includes a disproportionate number of sites with relatively rapid erosion rates. It was assumed that if the set of photogrammetric measurements were a more representative sample of erosion rates along the Virginia shore of the estuary, then the average photogrammetric recession rate would be slower than 0.46 m/a and the average photogrammetric volume-erosion rate would be slower than 1.44 $(m^3/m)/a$. The procedure described above was used to calculate adjusted values of average recession and volume-erosion rate for reaches along the Virginia shore of the estuary.

Weighted average recession rate, $\bar{x}$, and volume-erosion rate, $\bar{e}$, for the set of reaches along the Virginia shore of the estuary then were calculated using the length of shoreline in each reach, l_r, as a weight:

$$\bar{x} = \frac{\Sigma x_r l_r}{\Sigma l_r}, \quad (12)$$

$$\bar{e} = \frac{\Sigma e_r l_r}{\Sigma l_r}. \quad (13)$$

Average recession rates calculated by this method for the Virginia shore of the estuary were 0.52 m/a (cartographic) and 0.42 m/a (photogrammetric), and average volume-erosion rates calculated by the same method were 1.87 $(m^3/m)/a$ (cartographic) and 1.20 $(m^3/m)/a$ (photogrammetric) (table 7).

The length of shoreline along the Maryland side of the estuary included in the set of cartographic measurements is about 72,000 m, and the length included in the set of photogrammetric measurements is about 50,000 m; overlapping measurements included about 44,000 m (table 7). Weighted average recession rates based on all available data from each source were 0.40 m/a (cartographic) and 0.36 m/a (photogrammetric); average volume-erosion rates were 0.70 $(m^3/m)/a$ (cartographic) and 0.65 $(m^3/m)/a$ (photogrammetric). Averages based only on overlapping measurements were not significantly different from averages based on all data (table 7).

Despite the apparent closeness of average cartographic and photogrammetric rates, marked differences occur in the distributions of erosion rates along the Maryland shore of the estuary (fig. 20, table 6). Alternative values of the average rates were calculated by using the weighting method outlined above, with one modification. Where the non-overlap area included shoreline with extensive bulkheads and other protective structures that now prevent bank erosion, it was assumed in calculating the photogrammetric rates that this protected shoreline does not erode and does not contribute sediment to the system. The calculated rates were 0.41 m/a (cartographic) and 0.31 m/a (photogrammetric) and 0.73 $(m^3/m)/a$ (cartographic) and 0.56 $(m^3/m)/a$ (photogrammetric) (table 7).

Cartographic measurements along the tidal river and transition zone include about 147,000 m of shoreline, and photogrammetric measurements include about 66,000 m of shoreline. Overlapping measurments are present along about 62,000 m. Average recession rates based on all measurements are 0.12 m/a (cartographic) and 0.15 m/a (photogrammetric), and average recession rates based on overlapping coverage are very close to these values. Average volume-erosion rates based on all data are 0.55 $(m^3/m)/a$ (cartographic) and 0.74 $(m^3/m)/a$ (photogrammetric) (table 7), but average cartographic volume-erosion rates based on overlapping measurements are more than 50 percent larger than those based on non-overlapping measurements. The disagreement between average cartographic volume-erosion rates in the overlap and the non-overlap areas indicates that the areas chosen for photogrammetric measurements erode more rapidly than the areas not chosen for photogrammetric measurement. To correct for sampling bias in the photogrammetric data, volume-erosion rates were calculated by using the weighting scheme described earlier. Resulting values for average volume-erosion rates were 0.56 $(m^3/m)/a$ (cartographic) and 0.58 $(m^3/m)/a$ (photogrammetric) (table 7).

Average recession rates along the Virginia shore of the estuary are 0.05 to 0.19 m/a more rapid than along

Table 7. Average erosion rates for three major divisions of the Potomac shoreline

Type of data	Measured shoreline length (meters)	Measured area of erosion (square meters per annum)	Average recession rate (meters per annum)	Calculated volume of erosion (cubic meters per annum)	Average volume-erosion rate (cubic meters per meter per annum)
			Virginia shore of the estuary		
			Averages based on total measurements		
Cartographic	94,400	43,700	0.46	174,100	1.84
Photogrammetric	55,200	25,400	.46	79,600	1.44
			Averages based on overlapping measurements		
Cartographic	49,700	29,400	0.59	131,300	2.64
Photogrammetric	49,100	20,800	.42	68,400	1.39
			Averages based on nonoverlapping measurements		
Cartographic	44,700	14,300	0.32	42,800	0.96
Photogrammetric	6,200	4,600	.75	11,300	1.83
			Averages based on weighting scheme[1]		
Cartographic	--	--	0.52	--	1.87
Photogrammetric	--	--	.42	--	1.20
			Maryland shore of the estuary		
			Averages based on total measurements		
Cartographic	72,300	29,000	0.40	50,700	0.70
Photogrammetric	49,800	18,100	.36	32,300	.65
			Averages based on overlapping measurements		
Cartographic	44,000	17,800	0.40	32,100	0.73
Photogrammetric	43,600	16,200	.37	28,700	.66
			Averages based on nonoverlapping measurements		
Cartographic	28,300	11,200	0.40	18,600	0.66
Photogrammetric	6,200	1,900	.31	3,600	.58
			Averages based on weighting scheme[1]		
Cartographic	--	--	0.41	--	0.73
Photogrammetric	--	--	.31	--	.56
			Tidal river and transition zone		
			Averages based on total measurements		
Cartographic	147,000	17,500	0.12	81,400	0.55
Photogrammetric	65,600	9,900	.15	48,700	.74
			Averages based on overlapping measurements		
Cartographic	62,100	6,800	0.11	43,000	0.69
Photogrammetric	61,600	8,800	.14	46,200	.75
			Tidal river and transition zone--Continued		
			Averages based on nonoverlapping measurements		
Cartographic	84,900	10,700	0.13	38,400	0.45
Photogrammetric	4,000	1,100	.28	2,500	.61
			Averages based on weighting scheme[1]		
Cartographic	--	--	0.12	--	0.56
Photogrammetric	--	--	.13	--	.58

[1]Tabulated values are calculated using measured values shown above. Method is described in text.

the Maryland shore; average recession rates on both sides of the estuary are much more rapid than average recession rates in the tidal river and transition zone (table 8). Average volume-erosion rates on the Virginia shore of the estuary are at least twice those on the Maryland shore; average volume-erosion rates in the tidal river and transition zone are roughly comparable to those on the Maryland shore of the estuary.

Comparision with Results from Regional Studies

Historical recession rates based on map comparisons by previous authors investigating shore erosion in the Chesapeake Bay region are listed in table 9. Some volume-erosion rates have been published and these also are given in table 9. Average historical rates from the Maryland part of Chesapeake Bay are more rapid than average rates measured in the present study along either shore of the Potomac Estuary. Historical rates from the Virginia part of the Bay are comparable with those measured along the Potomac shoreline if tributary as well as outer bay shoreline in the Virgina part of the Bay are included in the average; average rates for the outer bay shoreline in Virginia are higher than those along the Potomac (compare tables 8 and 9).

