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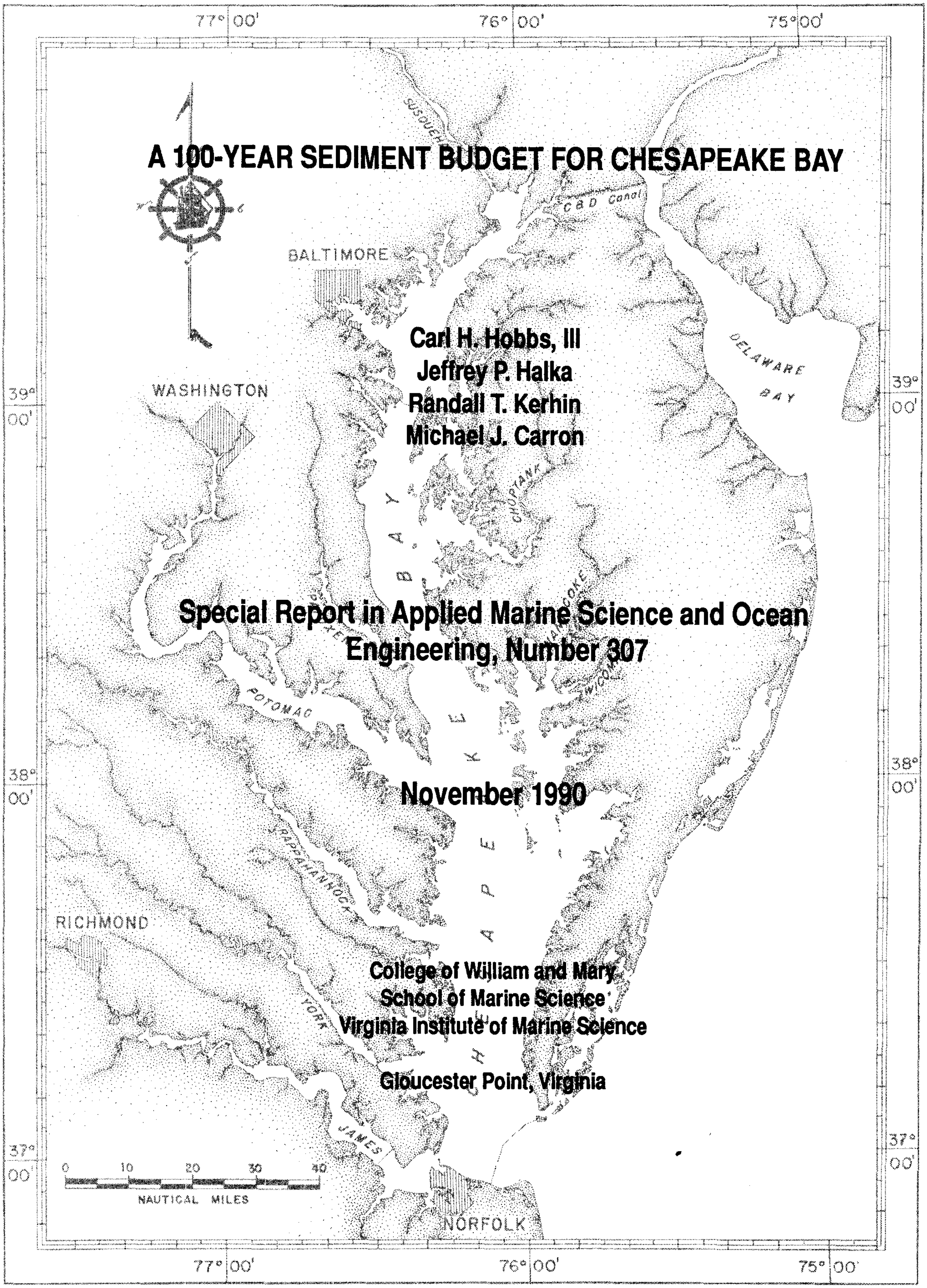

A 100-YEAR SEDIMENT BUDGET FOR CHESAPEAKE BAY

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ABSTRACT

Chesapeake Bay is a depositional basin that is filling from both ends and the sides. During the century ended in the mid-1950s between 1.0×10^9 and 2.92×10^9 metric tons of sediment accumulated in the bay. The bay's largest tributary, the Susquehanna River, is a major source of fine-grained sediments; its coarser load being trapped by dams. The continental shelf is the largest single source of sediment for the basin. A massive quantity of sand, perhaps as much of forty percent of the net deposition, enters the bay between the Virginia capes and works its way tens of kilometers upstream, potentially as far north as Tangier Island, near the Virginia-Maryland boundary. Other sources of sediment are shoreline erosion, biogenic production, pre-Holocene outcrops, and the other tributaries. These tributary estuaries do provide coarse sediment to the bay through longshore transport and bedload movement in the nearshore shallows and, perhaps, in the channel bottom. The contribution of suspended or fine-grained sediment by the tributary estuaries is unknown. Indeed they may be sinks and not sources.

The contribution of the tributary estuaries and the quantification of the bay-mouth sand-source and uncertainties associated with the bathymetric comparisons in the determination of the net mass of sediment deposition, make it difficult to balance a sediment budget for Chesapeake Bay. Most of the imbalance is in the sand fraction within the Virginia portion of the system; with far more sand being deposited than can be accounted for by the independently quantifiable sources. Not considering the continental shelf as a source of sand, the budget fails to balance by a factor of between 2.7 and 7.6. Making certain assumptions about the quantity of sand entering the bay through its mouth (the continental shelf source), the difference can be sufficiently reduced that the budget more nearly balances.

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INTRODUCTION

This paper presents a sediment budget, a statement of the net quantity of sediment deposited or eroded against the sum of sources and external sinks, for Chesapeake Bay during a 100-year interval. The work is a synthesis of separate, but parallel, and very similar studies that were conducted in their respective states by personnel from the Maryland Geological Survey (MGS) (Kerhin and others, 1983, 1988) and the Virginia Institute of Marine Science (VIMS) (Byrne and others, 1982; Hobbs and others, 1982). As such it is one of the first reports since Ryan (1953) to deal with the entire bay, not just a longitudinal transect or a discrete region. The present work addresses the question of assessing the quantity of sediment deposited with the quantity of sediment calculated to have been derived from various sources or lost to various sinks and attempts to balance the net change in this quantity of bottom sediments. The keystone of the determination of the residual mass is the comparison of water-depths recorded in successive bathymetric surveys.

Chesapeake Bay is a large coastal-plain estuary extending 315 kilometers from the mouth of the Susquehanna River to the Virginia Capes (Figure 1). The bay varies in width from 5 to 56 kilometers. Although its maximum depth exceeds 40 meters, the bay is exceptionally shallow, the average depth at mean low water being only 8.4 meters (Cronin, 1971). According to Wolman (1968), the ratio of width to depth is 3,000:1. The system's drainage basin exceeds 166,000 square kilometers in area (Seitz, 1971), approximately 42 percent of which is associated with the Susquehanna River. Rosen (1976) characterized the long and extremely irregular shoreline as that of a drowned, upland drainage system that is slowly being modified to a straight "secondary" shoreline. Shoreline erosion is a significant process with the yearly average rate of recession in Virginia being approximately 20 centimeters (Byrne and Anderson, 1977) and in some localities, for example Tangier Island, exceeding three meters. Singewald and Slaughter (1949) commented upon the unexpectedly high rates of erosion along the shores of Chesapeake Bay.

