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Suspended Sediment Load Contributed by Shore Erosion Chesapeake Bay, Maryland

by
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ABSTRACT

Recognizing the deterioration of water quality in Chesapeake Bay and the associated loss of such living resources as submerged aquatic vegetation, the U.S. Army Corps of Engineers has developed a numerical model of light attenuation in the Chesapeake Bay (Cerco and Noel, 2004). Water clarity, one key indicator of water quality, is, in part, a function of the amount of suspended sediment in the water column. Currently, the computer model uses a single, baywide value - 5.7 kg/m/day - to estimate the suspended sediment load contributed by shore erosion. That figure is applied to the entire length of shoreline, regardless of the degree of protection or stabilization. However, according to recent estimates, nearly one-third of the Bay shoreline is protected. To improve accuracy in computing water clarity, the Maryland Geological Survey (MGS) estimated the load of fine-grained sediment (silt- and clay-sized particles) contributed by both unprotected fastland and nearshore erosion to the Maryland portion of the Bay. In addition to topographic maps, MGS used several recently acquired data sets: (a) shoreline rates of change calculated for the period 1850-1990 along 250,000 shore-normal transects, (b) a shoreline inventory that identified erosion control structures erected along the Maryland shoreline, and (c) a study that measured the grain size composition (i.e., sand-silt-clay content) and bulk density of the Bay's eroding bluffs and marshes. MGS found that, in terms of fine-grained sediment, shore erosion contributes 1.34 kg/m/day, considerably less than the value currently used in the model. Moreover, input varies widely throughout the Bay, depending on erosion rate, bank height, shoreline type, and protected length.

INTRODUCTION

Recognizing the deterioration of water quality in Chesapeake Bay and the associated loss of such living resources as submerged aquatic vegetation, the U.S. Army Corps of Engineers has developed a numerical model of light attenuation in the Chesapeake Bay (Cerco and Noel, 2004). Water clarity, one key indicator of water quality, is, in part, a function of the amount of suspended sediment in the water column. Currently, the computer model uses a single, baywide value - 5.7 kg/m/day - to estimate the suspended sediment load contributed by shore erosion. That figure is applied to the entire length of shoreline, regardless of the degree of protection or stabilization. Using recent rates of shoreline change for unprotected shoreline only, the Maryland Geological Survey (MGS) tried to improve the accuracy of that estimate for the Maryland part of Chesapeake Bay and its tributaries.

This report discusses the methods using in recalculating the suspended sediment load, presents the main findings, and describes the two digital products delivered to the U.S. Environmental Protection Agency – Chesapeake Bay Program.

STUDY AREA

The study area consists of the Maryland portion of the Chesapeake Bay, as well as all major and many lesser tributaries of that section of the Bay. The exact area roughly coincides with the land/water boundary outlining the surface grid cells of the light attenuation model, north of the Maryland-Virginia state line. Not all tributary streams were included in the calculations. Guided by a map of the model's surface grid cells, MGS included only tributaries that contained such cells. These tributaries were truncated at the upper extent of the headmost grid cell. Furthermore, MGS included only the perimeter shoreline of large, marshy islands, like Smith and Bloodsworth, not the shorelines of their interior ponds and waterways.

METHODS

OVERVIEW

In broad terms, estimating the quantity of fine-grained sediment delivered to the Bay from erosion of the Maryland shoreline required (1) calculating the total volume of sediment lost from shore erosion, (2) converting sediment volume to mass, and (3) determining the proportion of the total mass represented by fine-grained sediment. In other words,

$$\mathbf{V = LWH} \qquad \textbf{(1)}$$

where,

- V = volume of sediment lost annually from shore erosion (m^3/yr)
- L = shoreline length (m)
- W = rate of shoreline retreat (m/yr)
- H = bank height or marsh elevation (m)

$$\mathbf{M_{total} = Bd * V} \qquad \textbf{(2)}$$

where,

- M_{total} = total mass of sediment (sand, silt, and clay fractions) lost annually from shore erosion (metric tonnes/yr)
- Bd = average dry bulk density of eroding bank or marsh fastland (g/cm^3)

$$\mathbf{M_{fine} = f * M_{total}} \qquad \textbf{(3)}$$

where,

- M_{fine} = mass of fine-grained sediment (silt and clay fractions) lost annually from shore erosion (metric tonnes/yr)
- f = average proportion of fine-grained sediment in eroding bank or marsh fastland (dimensionless)

In its calculations, MGS

- Distinguished between protected and unprotected shoreline,
- Recognized the different contributions of two fastland types – banks and marshes, and
- Accounted for both fastland (onshore) and nearshore (submerged, offshore) erosion.

DATA SOURCES

To quantify the parameters in Equations 1-3, MGS used four existing data sources:

- Shoreline rates of change determined for the period 1850-1990 along 250,000 shore-normal transects,
- A preliminary shoreline inventory that identified man-made structures erected along the Maryland shoreline,
- A study that measured the grain size composition (i.e., sand-silt-clay percentages) and bulk density of the Bay's eroding banks and marshes, and
- Topographic quadrangles.

Each of these is described in some detail below. Figure 1 shows the four sources and the parameters extracted from each one.

