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Inputs, Transformations, and Transport of Nitrogen and Phosphorus in Chesapeake Bay and Selected Tributaries

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ABSTRACT: In this paper we assemble and analyze quantitative annual input-export budgets for total nitrogen (TN) and total phosphorus (TP) for Chesapeake Bay and three of its tributary estuaries (Potomac, Patuxent, and Choptank rivers). The budgets include estimates of TN and TP sources (point, diffuse, and atmospheric), internal losses (burial in sediments, fisheries yields, and denitrification), storages in the water column and sediments, internal cycling rates (zooplankton excretion and net sediment-water flux), and net downstream exchange. Annual terrestrial and atmospheric inputs (average of 1985 and 1986 data) of TN and TP ranged from 4.3 g TN m^{-2} yr^{-1} to 29.3 g TN m^{-2} yr^{-1} and 0.32 g TP m^{-2} yr^{-1} to 2.42 g TP m^{-2} yr^{-1}, respectively. These rates of TN and TP input represent 6-fold to 8-fold and 13-fold to 24-fold increases in loads to these systems since the precolonial period. A recent 11-yr record for the Susquehanna River indicates that annual loads of TN and TP have varied by about 2-fold and 4-fold, respectively. TN inputs increased and TP inputs decreased during the 11-yr period. The relative importance of nutrient sources varied among these estuaries: point sources of nutrients delivered about half the annual TN and TP load to the Patuxent and nearly 60% of TP inputs to the Choptank; diffuse sources contributed 60–70% of the TN and TP inputs to the mainstream Chesapeake and Potomac River. The direct deposition of atmospheric wet-fall to the surface waters of these estuaries represented 12% or less of annual TN and TP loads except in the Choptank River (37% of TN and 20% of TP). We found direct, although damped, relationships between annual rates of nutrient input, water-column and sediment nutrient stocks, and nutrient losses via burial in sediments and denitrification. Our budgets indicate that the annual mass balance of TN and TP is maintained by a net landward exchange of TP and, with one exception (Choptank River), a net seaward transport of TN. The budgets for all systems revealed that inorganic nutrients entering these estuaries from terrestrial and atmospheric sources are rapidly converted to particulate and organic forms. Discrepancies between our budgets and others in the literature were resolved by the inclusion of sediments derived from shoreline erosion. The greatest potential for errors in our budgets can be attributed to the absence of or uncertainties in estimates of atmospheric dry-fall, contributions of nutrients via groundwater, and the sedimentation rates used to calculate nutrient burial rates.

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Introduction

During the last several decades, eutrophication of coastal environments has become a common phenomenon that is likely to intensify because of continued population growth along coastal margins (Nixon 1990). Loss of seagrass communities, occurrences of persistent algal blooms, development of hypoxic and anoxic conditions in deeper waters and declines in commercially and recreationally valuable species are typically associated with eutrophying systems, although the cause and effect linkages for some of these manifestations are not well understood (Kemp et al. 1983).

Degradation of these productive environments has stimulated the development of many monitoring and research programs designed to assess environmental conditions, detect trends and serve as a basis for implementing nutrient control programs (National Research Council 1990). As a result, large amounts of descriptive (e.g., nutrient concentrations) and process-oriented (e.g., rates of nutrient inputs and losses) data have become available for some systems, including portions of Chesapeake Bay. However, much of this information has been interpreted in terms of relatively narrow issues. From these sources it is difficult to gain a broad understanding of how nutrients influence coastal systems on the one hand and how, on the other hand, estuarine dynamics influence the fate of nutrients as they are transported from the land to the sea. Larger scale analyses are needed to improve our understanding of these issues. The construction and evaluation of nutrient budgets at the scale of whole ecosystems provides a conceptual framework from which to gain such a perspective. The type of budget considered here includes all major inputs, storages, and loss terms for annual time periods. Despite the potential utility of this approach, relatively few budgets have been developed that explicitly consider all major inputs and losses (e.g., Dutch Wadden Sea, Postma and Dijkema 1983; Baltic Sea, Larsson et al. 1985; Narragansett Bay, Nixon et al. 1986a). However, this situation may be changing because of increasing pressures to develop reasonable nutrient reduction plans to rehabilitate overly enriched systems and because more data are becoming available that are useful in constructing nutrient budgets (e.g., National Oceanographic and Atmospheric Administration/United States Environmental Protection Agency 1989).

The Chesapeake Bay is a large estuarine complex, having both a clearly defined mainstem and numerous tributary subsystems. Some of these subsystems exhibit characteristics typical of eutrophic estuaries, while others range from occasionally eutrophic in years of exceptionally high riverine nutrient loading to mesotrophic during periods of drought (United States Environmental Protection Agency 1983). Beginning in 1984 a long-term monitoring program was initiated in Chesapeake Bay for purposes of better characterizing current conditions and detecting trends in water quality, habitat conditions, and living resources that may develop in response to management actions (Maryland Department of the Environment 1987). As a result of these and other initiatives, much of the information needed to construct well-constrained nutrient budgets is now available. Several nutrient budgets have been developed previously for Chesapeake Bay (Smullen et al. 1982; Nixon 1987; T. Fisher et al. 1988). Each of these analyses employed a different approach and reached very different conclusions regarding the fate of nutrients in this system. It now seems possible to resolve some of these conflicts using recently improved datasets.

The overall goal of this work is to develop detailed budgets of nitrogen and phosphorus for selected tributary subsystems of Chesapeake Bay and for the full bay system using recent data for nutrient inputs, losses, storages, and recycling. Within the context of this analysis we have selected subsystems that have experienced different nutrient loading rates over the last several decades to investigate how estuaries exposed to different loading and water-quality conditions process nutrients as they are transported from the land to the sea. Several temporal perspectives are also considered including a recent 11-yr period and the pre-European settlement period when the watershed was in a pristine condition.

Conceptual Approach and Data Sources

Conceptual Approach

A conceptual model was used to guide development of TN and TP budgets (Fig. 1). This model represents a compromise between current understanding of major inputs, exports, storages, and cycling of TN and TP in Chesapeake Bay and the availability of data with which to evaluate model terms. This model considers three classes of nutrient inputs, four loss terms (three in the case of TP), eight storage categories, and four pathways of nutrient cycling.

Three classes of nutrient inputs, which are shown along the left and top sides of the diagram, include point, diffuse, and atmospheric sources. The designations AFL and BFL refer to above and below hydrologic fall-lines, respectively. This delineation provides spatial information with potentially important management implications. Atmospheric

