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Chesapeake Bay nutrient budgets — a reassessment

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Abstract. Recently published annual mass balances or budgets for nitrogen, phosphorus, and silicon in Chesapeake Bay have pictured the estuary as retaining a very large fraction, perhaps all, of the nutrients that enter from land drainage, the atmosphere, and anthropogenic discharges. However, these budgets have been based on estimates of the net exchanges of nutrients at the mouth of the bay or on the rates of accumulation of nutrients and sediments calculated from the distributions of various geochemical tracers in the sediments. While conceptually straightforward, the first approach is subject to large errors because it requires the determination of a small "signal" against a large background of tidal "noise". The second approach has led to overestimates of the nutrient trapping efficiency of the bay because tracer-derived sediment deposition rates have been multiplied by the surface area of the whole bay or various parts of the bay rather than by the smaller area of active sediment deposition. This approach is also incorrect because the average, long-term rates of sediment deposition measured by the geochemical tracers, including major floods, have been compared to shorter-term records of nutrient input.

The more appropriate calculation of nutrient retention based on contemporaneous measurements of nutrient and sediment input and the chemical compositon of sediments accumulated in the estuary shows that Chesapeake Bay retains only some 3–6% of the nitrogen, 11–17% of the phosphorus and 33–83% of the silicon brought into its waters during a year in which no major flood occurred.

This behavior suggests that current problems of estuarine eutrophication are more a consequence of present nutrient inputs than an inevitable or inescapable legacy of past enrichment. It also follows that the management or manipulation of nutrient loadings to esturies may lead to a more rapid response in environmental quality than previously predicted.

Introduction

An important result of the recently completed five-year long intensive study of Chesapeake Bay sponsored by the US Environmental Protection Agency was the development of annual mass balances or budgets for nitogen and phosphorus in the estuary (Smullen et al. 1982). A related effort by D'Elia et al. (1983) produced an annual silicon budget for the bay. The remarkable feature of all three of these budgets is that they show Chesapeake Bay retaining a very large fraction, perhaps all, of the nutrients that enter the system from upland drainage, the atmosphere, and direct anthropogenic discharges. As Smullen et al. (1982) concluded, "Nearly all of the materials that enter the Bay remain there; nutrients trickle out of the Bay mouth at a very slow rate."

This finding is important for several reasons, not the least of which is that it relates to practical concerns about eutrophication and environmental quality in one of the largest and most productive estuaries in the world. Smullen et al.

[1982] emphasized this point, writing that,"The minimal flux of nutrients out of the Bay has profound implications for management . . . even if nutrient loads were drastically reduced, bay-wide improvement of water quality would be very slow." It is not surprising that this conclusion has figured prominently in the evolution of environmental policy and regulatory initiatives resulting from the EPA study (EPA 1983; Gillelan and Macknis 1983; Tippie 1984).

The degree to which estuaries such as Chesapeake Bay modify or reduce the transport of nutrients between land and sea may also be an important influence on the productivity of near-shore shelf waters and, perhaps over long periods of time, the ocean itself. Recent hypotheses concerning interactions between oceanic primary production and global climate have emphasized the potential role of estuarine and near-shore sediments in sequestering phosphorus (Broecker 1982) and nitrogen (McElroy 1983).

I have called the Chesapeake Bay nutrient budgets remarkable because they describe the overall behavior of nitrogen, phosphorus and silicon in the estuary as similar to that of sediment. While it has been known for some time that virtually all of the sediment entering Chesapeake Bay is retained or trapped in the system (Biggs 1970; Schubel and Carter 1977; Meade 1981, etc.), it would require a surprising coincidence of nature for nutrients which are so active chemically and biologically to follow the sands, silts and clays so completely. In our own studies of Narragansett Bay, for example, it appears that while essentially all of the sediment carried into the bay is trapped, only some 5% of the annual nitrogen and phosphorus input is retained in the system (Nixon et al. 1986). Similar conclusions have been reached for the Dutch Wadden Sea (Postma and Dijkema 1982).

