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Chesapeake Bay Sediment Budget

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ABSTRACT

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Chesapeake Bay is a depositional basin that is filling from both ends and the sides. During the one hundred years ending in the mid-1950's between 1.0×10^9 and 2.92×10^9 metric tons of sediment accumulated in the bay. The water of the continental shelf, flowing into the bay's mouth, is the largest single source of sediment for the basin. A massive quantity of sand, perhaps as much as 40% of the net deposition, enters the bay with these waters and moves tens of kilometers up-estuary. The Susquehanna River is a major source of fine-grained sediments; its coarser load is trapped by dams.

Other sources of sediment are shoreline erosion, biogenic production, and, perhaps, the tributary estuaries. The tributaries do provide coarse sediment through longshore drift and bedload movement in the nearshore shallows and, perhaps, in the channel bottom. The quantity of suspended sediment supplied by the tributary estuaries is unknown. Indeed the tributaries may be sinks not sources.

ADDITIONAL INDEX WORDS: *Chesapeake Bay, sediments, erosion, deposition, sediment budget.*

INTRODUCTION

The sediment budget presented in this paper is a synthesis of separate but parallel and very similar studies conducted by the Maryland Geological Survey (MGS) (KERHIN *et al.*, 1983, 1988) and the Virginia Institute of Marine Science (VIMS) (BYRNE *et al.*, 1982; HOBBS *et al.*, 1982). As a sediment budget, it is a statement of the net quantity of sediment deposited or eroded balanced against the sum of the sources and external sinks. It is one of the first reports since RYAN (1953) to deal with the entire Chesapeake Bay as an integrated whole, not just a longitudinal transect. The present work assesses the quantity of material deposited in the bay in terms of mass, not volume, and attempts to balance the net change in the quantity of bottom sediment with the quantity of sediment calculated to have been provided by various sources or lost to various sinks. The key in determining the residual mass is the comparison of water depths as recorded in successive bathymetric surveys.

By discerning the relative importances of the several sources and sinks for sediments in Chesapeake Bay we gain a better understanding of the processes which fill coastal plain estuaries. The insight gained in Chesapeake Bay will be valuable as it assists in the study of other estuaries.

Chesapeake Bay is a large coastal-plain estuary extending 315 km from the mouth of the Susquehanna River to the Virginia Capes (Figure 1). The bay's width varies from 5 to 56 km. Although the maximum depth exceeds 40 m, the average depth at mean low water is only 8.4 m (CRONIN, 1971). The drainage basin exceeds 166,000 km^2 (SEITZ, 1971), roughly 42% of which is associated with the Susquehanna River. Shoreline erosion averages 20 cm per year in Virginia (BYRNE and ANDERSON, 1977) with some localities, *e.g.* Tangier Island, experiencing shoreline recession in excess of 3 m per year. SINGEWALD and SLAUGHTER (1949) discussed the high rates of shoreline erosion in Chesapeake Bay.

Chesapeake Bay has evolved as the rivers that became entrenched during the Wisconsin low stand of sea level were drowned. The deep portions of the estuary are the incised channels that flooded during the period of rapid sea-level rise prior to approximately 3,000 years ago and the