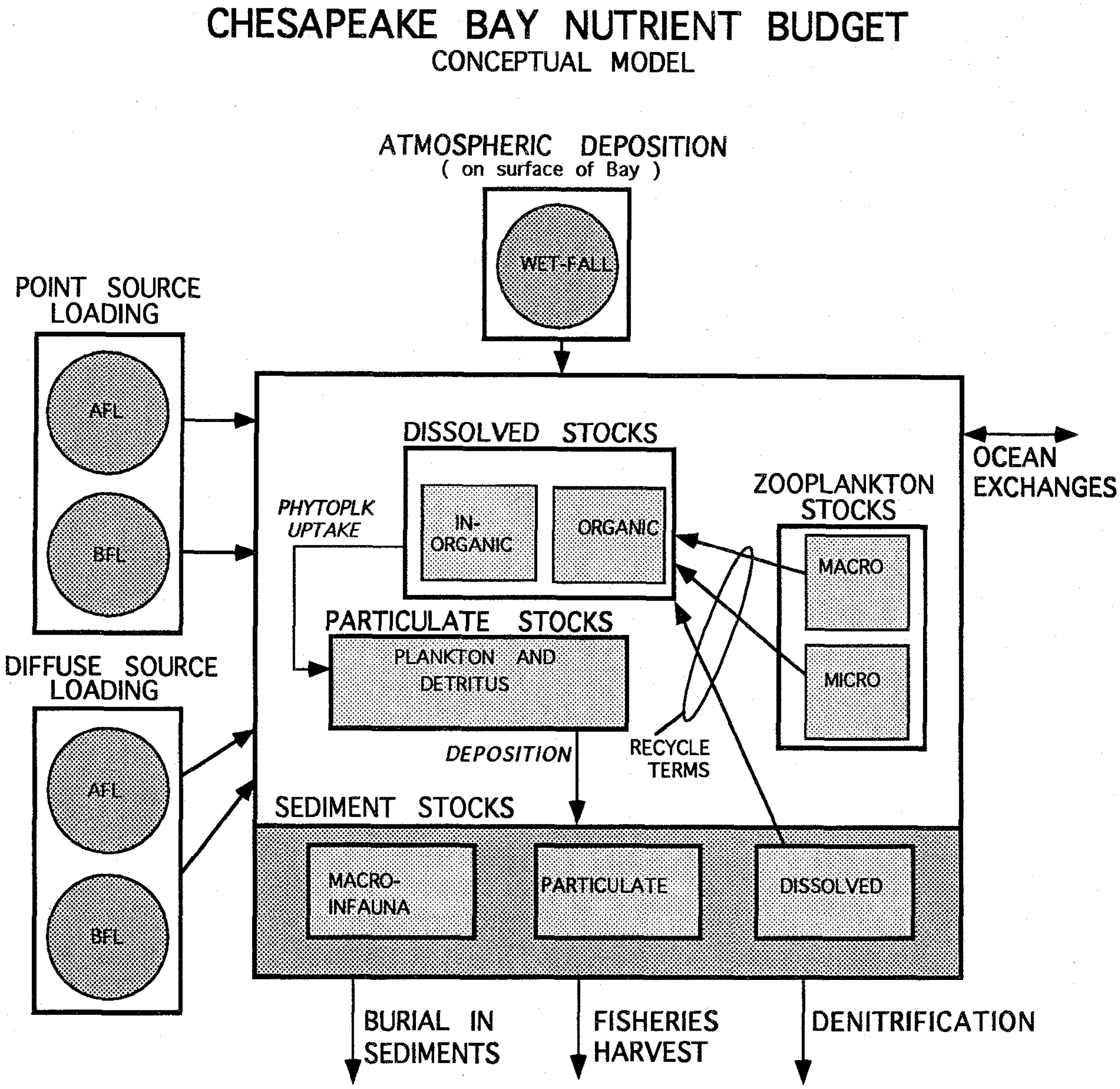


Fig. 1. A schematic diagram of nutrient budgets. Nutrient sources, storages, recycle pathways, internal losses, and exchanges across the seaward boundary are indicated. The pathways labeled in italics were not evaluated but were included in the diagram for completeness. The designations AFL and BFL refer to above and below hydrologic fall-lines, respectively. Further description of components of the budget is provided in Table 1.

deposition includes only wet-fall to surface waters of the estuaries; implications of dry-fall are qualitatively considered. That fraction of atmospheric deposition of N and P to watersheds that reaches streams is included in the AFL and BFL diffuse source terms (D. Fisher et al. 1988). Nutrients associated with groundwater entering streams draining into the bay were accounted for in the diffuse source terms. However, groundwater seepage of nutrients directly into waters of the bay was not evaluated because of a lack of information. Nitrogen fixation also was not evaluated for the same reason but is probably a small source as is the case in most nutrient-rich estuarine systems (Howarth et al. 1988).

Loss terms include burial of TN and TP in sediments in depositional portions of study areas, denitrification of N in sediments, fisheries harvests (recreational and commercial yields), and net exchanges of N and P at the downstream boundary of each study area. We recognize that a term should be included for the net growth (i.e., accu-

TABLE 1. A description of primary variables, data sources, measurement techniques, measurement frequencies and duration of data record. Entries in the table correspond to variables indicated in the conceptual model (Fig. 1); additional information is included here that is not shown in the conceptual model but that was used in developing these budgets.

Variable Name	General Description	Measurement Frequency	Duration of Record	Measurement Technique	Data Sources
Study site areas and volumes	Estimates of the volume (m^3) and surface areas (m^2) of the study sites. Specific areas and volumes included are indicated in the text and tables.	NA	NA	Based on USGS series 500 charts. Areas and volumes calculated on 1 nautical mile intervals.	Cronin and Pritchard 1975
Point source loading	Includes all major (>10^6 gpd) point discharges of TN and TP. Reported as entering above fall-line (AFL) or below fall-line (BFL).	Volume ~ continuous Concentration ~ weekly–monthly	>1 yr	Standard flow gauges and wet chemical techniques. Some concentrations estimated indirectly based on level of treatment.	United States Environmental Protection Agency 1982; Summers 1989
Diffuse source loading	Above fall-line diffuse sources were directly measured in the Patuxent, Potomac, Choptank and Susquehanna rivers. Below fall-line values were based on an algorithm that adjusted AFL loads to land-use and size of BFL areas.	River flow ~ continuous Concentration ~ weekly; measurements were flow-weighted.	1984–1990	Standard flow gauges and wet chemical techniques. Automatic flow-regulated samplers used at most sites.	Summers 1989
Atmospheric deposition (wet-fall only)	Estimates of TN and TP (wet-fall) directly to the surface of bay waters. Wet-fall collections were made at seven locations adjacent to the bay. Rainfall estimates were from southern, mid, and northern bay locations.	Rainfall ~ continuous Concentrations measured for many significant rainfall events.	1976–1981	Standard rain gauges and wet chemical techniques.	United States Environmental Protection Agency 1982; Summers 1989
Burial in sediments	Estimate of the rate of permanent burial of particulate nitrogen and phosphorus in accreting sediment column. Dissolved stocks were relatively small and were not included.	Estimates of PN and PP stocks from four sources collected between 1980 and 1988. Deposition rates measured occasionally since 1977.	NA	Deposition rates: ^{210}Pb ^{7}Be, pollen and sediment budget techniques. Sediment composition: box coring, 1-cm slicing, followed by standard chemical analyses. Depositional areas determined from 1-km^2 grid sediment sampling for the mainstem bay.	Kerhin et al. 1983; Halka personal communication; Brush 1984a, b; Brush et al. 1982; Boynton and Kemp 1985; Cornwell personal communication; Boynton et al. 1990; Officer et al. 1984; Dibbs 1988
Denitrification	Estimate of sediment denitrification; water-column rates were assumed to be negligible.	Monthly to seasonal	Occasional from 1984–1988	15N–N2 production, acetylene blockage technique, mass balance	Jenkins and Kemp 1984; Twilley and Kemp 1987; Kemp et al. 1990
Fisheries harvest	Includes the annual TN and TP content of fish and shellfish removed from each study area via commercial and recreational fishing. Potential losses due to emigration were not included.	Annual estimates	1985 and 1986 records used	Records collected by state agencies for commercial catch; recreational catch estimated by Maryland Department of Natural Resources staff.	Maryland Department of Natural Resources 1989; National Marine Fisheries Service 1991
Ocean exchanges	Estimate of the annual net exchange of TN and TP across the downstream boundary of each study area.	NA	NA	Estimated by difference between terrestrial and atmospheric inputs and internal losses	This study

TABLE 1. Continued.