The purpose of this note is to present a different interpretation of the data from Chesapeake Bay and to suggest that a credible argument can be made that it retains only a minor fraction of the nutrients that enter its waters. It is an argument that begins simply, then struggles through some complicating considerations to arrive at what I think is a convincing picture of Chesapeake Bay as a transporter of nutrients. It should be remembered, however, that nutrient budgets are simple only in concept. In practice, they add up and balance all of our uncertainty and ignorance as well as our knowledge. As James Johnstone cautioned in 1908, when he developed the first annual nutrient budget for a marine system, the North Sea, "It is not possible to set, in balance-sheet fashion, these receipts and outputs against each other. We know only imperfectly what are the approximate masses of nitrogen compounds in circulation."

A simple calculation

The EPA study made a serious effort to measure or estimate the delivery of nitrogen and phosphorus in all major forms from all important sources to Chesapeake Bay and its tributary estuaries. At the same time, an equal effort was made to determine the input of sediment. The results for nitrogen, pho-

sphorus and sediment are given by Smullen et al. (1982). If all of these materials are retained in the bay, it should be possible to calculate the average nitrogen and phosphorus content of the sediments found on the bottom of the bay by a simple division:

$$\text{Total N input} = 8.78 \times 10^9 \text{ moles y}^{-1} (123 \times 10^6 \text{ kg y}^{-1})$$

$$\text{Total P input} = 0.33 \times 10^9 \text{ moles y}^{-1} (10.3 \times 10^6 \text{ kg y}^{-1})$$

$$\text{Total sediment input} = 3.01 \times 10^9 \text{ kg dry weight y}^{-1}$$

$$\text{Average sediment composition} = 4.1\% \text{ N and } 0.34\% \text{ P}$$

$$\text{N:P} = 26.6 \text{ (moles) or } 11.9 \text{ (weight)}$$

Comparison of the calculated composition with the measured composition of sediments in Chesapeake Bay immediately reveals a problem with the hypothesis of complete nutrient retention (Table 1). If we take 0.25% N and 0.05% P as a rough average measured composition for sediments in the mid and upper bay where most deposition occurs (Biggs 1970), the sediments appear to contain only 6% of the nitrogen and 15% of the phosphorus required by the complete retention model.

Some of the large discrepancy between calculated and observed nitrogen content could be explained by denitrification (Boynton and Kemp 1985; Seitzinger in press), but this would also mean that the nitrogen was not trapped in the estuary. Only a small fraction of the missing nutrients could be removed from the bay in the fishery. Recent commercial landings have been between 135–225 $\times$ 10^6 kg fresh weight y^{-1} (Heinle et al. 1980) of which some 1–2% may be nitrogen. This amounts to 1–4% of the nitrogen input. The nutrients "missing" from the sediments can not be accounted for by accumulation in the water, since the increases in concentrations that have been observed in recent decades appear to be confined to tributaries and the upper bay (Heinle et al. 1980; D'Elia 1982). If the "missing" 85% of the annual phosphorus input were to accumulate in the water, it would increase the phosphorus concentration in the entire volume of the bay and tributaries (74 $\times$ 10^9 m^3, Cronin 1971) by about 4 μM y^{-1}, a very large change.

It may be objected that the measured concentrations of nitrogen and phosphorus given in Table 1 represent, for the most part, sediments collected in the mainstem of the bay, while the sediments carried by the major tributaries other than the Susquehanna River are largely deposited in the subestuaries (Schubel and Carter 1977). In order to introduce a serious error into the simple calculation, however, the sediments deposited in the tributaries would have to have an extraordinary chemical composition. Some 40% of the fluvial sediment brought into the total bay system during the E.P.A. study was carried by the Susquehanna (Smullen et al. 1982) and deposited directly in the upper and mid portions of the mainstem (Biggs 1970; Schubel and Carter). The Susquehanna River also carried over 70% of the total nitrogen and 55% of the total phosphorus (Smullen et al. 1982), yet the composition of the mainsteam mid and upper bay

Table 1. Measured composition of surface and near-surface (0–30 cm depth) sediments in various portions of Chesapeake Bay, % dry weight.