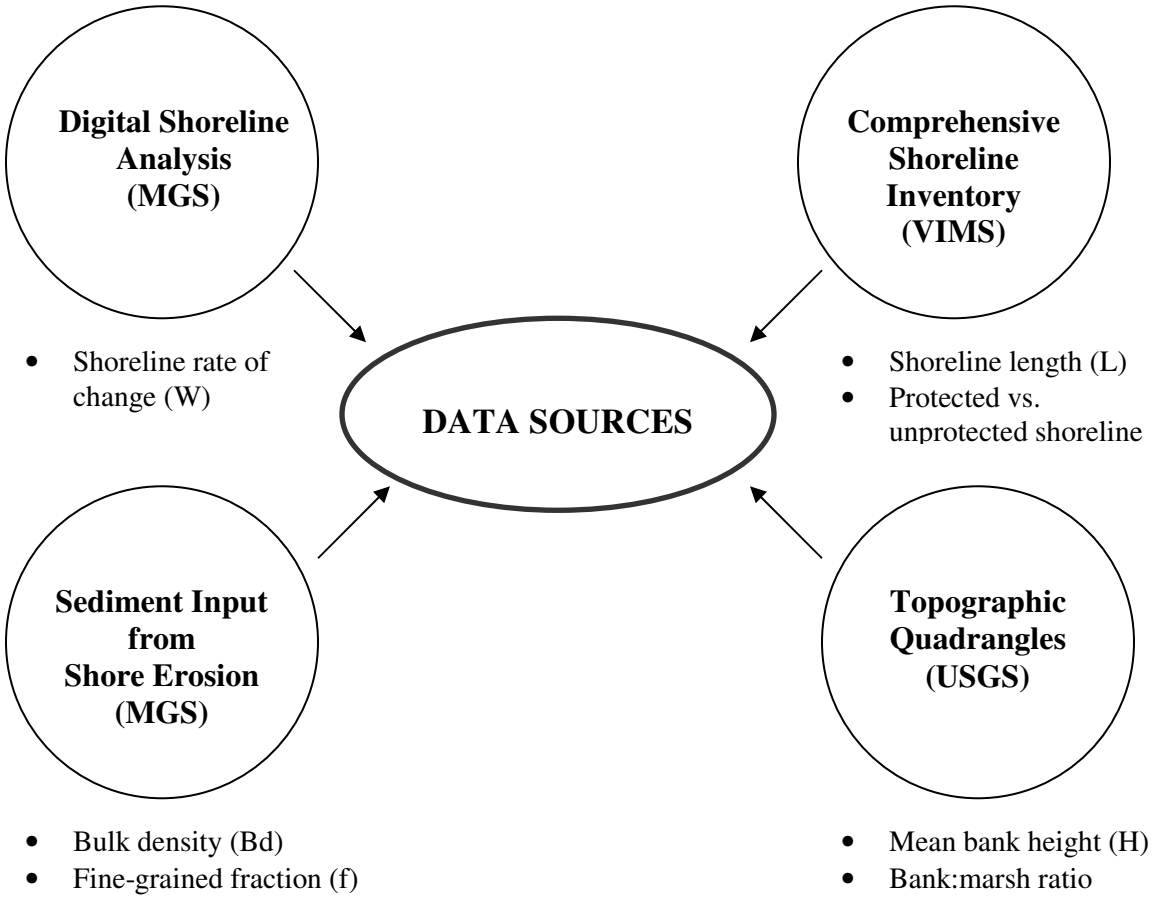

Figure 1: Data sources used to calculate the suspended sediment load contributed by shore erosion in Maryland:

Digital Shoreline Analysis

In 2003, MGS completed a decade-long project to update shore erosion information for coastal and estuarine Maryland. MGS digitized a series of historical shorelines for the State and, using those shorelines as input, ran a computer program that generated shoreline rates of change (Hennessee and others, 2002, 2003a&b). Shorelines dating from the mid-1800s to the 1970s were digitized either directly from National Oceanographic and Atmospheric Administration (NOAA) coastal survey maps (topographic or T-sheets) or from a derivative map series compiled by MGS from early NOAA maps (Conkwright, 1976). More recent shorelines, dating from 1988 to 1995, were interpreted from color infrared digital orthophotography (Hennessee, 2001). MGS then used the digital shorelines as input into the Digital Shoreline Analysis System (DSAS), a computer program written and supported by two researchers at the U.S. Geological Survey (Danforth and Thieler, 1992). DSAS created a "baseline" 50 m inland of the most landward shoreline, inserted nodes at 20-meter intervals along the baseline, and constructed a straight-line transect from each node, perpendicular to the baseline and across the available shorelines. For each consecutively dated pair of shorelines intersected by a transect, DSAS computed a rate of change by dividing the distance between the two shorelines by the time elapsed between them. In the example shown in Figure 2, DSAS recognizes two "eras", 1850-1900 and 1900-1990, and, for each transect, calculates a rate of change for each era. For coastal Maryland, including the Atlantic coast, the coastal bays, and the Chesapeake Bay and its tributaries, DSAS produced nearly 250,000 transects and associated rates of change.