Variable Name	General Description	Measurement Frequency	Duration of Record	Measurement Technique	Data Sources
Dissolved and particulate stocks	Dissolved stocks include all forms of dissolved N (NH_4, NO_2, NO_3, DON) and P (DIP, DOP) in the water column. Particulate stock included both living and dead material in the water column and was measured as PN and PP.	Bi-weekly spring–fall; monthly in winter. Total of 78 stations sampled in MD mainstem and tributaries.	1984–1990	From 1 to 5 samples taken depending on depth. Chemical analyses using standard oceanographic techniques.	Magnien et al. 1990
Sediment stocks	These stocks were considered in three categories. Particulate and dissolved stocks are estimates of the mass of total dissolved and particulate N and P in sediments to a depth of 5 cm. Macroinfaunal stocks represent the N and P content of the biota.	Occasional estimates of PN, PP concentrations from 1980 to 1988. Benthic stock measured quarterly–monthly.	1975–1990	Sediment composition: box coring, 1-cm slicing, followed by standard chemical analyses. Infauna sampled using a variety of cores and grabs.	Boynton and Kemp 1985; Boynton et al. 1990; Holland et al. 1989
Zooplankton stocks	Annual average stock of macro (>500 μm) and microzooplankton (<500 μm) expressed as N and P content.	Biweekly spring–fall; monthly in winter. Total of 16 stations sampled in the Maryland mainstem and tributaries.	1984–1990	Macrozooplankton sampled using 500 μm mesh net; vertical oblique tows. Microzooplankton sampled using high volume pump; vertically integrated pump samples.	Jacobs 1989; Sellner et al. 1989
Recycle terms	Three recycle terms were evaluated: net sediment-water fluxes of N and P; and excretion rates of N and P from macrozooplankton and microzooplankton.	As per zooplankton sampling frequency; benthic flux sampling weekly–seasonal	1984–1990	Zooplankton excretion rates calculated based on biomass and temperature at the time of sampling. Sediment net fluxes based on incubation of intact sediment cores.	Jacobs 1989; Brownlee personal communication; Boynton et al. 1990
Phytoplankton nutrient uptake	Estimated annual phytoplankton demand for N and P based on ^{14}C measurements of primary production converted to N and P equivalents.	Biweekly spring–fall; monthly in winter. ^{14}C production measured at 16 stations in Maryland mainstem and tributaries.	1984–1990	Calculation based on assumed Redfield Ratio of 106:16:1 for composition of phytoplankton.	Sellner et al. 1989

mulation of TN and TP) of fish populations that seasonally migrate into the bay when individuals are small, grow rapidly and then migrate from the system. However, satisfactory estimates of fish stocks were not available to attempt this calculation.

Nutrient pools and recycling processes in the bay were included in this analysis to allow estimates of turnover times and the relative importance of "new" versus "recycled" nutrients. The evaluation of nutrient recycling terms is not complete because activities of water column bacteria and soft bodied zooplankton were not included, again because sufficient data were not available.

The conceptual model of the nutrient budget can also be expressed as differential equations for TN and TP.

$$dTN/dt = (I_{pN} + I_{rN} + I_{aN}) - (L_{dN} + L_{bN} + L_{fN}) + I_{oN}$$

$$dTP/dt = (I_{pP} + I_{rP} + I_{aP}) - (L_{bP} + L_{fP}) + I_{oP}$$

where: I_{pN}, I_{pP} are mean annual TN and TP loads from point sources; I_{rN}, I_{rP} are mean annual TN and TP loads from diffuse sources; I_{aN}, I_{aP} are mean annual TN and TP loads from atmospheric deposition directly to surface waters of estuarine study sites (only wet-fall deposition is included in this value); L_{dN} is mean annual denitrification rate; L_{bN}, L_{bP} are mean annual rates of particulate N and P burial in sediments; L_{fN}, L_{fP} are mean annual rates of TN and TP removal due to commercial and recreational fishing; and I_{oN}, I_{oP} are mean net exchanges of TN and TP with adjacent seaward systems. In this analysis dTN/dt and dTP/dt are assumed to be equal to zero when averaged over several years.

Data Sources and Manipulations

Data sources used in this analysis are listed in Table 1. All of the variables shown in the conceptual model (Fig. 1) are listed in this table; in addition, a few variables not explicitly shown on the diagram but were used in our calculations are shown. Brief descriptions of the variables, and information regarding measurement frequency, duration of the data record, and measurement techniques, are also provided and calculations are noted. Budgets were evaluated as means for an annual time period. Although many of these estuarine processes and properties experience strong interannual variations (Boynton et al. 1991), there are insufficient data to resolve budgets for specific years (i.e., wet versus dry years). In this study data were averaged for the years 1985–1986 wherever possible, even though longer data records were available for some variables (Table 1). These were low flow years in the Patuxent and Choptank rivers, average flow years in the Potomac, and low to average years in the Susquehanna. Finally, these budgets were developed for total nitrogen (TN) and total phosphorus (TP) rather than for some components of TN and TP. Exceptions to this are noted wherever they occur.

Description of Study Areas

A summary of geographic, physical, and morphological characteristics of the study systems and selected features of adjacent drainage basins are presented in Table 2 and Fig. 2. Estuarine surface areas and volumes differ considerably among sites. The Maryland mainstem bay (which is defined arbitrarily by the boundary between Maryland and Virginia) is the largest in both categories, followed by the Potomac, Choptank, and Patuxent rivers. Freshwater inflows have a similarly large range among systems, but when flows are scaled to the volumes, the resulting freshwater "fill-times" are on the order of 2 yr for the Choptank and 1 yr for the other three sites.

There are also large differences in drainage basin sizes, the Susquehanna basin being about 40 times larger than the Choptank basin. However, the ratios of basin area (m^2) to estuarine volume (m^3), are more similar (1.32–4.41 m^{-1}). This ratio has been used as a first approximation of the influence diffuse sources have on estuarine receiving waters and has been found to be consistent with water-quality conditions in these portions of the bay (Magnien et al. 1990). Population densities and land-uses indicate the Patuxent River basin is the most urbanized and the Choptank the most rural. The Susquehanna and Potomac river basins are similar, with forested lands dominating the landscapes and urban and agricultural uses less extensive.

Budget calculations for the Potomac, Patuxent, and Choptank rivers included all of the area of the estuary extending from the upstream limits of tidal influence to the mouth. The morphology of these sites was used to determine the downstream boundaries which, in these cases, were obvious geographic features. However, the seaward boundary for the Maryland mainstem was set just upstream of the Potomac River mouth (Table 2; Fig. 2). The Maryland mainstem was defined in this fashion for two reasons. First, this portion of the mainstem contains the same physiographic features (turbidity maximum zone, a deeper, stratified and less turbid zone, and a shoal area at the seaward boundary) as do the other tributaries. By using only the Maryland portion of the mainstem some morphometric similarities have been retained. Additionally, the fresh water fill time and

TABLE 2. A summary of physical and morphological characteristics of estuarine sites and selected features of adjacent drainage basins.

Location	Estuarine Surface Area[a] ($m^2 \times 10^6$)	Volume (MLW)[a] ($m^3 \times 10^6$)	Freshwater Inflow[d] ($m^3 \times 10^6\ yr^{-1}$)	Fresh-water Fill-Time (yrs)	Drainage Area[e] ($m^2 \times 10^6$)	Land Area: Water Volume Ratio (m^{-1})	Population Density[f] (number ha^{-1})	Drainage Basin Land-Uses[g] % of total land area Cropland (%)	Pasture (%)	Forest (%)	"Other" (%)
Maryland Mainstem Bay[b]			35,870	0.70	70,189	2.8	0.54	21	7	57	15
Upper	1,193	4,868									
Lower	2,749	20,389									
Potomac River[c]			9,654	0.74	29,940	4.2	1.09	16	12	54	18
Upper	308	1,116									
Lower	902	6,026									
Patuxent River[c]			646	1.01	2,393	3.7	2.77	15	6	44	35
Upper	26	55									
Lower	111	597									
Choptank River[c]			740	1.82	1,779	1.3	0.37	← 66 →		29	4
Upper	16	55									
Lower	345	1,293									

[a] Surface area and volume data are from Cronin and Pritchard (1975).