Average recession rates measured by Singewald and Slaughter (1949) for the Maryland shore of the tidal Potomac River were 0.11 m/a (Charles County) and 0.50 m/a (St. Marys County) (table 9). Charles County includes most of the Maryland shore of the transition zone and part of the tidal river and extends into the estuary as far as the Wicomico River (fig. 1); the Charles County value is comparable to average values measured for the tidal river and transition zone in this study (table 8). The shoreline of St. Marys County includes reaches 9, 10, and 11 in this report; a weighted average cartographic recession rate for these three reaches, based on data given in the first part of table 6, is 0.5 m/a, about the same as the average rate from Singewald and Slaughter (1949).

Data from Byrne and Anderson (1977) for part of the Virginia shore of the Potomac Estuary yield an average recession rate, 0.44 m/a, and an average volume-erosion rate, 1.66 (m^3/m)/a, that are comparable to average rates measured for the same shore in this study (table 8); however, Byrne and Anderson (1977) include rates measured in tributary embayments that erode more slowly than the outer shoreline. Recession rates (Byrne and Anderson, 1977) for measured areas on the outer shoreline average 0.74 m/a and volume-erosion rates for measured areas on the outer shoreline average 3.34 (m^3/m)/a (table 9); these rates are much more rapid than the rates calculated from cartographic or photogrammetric measurements in the present study.

Table 8. Comparison of average erosion rates for three divisions of the Potomac shoreline

Shoreline division	Cartographic measurements		Photogrammetric measurements	
	Recession rate (meters per annum)	Volume-erosion rate (cubic meters per meter per annum)	Recession rate (meters per annum)	Volume-erosion rate (cubic meters per meter per annum)
	Averages based on total measurements			
Virginia shore of estuary--------	0.46	1.84	0.46	1.44
Maryland shore of estuary--------	.40	.70	.36	.65
Tidal river and transition zone--	.12	.55	.15	.74
	Averages based on overlapping measurements			
Virginia shore of estuary--------	0.59	2.64	0.42	1.39
Maryland shore of estuary--------	.40	.73	.37	.66
Tidal river and transition zone--	.11	.69	.14	.75
	Averages based on nonoverlapping measurements			
Virginia shore of estuary--------	0.32	0.96	0.75	1.83
Maryland shore of estuary--------	.40	.66	.31	.58
Tidal river and transition zone--	.13	.45	.28	.61
	Averages based on weighting scheme			
Virginia shore of estuary--------	0.52	1.87	0.42	1.20
Maryland shore of estuary--------	.41	.73	.31	.56
Tidal river and transition zone--	.12	.56	.13	.58

Table 9. Comparative shore-erosion rates in the Chesapeake Bay region
[-- indicates no data]

Location	Mean recession rate (meters per annum)	Mean volume-erosion rate (cubic meters per meter per annum)
	Maryland section of Chesapeake Bay[1]	
	Mainland shores (Data from Singewald and Slaughter, 1949)	
Western shore	0.58	--
Eastern shore	.70	--
Combined shores	.66	--
	Virginia section of Chesapeake Bay	
	Combined bay and tributary shores (Data from Byrne and Anderson, 1977)	
Western shore	0.28	0.44
Eastern shore	.31	.32
Southern shore	.44	.62
	Bay shores only (Data from Rosen, 1980)	
Western shore: beach	0.91	--
marsh	.64	--
Eastern shore: beach	.78	--
marsh	.45	--
	Potomac Estuary	
	Maryland shore (Data from Singewald and Slaughter, 1949)	
Charles County	0.11	--
St. Marys County	.50	--
	Virginia shore (Data from Byrne and Anderson, 1977)	
Outer shoreline and tributaries	0.44	1.66
Outer shoreline only (Northumberland and Westmoreland Counties)	.74	3.34
	Rhode River Estuary (Data from Donoghue, 1981)	
	0.08	0.10

[1]Maximum recession rates are as much as 10 meters per annum for some islands on the east side of the Bay; approximate mean volume-erosion rate for mainland shore of mid-Bay (Chesapeake Bay Bridge to Potomac Estuary) is 2.5 cubic meters per meter per annum (based on data from Singewald and Slaughter, 1949, and Biggs, 1970).

The average recession rate calculated by Donoghue (1981) for the Rhode River Estuary, a small estuary north of the Potomac River on the western shore of Chesapeake Bay, is slightly slower than recession rates measured in the tidal river and transition zone of the Potomac River (table 9). Donoghue's average volume-erosion rate of 0.10 $(m^3/m)/a$ is much slower than the average rate for any of the major sections of the tidal Potomac River, probably because of the very low average shoreline height, 1.35 m, along the Rhode River. Donoghue (1981) notes that the average recession rate measured by Singewald and Slaughter (1949) near the mouth of the Rhode River Estuary yields a volume-erosion rate of 0.24 $(m^3/m)/a$.

SEDIMENT CONTRIBUTIONS FROM SHORE EROSION

Shore erosion is episodic; frequency and magnitude of erosive events at any site may vary from year to year. Variations in frequency of these events may in turn cause variations in the total mass of sediment contributed by shore erosion from year to year. Discharge and sediment-load data are available for cross sections of the river as a time series, and annual or seasonal variations can be analyzed. Shore-erosion sediment-load data are not available in annual series, but shore-erosion rates averaged over a long period of time are treated in this report as annual rates for comparison with other components of the sediment load. The year-to-year variation in sediment contributions derived from shore erosion is unknown; however, two independent sets of erosion-rate measurements are available, as described earlier in this report, and these have been used to provide a range of estimates. These estimates are used hereafter to compare shore erosion with other sources of sediment to the tidal Potomac River.

Three alternative sediment-volume estimates are presented here. The first estimate, based primarily on erosion-rate data from cartographic measurements, is a long-term rate of sediment supply with a time scale comparable to the time scale of data from earlier studies (Singewald and Slaughter, 1949; Byrne and Anderson, 1977). This is termed the historical estimate. The second estimate, termed the modern estimate, is based on a combination of photogrammetric and cartographic erosion-rate data; cartographic measurements provide supplementary data in areas where photogrammetric measurements are not available. This estimate represents a supply rate applicable over a shorter time scale, from the 1950's to the 1970's; sediment volumes probably are more representative of contemporary rates than the volumes presented in the historical estimate. The third estimate is essentially the same as the second estimate; in this instance, it is assumed that shoreline segments protected by extensive seawalls and bulkheads do not provide sediment to the system. This is not necessarily an accurate assumption, as these structures can be breached or undermined, and they also may cause accelerated erosion in the downdrift direction. However, on a short time scale this assumption may provide a more accurate estimate of total erosion volume than a rate based on measurements spanning a time period that began before many of the structures were built. The third estimate, termed the adjusted modern estimate, is probably the most reasonable estimate of average annual sediment contribution under present conditions.