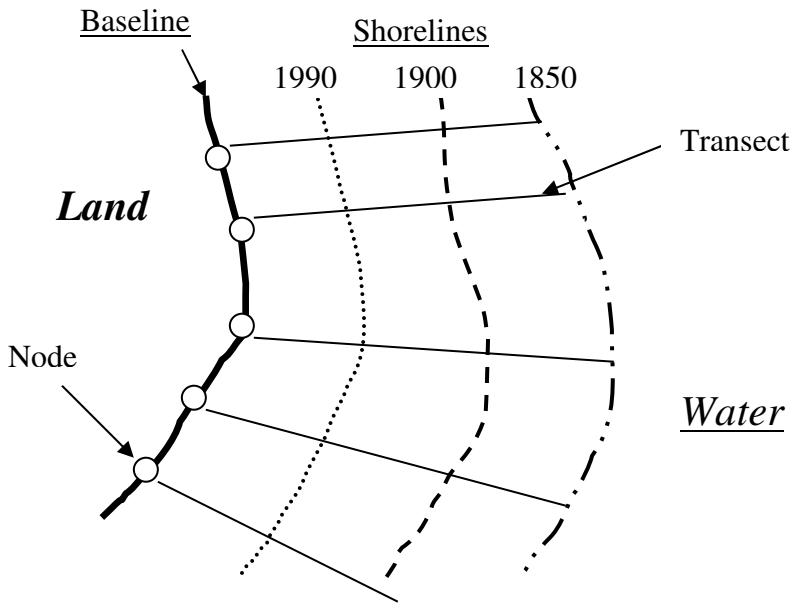

Figure 2: Features used or generated by DSAS to calculate shoreline rates of change

Comprehensive Shoreline Inventory
To assist with management and planning of tidal shorelines, the Virginia Institute of Marine Science (VIMS) is surveying waterfront conditions and use in both Maryland and Virginia. As part of this inventory, VIMS identified man-made structures along the tidal shoreline of navigable waterways in Maryland (http://ccrm.vims.edu/projects/shorelineinventory.html). Inventoried structures included those erected for shoreline protection or for recreational purposes, such as marinas. Structures were observed from a slow-moving boat traveling parallel to the shoreline. The field crew logged location and other information related to shoreline structures using a combination of Global Positioning System (GPS) and Geographic Information System (GIS) technology. The result was a geographically referenced set of shoreline data. Back onshore, VIMS processed the field data so that they reflected conditions along the shoreline, rather than the boat track. Digital structures were assigned as attributes to a digital shoreline – the land/water interface interpreted from recent digital orthophotography - to produce a final GIS coverage (*_sstruc).

At the time of this study, VIMS had finalized its inventory of six Maryland counties (Baltimore, Caroline, Dorchester, St. Marys, Somerset, and Wicomico) and posted results to the website cited above. For the remaining coastal counties, VIMS provided MGS with a draft, baywide structure file (md_sstru.shp, dated 11/15/2005).

Sediment Input from Shore Erosion
Developing appropriate strategies for reducing nutrient input and improving water clarity in Chesapeake Bay depends on understanding the relative contributions of various sediment and nutrient sources. Shore erosion is one such source. In 2001, MGS sampled 25 unprotected, eroding sites along the mainstem Bay shoreline in Maryland to estimate sediment and nutrient input from erosion (Hill and others, 2003). The sampling scheme included both banks and marshes. At each bank site, field geologists scraped a shallow, vertical trench in the bank face and collected a cylinder of unweathered sediment from each visually distinctive sedimentary layer. At each marsh site, the field crew collected a cylindrical sediment core, the top of which was aligned with the marsh surface. Generally, the length of the core was equivalent to the height of the erosional scarp at the edge of the marsh. Based on lithological changes observed in the split core, MGS collected several sediment subsamples. All sediment samples were analyzed for grain size composition, that is, the relative proportions of sand-, silt-, and clay-sized particles, and for bulk density. Other studies that have characterized eroding fastland sediments have estimated bulk density in the conversion of volume of eroded sediment to mass. Hill and others, in contrast, measured dry bulk density. The measurement was based on the dry weight of the sediment contained in a cylinder of known dimensions and, in the case of marsh samples, was corrected for compaction. For marsh samples, MGS also measured the fraction of plant material consisting of large plant roots and debris.

Topographic Quadrangles
For decades, the U.S. Geological Survey (USGS) has produced 7.5-minute topographic quadrangles of the country using a standard set of map symbols. Marshes and swamps, for example, are consistently depicted as tufts of grass on a background that varies from

white through several shades of green, depending on whether the area is submerged and/or wooded. For this study, MGS used two features depicted on the quadrangles – marsh and topographic contours along the shoreline (at contour intervals of 10 or 20 ft). These were used to estimate the bank:marsh ratio and average bank height of a reach, respectively.

Given the availability of these four data sets, MGS developed a simple, GIS-based methodology to estimate the quantity of fine-grained sediment delivered to the Bay each year from erosion of the Maryland shoreline.

QUANTIFYING PARAMETERS

MGS used two different GIS software packages to measure two of the needed parameters. ArcGIS (version 8.3) provided average rates of shoreline change from the DSAS dataset. MicroImages' TNTmips (version 7.1) provided shoreline lengths, based primarily on the VIMS shoreline structure files. All results were stored in or computed by a Microsoft Excel spreadsheet, ReachStatsGrouped.xls.

This section of the report describes the general methods used to generate the raw data stored in the spreadsheet, along with the assumptions that MGS made in calculating sediment load from shore erosion.