[b] Maryland mainstem area and volume incudes the portion of the bay from the northern shore of the Potomac River mouth (RM 65 in Cronin and Pritchard) to the Susquehanna mouth (RM 156). All tributary areas and volumes except those of the Patuxent and Choptank rivers are also included. Upper and lower portions of study sites refer to portions upstream, and including, the turbidity maximum zone and areas downstream of this zone, respectively. Specifically, the upper portions of the Maryland mainstem, Potomac, Patuxent and Choptank rivers begin at RMs 125, 50, 20 and 30, respectively, as shown in Cronin and Pritchard (1975).

[c] All secondary tributary volumes and areas are included.

[d] Includes flow measured at the fall-line (means for 1985–1986) plus estimated flows below the fall-line.

[e] Drainage basin areas are from United States Environmental Protection Agency (1982).

[f] Population density estimates are as follow: Potomac basin, Lugbill (1990); Susquehanna and Patuxent basins, United States Environmental Protection Agency (1983); Choptank basin, Maryland Statistical Abstract (1989).

[g] Basin land-uses from sources as in "f" except for the Choptank which is from Lomax and Stevenson (1982). The category "other" refers to commercial and residential development as well as roads and other hard surfaces.

land area:water volume ratio of the Maryland mainstem are similar to those of the other systems.

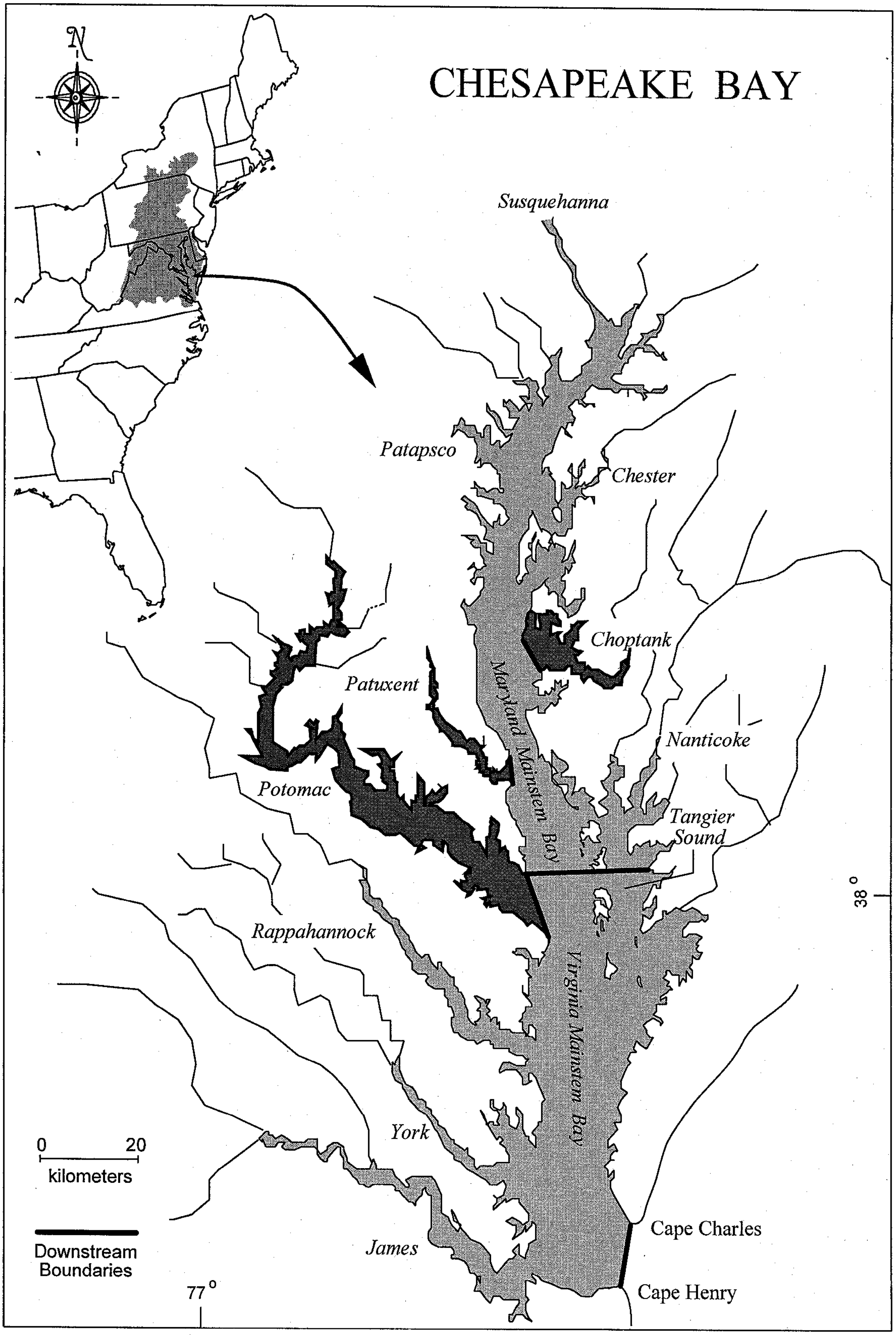
Results

Terrestrial and Atmospheric Sources of TN and TP

Annual inputs of TN and TP from point, diffuse and atmospheric sources to the study systems ranged from about 1.5×10^6 to 80×10^6 kg N yr^{-1} and 0.11×10^6 to 3.75×10^6 kg P yr^{-1} (Table 3). Total nitrogen yields per square meter of basin were more similar among systems, ranging from 0.7 to 1.2 g N m^{-2} yr^{-1}; areal yields of TP ranged from 0.05 to 0.1 g P m^{-2} yr^{-1}. Overall, TN yields from these watersheds were somewhat higher than the nitrate yields reported by Peierls et al. (1991) based on a global sampling of estuarine watersheds. Surprisingly, areal TN yields were highest in the two basins where forested lands dominate the landscape (Susquehanna and Potomac) and were lower in the most urbanized (Patuxent) and most agricultural (Choptank) watersheds. Areal phosphorus yields were not obviously related to land uses, but were higher in the two basins having the highest population densities (Patuxent and Potomac). In most of the study systems, diffuse sources of TN dominated, ranging from 60% to 69% of all inputs in all basins except the Patuxent (39%, Table 3). Point sources ranged form 9.7% to 48% of TN inputs, their relative importance directly proportional to population density. Similarly, the distribution of point-source TN loads between above and below fall-line sources were related to population distribution. For example, most of the point-source TN load enters the Potomac below the fall-line because of the location of Washington D.C. In the Patuxent, most point sources are associated with the urbanized upper portion of the watershed.

Diffuse sources also dominated (58% to 70% of inputs) in the TP budgets of all systems except the Patuxent (32%). Again, the relative importance of above and below fall-line diffuse sources was roughly proportional to the area of the watershed in these two categories. In contrast to point sources of TN, point sources of TP constituted about 50% of the total load in the Patuxent and Choptank systems and were significant sources (~27%) in both of the larger systems.