The present day Chesapeake Bay evolved as the river valleys that became entrenched during the last Pleistocene low stand of sea level drowned during the Holocene transgression. The deep portions of the estuary are these incised channels that flooded during the period of rapid sea-level rise and the shallower margins are areas that have been eroded or flooded since then (Rosen, 1976).

There is substantial evidence that a large proto-Chesapeake Bay existed during earlier high stands of sea level (Johnson, 1972; Schubel and Zabawa, 1973; Owens and Denny, 1979; Kerhin and others, 1980; Johnson and others,

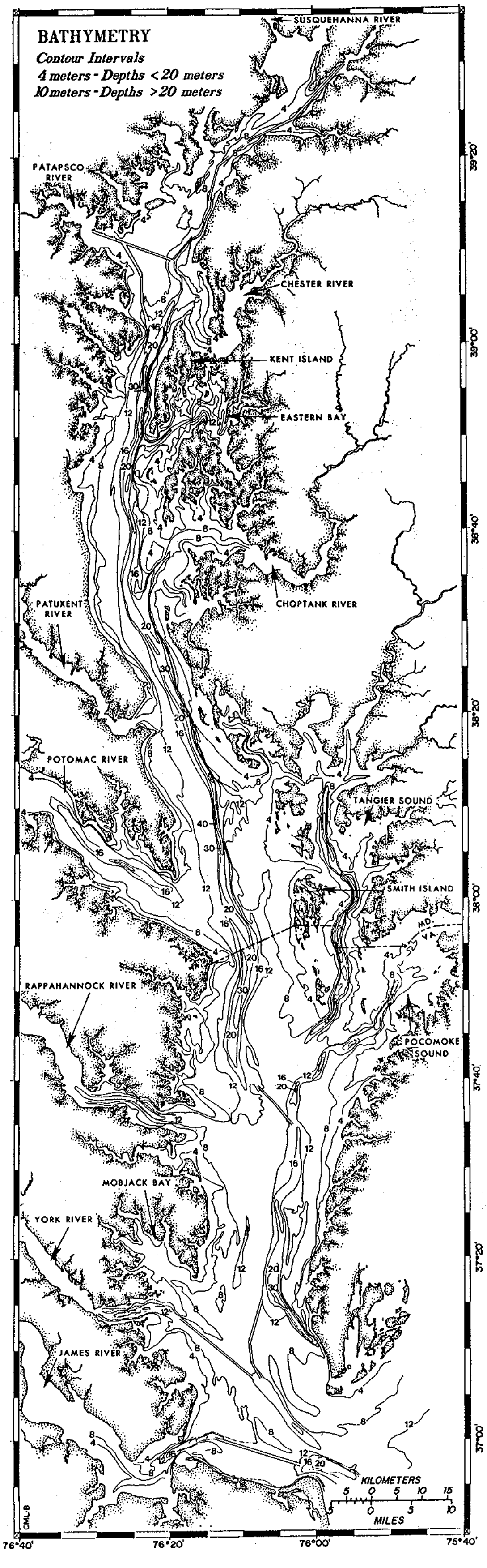

Figure 1: Location map and bathymetry.

1982; Mixon, 1985). The southward growth, particularly of Virginia's portion, of the Delmarva Peninsula has determined the locations of the bay's eastern margin and mouth (Mixon and others, 1982; Mixon, 1985; Colman and Hobbs, 1987, 1988; G.H. Johnson, personal communication). The several scarps in the scarp-and-terrace topography of the outer coastal-plain mark the positions of the shoreline at past high- or still- stands of sea level

Ryan's (1953) study used approximately 200 core and grab samples and demonstrated that sands generally occupy the shallow margins of the bay and muds the deep axial trough and associated channels. The many ensuing studies, reviewed in Byrne and others (1982) and in Kerhin and others (1983, 1988) generally have been concerned with specific geographical sections of the bay or with various technical aspects of the sedimentary system.

The United States Coast and Geodetic Survey first surveyed the hydrography of Chesapeake Bay and adjacent waters in the 1840s. Since then at least two other major surveys have been authorized and a few areas of high usage, such as Baltimore Harbor, have been surveyed as many as five times. Although not the intended purpose of hydrographic surveys, it is possible to use the data to estimate changes through time brought about by erosion and deposition. Hunter (1915), in calculating the bathymetric changes between 1847 and 1901 at the mouth of the Choptank River, was one of the first to use this method in the Chesapeake Bay system. Jordan (1961) studied approximately the same area but was able to use data from a 100-year span of time. Schubel and others (1972) compared plots of longitudinal profiles constructed from the 1847-1848 and 1944-1945 bathymetric data for a section adjacent to Calvert County, Maryland. In a project that formed one of the bases of the present study, Carron (1979) determined the bathymetric changes in Virginia's portion of the bay. In determining the rates of deposition in the vicinity of Thimble Shoal Channel, Virginia, Ludwick (1981) compared bathymetry from 1854 and 1978.

There are few previous attempts to develop a budget for the sediments on the bay's floor. Most have been concerned with the genesis, transportation, or fate of suspended materials in the water column. Some have had a limited areal extent within the larger system (Biggs, 1970; Schubel and Carter, 1976; and Yarbo and others, 1981). Ludwick (1981) approached the problem for the area near Thimble Shoals. Schubel and Carter (1976) formulated a budget based upon a model of estuarine circulation and measurements of suspended sediments along the bay's axis. They argued that in the lower, or Virginia, portion of the bay, shoreline erosion might be the greatest source of inorganic sediment. Additionally they calculated the amount of suspended sediment entering the bay from the waters of the continental shelf and speculated that some is lost to the tributary estuaries. Meade (1969, 1972) advanced the case for landward transport of suspended sediments in estuaries such as Chesapeake Bay. Harrison and others (1967) used bottom drifters released on the continental shelf to investigate bottom circulation on the inner continental shelf near the bay's mouth. Some of the drifters were recovered in areas as far north as Wolf Trap Light ($37^{o}22'$ N) and Tangier Island near the Virginia - Maryland boundary. Skrabal (1987) addressed the up-estuary transportation of clay.

METHODS

The determination of the volumetric change in the quantity of bottom sediments between bathymetric surveys provided the basis for the studies in Maryland and Virginia. It should be noted that in making calculations of sedimentation rates from comparisons of bathymetry from different dates, one is tacitly accepting the assumption that the change occurs at a constant rate between successive surveys. The specific methods for making the comparisons and then converting them to mass differed slightly in the two projects.

There are several implicit assumptions and sources for error involved in bathymetric comparisons. Neither the original data nor the copies were drafted on stable media. Presumably these errors would be reduced in the digitizing and area averaging procedures. Errors associated with rounding and converting from English to metric units would lead to some loss of precision but would not necessarily affect accuracy. Also it was necessary to "reposition" the grids as the standard projections of latitude and longitude had shifted. Additionally, there are errors and problems associated with the surveys themselves. As bathymetric surveys are primarily for navigation, the density of data tends to be less near the shoreline. Similarly the loss of the above-water land-mass is not recorded in the bathymetric changes. The change from lead line to echo sounding raises questions concerning the validity of comparing the measurements as different quantities originally were measured. And, as has been suggested previously, the comparisons yield a discrete difference between data points from two times, which is not a statement of uniform rate or even a uniform direction of change. Hence the normalization to a standard time interval is itself a spurious, though necessary, application of the results.