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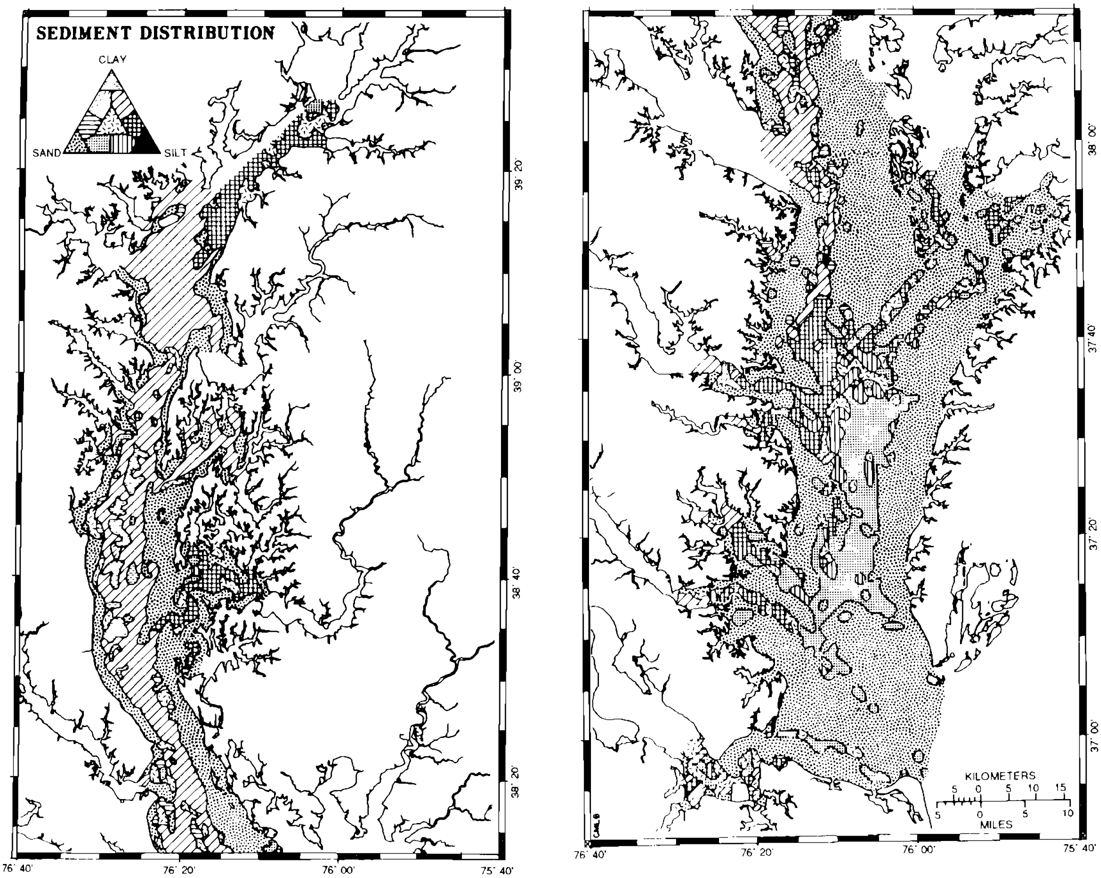

Figure 1. Map depicting the distribution of sediment types within Chesapeake Bay.

shallower margins are the 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 *et al.*, 1980; JOHNSON *et al.*, 1982; MIXON, 1985; COLMAN and HOBBS, 1987, 1988; COLMAN and HALKA, 1989). The growth of the Delmarva Peninsula has determined the locations of the bay's eastern margin and mouth (MIXON *et al.*, 1982; MIXON, 1985; COLMAN and HOBBS, 1987).

The first systematic surveys of Chesapeake Bay's hydrography were made in the 1840's. Subsequently there have been at least two other major surveys and a few areas of high usage have been surveyed several times. HUNTER (1915), studying the mouth of the Choptank River, was the first in the Chesapeake system to compare charts to estimate changes resulting from erosion and deposition. JORDAN (1961) studied approximately the same area but was able to make comparisons over a 100-year time span. SCHUBEL *et al.* (1972) compared longitudinal profiles constructed from the 1847–1948 and the 1944–1945 bathymetric data for a section adjacent to Calvert County, Maryland. CARRON (1979) determined the bathymetric changes in the Virginia portion of the bay. In determining the rates of deposition in the vicinity of Thimble Shoal Channel near the bay's mouth, LUDWICK (1981) compared bathymetry from 1854 and 1978.