	Upper Bay (to Baltimore Harbor)		
	C	*N*	*P*
Flemer and Biggs (1971)[1]	4.2–9.6	0.16–0.20	
Boynton and Kemp (1985)[2]	4–5	0.25	0.04–0.07
Helz et al. (1985)			
surface	3.4–6.4		
	Mid Bay (to Potomac River Mouth)		
	C	*N*	*P*
Flemer and Biggs (1971)[3]	1.2–3.3	0.09–0.22	
Boynton and Kemp (1985)[4]			
mainstem	2.5	0.25	0.05
tributaries	1–2.5	0.2–0.25	0.03–0.05
Helz et al. (1985)			
surface	1.3–3.4		
	Lower Bay		
	C	*N*	*P*
Young (1968)[5]			
surface	1.05 ± 0.56	0.13 ± 0.06	0.06 ± 0.02
10 cm	1.32 ± 0.49	0.12 ± 0.06	0.06 ± 0.01
Boynton and Kemp (1985)[6]			
mainstem	1.5	0.12	0.05
tributary	1–2.5	0.05–0.25	0.01–0.03
Helz et al. (1985)			
surface	0.4–2.8		

[1] Range for 3 cores, 0–30 cm.
[2] Two cores in mainstem, values read from a graph below 10 cm.
[3] Range for 4 cores, 0–30 cm.
[4] Two cores in mainstem, one core mouth of Potomac River, one core mouth of Choptank River. Values read from a graph below 5–10 cm.
[5] Mean ± 1 S.D. for 19 cores for C and 10–14 cores for N and P.
[6] One core each from mainstem and mouth of Pocomoke River. Values read from a graph below 10 cm.

sediments, while somewhat enriched, is not at all extraordinary (Table 1). There is no reason to suppose that the chemistry of the sediments in the estuaries of the James or even the Potomac could be enriched enough to challenge seriously the constraint of the simple calculation given here.

On the contrary, the fact that virtually all of the chemical data summarized in Table 1 came from fine-grained sediments in relatively deep water may overestimate the nutrient trapping capacity of the bay (J.C. Stevenson, personal communication). Biggs (1970) described silt and clay sediments as characteristic of the bottom in water depths greater than 5 m, with sand-sized erosion products which hold less nitrogen and phosphorus remaining in the inshore zone. Since the mean depth of the bay and its tributary estuary is only 6.5 m (Cronin 1971),

a considerable area of the bottom may have lower concentrations of nutrients than suggested by Table 1.

It is likely that the coarser sediments are largely derived from shore erosion in the upper and mid bay and from the ocean in the lower bay (Biggs 1970; Shubel and Carter 1977; Officer et al. 1984). While these sources may provide a considerable amount of material ($0.82 \times 10^9 kg\,y^{-1}$ according to Schubel and Carter 1977 or 27% of the fluvial input reported by Smullen et al. 1982), it is not known how much nitrogen, phosphorus or silica they already carry adsorbed on their surfaces when they enter the bay. It seems unlikely that the coarse materials serve as a major repository for nutrients draining from the watershed and I have not included them in the simple calculation based on fluvial sediment accumulation. Most of the deposition of fluvial sediments occurrs in the deeper areas where the nutrient measurements have been made.