Shoreline Reach

To demarcate shoreline reaches, MGS consulted an in-house set of *Shoreline Rates of Change* maps, which depict generalized rates of change for five county-based regions around Chesapeake Bay (Hennessee and Offerman, 2004). The mapped shoreline is color-coded, based on the following broad categories:

- Slight change (+2 to -2 ft/yr)
- Low erosion (-2 to -4 ft/yr)
- Moderate erosion (-4 to -8 ft/yr)
- High erosion (more than -8 ft/yr).

These categories are based on the same recent rates of change used in this project.

MGS used the regional maps as a general guide in grouping similarly classified segments of shoreline into longer reaches. Typically, a reach was first defined as extending from headland to headland, that is, from one point of land to another. If, within the reach, the rates of change shown on the regional map varied fairly widely, the reach was further subdivided. A marked change in shoreline orientation also prompted a break. Because all of the DSAS files and many of the VIMS files were available as county coverages, MGS set certain reach limits to coincide with county boundaries. Reach boundaries were also located at the mouths of tributaries, so that results could be made available by water body.

Initially, MGS divided the Maryland shoreline into over 300 "ungrouped" reaches, then collapsed these into 207 "grouped" reaches. Maintaining political boundaries was unnecessary for this project, particularly for shoreline segments that lay along the same body of water but in different counties. Most of the latter were grouped together to form

upstream-downstream reaches. For example, separate reaches along the east and west banks of the Patuxent River, which divides Calvert and St. Marys Counties, were grouped into Patuxent (upper mid-section), Patuxent (middle mid-section), etc. The 207 reaches were divided almost equally between the Eastern Shore (100 reaches) and the Western Shore (107).

MGS rejected several other approaches to demarcating reaches before deciding on the one described above. One option – setting reach limits to coincide with model cell boundaries – was rejected because the model cells were too numerous and too coarsely defined. For example, about 140 model cells line the shoreline in St. Marys County alone. If that number of cells is typical of each of the 15 counties in the study area, the approach would have generated more than 2,000 reaches. Another option – establishing reaches of consistent length (e.g., 1000-meter-long reaches) – meant ignoring natural breaks in the shoreline or in the known response of the shoreline to erosional processes. The last option – using reaches defined by earlier researchers, in particular, Singewald and Slaughter (1949) – was inadequate because that study area was limited to the mainstem and major tributaries of the Bay. Also, in demarcating reaches, they were unable to take into account differences in the erosional response of the shoreline.

Protected Shoreline

In the DSAS dataset, rates of change calculated for protected shorelines are almost certainly false. For instance, if, over a 50-year period, a shoreline has retreated 50 m, the rate of erosion equals –1 m/yr. However, if, after 25 years, a bulkhead had been erected along the reach, halting shoreline retreat, the 50 m of erosion would have occurred over a period of 25 years, not 50. The actual rate of erosion would be –2 m/yr before bulkhead construction and 0 m/yr afterwards. The biggest problem in determining rates of change for protected shorelines lies in not knowing the year in which a man-made structure was erected. To eliminate such spurious results, MGS based mean rates of change on unprotected shoreline only. That is, rates of change for transects that intersected protected shoreline were excluded from the calculations.

In its shoreline inventory, VIMS distinguished among several types of man-made structures. MGS considered a subset of those to be protective (Table 1). For purposes of this project, MGS eliminated groins and jetties and considered shorelines lined by offshore breakwaters to be unprotected. Dilapidated bulkheads were regarded as a form of protection; for some unknown period of time in the past they were intact and interrupted shoreline retreat. Doubly protected reaches, for example, a stretch of shoreline lined by both riprap and an offshore breakwater, were considered stabilized as long as one of the structures was among the types that MGS deemed protective.

Table 1: Shoreline structures inventoried by VIMS, included or excluded in MGS's definition of "protected" shoreline	
Shoreline structure	**Considered protected?**
Bulkhead	Yes
Debris	Yes
Dilapidated bulkhead	Yes
Marina	Yes
Miscellaneous (bricks, timber, concrete blocks, tires, etc.)	Yes
Riprap	Yes
Unconventional	Yes
Wharf	Yes
Breakwater	No
Groin field	No
Jetty	No

MGS assumed that only banks, and not marshes, were protected. For the most part, the data support this assumption. Of the 207 grouped reaches, 19 lie entirely along marshes (no banks). Of those 19 reaches, 15 are entirely unprotected. The remaining four reaches are protected along no more than 3% of their length.

Shoreline Rate of Change

ArcGIS software generated average rates of change for each shoreline reach. First, the computer operator displayed the VIMS shoreline, highlighting protected shoreline in red. She then overlaid the DSAS transects and hand-picked only those that intersected unprotected shoreline. To be chosen, a transect had to be flanked on both sides by unprotected shoreline. A transect with unprotected shoreline on one side and protected shoreline on the other was excluded. MGS selected transects in such a way that there was no overlap between reaches. Any given transect was associated with one reach and one reach only.

Some judgment on the part of the computer operator was required in deciding which minor tributaries to include or exclude. In part, this decision depended on the width of the tributary mouth. Tributaries with wide, cove-like mouths were included in the reach; those with narrow, restricted mouths were excluded. If an excluded feature was named on a USGS topographic quadrangle, it appears in the "Exclusions" column of the Excel spreadsheet.