Most of the previous attempts to develop a sediment budget within Chesapeake Bay were concerned with suspended materials in the water column and have been of limited geographical extent

(BIGGS, 1970; SCHUBEL and CARTER, 1976; YARBO *et al.*, 1981). SCHUBEL and CARTER (1976) formulated a budget using a model of estuarine circulation and measurements of suspended sediment concentrations along the bay's axis. They stated that in the Virginia portion of the bay, shoreline erosion might be the greatest source of inorganic sediment. They also calculated that a great deal of suspended sediment enters the bay from the waters of the shelf and that some of that is lost to the tributary estuaries. MEADE (1969, 1972) advanced the concept of landward transport of suspended sediments in Chesapeake Bay. HARRISON *et al.* (1967) used bottom drifters released on the shelf to investigate bottom circulation to document movement of bottom materials into and up the bay. They recovered bottom drifters as far up-estuary as Tangier Island. SKRABAL (1987) discussed the up-estuary transportation of clay.

METHODS

Volumetric change in the quantity of bottom sediments between bathymetric surveys was the basis for determination of the quantity of sediment deposited in the system. Although the methods used in the separate Maryland and Virginia projects differed slightly, they are compatible and the results merged without major adjustments. The dates of the charts used in making the comparisons varied with geographic area as Chesapeake Bay has not been surveyed as a unified whole. The oldest surveys were performed in 1845 and the most recent used were made in 1956. In Virginia the time difference between surveys ranged from 85 to 110 years with the preponderance between 95 and 100 years. Changes from comparisons in both Maryland and Virginia were normalized to indicate the change that would occur in a period of 100 years. In making calculations of sedimentation rates from comparisons of bathymetry from different dates, one is tacitly accepting the assumptions that both the sign and rate of change are constant. There are several other sources of error.

The comparisons used the grid-point method (SALLENGER *et al.*, 1975) in which depths on each survey are replotted on a user defined grid, depths within each cell of the grid are averaged, and the values for each cell at each date are compared. The final comparisons variously employed corrections for eustatic changes in sea level (RUSNAK, 1967) and subsidence (HOLDAHL and MORRISON, 1974).

The conversion to volume follows the determination of the linear change in depth. Finally, the mass of sediments eroded and deposited on the bay's bottom is calculated. This step requires assumptions concerning sediment density and the uniformity of sediment properties and type with depth. Sediment type, sand : silt : clay ratio, water content, *etc.* were determined from a network of over 6,000 grab samples, 4,000 from Maryland (KERHIN *et al.*, 1983) and 2,000 from Virginia (BYRNE *et al.*, 1982). A review of data from cores indicated that gross sediment type usually did not vary within the top several meters of the sediment column.

The determination of mass generally uses water content as an indicator of porosity (BENNETT and LAMBERT, 1971; VAN ANDEL *et al.*, 1975; HOBBS, 1983). As the natural compaction of the sediments resulting from burial results in a decrease in water content with depth, we applied corrections based upon the water content of the surficial sediment and the depth of burial in determining the mass of sediment. In calculating the mass of a volume of sediment, we assumed that the sediments were fully saturated with water and had a uniform mineral density. We assumed the density of the pore water to be 1.0 g cm^{-3} and the grain density to be 2.72 (Maryland) or 2.70 (Virginia) g cm^{-3}. A sensitivity analysis indicated an error of approximately 2 percent in the calculation of the dry mass of the sediment at the extremes of a water density of 1.02 g cm^{-3} and grain densities of 2.65 or 2.75 g cm^{-3}. The interested reader is referred to CARRON (1979), BYRNE *et al.* (1982), KERHIN *et al.* (1983, 1988), and HOBBS *et al.* (1990).

The volume of sediment contributed by shoreline erosion was determined from published data (SINGEWALD and SLAUGHTER, 1949; BYRNE and ANDERSON, 1977). After determination of sediment type by field observation, the mass of the eroded sediment was determined by multiplying the volume with a sediment-type specific factor either from the literature (TERZAGHI and PECK, 1948) or the Maryland State Highway Administration (unpublished).