The Upper Bay

It is possible to reduce some of the uncertainties involved in the analysis of the whole bay by applying the same calculation to just the mid and upper bay region. As noted earlier, studies by Biggs (1970) and Schubel and Carter (1977) have shown that virtually all of the sediment carried by the Susquehanna River is discharged directly into the main stem of the bay and deposited in the area above the mouth of the Potomac River. During the period of the EPA assessment, Smullen et al. (1982) reported that the Susquehanna carried $1.2 \times 10^9 kg\,y^{-1}$ of fine-grained sediment into the bay. During the same period, the input of total phosphorus and nitrogen into the upper bay from the river, from point sources in the upper bay and Delmarva drainage basins and from the atmosphere came to $140 \times 10^6 moles\,y^{-1}$ ($4.36 \times 10^9 kg\,y^{-1}$) of P and $4.92 \times 10^9 moles\,y^{-1}$ ($68.4 \times 10^6 kg\,y^{-1}$) of N. Combining the inputs and assuming complete retention gives a sediment composition of 0.36% P and 4.7% N. Again, the measured concentrations (Table 1) are only a small fraction of the calculated values (10–15% for phosphorus and about 5% for nitrogen).

Using the same methods as Smullen et al. (1982), D'Elia et al. (1983) calculated an input of H_4SiO_4—Si from the Susquehanna River of $1.76 \times 10^9 moles\,y^{-1}$ ($49.3 \times 10^6 kg\,y^{-1}$). Complete retention of silicon would require the sediments to have a composition of 4.1% Si, while D;Elia et al. (1983) measured values of 1–2.5% biogenic silica in upper and mid bay sediments, respectively.

The message in the mud seems clear—the sediments of Chesapeake Bay are not a strong sink for nutrients. But if most of the phosphorus and nitrogen and a large portion of the silicon that enters the bay eventually passes on to the coastal ocean (and for nitrogen, the atmosphere), why did Smullen et al. (1982) and D'Elia et al. (1983) conclude that most of the nutrients were retained? The answer lies in the different approaches used to obtain their budgets.

Box models and measurements at the Bay Mouth

Instead of trying to measure directly the amount of nitrogen and phosphorus accumulating in the bay, Smullen et al. (1982) tried to determine the net loss of nutrients at the bay mouth. In theory this is an appealing and direct approach and the retention in the bay (at least for phosphorus) can be obtained as the difference between the measured inputs and outputs. While Smullen et al. (1982) had available an extensive 38 day empirical study of water and nutrient exchanges at the mouth of the bay, and a large data set on nutrient concentrations over an annual cycle in the lower bay, I think the difficulty of measuring and numerically modeling small instantaneous net fluxes against a large background transport of water and nutrients led them to the erroneous conclusion that there was little or no export of nutrients. The problems involved in measuring and modeling net exchanges in much smaller tidal systems have been described by Boon (1978), Kjerfve and Proehl (1979) and others. In spite of the unequivocal wording of their conclusion, Smullen et al. (1982) were aware of the uncertainty of this term in their budget. As they put it, "It should be clear . . . that our understanding of transport through the Bay mouth is still quite rudimentary."

Sediment cores and geochemical tracers

In addition to the direct measurement of sediment inputs, the rate of net sediment accumulation in different parts of Chesapeake Bay has also been estimated by using the distribution of various geochemical tracers (^{210}Pb, ^{137}Cs, ^{239,240}Pu) with depth in sediment cores (Goldberg et al. 1978; Hirschberg and Schubel 1979; Helz et al. 1985). Officer et al. (1984) have recently reviewed the data obtained from some 30 cores distributed along the length of the bay.

By multiplying tracer-derived sediment mass deposition rates per unit area by the measured concentrations of nutrients at depth in the sediments, D'Elia et al. (1983) and Boynton and Kemp (1985) calculated high burial rates for silicon, nitrogen and phosphorus in various parts of the bay. When multiplied by the area of the bay and compared to the measured rate of nutrient input, these high burial rates make the bay appear to be a strong nutrient sink.

The situation is not simple, however, and an interesting problem arises in comparing the mass sediment deposition rates arrived at by the analysis of chemical tracers with the supply available for deposition according to measurements of sediment input. When the different types of measurement are expressed in common units, it is apparent that the geochemical tracer rates are many times greater than the sediment input measured by Biggs (1970), Schubel and Carter (1977) and Smullen et al. (1982) (Table 2).