For the selected unprotected transects within a reach, ArcGIS computed an average end-point rate of change based on the two most recent shorelines in the DSAS dataset. For most transects, the two most recent shorelines date from *ca*. 1940 and *ca*. 1990, though

intervals shorter and longer than 50 years occur. The average rate was reported and recorded in feet per year. Excel later converted the measurement to meters per year. In the spreadsheet, negative numbers indicate erosion and positive numbers, accretion.

The same average rate of change was applied to both banks and marshes. In other words, MGS did not distinguish between banks and marshes in calculating average change rates.

As a final step in the process, MGS printed two diagrams, one showing all of the transects in a reach and the other, only the transects that intersected unprotected shoreline. MGS referred to these diagrams in creating digital reach boundary markers.

Shoreline Length

MGS used MicroImages' TNTmips (version 7.1) to measure shoreline length. This required importing the VIMS shoreline file from its original shapefile format, clipping it to county boundaries (if necessary), creating a reach boundary marker file, merging that file with the VIMS shoreline file, assigning reach attributes to the merged shoreline/boundary marker file, and measuring the length of each reach.

With the VIMS shoreline and DSAS transects displayed as reference files, MGS referred to the rate-of-change diagrams and created a new reach boundary marker file. The file, ReachMarkers, consisted of short, bent-line "cut lines" located along the shoreline at reach boundaries, at the mouths of excluded tributaries, and at other shoreline discontinuities. The latter usually occurred at the mouths of minor tributaries. Such breaks were apparent because VIMS included short segments of the tributary shoreline upstream of the mouth. MGS excluded those short segments in measuring shoreline length. After drawing the cut lines, MGS created a ReachBound table and assigned all the reach markers the attribute "boundary."

MGS then edited the VIMS shoreline structure file prior to merging it with the reach marker file. After erasing groins, jetties, and offshore breakwaters, MGS created a ReachBound table and assigned the entire shoreline the attribute "unclassified." MGS merged the shoreline and the reach marker files, added ungrouped reach IDs (e.g., AA-1, AA-2) to the ReachBound table and assigned these to the shoreline. For the grouped reaches, MGS created a second table, GroupedReaches, and assigned an ID (GrReachID) and name (GrReachName) to each of the grouped reaches. Highlighting a reach and opening a TNTmips-generated LINESTATS table provided reach length in meters. MGS recorded the length of the entire reach. Then, by including or excluding protected structures in the md_sstru attribute table, MGS recorded the protected and unprotected lengths of shoreline within the reach, respectively.

For the most part, MGS used the VIMS shoreline in measuring reach length. VIMS, however, omitted several of the large, marshy islands, such as Smith and Bloodsworth, in its inventory of the lower Eastern Shore. MGS extracted these islands from a *ca*. 1990 Department of Natural Resources (DNR) digital shoreline and merged them with the VIMS coverage. Also, for three reaches of shoreline along the Wicomico River (Western Shore) and Chaptico Bay, unexplained gaps existed in the VIMS shoreline (see

"Comments" column in ReachStatsGrouped.xls spreadsheet). For these three reaches, MGS measured the length of the *ca*. 1990 DNR shoreline, assumed that the protected shoreline length from the VIMS file was correct, and subtracted protected length from total length to determine unprotected length.

Bank:Marsh Ratio

In estimating sediment loads due to shore erosion, MGS distinguished between two types of fastland – banks and marshes – which differ in their physical characteristics. MGS used 7.5-minute topographic quadrangles to determine the relative proportions of bank and marsh fastland along each shoreline reach. The proportions were applied to the total reach length to determine the lengths of bank and marsh shoreline.

Bank Height and Marsh Elevation

Likewise, to estimate average bank height within a reach, MGS examined elevation contours on the topographic quadrangles. For marshy stretches of shoreline, MGS assumed a constant marsh elevation of 0.5 m. The marsh elevation estimate was derived from examination of the NOAA tide gauge and vertical tidal benchmark data for McCready's Creek, located at Elliott's Island, Dorchester County, combined with LIDAR data obtained from the NOAA-Coastal Services Center Topographic Change Mapping website (http://ekman.csc.noaa.gov/TCM/).

Bulk density

Hill and others (2003) measured the dry bulk density of 88 sediment samples collected from eroding banks and marshes throughout the Maryland section of Chesapeake Bay. From this report, MGS calculated average dry bulk densities for all bank and all marsh samples, without weighting samples according to the thickness of the horizon from which they were collected. Overall, average dry bulk density at the 20 bank locations (66 sediment samples) was 1.38 g/cc. Average dry bulk density at the five marsh locations (22 sediment samples) was 0.62 g/cc. These results are summarized in Table 2, below.

Table 2: Average bulk density of banks and marshes, from Hill and others (2003)

Fastland type	Samples (N)	Locations (N)	Dry bulk density (g/cc)
Bank	66	20	1.38
Marsh	22	5	0.62

Grain Size Composition

MGS adopted the commonly held assumption that, of the sediment eroded from the shoreline, only silt- and clay-sized particles, smaller than 0.063 mm, remain suspended in the receiving waters. Again, MGS based the actual figures used in determining fine fraction input on the average grain size composition of banks and marshes, as measured by Hill and others (2003). Overall, based on 21 bank sites (76 sediment samples), fine sediments represented 56% of the typical sample. Coarse sediments – sand and gravel – accounted for the other 44%. In addition to mineral particles, marshes release organic

matter. The study of Hill and others (2003) assumed that organic matter represented only a negligible portion of the eroding banks and bluffs, but was a significant component of marshes. Thus, the organic component of eroding bank and bluff samples was not measured in that study, but was reported for the eroding marsh samples. At four marsh locations (20 sediment samples), 22% of the sample consisted of sand and gravel, 44% of silt and clay, and 34% of organic matter. These results are summarized in Table 3.