The mass of the 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 the ash-weight of zooplankton using data from JACOBS (1978).

Table 1. *Millions of metric tons of accumulation per century, Virginia portion of Chesapeake Bay.*

	±0 Meter	±0.57 Meter	±1.10 Meter
Sand	2,210	1,691	717
Silt	330	306	110
Clay	221	184	68
Total	2,760	2,181	895

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

Table 2. *Sediment accumulation in Chesapeake Bay millions of metric tons per century.*

A: Deposition

	±0 Meter	±0.57 Meter	±1.10 Meter
Sand	2,265	1,745	772
Silt	381	358	162
Clay	269	232	117
Total	2,915	2,335	1,050

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

B: Sources*

	Sand	Mud	Total
Shoreline erosion, Maryland	74.0	137.0	211.0
Susquehanna R. suspended sed	—	107.0	107.0
Shoreline erosion, Virginia	40.0	2.5	42.5
Biogenic silica, Virginia	0.8		0.8
Oceanic suspended sediment	—	22.0	22.0
Total	114.8	268.5	384.1

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
±1.10 meter	6.7	1	2.7

* After SCHUBEL and CARTER (1976)

RESULTS

In the Maryland portion of Chesapeake Bay net accumulation over the 100-year period was 428 × 10^6 m^3 which is the residual of 1.18 × 10^9 and 755 × 10^6 m^3 of erosion and deposition. Of the 2,710 km^2 of the bay included in Maryland's study, 52% was depositional, 42% erosional, and 6% had no discernable change. The average rate of accumulation in the depositional areas was 64 cm/century which agrees with the 0.71 cm/yr rate HELZ *et al.* (1981) determined using lead-210. OFFICER *et al.* (1984) calculated sediment accumulation rates of 0.1 to 1.2 g/m^2/yr.

Upon converting the volume of sediment to mass of inorganic material, the Maryland portion of the bay experienced deposition of approximately 805 × 10^6 metric tons and erosion of 650 × 10^6 metric tons for a net deposition of 155 × 10^6 metric tons; the net being 35% sand, 33% silt, and 31% clay.

CARRON (1979) determined that in Virginia the average rate of deposition in the mainstem of the bay was 0.55 m/century. This rate, however, is non-uniform and is very dependent upon depth. The highest rates of deposition were in the shallow (0–1.8 m) and the intermediate (5.5 to 12.8 m) depth classes with the lowest rates in the intermediate (1.8 to 3.7 m) class. Deposition also was relatively low in depths over 12.8 m.

In compiling the sediment budget in the Virginia portion of the bay, the calculations were made at three levels of possible error determined by assessing the errors within individual bathymetric surveys pooled in the comparison of different surveys. The range of error within an individual survey was determined by calculating the difference in the interpolated values for the point at which two survey lines crossed. The three sets of calculation were (1) the nominal values, (2) excluding all values less than 0.57 m/century and (3) excluding all values less than 1.10 m/century (BYRNE *et al.*, 1982). As an example, in the second set, an accumulation of 0.45 m/century would not have been included in the calculations as the accumulation, or erosion, was less than the 0.57 m/century limit of error. An area with an accumulation rate of 0.64 m/century, however, would have been included. The nominal mass of the sediment deposited in the Virginia portion of Chesapeake Bay during the 100-year period was 2.76 × 10^9 metric tons. Table 1 presents the distribution of sand, silt, and clay at the different levels of error.

The area between the Rappahannock and Potomac Rivers was the primary locus of clay deposition. The central basin between the York River and the confluence of the channels to Tangier and Pocomoke Sounds was the region with the greatest deposition of silt. Just inside the bay mouth was the most prominent site of sand deposition, but there were secondary loci near 37°20′N latitude and on the fringes of the large shield of sand just west of Tangier Island. As the calculations of mass in Virginia did not include a compensation for shell content, they are slight over estimates.