This discrepancy has been noted before e.g., Hirschberg and Schubel 1979, and attributed to the different time-scales involved in the two approaches. While the sediment input measurements such as those reported by Smullen et al. (1982) cover a period of a year or two, the tracer profiles yield rates that may be

Table 2. Estimates of net mass sediment accumulation rates in various portions of Chesapeake Bay. Units are g dry wt $cm^{-2} y^{-1}$. The first three studies involved measurements of sediment inputs while the last three are based on the distribution of geochemical tracers in sediment cores.

	Upper Bay	Mid Bay	Lower Bay	Total Bay
Schubel and Carter (1977)[1]				0.03
(including tributaries)				(0.02)
Biggs (1970)[2]	0.13	0.04		
Biggs (1970)[2*]	0.07	0.02		
Smullen et al. (1982)[3]	0.14			0.03
Officer et al. (1984)[4]	0.43	0.16		0.23
ranges	0.13–1.2	0.1–0.3	0.1–0.8	
D'Elia et al. (1983)[5]	0.50	0.04	0.05	
Boynton and Kemp (1985)[6]	0.38	0.06		

[1] Based on sediment inputs for 1969–1970 and a simple transport model. I have divided Schubel and Carter's depositon values by the surface areas given by Cronin (1971) (see Table 3).

[2] Based on sediment inputs for 1966 divided by Biggs' (1970) surface area estimates.

[2*] Sediment inputs from 1966 recalculated using Cronin's (1971) surface area estimates (see Table 3).

[3] I have divided the author's total fluvial sediment input (measured in the three largest rivers between Jan. 1979 and Apr. 1981 and in five next largest tributaries between June 1969 and Aug. 1970) by Cronin's (1971) surface area for the entire bay and tributaries. If Schubel and Carter's (1977) estimates of shore erosion and ocean input are included, the deposition increases from 0.026 to 0.033 g $cm^{-2} y^{-1}$. The value for the upper bay was calculated by using only the Susquehanna River input from Smullen et al. (1982) and Cronin's surface area estimate for the upper bay. Inclusion of upper bay shore erosion (Schubel 1968) would increase this result from 0.14 to 0.17 g $cm^{-2} y^{-1}$.

[4] Mean values from nonlinear estimation of optimum mass sedimentation rates using various published geochemical tracer profiles in sediments at 30 locations along the length of the bay. The authors consider these values averages over a 40–100 year period.

[5,6] Based on some of the same data used by Officer et al. (1984) and the authors sediment density measurements.

averaged over 40–100 years or more (Officer et al. 1984). Since Chesapeake Bay is subjected to periodic strong floods which can deliver very large amounts of sediment, it is thought that these flood deposits sharply increase the long-term average sedimentation rate calculated from tracer distributions (Hirsberg and Schubel 1979; Officer et al. 1984).

An excellent example of such episodic sedimentation appears to have been Hurricane Agnes, a storm accompanied by flooding of such great intensity that the Susquehanna River discharged more than 31×10^9 kg of material to the upper bay in the ten-day period between 21–30 June, 1972 (Schubel 1977). This is over 25 times the total annual sediment discharge from the Susquehanna reported by Smullen et al. (1982). In August following the storm, cores collected over a large area in the middle of the upper bay revealed a distinct sedimentary layer some 10–30 cm thick and containing approximately 13×10^9 kg of sediment (Schubel and Zabawa 1977). Additional sampling over the year showed that this layer gradually became less recognizable as bioturbation and resuspension mixed the sediments.