Estimates were arrived at in the following manner. The study area was broken into individual reaches and volume-erosion rates were calculated within each reach. Cartographic measurements generally included more of the shoreline than photogrammetric measurements. Where cartographic measurement of a reach was complete, the historical estimate of annual sediment volume for the reach, v_{cr}, was calculated by summing the annual cartographic erosion volumes, v_{ci}, from all individual cells in the reach:

$$v_{cr}=\Sigma v_{ci} \quad . \tag{14}$$

Where cartographic measurement was incomplete, measured volume was used as a guide to extrapolate total volume from the reach. The sum of measured cartographic volumes, Σv_{ci}, was multiplied by the ratio of total shoreline length, l_r, to measured length, Σl_i:

$$v_{cr}=(\Sigma v_{ci})\ (l_r/\Sigma l_i) \quad . \tag{15}$$

The modern estimate relied on photogrammetric measurements where such measurements were available. For reaches where photogrammetric measurements were available along part of the shoreline and cartographic measurements were available along all or almost all of the shoreline, the sample of photogrammetric measurements was supplemented by cartographic measurements from the nonoverlap area. The average photogrammetric volume-erosion rate, e_{pr}, was calculated by using the weighting scheme described earlier. The total annual photogrammetric erosion volume for the reach then was calculated as the product

$$v_{pr}=e_{pr}l_r \tag{16}$$

where l_r is the total length of shoreline in the reach.

The adjusted modern estimate was determined by calculating the total sediment contribution to the modern estimate from shoreline locations where extensive, continuous bulkheads, seawalls, or riprap protect the shoreline. This contribution was subtracted from the modern estimate for each reach.

Volume and mass estimates for individual reaches are presented in table 10. Sediment volumes were converted to mass estimates, using a conversion factor of 1.67 g/cm^3, equivalent to metric tons per cubic meter. The value of dry bulk density used in this study was based on examination of test results on samples taken from foundation test borings at two proposed powerplant sites located in the Maryland Coastal Plain (Potomac Electric Power Co., 1974; Baltimore Gas and Electric Co., undated). The first site was located at Douglas Point, on the Maryland shore of the Potomac River; the second site was the Perryman site, located in Harford County at the northern end of Chesapeake Bay. The conversion factor of 1.67 g/cm^3 used in this study is smaller than the values used by Schubel (1968), 2.65 g/cm^3; Biggs (1970), 2.5 g/cm^3; and Donoghue (1981), 2.5 g/cm^3; but it is comparable to values used by Kerhin and others (1982), 1.67 to 2.08 g/cm^3, and Byrne and others (1982), 1.43 to 1.99 g/cm^3.

To calculate the silt-clay component of the mass of sediment eroded from the shoreline, the mass percentage of silt and clay in the banks along each reach of the shoreline (fig. 18) was multiplied by the total mass calculated for that reach for each of the three estimates.

Table 10. Annual contributions to sediment budget from shore erosion, tabulated by reach in the tidal Potomac River and Estuary
[Parentheses indicate net accretion]

Reach	Length (meters)	Volume (cubic meters per annum)	Mass of total sediment (metric tons per annum)	Mass of silt-clay (metric tons per annum)
		Historical estimates		
		Virginia shore of estuary		
1	22,000	39,900	66,700	25,700
2	12,500	7,400	12,300	4,800
3	16,100	26,400	44,200	21,200
4	14,300	13,200	22,100	10,600
5a	7,500	5,800	9,700	3,600
5b	4,200	3,200	5,400	2,000
5c	900	100	200	0
6	9,200	76,000	126,900	47,200
7	8,600	17,900	29,900	11,100
8	13,500	9,200	15,300	5,700
		Maryland shore of estuary		
9	25,800	25,500	42,600	16,700
10	23,100	18,000	30,100	10,800
11	10,800	4,500	7,500	3,700
12	10,800	6,800	11,300	5,500
13	7,900	2,400	4,000	2,000
		Tidal river and transition zone[1]		
14	20,300	15,200	25,400	7,900
15	19,600	11,100	18,500	9,100
16	29,000	9,500	15,800	7,700
17	34,600	20,100	33,600	11,500
18	26,000	15,600	26,100	11,900
19	30,000	10,100	16,800	6,900
		Modern estimates		
		Virginia shore of estuary		
1	22,000	39,600	66,100	25,500
2	12,500	7,300	12,200	4,700
3	16,100	15,800	26,500	12,700
4	14,300	7,300	12,200	5,900
5a	7,500	5,800	9,700	3,600
5b	4,200	3,200	5,400	2,000
5c	1,200	(1,300)	(2,200)	0
6	9,200	29,300	49,000	18,200
7	8,600	13,400	22,300	8,300
8	13,500	5,700	9,600	3,600
		Maryland shore of estuary		
9	25,800	14,100	23,600	9,200
10	23,100	12,500	20,800	7,500
11	10,800	3,600	6,000	2,900
12	10,800	8,400	14,000	6,800
13	7,900	8,200	13,700	6,600
		Tidal river and transition zone[1]		
14	20,300	15,100	25,200	10,000
15	19,600	12,500	20,900	10,100
16	29,000	15,700	26,200	11,000
17	34,600	21,200	35,400	12,700
18	26,000	12,900	21,500	9,600
19	30,000	9,500	15,900	7,500
		Adjusted modern estimates[2]		
		Virginia shore of estuary		
1	22,000	33,700	56,400	21,800
2	12,500	4,600	7,700	3,000
3	16,100	11,300	18,800	9,100
4	14,300	4,700	7,800	3,800
5a	7,500	5,800	9,700	3,600
5b	4,200	3,200	5,400	2,000
5c	1,200	(1,300)	(2,200)	0
6	9,200	29,300	49,000	18,200
7	8,600	12,800	21,300	7,900
8	13,500	4,900	8,200	3,000
		Maryland shore of estuary		
9	25,800	9,600	16,100	6,300
10	23,100	10,600	17,700	6,400
11	10,800	3,600	6,000	2,900
12	10,800	1,400	2,300	1,100
13	7,900	6,600	10,900	5,300
		Tidal river and transition zone[1]		
14	20,300	15,100	25,200	10,000
15	19,600	12,000	20,100	9,600
16	29,000	15,700	26,200	11,000
17	34,600	19,300	32,200	11,400
18	26,000	12,900	21,500	9,600
19	30,000	8,900	14,800	7,000

[1]Reach 14 extends below the Route 301 Bridge to Lower Cedar Point; reach 15 extends below the Route 301 Bridge to Upper Machodoc Creek. The Potomac Estuary Study has established the Route 301 Bridge as the official boundary between the transition zone and the estuary; therefore, all sediment derived from the shoreline below the bridge is allocated to the estuary in table 11. The volume of sediment from reach 14 that is allocated to the estuary is 800 cubic meters per annum; the volume of sediment from reach 15 that is allocated to the estuary is 2,000 cubic meters per annum.

[2]Assuming no sediment contributed by shoreline with extensive, continuous erosion control structures.

The component of the sediment contribution consisting of silt- and clay-size particles is listed for each reach in table 10.

Estimates of average annual sediment contributions from shore erosion for the entire study area are (1) 0.565×10^6 metric tons (historical); (2) 0.434×10^6 metric tons (modern); and (3) 0.375×10^6 metric tons (adjusted modern) (table 11). In the tidal river and transition zone, the adjusted modern estimate actually is slightly larger than the historical estimate; however, in the estuary, the adjusted modern estimate is only about 55 percent of the historical estimate. The sediment loads in the silt-clay size range are (1) 0.226×10^6 metric tons per annum (historical estimate); (2) 0.179×10^6 metric tons per annum (modern estimate); and (3) 0.153×10^6 metric tons per annum (adjusted modern estimate). The rate during any given year does not necessarily fall between the large and small values from the set of estimates presented here; however, these estimates do provide a useful range of values for the sediment load averaged over a period of years.