Table 2 is a listing of the net accumulation in the entire bay and a summary of sources. Table

Table 3. *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 River Suspended sediment passed to Virginia*	—	10.7	10.7
Net bottom deposition in MD	(54.7)	(100.0)	(155.0)
Subtotal	19.3	47.7	66.7
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	60.1	72.2	132
II: Deposition in Virginia			
±0 meter	2,210	550.9	2,760
Net surplus	2,150	478.2	2,628
Multiple of Virginia source	36.8	7.6	20.9
±0.57 meter	1,691	490.0	2,181
Net surplus	1,631	417.3	2,048
Multiple of Virginia source	28.1	6.7	16.5
±1.12 meter	716.9	178.4	895.2
Net surplus	656.7	105.7	762.9
Multiple of Virginia source	11.9	2.5	6.8

*10% of SCHUBEL and CARTER (1976)

3 is a compilation of the net flux of sediment 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 the sediment within ±1.10 m of no change in bottom depth, the quantity of sediment deposited exceeds the sum of the sources by a factor of 6.8 (895 × 10^6 tons deposited versus a supply of 132 × 10^6 tons) . Eighty seven percent of that difference is sand. Using the nominal values of bottom change, the difference increases to a factor of 20.9, 132 × 10^6 tons available against 2.63 × 10^9 deposited.

DISCUSSION

In attempting to reconcile the differences between the potential sources and the quantity of sediment deposited, it becomes obvious that there are at least three potentially significant terms that are not included either as sources or sinks: (1) suspended sediment supplied by or to the tributaries other than the Susquehanna, *e.g.* the Potomac, Rappahannock, *etc.*, (2) the bed or tractive load of the these tributaries including sediment moving along the shallow banks, and (3) sand brought into the bay from the continental shelf.

There are few specific data on the net, long-term flux of material through the mouths of the tributary estuaries. OFFICER and NICHOLS (1980) noted "... in dealing with estuarine phenomena one usually is constrained by (1) an imperfect or incomplete data set, and (2) variable freshwater inflows and sediment fluxes." Nonetheless they 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 sediment to the bay. SCHUBEL and CARTER (1976) calculated that in a "typical" year the tributaries were sinks for suspended sediment derived from the bay. We are left with the question of the importance of infrequent large events, major floods, in estuarine sedimentation. Is the quantity of sediment supplied by a few major pulses great enough to reverse typical, yearly trends? Our interpretation of NICHOL's (1977) data suggests that at all conditions the flux through the upper (seaward flowing) layer of tributary estuarine circulation exceeds the flux through the upstream flowing lower layer in terms of tons of suspended sediment per tide. The question of the net contribution of suspended sediment through the tributaries is unresolved.