It is possible to compare the tracer-derived deposition rates with a longer-term estimate of sediment input if we restrict the analysis to the upper and middle portions of Chesapeake Bay above the Potomac River mouth (Officer et al. 1984). For this part of the bay, the Susquehanna River is the major source of sediment, and Gross et al. (1978) provide data on sediment discharge from the Susquehanna from 1966 to 1976, including tropical storm Agnes. In making this comparison, Officer et al. (1984) inadvertently demonstrated an important limitation on the use of dated cores. These authors multiplied their calculated mean sediment deposition rates for the upper and mid bay (Table 2) by the surface area estimates of Biggs (1970) (Table 3) and arrived at a total long-term deposition of 3.1×10^6 metric tons per year. They concluded that this value was "in reasonable agreement with the total source budget figure of 2.6 million metric tons per year" that they estimated from Gross et al. (1978) for the Susquehanna (2×10^6 t) and from Biggs (1970) for shore erosion (0.6×10^6 t).

The problem with this "agreement" is that it rests on a calculation which is sensitive to the total surface area over which the deposition rate is assumed to apply, and the estimates given by Biggs (1970) are much smaller than reported

Table 3. Various estimates of the surface area of different portions of Chesapeake Bay. Values in ( ) include tributaries and embayments.

	Surface Area, $m^2 \times 10^9$			
	Upper Bay	Mid Bay	Lower Bay	Total
Biggs[1]	0.44	0.75		
Cronin (1971)[2]	0.81	1.66	4.02	6.5
	(0.88)	(2.81)	(7.74)	(11.5)
Burger (1982)[3]				5.8
				(11.3)
D'Elia et al. (1983)				5.8
				(9.3)
Kemp et al. (1984)[4]		(1.5)		
Helz et al. (1985)	0.84	2.30	4.30	7.4
NOAA (1985)				(9.9)

[1] Upper Bay region shown as extending from the mouth of the Susquehanna River to the southern side of Baltimore Harbor. Mid-Bay described as the region between the Upper Bay and the northern side of the Potomac River mouth.

[2] Boundaries similar to those of Biggs. I have set the lower Bay to include Cronin's segments 0–70; mid-Bay to include segments 70–130; and upper Bay to run from segment 130 to Port Deposit.

[3] Modified Cronin's analysis to conform to the EPA Chesapeake Bay Program segmentation scheme. He reports total area as rounded to $11 \times 10^9 m^2$, but his mainstem and tributaries sum to $11.3 \times 10^9 m^2$.

[4] Kemp et al. (1984) describe their value as including the mainstem and tributaries above the Potomac River mouth. This is approximately the same boundary used by Biggs and Cronin for the combined upper and mid Bay.

by Cronin (1971) in his detailed analysis of area and depth distributions in Chesapeake Bay. While the discrepancy is particularly large for Bigg's estimates, anyone attempting to develop mass balances must deal with a disconcerting elasticity in the reported sizes of various parts of Chesapeake Bay (Table 3) and other estuaries (for example, see Pilson (1985) for Narragansett Bay).

If the larger, and presumably correct, mainstem areas given by Cronin (1971) are used, the mean deposition rates of Officer et al. (1984) produce a total long-term mean deposition of 6.14×10^6 metric tons per year, a value 2.4 times larger than the best estimate of long-term sediment input, including floods.

The picture is not as neat as it first appeared, but it is instructive. If we accept the sediment input from Gross et al. (1978), the mean mass-deposition rates of Officer et al. (1984) and the surface areas from Cronin (1971) as being approximately correct, the most reasonable interpretation is that it is not appropriate to apply the deposition rates from cores to a large geographical area. Unless they are multiplied by the much smaller areas of active deposition, perhaps approximated by the area covered by fine-grain sediment (for example, Santschi et al. 1984 for Narragansett Bay), the tracer-derived burial rates will lead to a large overestimate of total sediment and nutrient trapping. While this is true of all estuaries, it may be particularly important in Chesapeake Bay, where the substrate characteristics vary with water depth (Reinharz and O'Connell 1981) and the bay bottom consists of very broad shallows and a deep channel.