Maryland

In Maryland there are three sets of surveys of the bathymetry: total coverage with a set of 13 surveys made between 1845 and 1849, about 80 percent coverage with a set of 17 surveys made between 1896 and 1902, and about 80 percent coverage with a set of 63 surveys from 1932 to 1956. Thus the interval of time covered by a comparison varied from area to area. In order to compensate for this disparity, the comparative data were normalized to indicate change over a period of 100 years. The survey-to-survey comparisons used the grid-point method (Sallenger and others, 1975) wherein the depths on each survey are replotted on a user defined grid system. This method yields a qualitative image of regional patterns. The grid used in the Maryland study was a network of cells that were six seconds of latitude and six seconds of longitude on a side. As the network was derived from a Mercator projection, there is a slight variation from north to south in the area covered by a cell. These differences are on the order of 10^{-4} km^2 and are insignificant in comparison to the 3×10^{-2} km^2 area of an average cell. Surveys and charts postdating 1930 were acquired from NOAA in digitized form and those predating 1930 were digitized at MGS. All the soundings within an individual cell were averaged and converted from traditional English to metric units. The comparisons were made by subtracting the recent from the historic data on a cell by cell basis. As the chart and survey data refer to a mean-low-water datum, the comparison yields the simple change in the height of the water column over each cell through a specific interval of time. A correction factor of one millimeter per year (Rusnak, 1967) was used to account for the effect of sea-level rise. The result for each cell then was normalized to a 100-year interval.

In calculating the quantity of sediment deposited on the bay's floor, it is necessary to convert the adjusted vertical change to a volumetric change and then to convert volume to mass of dry sediment. A unit volume of bay-bottom sediment is composed of sedimentary particles, interstitial water, and biogenic matter. The sediments consist of sand, silt, clay, and organic particles. The conversion from volume to mass required the use of four assumptions: first, the sediments are water saturated; that is all the void spaces between particles are filled with water, not gas; second, an arbitrary statement for the specific gravity of the inorganic particles, 2.72 g cm^{-3}; third, that the density of the interstitial water is 1.00 g cm^{-3}; and fourth, that the lithology of the sediment at the surface is constant across the observed-normalized depth change. The first assumption is unavoidable. The second is based upon information presented by Supp (1955) and Harrison and others (1964). Although the salinity of the interstitial waters ranges from 2 to 25 parts per thousand (Hill and Conkwright, 1981), preliminary calculations and work summarized in Hobbs (1983) show that error introduced by not correcting for the salt-related density of the interstitial water is negligible relative to the overall mass of the sediment. The fourth assumption is borne out by the examination of the lithologic descriptions of short (< 1 meter) cores in Ryan (1953), Biggs (1970), and Hill and Conkwright (1981). Examination of the data available from the few longer cores indicated that although the lithology may vary with depth, it usually is uniform within ten meters of the surface. Finally, as sediments become increasingly compacted with increasing depth of burial, there is a decrease in water content and a concomitant increase in the mass of the dry sediment per unit thickness. A set of regression lines was developed for the change in water content with depth in several cores in different sediment types. The regression equations are valid only for the finer-grained sediments. The coarser-grained sediments, sands, are less subject to compaction; hence the surface layer's water content was considered representative of the entire unit. In areas where the change in sediment thickness was one meter or less, the water content was estimated from the equation for the short core closest to the site in question. The depth chosen as representative of the local sediment-package was the intermediate value of averaged depth change. In areas where the depth change exceeded one meter, water contents for each one-meter interval to the observed depth of change were estimated with the regression equation developed from Supp's (1955) long borings for the Chesapeake Bay Bridge at Kent Island.

Using the assumed grain density of 2.72 g cm^{-3}, the bulk density and porosity of the sediments were determined with the equations of Bennett and Lambert (1971). These calculations were preformed for each one meter interval or fraction thereof. The density and porosity values were then used in the equation of van Andel and others (1975) to determine the mass of solids within each given volume change. The mass of the included organic matter then was deleted by subtracting the average organic-carbon content of the sediment multiplied by 1.82 (Bezrukov and others, 1977).

Finally, the individual contributions of sand, silt, and clay were determined using the sand:silt:clay ratios from surface samples. The surface water contents, sand:silt:clay ratios, organic-carbon contents, and other data were derived from a set of approximately 4,000 surficial-samples acquired for another phase of the larger study (Kerhin and others, 1983, 1988).

Virginia

Although also using the method of comparing bathymetric data, patterns and volumes of sedimentation and erosion, and conversion of calculated volumes to mass, the details of the work in Virginia differ, albeit slightly, from the system used in Maryland. As with the work in the northern portion of the bay, the work in Virginia is a synthesis of several sets of data and requires acceptance of a similar set of assumptions.

Bathymetric surveys in the Virginia portion of the bay generally have been less frequent, but more complete; hence the comparisons more closely approach a nominal 100-year interval. The time difference between surveys ranged from 85 to 110 years with the predominance between 95 and 100 years. As in Maryland, the bathymetric comparisons in Virginia were made using a grid of six-second latitude and longitude cells. Each cell is approximately 150 by 200 meters. It was possible to make comparisons in roughly 40,000 of a total 420,000 cells.

In order to rectify the soundings to the same mean-low-water datum, three corrections were applied: one for the change in eustatic (mean) sea level, another for crustal subsidence, and the third for annual and semi-annual tidal variations. The same one millimeter per year eustatic increase in sea level that was used in Maryland was used in Virginia except that it was applied to the elapsed number of years since 1950, the middle of the 1941-1959 tidal epoch (the period of the most recent soundings) to the survey date of the 1850 series bathymetry. Crustal changes, all of which were subsidence, were accounted for by applying a fifth-order, trend-surface equation to the data of Holdahl and Morrison (1974) and using the equation to estimate the vertical change for the period of comparison. Seasonal variations in tides were corrected on the 1850 series bathymetry with data calculated by Carron (1979).

In addition to these corrections and other uncompensated sources of error, such as compaction, it is necessary to consider propagation of error in the actual soundings. Each separate survey contains error and comparison embodies error. In individual surveys the principal errors are those of location of the site and the variability of soundings at a fixed site. The surveyors were aware of the problem of accuracy and as a check on their data ran survey lines that crossed one another. If the differences of the values at crossings were within given limits which are dependent upon water depth, the bathymetry is acceptable (Sallenger and others, 1975).