The relative order of importance of contributions from each of the three main shoreline divisions follows a consistent pattern among historical, modern, and adjusted modern estimates, although the actual percentages vary somewhat (table 12). The Virginia shore of the estuary contributes 49 to 60 percent of the sediment derived from shore erosion, the Maryland shore of the estuary contributes 15 to 18 percent, and the tidal river and transition zone contributes 23 to 36 percent. The silt-clay component varies only slightly among the three estimates and among the three main shoreline divisions of the study area, ranging between 40 and 42 percent of the total sediment contribution. Estimates of the silt-clay component of shoreline sediment contributions in different parts of Chesapeake Bay include a broader range of values. Schubel (1968) estimated that 36 percent of the sediment eroded from the shoreline in the northern part of Chesapeake Bay was silt and clay. Biggs (1970) estimated that the mass of silt and clay eroded from the banks of the middle part of the Bay was only 21 percent of the total eroded mass. Kerhin and others (1982), using a different computation method, estimated that 64 percent of the eroded shoreline sediment from the Maryland part of the Bay was silt and clay; Byrne and others (1982) estimated that only 6 percent of the mass contribution from the Virginia shoreline of the Bay was silt and clay.

Comparison With Other Components of the Sediment Budget

Other sources of suspended sediment to the tidal Potomac River have been evaluated for water years 1979, 1980, and 1981 by members of the Potomac Estuary Study group (table 13). Bennett (1983) used sediment and

Table 11. Summary of sediment-contribution estimates

Reach	Historical estimate			Modern estimate			Adjusted modern estimate		
	Volume (cubic meters per annum)	Mass of total sediment (metric tons per annum)	Mass of silt-clay (metric tons per annum)	Volume (cubic meters per annum)	Mass of total sediment (metric tons per annum)	Mass of silt-clay (metric tons per annum)	Volume (cubic meters per annum)	Mass of total sediment (metric tons per annum)	Mass of silt-clay (metric tons per annum)
Gunston Cove to Quantico[1]	25,700	42,900	18,800	22,400	37,400	17,100	21,800	36,300	16,500
Quantico to Route 301 Bridge	53,100	88,700	34,300	61,700	103,100	41,900	59,300	99,100	40,100
Subtotal, tidal river and transition zone	78,800	131,600	53,100	84,100	140,500	59,000	81,100	135,400	56,600
Maryland shore, Route 301 Bridge to Piney Point	32,500	54,300	22,600	33,500	55,900	24,600	23,000	38,300	16,300
Piney Point to Point Lookout	25,500	42,600	16,700	14,100	23,600	9,200	9,600	16,100	6,300
Subtotal, Maryland shore of estuary	58,000	96,900	39,300	47,600	79,500	33,800	32,600	54,400	22,600
Virginia shore, Route 301 Bridge to Ragged Point	127,400	212,800	81,500	65,400	109,200	42,700	61,400	102,500	39,800
Ragged Point to Smith Point	73,700	123,200	51,700	62,700	104,800	43,000	49,600	82,900	33,800
Subtotal, Virginia shore of estuary	201,100	336,000	133,200	128,100	214,000	85,700	111,000	185,400	73,600
Total for estuary	259,100	432,900	172,500	175,700	293,500	119,500	143,600	239,800	96,200
Grand total for study area	337,900	564,500	225,600	259,800	434,000	178,500	224,700	375,200	152,800

[1]Landmarks are in Virginia, but the reaches measured include both the Maryland shore and the Virginia shore.

nutrient concentration data, water-discharge data, and data on sediment inputs from various sources to calibrate a computer model for the tidal Potomac River. The model produces estimates of the discharge of water, suspended sediment, and nutrients past several cross sections in the tidal Potomac River. Shore-erosion contributions used as input to the model were based on the silt-clay fraction of the adjusted modern estimates as reported in this study (table 11).

Suspended-sediment concentrations were monitored at Chain Bridge (fig. 1) during the 3 water years of the study (D. C. Hahl, U.S. Geological Survey, written commun., 1982); the average annual suspended-sediment discharge at this site (table 13) is very close to the estimated average annual suspended-sediment discharge of 1.34×10^6 metric tons past Great Falls for the period 1964 through 1976 (Feltz and Herb, 1978). Hickman (1984) used sediment-concentration data and other information from tributary watersheds to calculate the annual mass of sediment delivered to all tidewater tributaries of the Potomac during water years 1979 through 1981. These data are listed in table 13 as tributary contributions to the tidal river, transition zone, and estuary. Estimates of suspended-sediment input to the estuary from Chesapeake Bay and of suspended sediment carried from the transition zone into

Table 12. Percentage of shore-erosion sediment mass contributed by the three divisions of the shoreline to the tidal Potomac River

Shoreline division	Historical estimate		Modern estimate		Adjusted modern estimate	
	Mass of total sediment (percent)	Mass of silt-clay (percent)	Mass of total sediment (percent)	Mass of silt-clay (percent)	Mass of total sediment (percent)	Mass of silt-clay (percent)
Virginia shore of estuary	59.5	59.1	49.3	48.0	49.4	48.1
Maryland shore of estuary	17.2	17.4	18.3	18.9	14.5	14.9
Tidal river and transition zone	23.3	23.5	32.4	33.1	36.1	37.0

Table 13. Components of sediment budget for the tidal Potomac River

Shore-erosion sediment contribution (metric tons per annum)			
Source	Historical estimate	Modern estimate	Adjusted modern estimate
Tidal river and transition zone:			
Total----------	0.13×10^6	0.14×10^6	0.14×10^6
Silt-clay------	$.05 \times 10^6$	$.06 \times 10^6$	$.06 \times 10^6$
Estuary:			
Total----------	0.43×10^6	0.29×10^6	0.24×10^6
Silt-clay------	$.17 \times 10^6$	$.12 \times 10^6$	$.10 \times 10^6$

Other suspended-sediment contributions (metric tons per annum)				
Source	Water year 1979	Water year 1980	Water year 1981	Average
Potomac River at Chain Bridge[1]--	2.40×10^6	1.29×10^6	0.36×10^6	1.35×10^6
Tributary inputs to tidal river[2]---	$.92 \times 10^6$	$.19 \times 10^6$	$.04 \times 10^6$	$.38 \times 10^6$
Tributary inputs to transition zone[2]------------	$.43 \times 10^6$	$.07 \times 10^6$	$.01 \times 10^6$	$.17 \times 10^6$
Tributary inputs to estuary[2]-------	$.83 \times 10^6$	$.13 \times 10^6$	$.03 \times 10^6$	$.33 \times 10^6$
Input from Chesapeake Bay[3]---	([4])	$.19 \times 10^6$	([5])	$.01 \times 10^6$
Sediment carried past Route 301 Bridge[3]----------	$.72 \times 10^6$	$.47 \times 10^6$	$.15 \times 10^6$	$.44 \times 10^6$

[1]D. C. Hahl, U.S. Geological Survey, written commun., 1982.

[2]R. E. Hickman, U.S. Geological Survey, written commun., 1982.

[3]Bennett (1983).

[4]Net transportation of 0.09×10^6 metric tons from the tidal Potomac River into Chesapeake Bay.

[5]Net transportation of 0.06×10^6 metric tons from the tidal Potomac River into Chesapeake Bay.

the estuary at the Route 301 Bridge are based on results produced by Bennett's model (1983) and also are listed in table 13.