Episodic Inputs and the Calculation of Annual Nutrient Budgets

Even if the appropriate depositional areas for the various parts of the bay were known and used with the long-term, tracer-derived deposition rates, it would not be correct to compare the nutrient burial rate calculated from those numbers with the nutrient input measured over a short period that did not include the episodic events captured in the sediment. The sediments carried into the bay during floods are derived largely from erosion of the upstream riverbeds where they have rested for a long enough time to reach some equilibrium with overlying nutrient-rich river water. For example, Hirshberg and Schubel (1979) have estimated that the riverbed residence time of sediments eroded from the bottom of the Susquehanna and carried into the bay during tropical storm Agnes was at least 16 years, or 40% of the time elapsed since the previous major flood in 1936. In addition to the nutrients found on their surfaces, the flood-driven sediments come into the bay with large amounts of dissolved nutrients and nutrients incorporated in particulate organic matter (Lang 1982). Since no long-term (including floods) record of total nutrient input appears to be available, the long-term sediment accumulation rate should not be used to calculate the nutrient retention efficiency of the bay. Even the long-term sediment input record presented by Gross et al. (1978) can not be used with nutrient concentrations on sediments buried in the mid and upper bay to calculate a nutrient burial

rate that can be compared meaningfully to the single annual inventory of upper bay nutrient inputs given by Smullen et al. (1982).

The only documented and approximately contemporaneous record of total nutrient and sediment input to Chesapeake Bay that I have found is that obtained by the EPA project and reported by Smullen et al. (1982). The simple calculation given in the beginning of this paper and using those data clearly shows that under the conditions which prevailed during the time of EPA study, Chesapeake Bay retained only a small fraction of the nutrients that entered the system.

Calculation of the actual amount retained is more tenuous and requires assumptions regarding the concentrations of nutrients on the sediments that are buried. Because of biomixing and resuspension this could be a complex problem in a system where nutrient inputs have been increasing. Fortunately, once one gets below the surface 5–10 cm, profiles of nutrient concentrations with depth in the sediment appear to be remarkably constant in much of Chesapeake Bay (Boynton and Kemp 1985), Narragansett Bay (Nixon and Pilson 1984), and, presumably, other coastal areas. The interpretation of this behavior is that the surficial sediments are enriched with recently deposited material which is being rapidly mixed and decomposed (Kelly and Nixon 1984). With the exception of some cores in lower Chesapeake Bay, the mixed layer depths indicated by radio-tracers are in agreement with this interpretation (Officer et al. 1984).

If virtually all of the labile organic matter reaching the bottom has been consumed on and within the sediment and the available nutrients released within a few years (Garber 1982; Kelly and Nixon 1984), it seems acceptable to follow the common procedure of using the background nutrient concentrations below the mixed layer in calculating a burial rate (D'Elia et al. 1983; Boynton and Kemp 1985; Nixon et al. 1986). The fact that different areas of the bay also differ in background nutrient concentrations (Table 1, D'Elia et al. 1983) complicates the situation, however, and increases the uncertainty of the calculations. If we assume that most of the fluvial and anthropogenic nutrient input that is buried accumulates in fine-grained sediments with a composition similar to those of the middle and upper mainstem of the bay (Table 1 for N and P and D'Elia et al. 1983 for Si), a concentration range of 0.15–0.25% N, 0.05–0.075% P, and 1–2.5% Si is reasonable. Combined with the sediment input of Smullen et al. [1982], this suggests an accumulation range of:

$$N = 320\text{–}535 \times 10^6 \text{moles y}^{-1} \ (4.5\text{–}7.5 \times 10^6 \text{kg y}^{-1})$$

$$P = 48.4\text{–}72.9 \times 10^6 \text{moles y}^{-1} \ (1.5\text{–}2.26 \times 10^6 \text{kg y}^{-1})$$

$$Si = 1.1\text{–}2.7 \times 10^9 \text{moles y}^{-1} \ (30.1\text{–}75.2 \times 10^6 \text{kg y}^{-1})$$