We estimated atmospheric deposition using Smullen et al.'s (1982) data for TN and TP in rainfall. Although various measurements are available for inorganic N and P concentrations in rainfall to the Chesapeake watershed (Table 4), there are no di-



CHESAPEAKE BAY
N
Susquehanna
Patapsco
Chester
Choptank
Patuxent
Maryland Mainstem Bay
Nanticoke
Potomac
Tangier Sound
38°
Rappahannock
Virginia Mainstem Bay
York
0 20
kilometers
Downstream Boundaries
James
Cape Charles
Cape Henry
77°

TABLE 3. Summary of annual loadings of TN and TP from terrestrial and atmospheric sources. Point and diffuse sources located above and below the fall-line are differentiated. The atmospheric source (wet-fall) includes deposition directly to surface waters. All entries have units of kg $\times$ 10^6 TN or TP yr^{-1}.

Location	Point Sources TN[a]		Diffuse Sources TN[a]		Atmospheric Sources TN[c] (wet-fall)	Total Load kg yr^{-1}	Areal Load g m^{-2} yr^{-1}
	AFL[b]	BFL[b]	AFL[b]	BFL[b]			
			Nitrogen Inputs				
Maryland Mainstem Bay	9.48	9.67	50.72	4.49	6.24	80.60	20.54
Potomac River	2.64	9.30	19.76	1.87	1.92	35.49	29.33
Patuxent River	0.61	0.22	0.21	0.47	0.22	1.73	12.63
Choptank River	0.00	0.14	0.12	0.71	0.57	1.54	4.27
			Phosphorus Inputs				
Maryland Mainstem Bay	ND	1.041	2.100	0.360	0.251	3.752	0.96
Potomac River	0.620	0.140	1.880	0.210	0.077	2.927	2.42
Patuxent River	0.070	0.046	0.010	0.060	0.090	0.195	1.42
Choptank River	0.000	0.052	0.010	0.030	0.023	0.115	0.32

[a] Point and diffuse data are from Summers (1989) and were averaged for 1985 and 1986.

[b] Above fall-line (AFL) point and diffuse sources are measured as a composite at the fall-line. The relative contributions of point and diffuse sources were estimated by subtracting known above fall-line point sources from the total load measured at the fall-line. In one case the point source load slightly exceeded the combined load presumably because of TP losses during transport in the river. In all cases the sum of above fall-line point and diffuse sources is equal to the load measured at the fall-line. BFL refers to below the fall-line.

[c] Atmospheric deposition data are from Smullen et al. (1982) and were averaged for the period 1976–1981.

rect measurements of atmospheric dry fall available for the Chesapeake region. Our estimates therefore include only wet-fall deposition. Atmospheric inputs of TN and TP ranged from 0.22 $\times$ 10^6 kg yr^{-1} to 6.16 $\times$ 10^6 kg yr^{-1} and 0.019 $\times$ 10^6 kg yr^{-1} to 0.248 $\times$ 10^6 kg yr^{-1}, respectively (Table 3). As a percentage of total nutrient input, atmospheric deposition of TN and TP directly to the surface waters of these sites was small (5.1–12.7% for TN and 2.5–6.6% for TP) except for the Choptank, where atmospheric deposition represented 33.1% and 17.1% of TN and TP inputs, respectively. Direct deposition in the Choptank was particularly important because other inputs were small and because the estuary has a large surface area (Table 2).

At the scale of the whole drainage basin the importance of atmospheric deposition of nutrients may be considerably larger than indicated here. This is because a portion of the diffuse source inputs in our budget probably arises from runoff of TN and TP delivered as precipitation onto the watershed. For example, Fisher and Oppenheimer (1991) estimated that atmospheric deposition to the entire watershed and estuary ultimately accounted for some 34% of all nitrogen inputs to the Chesapeake Bay. However, these authors had to make assumptions concerning nitrogen loss rates from various land uses.

We averaged nutrient input data for the years 1985–1986, a period of low to moderate inputs. However, there is considerable interannual variability associated with these inputs, particularly those from diffuse sources, because of changes in the magnitude of annual rainfall in each basin as well as changes in activities in the basins. An example of this type of variability is shown for TN and TP loading rates measured at the mouth of the Susquehanna River at the head of the bay (Fig. 3). During this 11-yr record annual mean TN and TP loads varied by factors of about 2 and 4, respectively. Similar degrees of interannual variability are associated with diffuse source loads in the other tributary systems (Summers 1989). Included within this interannual variability may be systematic changes in nutrient concentrations due to changes in land uses and management programs (Fig. 4). For example, statistical trend analyses of TN and TP concentrations in the Susquehanna River indicate significant increases and decreases, respectively, over the 11-yr record (Summers et al. 1991), and the TN:TP ratio of the input has increased as a result. Increases in TN concentrations probably result from land-use changes; the decreases in TP concentration from the phosphate ban in detergents and improved sediment erosion practices (Summers 1989).

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Fig. 2. Map of Chesapeake Bay system. Stippled areas show the portion of the mainstem and specific tributary areas for which detailed nutrient budgets were developed. The bold lines indicate the downstream or seaward limits of each system. A simplified nutrient budget for the full Chesapeake system was also developed and included all tributary areas and all mainstem areas shown on the map with a seaward boundary between Cape Charles and Cape Henry.

TABLE 4. Summary of nitrogen and phosphorus concentrations in rainfall determined from four monitoring programs conducted in the Chesapeake Bay region.

Date	Annual Rainfall ($m\ yr^{-1}$)	Nutrient Concentrations NH_4^+	$NO_2^- + NO_3^-$	TKN	TN	PO_4^{3-}	TP	Source
1976–1981	1.00	0.35	0.57	1.02	1.59	0.016	0.064	Smullen et al. 1982
1984	1.05	0.20	0.37	—	—	—	—	Maxwell and Mahn 1987
1984	1.27	0.20	0.35	—	—	—	—	Fisher et al. 1988
1988	—	0.18	1.03	—	—	0.036	—	Wies and O'Melia 1989

There were large variations in the TN:TP (atomic basis) ratio of nutrient sources. Overall, annual mean TN:TP ratios of inputs ranged from 20 in the Patuxent to 48 in the Maryland mainstem bay. Ratios for the Potomac and Choptank were intermediate (27 to 29). At all sites, input ratios exceeded the Redfield Ratio (~16), indicating that if all components of the TN and TP loads were available to phytoplankton, nitrogen would be present in excess of stochiometric demands. However, Fisher et al. (1994) have shown that both N and P limit phytoplankton growth during different seasons and in different locations in the Chesapeake system. There were also intersite differences in TN:TP ratios from diffuse and point sources. For example, point-source discharges in the Choptank had a ratio of about 6 while the ratio of this source in the Potomac and Maryland mainstem