The relative importance of each sediment source is indicated in table 14. Data are presented for the tidal Potomac River as a whole and for the estuary, indicating that shore erosion is more important as a sediment source to the estuary than as a sediment source to the rest of the system. Two alternative sets of budgets, based on alternative estimates of the shore-erosion contribution, are shown in table 14. Both lead to similar conclusions. Most of the suspended sediment in the tidal Potomac River comes from part of the watershed located upstream from Chain Bridge, and most of the remaining sediment comes from tidewater tributaries. Depending on which shore-erosion estimate is used, shore erosion contributes either 6.3 percent (adjusted modern estimate) or 9.3 percent (historical estimate) of the total input of suspended sediment. If sediment inputs to the estuary are considered separately, shore erosion contributes either 11.3 percent (adjusted modern estimate) or 17.9 percent (historical estimate) of the total input of suspended sediment.

Several qualifying statements need to be made in considering these results. First, the estimated average annual suspended-sediment input from tributaries between Route 301 Bridge and Chesapeake Bay is an extrapolation based on measurements from a single watershed and probably was influenced by anomalously large sediment concentrations (R. E. Hickman, U.S. Geological Survey, written commun., 1982). Thus, the relative importance of tributary inputs to the estuary (table 14) may be exaggerated. Second, the estimate of sediment carried past the Route 301 Bridge includes components derived from all upstream sources, including the Potomac River above tidewater, tidewater tributaries, shore erosion, plankton populations, and resuspension of bottom material. Relative

Table 14. Suspended-sediment budgets for the tidal Potomac River

Source	Budget calculated using adjusted modern estimate of shore erosion		Budget calculated using historical estimate of shore erosion	
	Suspended sediment (metric tons per annum)	Total (percent)	Suspended sediment (metric tons per annum)	Total (percent)
	Average annual load for the entire study area, 1979-81			
Potomac River at Chain Bridge	1.35×10^6	56.4	1.35×10^6	54.6
Tributary inputs[1]	$.88 \times 10^6$	36.8	$.88 \times 10^6$	35.6
Input from Chesapeake Bay	$.01 \times 10^6$	.5	$.01 \times 10^6$	.5
Shore erosion[2]	$.15 \times 10^6$	6.3	$.23 \times 10^6$	9.3
Total	2.39×10^6	100.0	2.47×10^6	100.0
	Average annual load for the estuary, 1979-81			
Sediment carried past Route 301 Bridge	0.44×10^6	50.0	0.44×10^6	46.3
Tributary inputs to estuary	$.33 \times 10^6$	37.5	$.33 \times 10^6$	34.7
Input from Chesapeake Bay	$.01 \times 10^6$	1.2	$.01 \times 10^6$	1.1
Shore erosion along estuary	$.10 \times 10^6$	11.3	$.17 \times 10^6$	17.9
Total	0.88×10^6	100.0	0.95×10^6	100.0

[1]Subtotals for tidal river, transition zone, and estuary are shown in table 13.

[2]Subtotals for tidal river and transition zone and for estuary are shown in table 13.

importance of these components has not been determined, and the output of the computer model that produced this estimate does not distinguish among these sources. Any uncertainty in the amount of sediment contributed by these sources may contribute to the uncertainty of the estimate. Third, sediment may move across the mouth of the Potomac Estuary in either direction. Model results indicate a small net inflow of sediment from Chesapeake Bay (tables 13 and 14), but the long-term trend of suspended-sediment exchange with Chesapeake Bay is unknown; no data are available to document rates of sediment transportation in and out of the mouth of the Potomac Estuary.

There is some evidence to indicate that, in the tributaries of the estuary and of the transition zone, most of the sediment probably settles out before reaching the main trunk of the tidal Potomac River. DeFries (1980), using an exotic pollen type as a natural tracer of sediment from the Port Tobacco River (fig. 1), suggested that most of the sediment that reached the head of tide in the Port Tobacco River during the last 100 years was deposited before reaching the Potomac River. If this result is applicable to other tributary embayments, then input from shore erosion is a more important component of the suspended-sediment budget of the tidal Potomac River, and particularly of the estuary, than the numbers in tables 13 and 14 might indicate. The shore-erosion contribution of silt and clay to the estuary is roughly 11 percent (adjusted modern estimate) or 18 percent (historical estimate) of the estimated suspended-sediment input for 1979 through 1981. If none of the sediment input from tributaries of the estuary actually reaches the estuary, the shore-erosion contribution of silt and clay is about 18 percent (adjusted modern estimate) or about 28 percent (historical estimate) of the suspended-sediment input to the estuary. The combined shore-erosion sediment contribution, including sand, silt, and clay, represents 23 percent (adjusted modern estimate) or 36 percent (historical estimate) of the total sediment input to the estuary if tributaries are included, and 34 or 49 percent if tributaries are excluded.

The relative importance of shore erosion varies from year to year, although changes in the absolute amount of sediment contributed by shore erosion cannot be demonstrated without a time series of erosion-rate measurements. During the three water years for which data are available, the suspended-sediment discharge of the Potomac River at Chain Bridge varied by a factor of almost 7, and estimated tributary suspended-sediment inputs varied by a factor of more than 20 (table 13). Most of the suspended sediment delivered to tidal waters from upland drainage arrives during high-flow events, which typically occur in late winter and early spring; at other times of the year, shore erosion is relatively more important as a source of sediment. The 1981 water year was a year without any major high-flow events, and estimated suspended-sediment input to the tidal Potomac River from upland drainage was only 0.45×10^6 metric tons. The shore-erosion contribution during the same year may have been smaller than any of the estimates in table 11; however, shore erosion is affected by winds and tides as well as by precipitation and water discharge, and the sediment load derived from shore erosion did not necessarily depart dramatically from the average, as did other components of suspended-sediment load in the tidal Potomac River. If the adjusted modern estimate is applicable, shore erosion could have been responsible for 25 percent of the total suspended-sediment load of the tidal Potomac River during the 1981 water year, and as much as 35 percent of the suspended-sediment load in the estuary during that year. If sand is included as a component, shore erosion may have accounted for as much as 46 percent of the total sediment load of the tidal Potomac River and 58 percent of the sediment load in the estuary during the 1981 water year.

Previous authors (Gottschalk, 1945; DeFries, 1980; Froomer, 1980; Donoghue, 1981; Yarbro and others, 1981) have suggested, on the basis of historical or stratigraphic evidence, that the supply of sediment to rivers and streams in the Chesapeake Bay area from upland sources increased rapidly during the post-settlement period. Most stratigraphic evidence comes from small tributaries of the Potomac River or of Chesapeake Bay and does not necessarily apply to sediment load of major rivers like the Potomac River and the Susquehanna River; indeed, a short core (less than 1 m) taken from near the mouth of the Potomac River (G. S. Brush, Johns Hopkins University, written commun., 1982) contradicts or, at best, fails to support this hypothesis. Longer cores obtained from the tidal Potomac River and tributaries have been dated (Glenn and Martin, 1983); results indicate that historical rates of sediment accumulation are 3 to 15 times larger than prehistoric rates of sediment accumulation, but the authors do not attribute these changes to any one cause. DeFries (1980) states that changes in land use have caused accelerated sedimentation in localized areas, primarily in tributaries, and have not affected rates of sediment accumulation in the Potomac Estuary.