As a means of quantifying the error in the soundings we examined the differences in the depth values at points of crossings from selected subsets of both the 1850s and 1950s bathymetry. The crossing differences are the absolute values of the differences of depths from two survey lines where they cross. As soundings from the separate lines seldom coincided, crossing values were determined by linear interpolation. The variances of the crossing values for the 1850s and 1950s data were, respectively, 3.03 and 0.52 ft^2 (values are in feet as the raw data are in English units). The pooled variance arising from the comparison of individual soundings at a given location is 3.55 ft^2 and the standard deviation is 1.88 ft (0.57 meter). The 95 percent confidence interval is 1.96 times the standard deviation or 1.12 meter. Thus, for a comparison of co-located individual depths on separate surveys, a difference of greater than 1.12 meters has a 5 percent probability of being due to survey error. It should be noted that the regions with the greatest errors on the 1850s data were those of steep slopes where a small horizontal displacement results in a substantial change in depth. While this applies to the comparison of individual co-located depths, the grid method should reduce the error as it compares the averages of all depths within six-second cells. Also, the grid-cell sampling density was further smoothed to a 0.5 minute cell by the use of a pseudo-two-dimensional, bicubic, spline-fitting program. Thus for the center of each 0.5 minute cell, there were interpolated values of sedimentation (based on bathymetric comparisons), water content, and sand:silt:clay ratios for the surface sediments.

The volume of sediment calculated from the sedimentation rates deposited during the 100-year interval was converted to mass using the method of Hobbs (1983). This method yields results that are nearly identical to those from the method used in Maryland. The water content used in the calculations was the depth-averaged water content, which was determined from a nomogram developed from empirical data.

The quantities of sediment contributed by erosion of the shoreline were calculated from previously published data. In Maryland, the rates and volumes of shoreline erosion were taken from Singewald and Slaughter (1949) and Conkwright (1975). Mass was determined by multiplying volume of different sediment types, from field observation, by values of dry density that are used by the Maryland State Highway Administration. In Virginia, rates of shoreline erosion were taken from Byrne and Anderson (1977) and supplemented with new field-data to determine various characteristics of the sediments. Volume was converted to mass using data from Terzaghi and Peck (1948). The values are consistent with those used in Maryland.

In general, the mass of suspended sediment added to the system was taken from the previously mentioned published works. Additionally, in Virginia, the mass of biogenic sediment was calculated as ash-weights of zooplankton using data from Jacobs, (1978).

RESULTS

Deposition and Erosion

Maryland

Of the 2,710 square kilometers included in the study area of the Maryland portion of chesapeake Bay, 52 percent was depositional, 42 percent erosional, and 6 percent did not exhibit a measurable change during the 100-year period of comparison. Volumes of 1,183.3 x 10^6 and 754.9 x 10^6 cubic meters were deposited and eroded for a net accumulation of 428.4 x 10^6 cubic meters. If evenly spread over the entire study area, the average vertical rate of fill including coarse- and fine-grained sediments would have been 0.08 meter per 100 years. However when limiting the view exclusively to areas of deposition, the average rate of fill is 0.84 meter per hundred years, which agrees very well with the 0.71 centimeter per year average of the rates of sedimentation that Helz and others (1981) determined using lead-210. Officer and others (1984) using cesium-147, lead-210, and plutonium-239 and -240 calculated rates of sedimentation of 0.3 to 1.2, 0.1 to 0.3, and 0.1 to 0.8 grams per square meter per year of fine-grained sediments in the upper, middle, and lower portions of the bay, respectively.

The conversion of volumes to mass of inorganic material (Table 1), yields approximately 805.18 x 10^6 metric tons, the net being 35 percent sand, 33 percent silt, and 31 percent clay. These data do not include the calculations for Eastern Bay and the Choptank River.

Although Kerhin and others (1988), incorporated in the present report, is the first attempt to use the record of the bottom sediments to determine the mass of sediment deposited in the Maryland portion of Chesapeake Bay, two earlier studies (Biggs, 1970; Schubel and Carter, 1976) used another technique. Both attempted to determine the mass of sediments deposited by analyzing the difference between the quantities of sediment calculated to be suspended in the bay's waters and that calculated to have been derived from various sources. These investigators reasoned that when the mass of suspended sediment calculated to be in the area was subtracted from the total of several contributing sources, the residual represented the mass of fine-grained, inorganic

TABLE 1

EROSION AND DEPOSITION IN THE MARYLAND PORTION OF CHESAPEAKE BAY
MILLIONS OF METRIC TONS DURING A 100-YEAR PERIOD

	Total	Organic	Inorganic	Sand	Silt	Clay
Deposition	822.15	16.98	805.18	524.13	121.61	159.46
Erosion	661.11	10.62	650.49	469.46	69.90	111.13
Net	161.04	6.35	154.69	54.67	51.71	48.33

sediment deposited on the bay's bottom. Their results, extrapolated to a period of 100 years, are shown in Table 2. As Schubel and Carter's (1976) work included the Virginia portion of the bay, the data in Table 2 have been adjusted to depict only the Maryland portion. It should be noted that these earlier works addressed only the fine-grained sediments transported as suspended materials whereas the present work includes coarser materials.

Virginia

According to Carron (1979) the average rate of deposition in the Virginia portion of the mainstem of Chesapeake Bay is 0.55 meter per hundred years. This rate is not areally uniform and is highly dependent upon depth. The highest rates of deposition were in the 0 to 1.8 meter (0 to 6 foot) and 5.5 to 12.8 meter (18 to 42 foot) depth intervals and the lowest in the 1.8 to 3.7 meter (6 to 12 foot) interval. Also the rates of deposition in depths over 12.8 meters (42 feet) were relatively low.

When normalized to a 100-year period, the nominal mass of deposition in the Virginia portion of the bay is 2,760.47 x 10^6 metric tons. Table 3 presents the breakdown of the sand, silt, and clay components and further shows the comparable values if deposition or erosion of less that 0.57 and 1.12 meters, as previously discussed, is excluded.

Table 4 is a tabulation of the net sediment flux into the Virginia portion of Chesapeake Bay paired with the quantity of sediment calculated to have been deposited. Even at the lowest level of confidence, that is not counting sediment within +/- 1.12 meters of no change in bottom depth, the quantity of sediment exceeds the sum of the sources by a factor of 6.8 (895.23 x 10^6 tons deposited from an available supply of 132.31 x 10^6 tons). Approximately 86 percent of the difference (656.72 x 10^6 tons) being sand as opposed to silt and clay. Using the nominal values for sources and sinks, a multiple of 20.9 times the 132.31 x 10^6 tons available, or 2,760.47 x 10^6 tons, was deposited. Again, most of difference, approximately 82 percent, being sand.

Figures 2, 3, and 4 indicate the rates of accumulation of sand, silt, and clay. The main locus of clay deposition is between the Potomac and Rappahannock Rivers. Silt accumulates throughout the central basin between the York River and the confluence of the channels to Tangier and Pocomoke Sounds as well as in the deep axial channel leading from the Maryland portion of the bay. The most prominent accumulation of sand is near the bay's mouth, but there are secondary loci at about 37°20' latitude and on the fringes of the sand shield along the western shore of Tangier Island. As the calculations of the accumulated mass did not

TABLE 2

MASS OF SILT AND CLAY DEPOSITED IN THE MARYLAND PORTION OF CHESAPEAKE BAY AS DETERMINED BY DIFFERENT STUDIES

Biggs, 1970		83.8 x 10^6 metric tons/century
Schubel and Carter, 1976		141.0 x 10^6 metric tons/century
Kerhin and Others, 1988	Total	281.07 x 10^6 metric tons/century
Kerhin and Others, 1988	Net	100.03 x 10^6 metric tons/century

TABLE 3

MILLIONS OF METRIC TONS OF DEPOSITION PER CENTURY FOR THE VIRGINIA PORTION OF CHESAPEAKE BAY

	+/- 0 Meter	+/- 0.57 Meter	+/- 1.12 Meter
Sand	2,210.38	1,690.74	716.85
Silt	329.58	305.94	110.17
Clay	220.51	184.09	68.21
Total	2,760.47	2,180.77	895.23

Contributions from areas with a change in depth less than the values at the head of the columns are excluded from the tabulation.