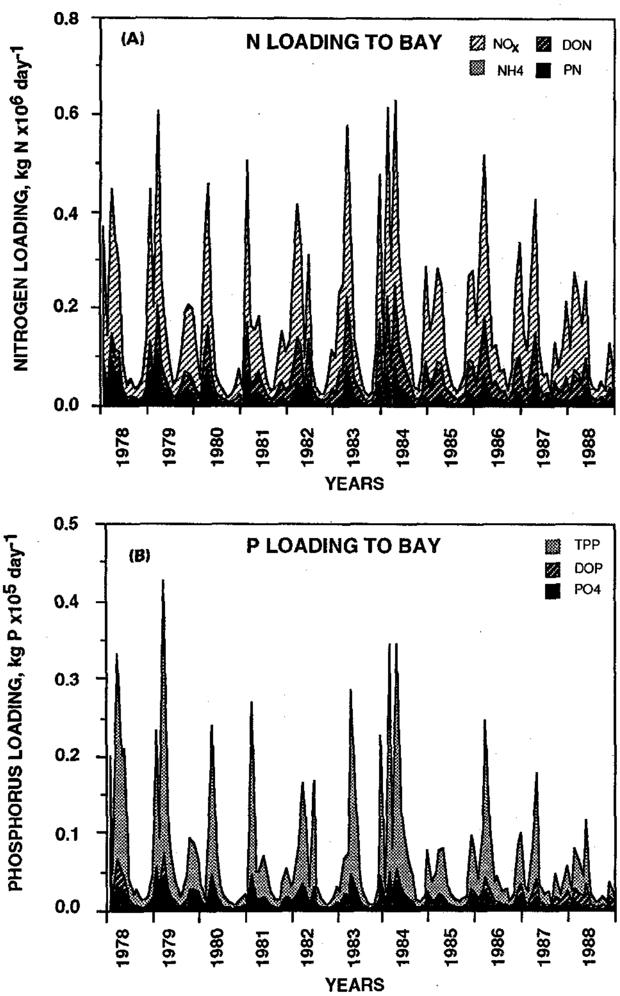


Fig. 3. An 11-yr record (1978–1988) of monthly average (A) nitrogen and (B) phosphorus inputs to the mainstem Chesapeake Bay measured at the fall-line of the Susquehanna River. Data are from Summers (1989).

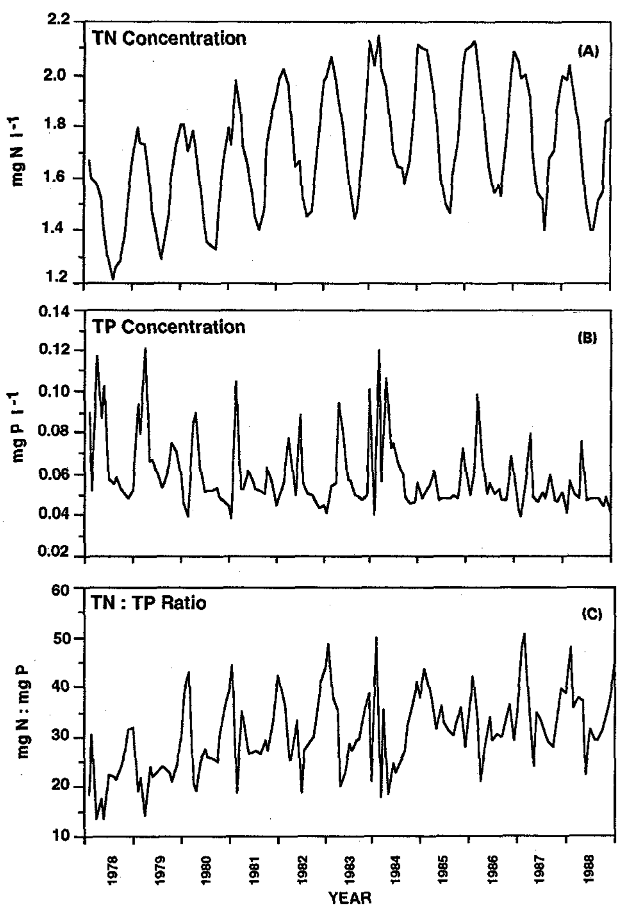


Fig. 4. An 11-yr record showing monthly average values of (A) total nitrogen concentrations, (B) total phosphorus concentrations, and (C) total nitrogen : total phosphorus ratios of inputs to the mainstem Chesapeake Bay measured at the fall-line of the Susquehanna River. Data are from Summers (1989).

TABLE 5. A comparison of estimates of annual TN and TP inputs to several Chesapeake Bay tributaries and the Chesapeake Bay system.

Location	Study Period	Annual Nutrient Loading: Total Nitrogen Load ($kg\ N \times 10^6\ yr^{-1}$)	Total Phosphorus Load ($kg\ P \times 10^6\ yr^{-1}$)	Reference
Patuxent River	1963	0.91	0.17	Jaworski et al. 1992
	1969–1971	1.11	0.25	Jaworski et al. 1992
	1978	1.55	0.42	Jaworski et al. 1992
	1985–1986	1.73	0.21	This study
Potomac River	1913	18.6	0.91	Jaworski et al. 1992
	1954	22.6	2.04	Jaworski et al. 1992
	1969–1971	25.2	5.38	Jaworski et al. 1992
	1977–1978	32.8	2.51	Jaworski et al. 1992
	1985–1986	32.1	3.35	Lugbill 1990
	1985–1986	35.5	2.93	This study
Choptank River	1976–1979	1.81	0.29	Lomax and Stevenson 1982
	1980–1987	1.32	0.08	Fisher et al. 1988
	1985–1986	1.54	0.12	This study
Chesapeake system	1979–1981	123	10.30	Smullen et al. 1982
	1985–1986	152	11.25	This study

was about 40, reflecting different degrees of wastewater treatment. Diffuse source ratios ranged from about 20 in the Potomac and Patuxent to almost 50 in the Maryland mainstem and Choptank, possibly reflecting the more urban and agricultural aspects of these two groups of watersheds, respectively.

There have been at least six previous evaluations of annual nutrient input rates completed for portions of Chesapeake Bay as well as for the entire Chesapeake system (Table 5). In general, results from different studies from similar time periods reported similar loading rates to several systems. In addition, input estimates for several systems have been constructed for several different time periods, spanning as many as 70 yr. In most systems, loadings of TN have increased and loadings of TP increased through the 1970s and then decreased sharply in recent years.

Internal Losses of Total Nitrogen and Total Phosphorus

In this analysis, internal nutrient losses included denitrification, burial in sediments, and fishery yields. Nutrient exports to the next seaward system or the coastal ocean are treated separately because they are based on difference calculations rather than direct measurements. Average annual denitrification estimates indicated that areal rates tended to be higher in the low salinity zones than in mesohaline zones, although differences were not large (Table 6). In general, rates tended toward the low end of the range of values reported by Seitzinger (1988). Denitrification was an important internal loss at all sites, ranging from 13% of terrestrial plus atmospheric inputs in the Potomac to 79% in the Choptank; the Maryland mainstem and Patuxent denitrification losses were 24% and 31%, respectively. Burial of particulate nitrogen (PN) and phosphorus (PP) in depositional areas of the bay and tributaries also amounted to a significant loss term, especially for phosphorus (Table 6; footnote b). Burial losses of PN ranged from 28% to 53% of total inputs from terrestrial and atmospheric sources. Burial represented the major internal loss term for PP; as a percent of terrestrial plus atmospheric inputs, burial of PP represented 104% to 131%. Areal burial losses were higher in the low-salinity portions of all study areas and generally higher in the tributaries than in the mainstem because both deposition rates and particulate nutrient concentrations were higher in these areas (Table 6; footnote b). These estimates of PP burial in excess of terrestrial and atmospheric inputs indicate that TP must be entering these systems from some other source. With the exception of the Choptank River, losses of TN and TP in both commercial and recreational fishery yields were small compared to terrestrial plus atmospheric inputs (3–5% of TN; 1–3% of TP). Fisheries losses of TN and TP were a larger fraction of inputs (14% of TN; 8% of TP) in the Choptank (Table 6; footnote c).

Exchanges of Total Nitrogen and Total Phosphorus Across Seaward Boundaries

The final loss term addresses the exchange of TN and TP between the study areas and adjacent downstream waters (Table 7; see Fig. 2 for location of downstream boundaries). Estimates of this exchange were made by subtracting all internal sinks from total terrestrial and atmospheric inputs. The

TABLE 6. Summary of annual internal losses for TN and TP for selected areas of Chesapeake Bay. All entries have units of kg N or P × 10^6 yr^{-1}. Losses that occurred in tributaries of the upper and lower portions of all locations are included in these calculations except for the Maryland mainstem where losses in the Potomac, Patuxent, and Choptank rivers are reported separately.