Evidence acquired to date is not conclusive, but it is possible that the suspended-sediment load carried by the Potomac River today is substantially larger than it was prior to widespread land clearance during the 18th and 19th centuries by European settlers, and the amount of sediment entering the estuary from the transition zone also may be larger now than it was then. If a historical trend toward increasing sediment load from upland sources has occurred, sediment derived from shore erosion formerly may have been a more important component of the sediment budget than it is today.

Projected Effect of Sediment Input on Changes in Water Volume

Historical increases in sedimentation rates in the main channel of the tidal Potomac River have not been proven. However, calculations described below indicate that the average annual sediment input for water years 1979 through 1981 is large enough that the entire volume of the tidal Potomac River could be filled with sediment within a few thousand years if this rate of input were maintained, even if sea level continued to rise with respect to the land surface. The present rate of sea-level rise is attributable to a combination of eustatic sea-level rise and local subsidence along the Atlantic Coastal Plain (Hicks, 1978; Holdahl and Morrison, 1974).

The changing volume of the tidal Potomac River can be described as follows. At time, t_o, the tidal Potomac River has a known volume, V_o. Changes in the volume of the basin over time are caused by relative sea-level rise, lateral retreat of the margins of the basin because of either erosion or transgression by rising sea level, and deposition of sediment on the basin floor. Volume of the tidal Potomac River as a function of time, $V(t)$, can be expressed as follows:

$$V(t) = V_o + \int_{t_o}^{t} (kBy + kA_o - s)dy \qquad (17)$$

where

- k is the rate of relative sea-level rise, in meters per annum;
- B is the rate of increase in water surface area, in square meters per annum;
- y is a dummy variable of integration;
- A_o is the initial surface area at time, t_o, in square meters; and
- s is the rate of sediment supply, in cubic meters per annum.

B, k, and s vary over time in complex ways, and these variations have no known particular functional form; k must eventually decline to 0, when maximum sea level for the current transgression is attained, which has not happened yet. For the foreseeable future, continued sea-level rise is to be expected. B is a function of the rate of sea-level rise, the relief of the land surface, and the rate of shore erosion, but no explicit statement about B as a function of time can be derived from information presently available. The rate of sediment supply, s, probably will change over time, but cannot be predicted from past trends; and the nature of past and present trends in sediment delivery is still under discussion (Meade, 1982). It is assumed here that no sediment leaves the Potomac Estuary to enter Chesapeake Bay. Estimates of sediment transport across the mouth of the Potomac indicate that there was a small net inflow of sediment from Chesapeake Bay in water years 1979 and 1981 and a small net export from the Potomac to Chesapeake Bay in water year 1980 (table 13). There is no basis for assuming long-term net export of sediment from the Potomac to the Bay.

In the absence of detailed predictions of the behavior of these variables, the following analysis assumes that *B*, *k*, and *s* are constant. Different scenarios for the change in volume of the tidal river and estuary over time are based on alternative values for the constants. The volume formula is expressed below as a simple quadratic function of time:

$$V(t)=k\frac{B}{2}(t-t_o)^2+(kA_o-s)(t-t_o)+V_o \ . \tag{18}$$

Sediment load is usually expressed in units of mass, but s can be expressed as a volume of bottom sediment by using a bulking factor to account for water content. For estuarine muds on the floor of the Potomac Estuary, Knebel and others (1981) used a value of 0.50 t/m^3 of sediment, based on a particle density of 2.65 g/cm^3 and an average water content of 62 percent. The same value is used here with reference to bottom muds throughout the tidal river and estuary. This assumed value is equivalent to the average measured density for a set of 1-m-long cores described by Knebel and others (1981); potential volume reductions by sediment compaction are not considered in the analysis. For sands deposited near the margins as the residuum of shore erosion, a regression equation relating water content with mud content of bottom samples from Chesapeake Bay (Byrne and others, 1982) was used to estimate a water content of 18.6 percent. The calculated mass of sediment per cubic meter of wet sand is 1.65 t/m^3. To convert the rate of sediment supply from metric tons to volume of wet sediment, V_w, the following formula was used:

$$V_w=(n/0.50+P/1.65)\ m^3 \ , \tag{19}$$

where

n is the mass of wet mud, in metric tons; and
P is the mass of wet sand, in metric tons.

Future sediment loads will depend, in part, on changes in land use and on the rate of delivery of sediment presently in storage as bottomland alluvium. Historical trends during this century indicate eventual reductions in the rate of sediment supply, because of soil-conservation practices and reductions in the area of land under cultivation; however, sediment loads in major rivers of the Atlantic drainage have not decreased to an extent commensurate with these historical trends (Meade and Trimble, 1974). Urban development has caused rapid increases in soil erosion and sediment yield from road and building construction sites, but the increased yield is short-lived and generally declines again following paving and landscaping (Wolman, 1967). Presumably most of the eroded sediment is still in storage in upland valleys; Meade (1982) suggests that centuries may pass before this sediment is removed from storage. Given this scenario, alternative values of s may be based on: (1) Constant sediment supply at the current annual rate; or (2) constant sediment supply at a slower annual rate.

Average Potomac River suspended-sediment discharge for 1979 through 1981 at Chain Bridge (fig. 1) is comparable to the average a short distance upstream at Great Falls, Maryland, for 1964 through 1976 (Feltz and Herb, 1978). In the absence of a longer record, this rate of sediment supply (table 13) is used as the basis for calculating a current annual value of *s*. Suspended-sediment load for the 1981 water year was much smaller than the 3-year average, and this average annual rate of sediment supply is used as the basis for calculating a lower annual value of *s*. Values of *s*, expressed as volume of bottom sediment per year, were calculated from mass estimates of sediment contributions from all sources in table 13, using formula (19). The estimated average annual volume of bottom sediment trapped in the tidal river and transition zone during water years 1979 through 1981, including shore-erosion contributions of sand as well as silt and clay, amounted to 3.08×10^6 m^3 of wet bottom sediment. The estimated average annual volume of bottom sediment carried into the estuary during the same period was 1.84×10^6 m^3. Similar estimates for the 1981 water year amounted to 0.70×10^6 m^3 for the tidal river and transition zone and 0.63×10^6 m^3 for the estuary.

Estimates of B, the rate of increase of surface area of the tidal Potomac River, are based on shoreline-recession rates from photogrammetric measurements; they were calculated by the same procedure used to produce the modern estimate of shore-erosion sediment load from volume-erosion rates. The value of *B* used in the tidal river and transition zone (extrapolated to include the entire length of the tidal river) is 2.8×10^4 m^2/a, and the value used in the estuary is $6.8\times10\ m^4\ m^2/a$. Estimates based on alternative values of *B* are not presented here, but several projections were made using cartographic data to derive a value of *B*, and using the historical estimate of shore-erosion sediment load as a component of *s*. These projections differed only slightly from the projections described hereafter.

Three alternative estimates of *k*, the rate of sea-level rise, are used in the projections. The rate $k=0$ mm/a is used to demonstrate the maximum rate of filling of the present volume of the tidal Potomac River; the rate $k=1.25$ mm/a is based on an estimate by Belknap and Kraft (1977) for the average rate of relative sea-level rise in the mid-Atlantic region during the past 2,000 years; the rate $k=2.74$ mm/a is based on an estimate by Froomer

(1980) for the past three centuries and is roughly comparable with rates based on increasing tide levels in the Chesapeake Bay area during recent decades (Hicks, 1972, 1978). Total water volume in the tidal river and transition zone is 1.33×10^9 m^3; total water volume in the estuary is 5.73×10^9 m^3 (table 1).