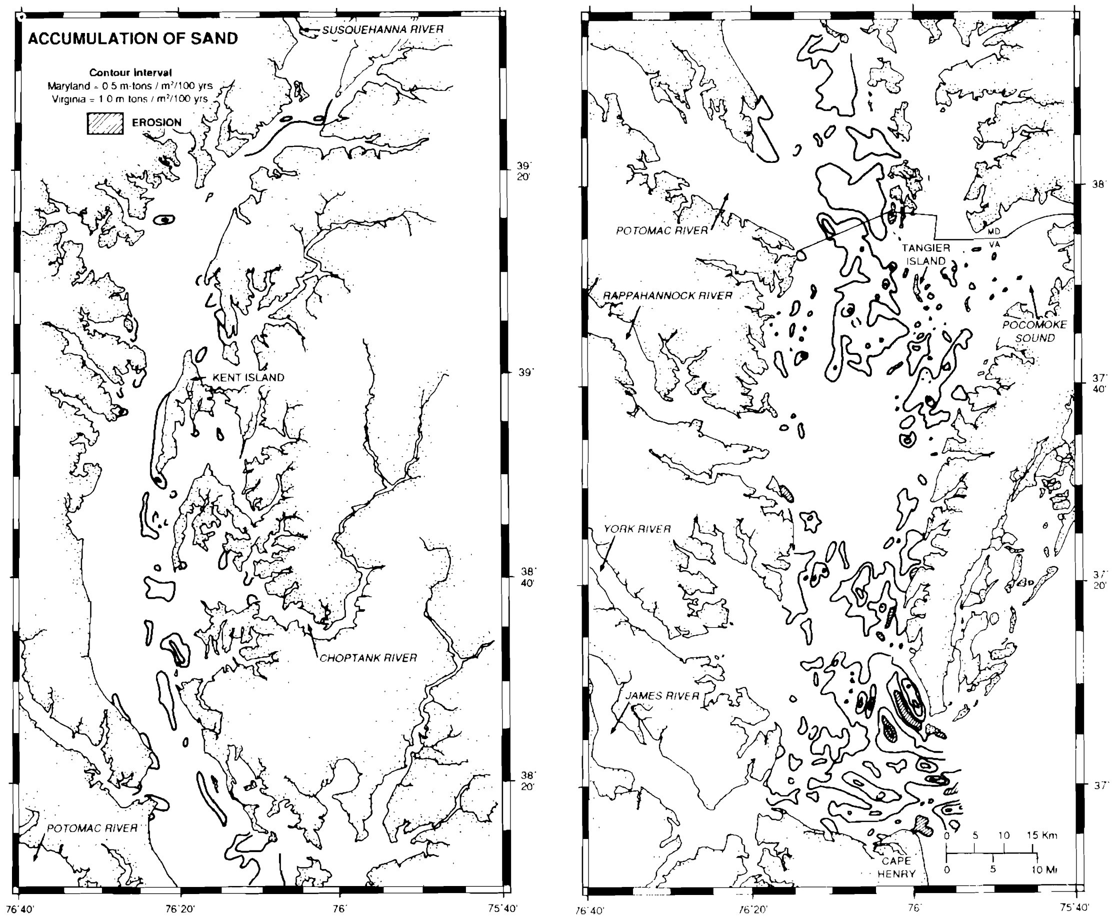

Figure 2. Map depicting the rate of deposition (metric tons per square meter per year) of sand within Chesapeake Bay.

Similarly the question of the net flux of coarser sediments in the bed load of the tributary channels is unanswered. Indeed there is less quantitative information for this problem than for the suspended sediment. Values of net flux might be impossible to determine because the difference between the upstream and downstream components might be "lost" within the limits of confidence about the measurements.

It is clear that the shallow flanks of the tributaries are sources for the main bay. The evidence is from erosion rates (Byrne and Anderson, 1977) and some is empirical, *e.g.* the lobe of sand extending into the main bay from the south shore of the Potomac.

The distribution of sediment types within the southern portion of the bay (Figure 1), when compared to the patterns of deposition, especially of sand (Figure 2), suggests that there is a large quantity of sand moving into the bay from outside the Virginia Capes. Although there are no comprehensive data on flux of other than suspended sediment there is no other proximal source and no obvious pathways from more distant potential sources. Also the work of Harrison *et al.* (1967) indicates active transportation from the shelf into the bay. Similarly work by Halka (1985) and Halka *et al.* (1985) suggests up-estuary movement of sediment. Shallow seismic work (Hobbs *et al.*, 1986; Colman and Hobbs, 1987; Colman *et al.*, 1988) indicates that there is a large body of sand in and near the bay mouth that has formed as a result of transportation of sands into the bay.

If one assumes there is significant transport into

Chesapeake Bay from the inner shelf, it becomes possible to approach a balanced sediment budget. This is done by assigning the quantity of material deposited in the southernmost bay to the "bay mouth" source.

SUMMARY AND CONCLUSIONS

Chesapeake Bay is a major depositional basin that is filling from both ends in a pattern similar to that which Roy *et al.* (1980) described in smaller Australian estuaries. The bay's largest tributary, the Susquehanna River, provides a large quantity of fine-grained sediment and the proximal continental shelf supplies vast quantities of sand and suspended sediment.