Location	Denitrification Rate[a] N	Sediment Burial Rate[b] N	Sediment Burial Rate[b] P	Fisheries Yield[c] N	Fisheries Yield[c] P
Maryland Mainstem Bay				2.427	0.100
Upper	7.32	13.06	3.06		
Lower	12.06	9.51	1.88		
Potomac River				1.631	0.067
Upper	1.63	4.86	1.94		
Lower	3.98	9.32	1.51		
Patuxent River				0.060	0.002
Upper	0.14	0.36	0.13		
Lower	0.40	0.56	0.12		
Choptank River				0.209	0.009
Upper	0.12	0.13	0.03		
Lower	1.25	0.60	0.09		

[a] Annual average areal denitrification rates are as follows (in units of μMN m^{-2} h^{-1}): Maryland mainstem (upper = 50; lower = 36, from Kemp et al. 1990); Patuxent (upper = 43; lower = 29, from Twilley and Kemp 1987); Choptank (upper = 60; lower = 30, from Twilley and Kemp 1987); upper and lower Potomac rates were assumed to be the same as those in the upper Patuxent and lower Maryland mainstem, respectively. Annual average denitrification rates were multiplied by estuarine surface area (Table 2) to calculate total rates (LdN).

[b] Burial rates were calculated using the following formula: Annual Burial Rate (LbN and LbP) = depositional area × annual deposition rate of dry sediments × % PN or PP in sediments (at sediment depth where vertical concentration gradient approaches zero, usually between 5–10 cm). Depositional areas (m^2 × 10^6) were as follows: Maryland upper mainstem (without tributaries) = 446; Tributaries of upper Maryland mainstem = 458; Maryland lower mainstem (without tributaries) = 798; Tributaries of lower Maryland mainstem (excluding Potomac, Patuxent and Choptank rivers) = 842; Potomac (upper = 246; lower = 722); Patuxent (upper = 21; lower = 89); Choptank (upper = 13; lower = 276). Depositional areas of the mainstem were from Kerhin et al. (1983); Maryland Geological Survey estimated that approximately 80% of all tributary areas were depositional (Halka personal communication). Deposition rates of dry sediments (g m^{-2} yr^{-1}) are as follows: Maryland upper mainstem (without tributaries) = 8,500 (Officer et al. 1984 and Dibbs 1988); Tributaries of upper Maryland mainstem = 2,400 (Brush 1984a, b); Maryland lower mainstem (without tributaries) = 3,500 (Officer et al. 1984 and Dibbs 1988); Tributaries of lower Maryland mainstem (excluding Potomac, Patuxent and Choptank rivers) = 1,600 (Brush 1984b); Potomac (upper = 6,800; lower = 3,800, Brush et al. 1982); Patuxent (upper = 4,886; lower = 2,500, Brush 1984b and U.S. Army Corps of Engineers 1990); Choptank (upper = 2,445; lower = 1,040, Yarbro et al. 1983). Composition of sediments (expressed as % PN and PP) was as follows: Maryland upper mainstem (without tributaries) = 0.26 and 0.047; Tributaries of upper Maryland mainstem = 0.29 and 0.116; Maryland lower mainstem (without tributaries) = 0.22 and 0.041; Tributaries of lower Maryland mainstem (excluding Potomac, Patuxent and Choptank rivers) = 0.25 and 0.055; Potomac (upper = 0.29 and 0.116; lower = 0.34 and 0.055); Patuxent (upper = 0.35 and 0.125; lower = 0.25 and 0.055); Choptank (upper = 0.43 and 0.098; lower = 0.21 and 0.033). Sediment composition data were from Boynton and Kemp 1985; Boynton et al. 1990 and J. Cornwell (personal communication).

[c] Values are of commercial and recreational catches (LfN and LfP) expressed as N and P. Commercial catch data are from the Maryland Department of Natural Resources, Tidewater Administration (1989); recreational catch estimates were developed by Lubbers and Dintaman (personal communication, Maryland Department of Natural Resources); dry weight of catch assumed to be 20% of wet weight and N and P content of catch assumed to be 15% and 0.62%, respectively, of dry weight.

TABLE 7. Estimates of annual net exchanges of TN and TP at downstream boundaries of four Chesapeake Bay tributaries and the full Chesapeake Bay system. All entries have units of kg × 10^6 TN or TP yr^{-1}. Exchanges (− = import; + = export) were estimated as the difference between terrestrial plus atmospheric inputs and internal losses (see Table 3 and 6 and Fig. 11).

Location	Seaward Exchanges TN	Seaward Exchanges TP
Maryland Mainstem Bay	36.2	−1.29
Potomac River	14.1	−0.59
Patuxent River	0.21	−0.06
Choptank River	−0.77	−0.01
Chesapeake system	45.88	−4.11

mass balance estimates indicate that three of the four systems export TN and all import TP. It appears that 12%, 40%, and 45% of TN inputs are exported in the Patuxent, Potomac, and Maryland mainstem, respectively. Inputs of TP from seaward sources (estimated from mass balances) appear to be substantial, representing from 9% to 34% of inputs from terrestrial and atmospheric sources. In all cases, estimates of internal losses of TP more than accounted for all inputs, suggesting that there are other sources or that estimates of landside and atmospheric inputs are too low, internal losses too large, or both. While there is undoubtedly some error associated with all terms, none appear large enough to balance internal losses with landside and atmospheric inputs. It appears more likely that TP is imported from adjacent downstream systems via deep water flows associated with two-layer estuarine circulation.

Storages of Total Nitrogen and Total Phosphorus

Annual mean pool sizes for TN and TP in the water column, sediments (top 5 cm of the sediment column), and biota at the four study areas were estimated for the 1985-1986 period (Table 8). Most of the TN in these systems is contained in sediments (>87%) followed by water column (<12%) and biota (<1%). Stocks of TP are similarly distributed but sediment stocks are even more dominant. This distribution of nutrient pools is, of

TABLE 8. Summary of average annual stocks (1985 and 1986) of particulate and dissolved nitrogen and phosphorus in the water column, sediments and biota for selected areas of Chesapeake Bay. All entries have units of kg × 10^6 N or P.

		Maryland Mainstem Bay		Potomac River		Patuxent River		Choptank River	
	Nutrient Stocks	N	P	N	P	N	P	N	P
Water Column[a]	Dissolved								
	Inorganic	9.11	0.333	2.76	0.159	0.13	0.018	0.26	0.028
	Organic	7.51	0.159	2.92	0.201	0.26	0.024	0.56	0.052
	Particulate	3.26	0.606	0.95	0.295	0.16	0.031	0.29	0.037
	Total	19.73	1.098	6.63	0.655	0.55	0.073	1.21	0.117
Sediment[b]	Dissolved	0.52	0.014	0.39	0.004	0.01	0.003	0.04	0.016
	Particulate	214.01	36.370	57.88	11.830	7.38	2.120	18.80	3.660
	Total	214.53	36.384	58.27	11.834	7.39	2.123	18.84	3.676
Biota	Macrozooplankton[c]	0.17	0.020	0.03	0.003	0.00	0.001	0.02	0.002
	Benthic	3.34	0.406	0.68	0.083	0.10	0.012	0.10	0.012
	Total macrofauna[d]	3.51	0.426	0.71	0.086	0.10	0.013	0.12	0.012

[a] Water-column data are from Magnien et al. (1990).
[b] Sediment data are from Boynton and Kemp (1985), Boynton et al. (1990) and J. Cornwell (personal communication).
[c] Macrozooplankton data are from Jacobs (1989).
[d] Benthic macrofauna data are from Holland et al. (1989).

course, dependent on the depth to which nutrients are included in the sediment column. If only 1 yr of sediment and organic matter deposition are considered (Table 6), sediments are a less dominating storage. However, a single year's deposition seems too short a time period to consider because resuspension events and bioturbation effectively keep more than the top few millimeters biologically and chemically active.