Curves representing changes in $V(t)/V_o$ over time are shown in figure 22. As volume, $V(t)$, decreases over time, the ratio $V(t)/V_o$ decreases from a value of 1.0 at $t=t_o$ (present) to approach 0. If volume increases over time, the curve rises above the line $V(t)/V_o=1.0$. Six alternative projections of volume change over time are based on three different values of the rate of sea-level rise, k, and on two values of the rate of sediment supply, s; separate curves on each plot depict changes in volume of the tidal river and transition zone and changes in volume of the estuary. The curves, which are based on calculations that do not correct for compaction of bottom sediment over time, are presented to illustrate trends rather than to predict actual events.

These curves indicate that the tidal river and transition zone are filling much more rapidly than the estuary; this conclusion is supported by measured sedimentation rates based on pollen and lead-210 dating (Brush and others, 1982). If present rates of sediment supply and sea-level rise remain constant (fig. 22C), the tidal river and transition zone will be filled with sediment in less than 600 years. However, as the tidal river and transition zone gradually fill with sediment, an increasing fraction of the total sediment load must reach the estuary without being deposited in the tidal river or the transition zone. Projected changes in volume assume no such increase and are based on present rates of sediment discharge past the Route 301 Bridge; changes in transport rate, as the transition zone fills under conditions of constant sediment load, have not been modeled. Instead, a third curve, projecting changes in total volume of the tidal Potomac River, is shown on each plot without allocating sediment separately to different hydrologic divisions of the system.

Changes in volume under different assumed rates of sea-level rise, using an average sediment load based on data from water years 1979 through 1981, are shown in figure 22*A*, *B*, and *C*. If sea-level rise stops, the tidal river and transition zone could be completely filled in less than 500 years, and the entire tidal Potomac River could be filled in less than 1,500 years. Presumably, some of the sediment would leave the Potomac River to enter Chesapeake Bay as the Potomac River filled, but these projections assume that all sediment is trapped in the tidal Potomac River. If the rate of relative sea-level rise were 1.25 mm/a, the tidal river and transition zone would be filled in about 500 years, and the entire Potomac River would be filled in less than 2,000 years. A rate of 2.74 mm/a would not substantially affect the rate of filling in the tidal river and transition zone, allowing this part of the system to be filled in less than 600 years; however, filling the entire system under these projected conditions would require nearly 4,000 years. If none of the sediment presently being trapped in the transition

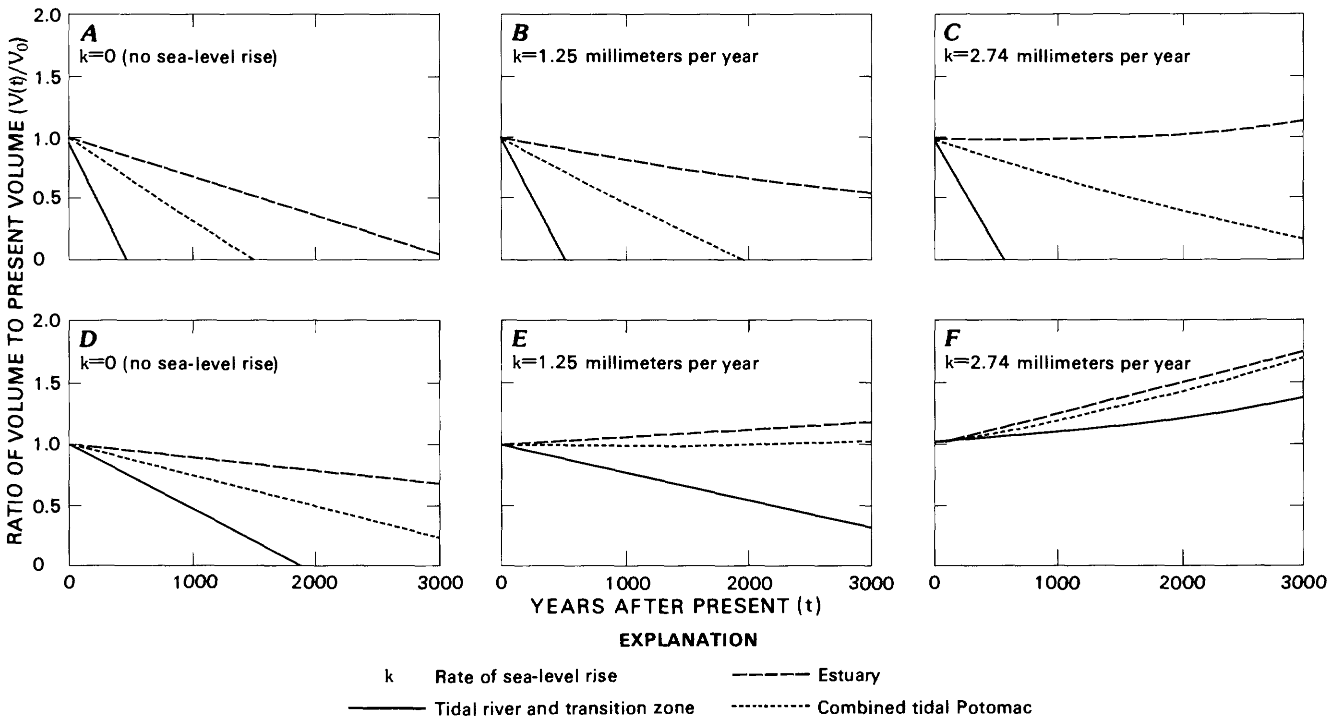


Figure 22. Projected changes in water volume ($V(t)/V_0$) of the tidal Potomac River over time: A, B, C, assumed constant sediment load based on water years 1979–81; D, E, F, assumed constant sediment load based on water year 1981. Three alternative assumptions about the rate of relative sea-level rise are incorporated in the projections. See text for complete explanation.

zone were to reach the estuary, the volume of the estuary would increase over time with this rate of sea-level rise.

Comparable projections of volume change over time are shown in figure 22*D*, *E*, and *F*, based on a smaller long-term average sediment load, similar to the load for the 1981 water year. With no change in sea level, the tidal river and transition zone would be filled in slightly less than 1,900 years, and the entire system would be filled in about 5,300 years. However, even a relatively slow rate of sea-level rise would extend the life of the tidal river and transition zone to more than 4,800 years; total volume of the system would remain almost constant for about 3,000 years and then would gradually increase. After 3,000 years, average depth of the system would have decreased by 33 percent, and the tidal Potomac River would be broader and flatter than at present, with sea level 3.75 m above its present elevation. With a rate of sea-level rise of 2.74 mm/a, the rate of sediment supply assumed in figure 22*F* would be insufficient to compensate for increasing volume of the tidal river and transition zone or of the estuary, and the volume would increase at an accelerating rate.