TABLE 4

SUMMARY OF SOURCES AND DEPOSITION IN THE VIRGINIA PORTION OF CHESAPEAKE BAY

MILLIONS OF METRIC TONS PER HUNDRED YEARS

	Sand	Mud	Total
I: Sources			
A: Shoreline Erosion (Maryland)	74	137	211
Susquehanna R. Suspended sed. passed to Virginia*	-	10.7	10.7
Net bottom deposition in Md.	(54.67)	(100.03)	(154.69)
SUBTOTAL	19.32	47.67	67.01
B: Virginia shoreline erosion	40.0	2.5	42.5
Biogenic silica	0.8	-	0.8
Suspended sediment from ocean	-	22.0	22.0
SUBTOTAL	40.8	24.5	65.3
TOTAL VIRGINIA SOURCE	60.13	72.17	132.31
II: Deposition in Virginia			
+/- 0 meter	2,210.38	550.9	2,761.28
net surplus	2,150.25	478.19	2,628.44
multiple of Virginia source	36.8	7.6	20.9
+/- 0.57 meter	1,690.74	490.03	2,180.77
net surplus	1,630.61	417.32	2,047.93
multiple of Virginia source	28.1	6.7	16.5
+/- 1.12 meter	716.85	178.38	895.23
net surplus	656.72	105.67	762.39
multiple of Virginia source	11.9	2.5	6.8

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*10% of Schubel and Carter (1976).

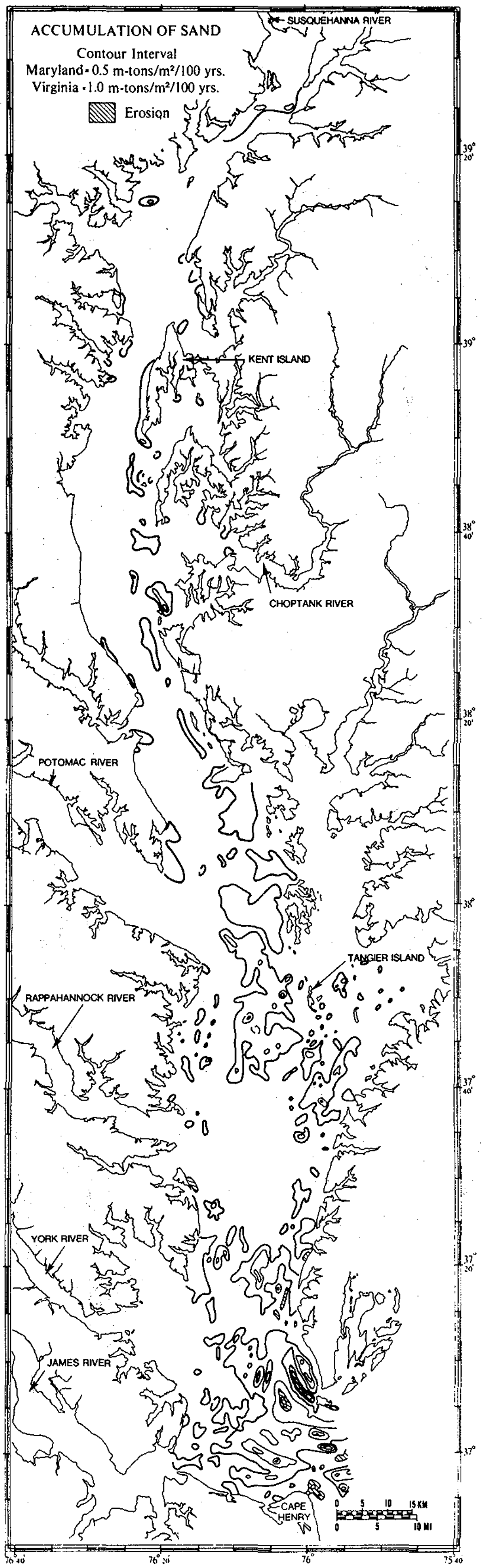

Figure 2: Map depicting the rate of accumulation of sand in Chesapeake Bay.

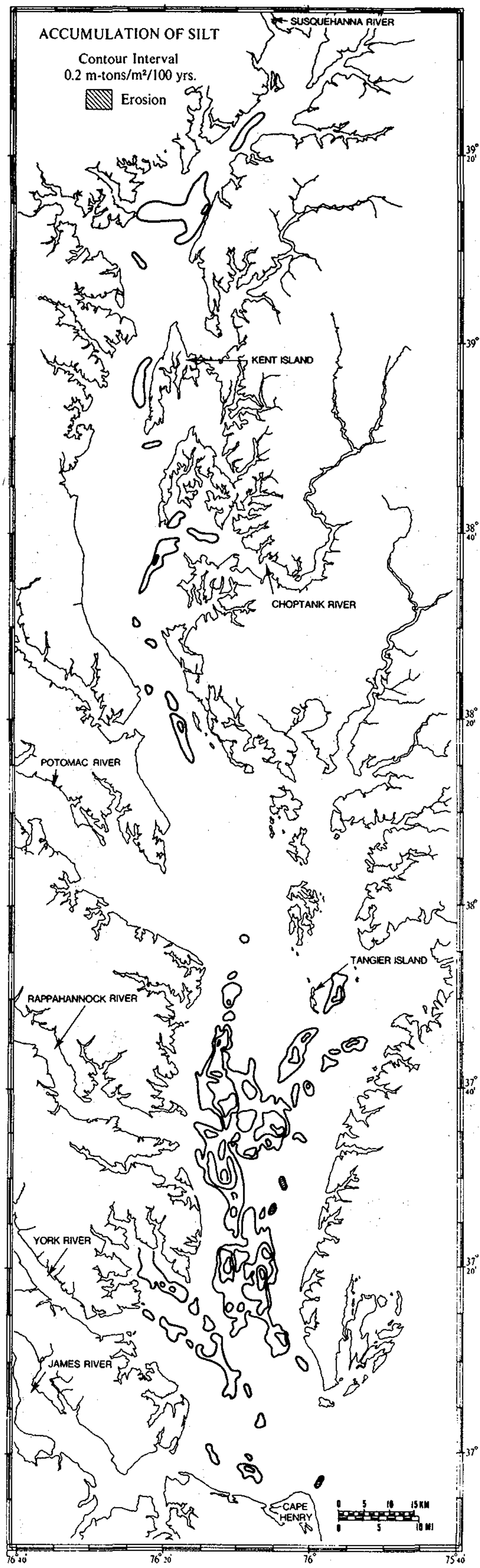

Figure 3: Map depicting the rate of accumulation of silt in Chesapeake Bay.