Table 3: Average grain size composition of banks and marshes, from Hill and others (2003)

Fastland type	Samples (N)	Locations (N)	Coarse sediment fraction (sand & gravel) (%)	Fine sediment fraction (silt & clay) (%)	Organic content (%)
Bank	76	21	44	56	---
Marsh	20	4	22	44	34

Nearshore Erosion

Shore erosion includes erosion of both fastland (onshore, above the water line) and nearshore (offshore , submerged) sediments (Fig. 3). The U.S. Army Corps of Engineers shoreline erosion report (USACOE, 1990), stated that fastland erosion accounts for 43% and nearshore erosion 57% of the sediment load delivered by shoreline erosion. However, no data was presented to support or verify this ratio. In discussions between Jeffrey Halka of MGS and Scott Hardaway of VIMS, the ratio of fastland:nearshore erosion baywide was modified to 65:35. This ratio was based on studies conducted by VIMS in the Virginia portion of the Bay, and on a shoreline erosion study underway in the Choptank River being conducted by MGS.

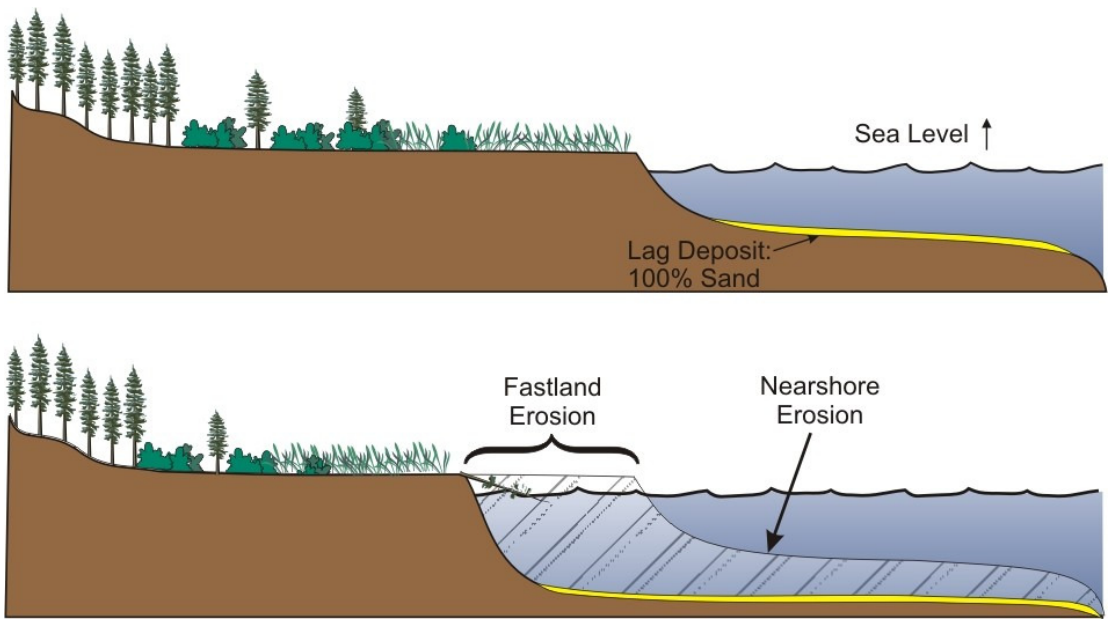

Figure 3 : Fastland and nearshore erosion (from Langland and Cronin, 2003)

MGS determined the mass of sediment eroded from marsh fastland and applied the 65:35 ratio to calculate the mass eroded from the marsh nearshore. For banks, MGS assumed that (1) protected fastland contributed no sediment to the Bay and (2) the protected nearshore eroded at the same rate as the unprotected nearshore. After determining the mass of sediment lost from unprotected banks, MGS applied the fastland:nearshore ratio to the immediate nearshore. Once the loss from the unprotected nearshore was calculated, MGS used the results in conjunction with the lengths of protected and unprotected bank shoreline to estimate erosion of the nearshore in the vicinity of protected banks.

ASSUMPTIONS

This section of the report summarizes the assumptions that MGS made in calculating the suspended sediment load from shore erosion in Maryland:

1. Within any particular reach of eroding, unprotected shoreline, erosion of the fastland represents 65% of the total load delivered to the system, and erosion of the nearshore, 35%.
2. Along accreting shorelines, no sediment is eroded from either the fastland or the nearshore.
3. All protected shoreline lies along banks; none lies along marshes. The assumption is supported by the data. Of the 207 reaches in Maryland, 19 lie entirely along marshes (no banks or bluffs). Of those 19 reaches, 15 are entirely unprotected. The remaining four reaches are protected along no more than 3% of their length.
4. Along protected shoreline (banks), (a) no fastland sediment is delivered to the Bay and (b) the nearshore erodes at the same rate as the nearshore along adjacent unprotected banks with similar geomorphological characteristics.