During the 100-year period ending in the mid-1950's, net deposition was between 1.05 and 2.92 $\times 10^9$ metric tons. This exceeds the sum of measurable sources by factors of 2.7 to 7.6. Most of the differences are in the sand fraction and within the southern Virginia portion of the bay. This is not unexpected as the un- or less well measured, perhaps unmeasurable sources, the bay's mouth and the sub-estuaries, open into the Virginia portion of the bay. Although the budget for sand cannot be balanced within an order of magnitude, the budget for mud can be balanced within factors of 1 to 2.4. Most of the discrepancy with sand can be accounted for with sand entering the bay through the mouth.

That estuaries fill and that they fill from both ends is no surprise. The relative magnitude of the mouth as a significant "source" of estuarine fill has not been widely known or suggested. The difficulties in assessing the role of the tributary estuaries as sources or sinks and the question of the importance of infrequent, major events versus normal conditions are problems that remain to be solved.

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□ RESUMEN □

La Bahía de Chesapeake es una cuenca deposicional que se está colmatando desde ambos extremos y los laterales. Al cabo de 100 años, en la mitad de 1950, se acumuló en la bahía, un volumen de sedimentos entre 1.0×10^9 y 2.92×10^9 toneladas métricas. El agua de la plataforma continental, fluyendo hacia la desembocadura de la bahía, es la fuente más importante de sedimentos. Una cantidad masiva de arena, entra en la bahía con esas aguas y la mueve decenas de kilómetros aguas arriba del estuario, con una depositación neta del orden del 40%. El Río Susquehanna es una fuente importante de sedimentos de granos finos, los más gruesos son entrampados por los diques. Otras fuentes de sedimentos son: la erosión costera, la producción biogénica y quizás los tributarios del estuario. Los tributarios proveen sedimentos gruesos por medio de la deriva litoral y el transporte de fondo, en las bajas profundidades cercanas a la costa, y quizás en el fondo del canal. Se desconoce la cantidad de sedimentos en suspensión suministrados por los tributarios. En realidad los tributarios pueden ser sumideros y no fuentes.—*Department of Water Sciences, University of Cantabria, Santander, Spain.*

□ ZUSAMMENFASSUNG □

Die Chesapeake-Bucht stellt einen Sedimentationsraum dar, der von beiden Enden sowie den Seiten verfüllt wird. In einem Zeitraum von ca. hundert Jahren wurden bis Mitte der 50er Jahre unseres Jahrhunderts zwischen 1×10^9 und $2{,}92 \times 10^9$ Kubiktonnen Sedimente in der Bucht abgelagert. Die Wassermassen des Kontinentalschelfes, die im Bereich der Seemündung in die Bucht gelangen, stellen die größte Einzelquelle für den Sedimenttransport in die Bucht dar. Ein erheblicher Anteil des Sandes, vielleicht bis 40% der Netto-Ablagerung, gelangt durch diese Wässer in die Bucht und wandert mehrere Zehnerkilometer ästuaraufwärts. Der Fluß Susquehanna bildet die Hauptquelle für feinkörnige Sedimente. Seine grobkörnige Sedimentfracht wird durch Dämme zur vorzeitigen Ablagerung gebracht. Weiterhin werden durch die Küstenerosion, die biologische Produktion und vielleicht tributäre Ästuare Sedimente bereitgestellt. Letztere liefern grobkörnige Sedimente durch die küstenparallele Materialverlagerung und den Bodenfracht-Transport in den küstennahen Flachbereichen und den Kanalsohlen. Das Ausmaß der suspendierten Sedimente, welche durch die tributären Ästuare geliefert werden, ist unbekannt. Es ist wahrscheinlich richtiger anzunehmen, daß diese eher Sedimentfallen als -quellen darstellen.—*Ulrich Radtke, Geographisches Institut, Universität Düsseldorf, F.R.G.*