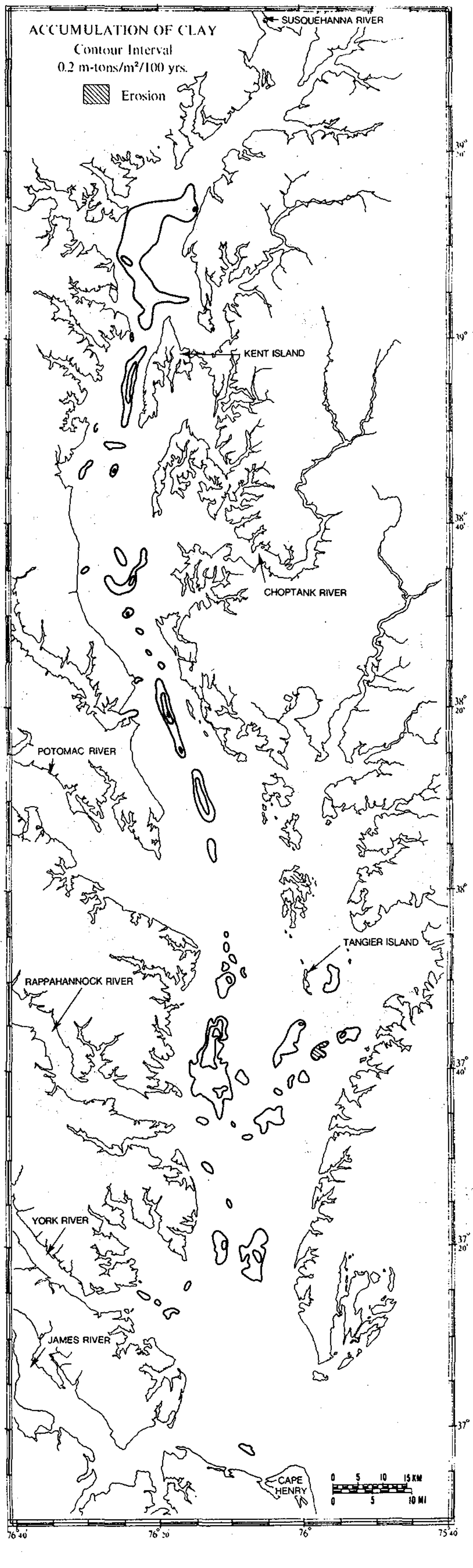

Figure 4: Map depicting the rate of accumulation of clay in Chesapeake Bay.

compensate for shell content, the figures for sand are, to some extent, an overestimate.

Entire Bay

Table 5 presents a summary of the total net deposition for the 100-year period in the combined Maryland and Virginia portions of Chesapeake Bay and the various sources able to provide that material. As can be seen in part C of the table, the 2,915.17 x 10^6 tons deposited is 7.6 times the available sources, 384.1 x 10^6 tons. As above, most of the over abundance is sand.

TABLE 5

SEDIMENTATION IN CHESAPEAKE BAY
MILLIONS OF METRIC TONS PER CENTURY

A: Deposition

	+/- 0 meter	+/- 0.57 meter	+/1.12 meter
Sand	2265.056	1,745.41	771.52
Silt	381.29	357.65	161.88
Clay	268.83	232.41	116.53
TOTAL	2,915.17	2,335.47	1,049.93

Columns refer to the cut-off limits for the Virginia data.

B: Sources*

	Sand	Mud	Total
Shoreline erosion, Maryland	74.	137.	211.
Susquehanna R. suspended sed	-	107.	107.
Shoreline erosion, Virginia	40.0	2.5	42.5
Biogenic silica, Virginia	-	0.8	0.8
Oceanic suspended sediment	-	22.0	22.0
Total	114.0	269.3	383.3

*after Schubel and Carter (1976)

C: Multiple of source required to yield mass deposited

confidence cut-off	Sand	Mud	Total
+/- 0 meter	19.7	2.4	7.6
+/- 0.57 meter	15.2	2.2	6.1
+/- 1.12 meter	6.7	1	2.7

DISCUSSION

In reviewing the data and attempting to reconcile the large differences between the quantity of sediment deposited and that available from the several sources, it becomes apparent that at least three potentially important terms are not included either as sources or sinks: 1) suspended sediment supplied by or to the tributaries, e.g. the Potomac, Rappahannock, Chester, and Choptank rivers; 2) the bed or tractive load of these tributaries, including sand moving along their shallow flanks; and 3) sand brought into the bay from the continental shelf. Also graphic presentations of the data lead one to contemplate upon the processes and pathways of sediment movement within the estuarine system.

Unfortunately there is little specific data on net, long-term flux of material through the mouths of the tributaries. Officer and Nichols (1980) pointed out that, "... in dealing with estuarine phenomena one usually is constrained by (1) an imperfect or incomplete data set, related often to the tidal time scale within which one has to work, and (2) variable freshwater inflows and sediment influxes." Schubel and Carter (1976), using data from a "typical" year, calculated that the tributaries were a sink for suspended sediment derived from the bay and that the bay was a sink for suspended sediment from the waters overlying the continental shelf. They determined that net loss to the tributaries was 0.07 to 0.21 x 10^6 metric tons per year. During the same period the Susquehanna River supplied 1.07 x 10^6 and the ocean 0.11 to 0.47 x 10^6 metric tons. Additional quantities of silt and clay were derived from shoreline erosion and other sources. Hence the quantity of material lost to the tributary rivers is small relative to the total system. Schubel and Carter's (1976) model is based upon movement of suspended sediment paralleling that of dissolved salt and does not include settling or scour lags and other inertial effects; thus the absolute flux of suspended sediment through the mouths of the tributaries is still unknown.

In discussing the James and Rappahannock rivers, Officer and Nichols (1980) concluded that at moderate discharges the estuaries are sinks for suspended sediment from the bay and that during periods of high discharge the estuaries supply suspended sediment to the bay. Several other researchers, reviewed in Lukin (1983) reached similar conclusions.

This leads to the presently unanswerable question of the importance of infrequent, large events, i.e. major floods, in estuarine sedimentation. In attempting to calculate a long-term sediment budget, is the quantity of sediment supplied by a few major pulses sufficiently great to over-ride or even reverse the typical, yearly trends?

In his study of the response of the Rappahannock River to the flooding associated with Tropical Storm Agnes, Nichols (1977) addressed the flux of (suspended) sediment through the upper and lower estuarine layers at different river discharges. At higher discharges a greater percentage of the river-borne sediment is trapped than at lower discharges. But in any circumstance some quantity of sediment does move from the river-estuary into the bay. Although not explicitly stated, this is highly suggestive of a net flux of suspended sediment into the bay from the tributary. Nichols estimated that 10 percent of the 110,000 tons supplied to the estuary by the river during the 16 days of the Agnes flood escaped into the bay. During the flood, concentrations of suspended sediment at the surface and bottom of the estuary at its mouth were 7 to 12 times greater that "normal values." It is very interesting to note that his (Nichols, 1977) data for all conditions show flux through the upper layer (the layer flowing seaward) exceeds the flux through the landward or upstream flowing lower layer and that in terms of tons per tide, the greatest net flux is at a moderately low river flow.

Thus, although there are indications that the sub-estuaries may trap suspended sediment from the main-stem of the bay during "normal" conditions, there is little data with which to judge the true, long-term trend. For the work at hand, short of initiating a major, new research effort, the question remains unanswered.