The assumed sediment loads cannot be verified; therefore, the long-term validity of the projections in figure 22 cannot be tested. Differences between projected and actual values of shore-erosion sediment load probably would have less effect on the result than changes in the supply of upland sediment over time. At current rates of supply, with current or historically slower rates of sea-level rise, filling of most of the tidal river and transition zone could occur over a period of time measured in centuries rather than millennia, and filling of most of the Potomac Estuary appears possible within a time span of 2,000 to 4,000 years, considerably less than the present age of the estuary. Should the global rate of sea-level rise accelerate as a result of climatic change induced by increased atmospheric concentrations of carbon dioxide, the rate of volume increase of the tidal Potomac River probably will outweigh the rate of filling.

SUMMARY AND CONCLUSIONS

Major findings of the present study concern shore-erosion processes and rates measured in the field, distribution of recession rates and volume-erosion rates along the shoreline of the study area, amount and relative importance of shore-erosion sediment contribution to the sediment budget of the tidal Potomac River system, and possible implications of contemporary estimated rates of sediment supply and sea-level rise for future volume changes in the tidal Potomac River.

Wind-driven waves break down and remove accumulated debris in the shore zone and abrade and undercut the base of the bank. Slope processes, including surficial erosion and mass movement, play an important role in mobilizing and delivering debris to the base of the bank. These processes are most active at sites with high bank relief and at sites marked by seepage or zones of concentrated ground-water flow from the face of the bank. Seasonal patterns of temperature and precipitation influence the level of activity of slope processes, and local patterns of sediment transport and beach elevations affect the frequency of wave attack and the amount of undercutting at the base of the bank. The cycle of slope erosion has a variable time scale, and the time period for completion of a cycle initiated by basal erosion increases with height and complexity of the slope.

Field measurements at monitoring sites at Swan Point Neck, Maryland, and Mason Neck, Virginia, indicate that short-term (10- to 18-month) recession and volume-erosion rates along a rapidly eroding reach of shoreline less than 1,000 m long may vary greatly [0 to 4.6 m/a and 0 to 13.2 $(m^3/m)/a$], and that local factors, such as the capacity of the beach to buffer wave impact, presence or absence of obstructions that modify patterns of sediment transport, and trees at the top of the bank, may be primarily responsible for these variations. At Mason Neck, two bank profiles only 10 m apart had recession rates of 0.1 and 0.9 m/a and volume-erosion rates of 1.2 and 8.9 $(m^3/m)/a$. Although such variations are not likely to persist over a period of decades, they illustrate the importance of longer term measurements and synoptic measurement for estimating average erosion rates and sediment loads.

Weighted average recession rates along the Virginia shore of the estuary were 0.52 m/a (cartographic) and 0.42 m/a (photogrammetric); comparable rates for the Maryland shore of the estuary were 0.41 m/a (cartographic) and 0.31 m/a (photogrammetric); average rates for the tidal river and transition zone were 0.12 m/a (cartographic) and 0.13 m/a (photogrammetric). Maximum average rates for an individual reach, 1.2 m/a (cartographic) and 1.0 m/a (photogrammetric), were measured along the Virginia shore near the mouth of the river, facing northeast across Chesapeake Bay.

Weighted average volume-erosion rates along the Virginia shore of the estuary were 1.87 $(m^3/m)/a$ (cartographic) and 1.20 $(m^3/m)/a$ (photogrammetric); comparable volume-erosion rates along the Maryland shore of the estuary were 0.73 $(m^3/m)/a$ (cartographic) and 0.56 $(m^3/m)/a$ (photogrammetric); average rates along the tidal river and transition zone were 0.56 $(m^3/m)/a$ (cartographic) and 0.58 $(m^3/m)/a$ (photogrammetric). Maximum average volume-erosion rates for an individual reach, 8.3 $(m^3/m)/a$ (cartographic) and 3.2 $(m^3/m)/a$ (photogrammetric), were measured along the Nomini Cliffs, where maximum elevations were 45 m. The Virginia shore of the estuary had locally slower recession rates and, in several areas, had much higher shoreline relief than the Maryland shore of the estuary, thus accounting for the difference in volume-erosion rates. Although relief along the tidal river and transition zone was higher than along the Maryland shore of the estuary, recession rates were much slower; therefore, volume-erosion rates in the two areas were roughly comparable.

Three estimates of shoreline sediment contribution were prepared. The historical estimate, based on cartographic measurements, amounted to 0.565×10^6 metric tons per annum, of which 0.226×10^6 metric tons were silt and clay. The modern estimate, based on photogrammetric measurements supplemented by cartographic measurements, amounted to 0.434×10^6 metric tons per annum; 0.179×10^6 metric tons of this amount were silt and clay. The adjusted modern estimate, based on the modern estimate but assuming that shoreline areas protected by extensive bulkheads and seawalls provided no sediment to the system, amounted to 0.375×10^6 metric tons per annum, including 0.153×10^6 metric tons of silt and clay. Between 49 and 60 percent of the shore-erosion sediment load was derived from the Virginia shore of the estuary; 14 to 18 percent was derived from the Maryland shore of the estuary. The tidal river and transition zone accounted for 23 to 36 percent of the total.

Silt and clay derived from shore erosion accounts for 6 to 9 percent of the average annual suspended-sediment input to the tidal Potomac River for water years 1979 through 1981. Annual suspended-sediment contributions from upland discharge fluctuated by about an order of magnitude during the 3 years of record. Shore erosion probably represents a more important component of the suspended-sediment load of the tidal Potomac River during some years than a comparison of the average loads might indicate. If the rate of sediment delivery from upland drainage has increased since European settlement as a result of land-use practices, silt and clay derived from shore erosion may have been a more important component of the suspended-sediment load in the past than it is today.

Future changes in the volume of the tidal Potomac River can be projected from assumptions of constant sediment supply, constant rate of increase of surface area, and constant rate of relative sea-level rise. Although these parameters will not remain constant over thousands of years and probably are related in complex ways, a range of scenarios can be projected by using a range of values for the constants. At present rates of sediment supply, sea-level rise, and increase in surface area, the tidal river and transition zone could be filled with sediment in less than 600 years, and the entire volume of the tidal Potomac River could be filled in less than 4,000 years. If relative sea-level rise continued at a slower rate more typical of the past 2,000 years, the system would fill even more rapidly. With smaller sediment loads, volume of the tidal Potomac River might remain relatively stable or even increase over time. Changes in rate of sediment supply from upland sources probably will have a more profound effect on the future of the tidal Potomac River than changes in rates of shore erosion.

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Conversion Factors

Multiply SI units	By	To obtain inch-pound units
cubic meter (m^3)	35.31	cubic foot
cubic meter per meter (m^3/m)	10.76	cubic foot per foot
cubic meter per meter per annum [(m^3/m)/a]	10.76	cubic foot per foot per year
gram per cubic centimeter (g/cm^3)	62.43	pound per cubic foot
kilometer (km)	0.6214	mile
meter (m)	3.281	foot
meter per second (m/s)	2.237	miles per hour
meter per annum (m/a)	3.281	foot per year
metric ton (t)	1.1023	ton
metric ton per cubic meter (t/m^3)	0.0312	ton per cubic foot
metric ton per annum (t/a)	1.1023	ton per year
micrometer (μm)	3.281×10^{-6}	foot
millimeter per annum (mm/a)	0.0394	inch per year
square meter (m^2)	10.76	square foot
square meter per annum (m^2/a)	10.76	square foot per year

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