5. Shoreline faced by a dilapidated bulkhead is protected. Shoreline lined by an offshore breakwater is unprotected.
6. Average bank height (as opposed to marsh elevation) reflects only non-marsh fastland elevations.
7. Marsh elevations are a constant 0.5 m baywide. The 0.5 m represents the height of the marsh scarp above the water line and constitutes the fastland marsh.
8. On average, the dry bulk density of bank samples is 1.38 g/cc and of marsh samples, 0.62 g/cc.
9. On average, silts and clays constitute 56% of the sediment eroded from banks and 44% of the sediment eroded from marshes.
10. Organics are delivered to the system only from eroding marshes, not from eroding banks. Organic matter constitutes 34% of the sediment, broadly defined, eroded from marshes.
11. The bulk density and grain size composition of fastland bank and fastland marsh sediments apply to their respective nearshore sediments.

RESULTS

The Excel spreadsheet contains a great deal of information about shore erosion in the Maryland part of the Chesapeake Bay. This section of the report focuses, not on an exhaustive analysis of the data, but on summarizing the results that seem most pertinent to the purpose of the study.

SHORELINE LENGTH

The digital shoreline file, that is, the VIMS shoreline plus the lower Eastern Shore islands added from the *ca*. 1990 DNR coverage, represents a total length of 8,147 km. Only 3,081 km (38%) of that shoreline is included in the present study. No historical shorelines exist for the headward reaches of many of the larger Bay tributaries. Hence, no rates of change were available for those shorelines. The interior ponds and waterways of marshy islands were omitted for the same reason. And, finally, MGS ignored small tributaries not represented by model cells.

Of the total length of shoreline included in the study, 31% (970 km) is protected, primarily by bulkhead or riprap (Table 4).

Table 4: Length of protected and unprotected shoreline in study area

Area	Unprotected shoreline		Protected shoreline		Total	
	km	%	km	%	km	%
Total	2,111	69	970	31	3,081	100

Of the two fastland types, banks are more common than marshes in the study area, accounting for 2,178 km (71%) of the shoreline (Table 5).

Table 5: Length of bank and marsh shoreline in study area

Area	Bank		Marsh		Total	
	km	%	km	%	km	%
Total	2,178	71	903	29	3,081	100

MGS divided the study area shoreline into 207 reaches, which range in length from 2 to 87 km, averaging 15 km.

SHORELINE RATES OF CHANGE

Of the nearly 250,000 rate-of-change transects for Maryland, 94,070 were located within the study area. Of these, 63,296 (67%) intersected unprotected shoreline. The percentage of unprotected transects corresponds well with the proportion of unprotected shoreline (69%) based on the VIM inventory (see Table 6).

Along unprotected fastland (eroding and accreting banks and marshes), the average annual rate of change, baywide, weighted by unprotected shoreline length, is 0.35 m/yr.

ERODED SEDIMENT VOLUME

Although quantifying the mass of fine-grained sediment was the ultimate goal of this project, MGS also generated sediment volumes for the fine-grained, coarse-grained, and organic fractions. Calculations of sediment mass were based on MGS's measurements of bulk density. Other researchers have used different bulk density values. To facilitate comparisons between those data sets and this one, the eroded sediment volume is reported in Table 6.

Table 6: Average volume of sediment contributed annually by shore erosion, baywide (x 10^3 m^3/yr)

Source area	Coarse-grained volume (sand + gravel)	Fine-grained volume (silt + clay)	Organic volume	TOTAL VOLUME
Fastland				
Unprotected banks	398	506	0	904
Marshes	52	104	81	237
Fastland subtotal	450	610	81	1,141
Nearshore				
Unprotected banks	214	273	0	487
Protected banks	187	238	0	425
Marshes	28	56	43	127
Nearshore subtotal	429	567	43	1,039
Fastland & Nearshore				
Bank subtotal	799	1,017	0	1,816
Marsh subtotal	80	160	124	364
TOTAL	879	1,177	124	2,180

ERODED SEDIMENT MASS

The mass of sediment delivered by shoreline erosive processes is the objective of the overall study. Table 7 summarizes the masses of coarse and fine sediment as well as organic material delivered to the Bays waters from shoreline processes. On average, shore erosion in Maryland contributes 2,738 x 10^3 metric tonnes of sediment annually to

the Chesapeake Bay and its tributaries. Of that total, 55% (1,503 x 10^3 metric tonnes) consists of fine-grained particles. The coarse-grained fraction represents 42% of the total load (1,153 x 10^3 metric tones), and the organic fraction, 3% (77 x 10^3 metric tones).

Overall, erosion of fastland banks and marshes accounts for 1,395 x 10^3 metric tonnes, or 51% of the total load. Nearshore erosion along marshes and protected and unprotected banks generates nearly as much sediment – 1,338 x 10^3 metric tonnes (49%).

Looking at sediment delivery from another point of view, banks overwhelm the contribution of marshes. In Maryland, banks lose 2,507 x 10^3 metric tonnes/yr (92%), compared to the 226 x 10^3 metric tonnes/yr lost from marshes (8%).