Similarly great is the question of the net flux of coarser sediments, bed or tractive load, in the channels and along the flanks of the sub-estuaries. Indeed there is less quantitative information here that there is for suspended material. By virtue of their differences in geomorphic position, shallow versus deep, the two areas differ in dynamic regime and, perhaps, net result. The downstream portions of the sub-estuaries are subject to the interaction of tidal currents and currents, usually upstream at depth, owing to "estuarine circulation." Hence it is possible that there is bi-directional movement of sand in the channel. Alas there are no measurements of flux. Indeed true values of net flux might be impossible to determine as there might be a small enough difference between the two primary components that the net would be "lost" within the limits of confidence about the measurements.

The situation on the flanks is different. These shallow areas, often less than two meters in depth, experience reversing tidal currents, downstream, estuarine surface-flow (river discharge), and currents generated by wind-waves. It is the last that probably have the dominant influence on the nearshore transport of sand. There is evidence (Byrne and Anderson, 1977) that the southern shores of the sub-estuaries erode more rapidly than the northern shores. Presumably this is due to the dominance of the northerly, more specifically the northwesterly, winds associated with the passages of low-pressure systems and cold fronts. The waves and associated high water-levels generate longshore currents in addition to eroding the shore. These currents usually are directed downbay and are significant agents for the transportation of sand. Although there are no quantitative data, observations of bedforms, geomorphology, and the accumulation of sediment behind obstruction (groins) demonstrate the net direction of sediment movement. Thus it is reasonable to us that the sub-estuaries are sources of sand for the bay proper.

The distribution of sediment types within the southern portion of the bay (Figure 5) also suggests an export of sand from the sub-estuaries. Specifically the protrusion of sand extending from the southern shore of the Potomac River into the deep channel of the bay's mainstem can be interpreted as being the result of the movement of sand from the tributary's flank into the bay.

The distribution of surface sediments (Figure 5) coupled with the map of rates of deposition of sand (Figure 2) is highly suggestive that there is a large quantity of sand moving into the bay between the Virginia capes. The large lobe of sand extending into the bay from its mouth primarily is depositional. Although there are no comprehensive data on the flux, net or gross, through the bay mouth, there is no other proximal source and no obvious pathways from possible more distant sources. Also the work of Harrison and others (1967) suggests the movement of bed-sediment into the bay from the continental shelf. Shallow seismic work (Colman and Hobbs, 1985, 1987; Colman and others, 1988) showing sediment prograding into the bay supports the high estimates of the quantity of sand entering the bay through its mouth. Various heavy-mineral studies (Berquist, 1986; Ozalpasan, 1989; Calliari and others, in press) also indicate movement of sediment from the inner continental shelf into Chesapeake Bay. Work by Halka (1985) and Halka and others (1985) suggests that silts are transported much farther up-estuary than had previously been reported.

One way to attempt to measure this flux and to help balance the budget is to examine the quantity of sediment, mostly sand, deposited in the southern reaches of the bay (Table 6). By equating the quantity of sand transported into the bay from the continental shelf with the quantity of sand deposited in the southernmost portions of Chesapeake Bay, the size of the discrepancy between the sum of the

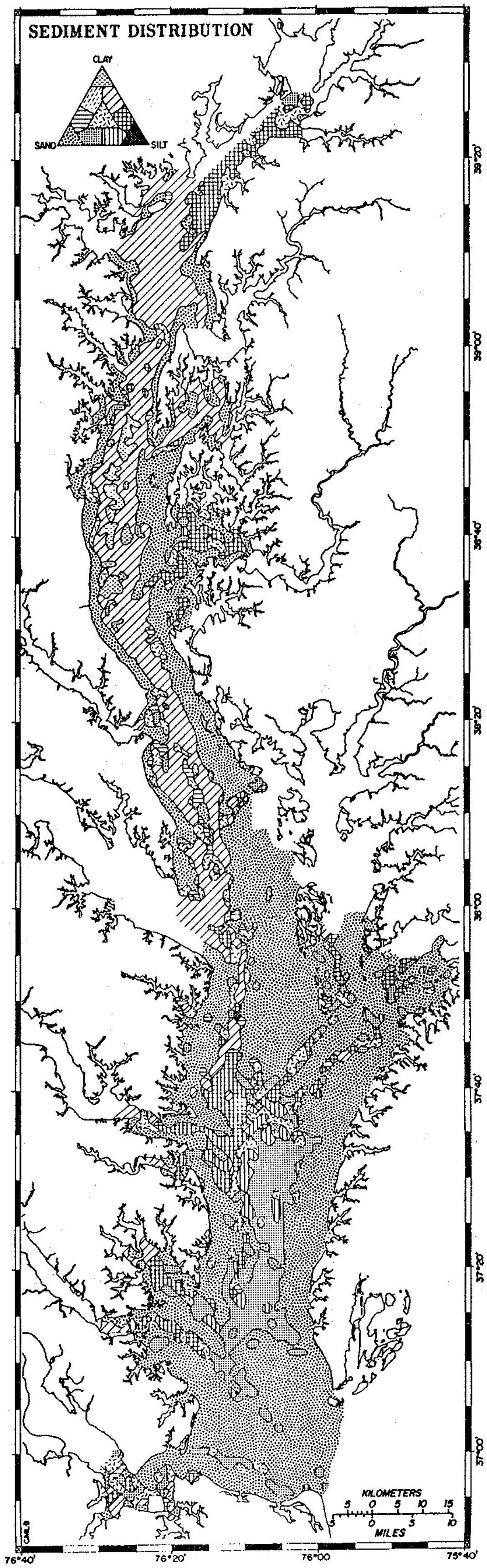

Figure 5: Map depicting the distribution of sediment types in Chesapeake Bay.

TABLE 6

DEPOSITION IN THE SOUTHERN PORTION OF CHESAPEAKE BAY

MILLIONS OF METRIC TONS PER CENTURY

Deposition South of	37°16'	37°11'	37°06'	37°01'
+/- 0 m	1,212.07	970.80	732.39	601.63
+/- 0.55 m	844.43	693.27	596.48	346.74
+/- 1.12 m	478.19	405.72	371.04	281.26
Diference Between Virginia Net Surplus and Deposition South of				
+/- 0 m	1,416.09	1,657.36	1,895.77	2,026.53
+/- 0.55 m	1,204.03	1,355.19	1,451.98	1,701.72
+/- 1.12 m	284.73	357.2	391.88	481.66

sources and the amount of sediment deposited is diminished. The depositional area extending in from the bay's mouth probably extends farther north than 37°16', but for discussion purposes, the quantity of sediment deposited south of 37°16' is indicative of the magnitude of the source.

The pathways and processes of sediment transport within the estuarine system (Figure 6) are equally interesting but somewhat less speculative than the flux of material through the various gates. The distribution and mechanics of suspended sediments within the Chesapeake Bay and other estuaries are well studied, as previously noted, and need no discussion here.

The major pathways of sediment movement obviously are tied to the active processes of sediment transportation. Three significant routes of transport for sand sediments are the deep channel near the bay mouth, the Smith Island - Tangier Island sand-shield, and the flanks of the tributary, sub-estuary rivers. An additional pathway stems from the erosion of the walls of the deeper channels.