During the approximately same period nutrient inputs according to Smullen et al. (1982) and D'Elia et al. (1983) amounted to:

$$N = 9857 \times 10^6 \text{moles y}^{-1} \ (138 \times 10^6 \text{kg y}^{-1})$$

$$P = 442 \times 10^6 \text{moles y}^{-1} \ (13.7 \times 10^6 \text{kg y}^{-1})$$

$$Si = 3.23 \times 10^9 \text{ moles } y^{-1} (90.4 \times 10^6 \text{ kg } y^{-1})$$

Expressed as a per cent of the annual input, the accumulation within the bay was on the order of 3.3–5.4% for nitogen, 10.9–16.5% for phosphorus and 33–83% for silicon. It is not surprising that the relative amount of retention among the three elements should be in this order since nitrogen is lost from the bay through denitrification as well as by flushing to the ocean and the dissolution of silica is neither as fast nor as complete as the biological regeneration of nitrogen and phosphorus.

Implications of the revised budgets

The fact that Chesapeake Bay is not a strong sink for nutrients, especially nitrogen and phosphorus, suggests that eutrophication problems currently seen in the bay are more a consequence of recent rates of nutrient input than the legacy of decades of accumulation. It also suggests that estuaries do not necessarily become more eutrophic as they "age", or at least that they age geologically (fill in) at a faster rate than they age ecologically (become eutrophic).

A particularly encouraging implication of this revised assessment of nutrients in the bay is that the response of the system to changes in nutrient loading should be much more rapid than suggested by the E.P.A. study. It is probably not correct that, "even if nutrient loads were dramatically reduced, Bay-wide improvement of water quality would be very slow. It would take many years for the accumulated mass of nutrients to leave the system" (Smullen et al. 1982). Moreover, it is not clear that the slow response time predicted by EPA would follow even if the sediments of the bay were a strong sink for nutrients. If large amounts of nitrogen and phosphorus remain tightly bound and buried in the sediment, they may have little influence on events in the overlying water. For example, while it has been estimated that over 90% of the total phosphorus entering Lake Erie in 1970 was retained in the lake (Burns et al. 1976), a reduction in phosphorus input of about 50% between 1970 and 1980 was accompanied by a marked decrease in total phosphorus concentrations in the lake waters (Burns 1985).

That coastal marine systems respond rapidly to increase and decreases in nutrient loading with little long-term "memory" or accumulation is also supported by the results of two experiments carried out using the large ($13\,m^3$) mesocosms at the Marine Ecosystems Research Laboratory (MERL) at the University of Rhode Island. In the first of these, polluted, nutrient-rich sediments from upper Narragansett Bay were exposed to the relatively much cleaner and lower-nutrient waters near the mouth of the bay. After five months, Oviatt et al. (1984) found the mesocosms with polluted sediments to be much more like systems containing sediments from mid-bay or Rhode Island Sound than they were like the upper bay area. They concluded that, ". . . new pollutants dictate environmental conditions much more strongly than old pollutants trapped in sediments."

In the second MERL experiment, different amounts of inorganic nutrients (N, P, Si) were added to a series of mesocosms for over two years. While the systems responded quickly (and in some cases dramatically) to the enrichment (Nixon et al. 1984), there was little long-term accumulation of nutrients or organic matter in the tanks (Nixon et al. in press). The MERL mesocosms are run as open systems with a water exchange rate of 3–4% day^{-1}, and most of the nutrients were flushed from the tanks and, for nitrogen and carbon, lost to the atmosphere. Only a small fraction of the nutrient inputs accumulated in the sediments.

This exercise began with a cautionary quotation from James Johnstone, and I have forgotten it. But if the evidence and conclusions given here are correct, there is a hopeful message for management in the "humble muds" of Chesapeake Bay and Narragansett Bay. If the eutrophication of our estuaries is not a problem we have inherited from past practices, it is also not one that we must pass on to future generations.

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