Table 7: Average mass of sediment contributed annually by shore erosion, baywide (x 10^3 metric tonnes/yr)

Source area	Coarse-grained mass (sand + gravel)	Fine-grained mass (silt + clay)	Organic mass	TOTAL MASS
Fastland				
Unprotected banks	549	699	0	1,248
Marshes	32	65	50	147
Fastland subtotal	581	764	50	1,395
Nearshore				
Unprotected banks	296	376	0	672
Protected banks	259	328	0	587
Marshes	17	35	27	79
Nearshore subtotal	572	739	27	1,338
Fastland & Nearshore				
Bank subtotal	1,104	1,403	0	2,507
Marsh subtotal	49	100	77	226
TOTAL	1,153	1,503	77	2,733

In terms of daily input, each meter of shoreline in the study area supplies an average of 2.43 kg/m/day of sediment and organic material. Average coarse sediment delivery is 1.02 kg/m/day, fine sediment provides 1.34 kg/m/day, and organic material the remaining 0.07 kg/m/day.

The two stretches of shoreline that make the greatest daily contributions of sediment (>5 kg/m/day) lie on opposite sides of the Chesapeake Bay mainstem. On the Eastern Shore, the relatively low (less than 2 m) banks of Taylors Island are eroding at a rapid rate, over 3.5 m/yr. In contrast, Calvert Cliffs, on the Western Shore, contributes a great mass of sediment, not because of rapid erosion (less than 1 m/yr), but because of the great height (25-30 m) of the banks. To some extent the disproportionately large contribution of Calvert Cliffs is an artifact of one of the assumptions used in the calculations, namely, that the mass eroded from the nearshore is a function of the mass eroded from the adjacent fastland).

DISCUSSION

In terms of improving the accuracy of the eutrophication model, the most important findings of this study are that (1) the estimate of suspended sediment load from shore erosion currently used in the model (5.7 kg/m/day) exceeds the newly estimated load from this study (1.34 kg/m/day) by four-fold, at least in Maryland, and (2) the suspended sediment load varies widely from reach to reach, depending on erosion rate, bank height, shoreline type, and protected length. So, a single-number estimate of erosion is a poor representation of reality.

This shore erosion study is unique in that it takes protected shoreline into account. At the time of the VIMS inventory, nearly one-third (31%) of the shoreline in the Chesapeake Bay and its tributaries was protected. Eliminating the considerable length of protected fastland shoreline as a sediment source accounts in part for the reduced estimate of suspended sediment load from shore erosion. Furthermore, it seems reasonable to suppose that erosion control structures are more likely to be located along reaches that, historically, have eroded rapidly, rather than along reaches that have eroded more slowly or not at all. One reason that a shoreline reach remains in its natural state, then, may be because it is accreting or, at least, eroding very slowly. So, along well-armored shorelines, rates of change for the intervening natural shoreline may indicate either accretion or very little shoreline retreat. Also, the VIMS survey included only hardened shoreline in its inventory of structures, not non-structural or vegetative approaches to shoreline stabilization. Such bioengineered reaches, which VIMS classified as unprotected, could appear to be eroding slowly or accreting.

Another factor contributing to the lower estimate of sediment load is related to the bulk density values used in calculating erosion of bank and, particularly, marsh fastland. Previous studies have generally estimated bulk density to be between 1.5 and 2.5 g/cc. In this study, the bulk density associated with banks (1.38 g/cc) and marshes (0.62 g/cc) was lower than that range of values. Furthermore, including organic matter as one of the

constituents in the grain size distribution of marsh samples diminishes the relative proportions of the fine- and coarse-grained fractions.

DELIVERABLES

In addition to this report, MGS delivered two data sets to the Environmental Protection Agency, to the Corps of Engineers-Waterways Experiment Station, and to the Maryland Department of the Environment:

- Microsoft Excel spreadsheet, ReachStatsGrouped (dated 5/18/2006)
  This spreadsheet contains measurements or computations related to the calculation of both the coarse and fine fractions of sediment delivered to the Chesapeake Bay from erosion of Maryland shorelines.
- Arc shapefile, MDBaywideSL.shp
  This vector file includes the entire Chesapeake Bay in Maryland and its tributaries. It is georeferenced to UTM, zone 18, NAD83, meters. The associated line table contains two fields:
  1. GrReachID - Reach ID - an integer number between 1-207, inclusive, that uniquely identifies each record in the attribute table. Each record represents a particular reach of shoreline. This field corresponds to Reach ID (Column A) in the Excel spreadsheet.
  2. GrReachNam - Reach Name - a 7-character string in the form XXXXX-#, where XXXXX = (usually) the first five letters of the name of the stream/bay bordered by the reach and # = 1, 2, 3, etc. Usually, the headmost reach of a stream is labeled 1 and each successive downstream reach is labeled using the next highest number. Sometimes the naming convention is different, usually because more than one stream with the same name is found in the State. This field corresponds to AKA (Column B) in the Excel spreadsheet. Unabbreviated names, along with a description of the reach boundaries, are provided in the Excel spreadsheet.

  In addition to the 207 named reaches, the file also includes unclassified stretches of shoreline, for which no erosion data is provided. Usually, these are the headmost reaches of tributaries and/or tributaries too small to be represented by model cells. Also, the file includes reach boundary markers, irregular line segments that serve to separate the reaches from one another or to cut off minor tributaries at their mouths.

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