The deeper channel along the eastern edge of the bay in the vicinity of the city of Cape Charles is unique in that it is the only one of Chesapeake Bay's deep channels that is not floored with muddy sediments (Hobbs and others, 1982). Indeed some of the sandy bottom may be scoured into pre-Holocene strata (Byrne and others, 1982). This channel leads directly to a major depositional lobe that is over 60 percent sand. It is our contention, supported by Harrison and others's (1967) study of bottom drifters, that this channel is a significant conduit through which sand sediments enter the bay and move up-estuary. The active agents of transportation are the net, up-bay, bottom-water circulation, which is strongest along the eastern side of the bay, and the strong flood-tidal currents.

The shallow, mid-bay sand-shield that lies west of Bloodsworth, South Marsh, Smith, and Tangier islands also appears to be a major pathway along which sand moves. This shield functions in a manner not unlike the flanks of the sub-estuaries as discussed above. New sand is provided to the system through erosion of the west-facing shores of the islands. Once on the beach and in the nearshore zone, wind- and wave-generated currents combine to drive the sediment southward. In general the inner nearshore is characterized by erosion with deposition immediately seaward. There are sub-bottom profiles that indicate southward transportation of material and growth of the shield (R.A. Gammisch, VIMS, personal communication).

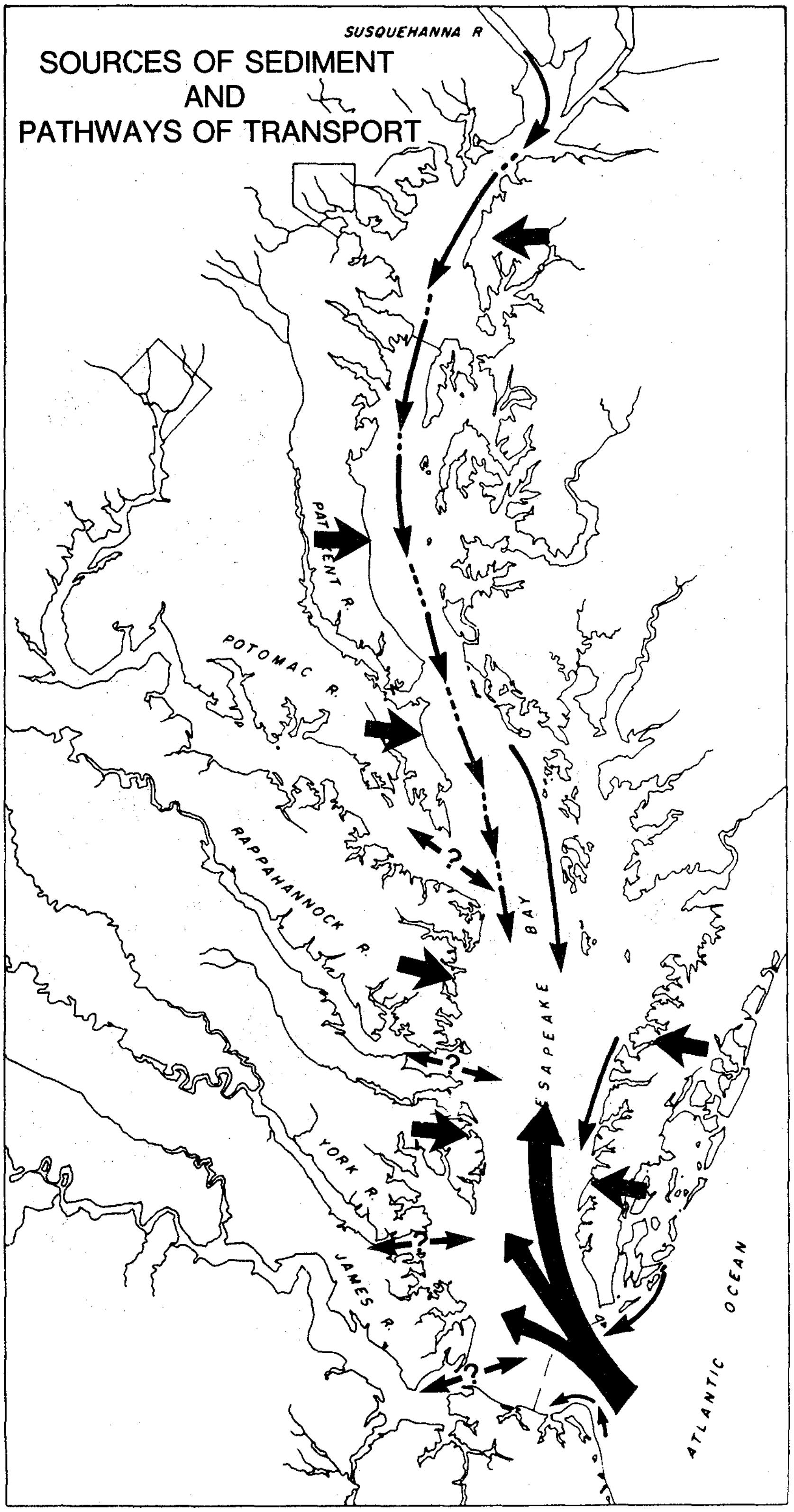

Figure 6: A map depicting the sources and pathways of transport of sediment deposited in Chesapeake Bay.

In Maryland the areas where deposition or erosion exceeds 2.4 meters per century generally are confined to the main, axial channel of Chesapeake Bay, deposition being more commonplace than erosion.

The only area in Virginia's waters of significant deposition of very fine sediment is centered near 37°40' latitude between the Potomac and Rappahannock rivers (Figure 4). This is in agreement with (unpublished) data on the dynamics of water motion in Chesapeake that indicated this area to be one of minimum tidal currents.

Thus using these few examples it can be seen that the distribution of sediment types and the patterns of erosion and deposition are in consonance with one another and describe a rational picture.

SUMMARY AND CONCLUSIONS

Chesapeake Bay is a major depositional basin that is filling from both ends; its major tributary, the Susquehanna River, providing a large quantity of fine-grained material, and the proximal continental shelf supplying significant quantities of sand and suspended sediment. This pattern is similar to that Roy and others (1980) describe for smaller estuarine systems in Australia. Shoreline erosion is another large, quantifiable contributor; whereas the role of the tributary sub-estuaries is unclear.

During the hundred-year period ending in the mid-1950s, net deposition was between 1,049 and 2,915 x 10^6 metric tons, the range of values depends upon the level of confidence with which one is willing to accept the determinations of bathymetric change. This mass exceeds the sum of quantifiable sources by factors of 2.7 to 7.6. Most of the differences are in the sand fraction and are within the Virginia portion of the bay. This is not unexpected as the un- or less-measurable sources, the major sub-estuaries and the bay's mouth, open directly to the southern portion of Chesapeake Bay. Although the budget for sand in the Chesapeake Bay system cannot be balanced within an order of magnitude, the budget for mud can be balanced within a factor of 2.4.

Much of the discrepancy may be accounted for by two unquantifiable terms: sand entering the bay through its mouth and sand moving into the bay along the flanks of the sub-estuaries. Unquestionably, the quantity of sand entering the bay from the continental shelf is great and is sufficient to bring the sources and sinks for Chesapeake Bay's recent sediments into balance. Additionally the net flux of sediment through the mouths of the sub-estuaries is unknown. Even the sign of this flux is unclear.

Finally the pathways and processed of sediment movement are congruent with both patterns of erosion and deposition and the distribution of sediment types.

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