Concentrations and speciation of nitrogen and phosphorus compounds vary seasonally along the longitudinal axis of the mainstem bay and tributaries (Fig. 5; Magnien et al. 1990). Total concentrations decrease in a seaward direction, particularly for TP. Dissolved inorganic forms of nitrogen are prevalent mainly in the upper river and then only during winter and spring. During the rest of the year particulate and dissolved organic forms of nitrogen dominate. In contrast, particulate and dissolved organic phosphorus are the major forms of

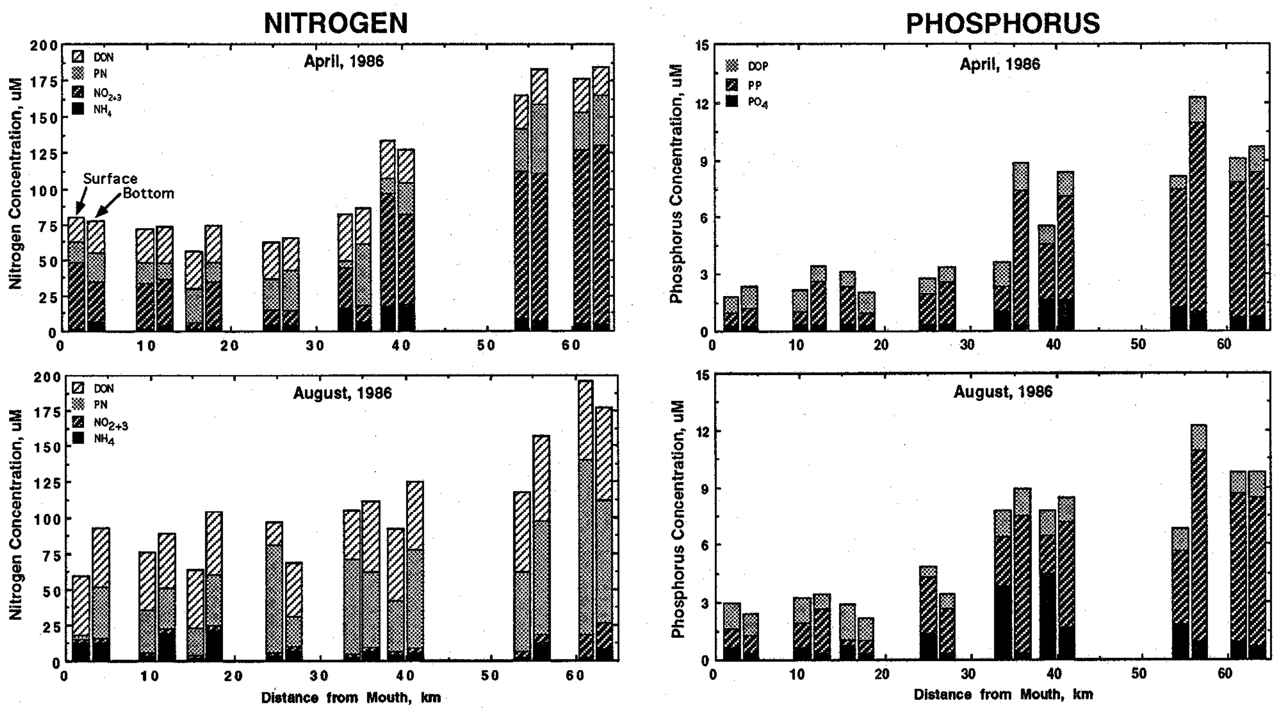


Fig. 5. Longitudinal plots of surface and bottom water nitrogen and phosphorus concentrations along the channel of the Patuxent River during April and August 1986. Data are from Magnien et al. (1990).

phosphorus present at all times of the year except during summer in the middle reaches of these systems. Differences in surface and bottom water concentrations are variable, but phosphorus gradients appear largest because of occasional high bottom-water concentrations. On an annual average basis in these systems, far more nitrogen is present in the water column as dissolved nitrogen (DN) than particulate N. About equal portions of the dissolved fraction are present as inorganic and organic fractions. There is a more equal division between dissolved and particulate P fractions. Dissolved organic phosphorus constitutes somewhat more than half of the dissolved phosphorus mass in the water column.

There are some striking differences in TN:TP ratios among nutrient pools as well as among estuarine sites. For example, annual average water-column TN:TP ratios ranged from 17 in the Patuxent to 40 in the Maryland mainstem. The Potomac and Choptank had ratios of about 23 and 21, respectively. All were just slightly lower than the respective input TN:TP ratios for these systems. Ratios for the biota were all the same (~18) due to the constant stochiometry used in calculating biota TN and TP masses. However, sediment TN:TP ratios were considerably lower than those of the water column, biota, or inputs, ranging from 5.5 in the upper Potomac to 13.4 in the lower Choptank. Sediment TN:TP ratios in each system still reflected the input ratio of that system. It appears that as nitrogen and phosphorus move from sources through the water column and biota to the sediments, the abundance of nitrogen relative to phosphorus continuously decreases.

Turnover-times for these nutrient pools can be calculated by comparing stock sizes to terrestrial and atmospheric nutrient inputs. If total nutrient pools are considered (including sediments), turnover-times range from 2 yr to 12 yr and 3 yr to 29 yr for TN and TP, respectively. A more dynamic picture emerges when water-column stocks are compared to inputs. In this case, terrestrial plus atmospheric inputs could replace TN pools 1.5–6 times per year and TP pools 1–5 times per year.

Water-Column and Sediment Recycling Rates

The relative importance of nitrogen and phosphorus recycling processes varied among the systems studied here (Table 9). In most study areas the largest nitrogen and phosphorus recycle pathway (of those considered here) was associated with microzooplankton, followed by releases from sediments; macrozooplankton nitrogen and phosphorus releases were relatively small in all systems. Microzooplankton excretion ranged from 51% to 298% and 205% to 1130%, respectively, of annual terrestrial plus atmospheric inputs. Annual sediment releases of nitrogen and phosphorus, which occur primarily during the summer months, ranged from 55% to 233% and 44% to 214%, respectively, of annual terrestrial plus atmospheric inputs. While recycled nutrients represent a very large internal nutrient source compared to terrestrial and atmospheric inputs, the influence of recycled nutrients on primary production may be even larger than suggested here. The reason for this is that a substantial fraction of TN (~25%) and most of the TP (~90%) entering from diffuse sources is in a form not directly available to phytoplankton, being either dissolved organic or some form of particulate material. In contrast, virtually all of the nitrogen and phosphorus released from

TABLE 9. Annual average sediment N and P fluxes and macrozooplankton and microzooplankton excretion rates for selected areas of Chesapeake Bay. Sediment nutrient fluxes include NO_3^- and NH_4^+ for N and PO_4^{3-} for P. Zooplankton excretion rates include only NH_4^+ for N and PO_4^{3-} for P.

Location	Benthic Flux[a] (μM m^{-2} h^{-1})	Macrozooplankton Excretion Rate[b] (mg m^{-2} d^{-1})	Microzooplankton Excretion Rate[c] (mg m^{-2} d^{-1})	Annual Benthic Flux (kg × 10^6 yr^{-1})	Annual Macrozooplantkon Flux (kg × 10^6 yr^{-1})	Annual Microzooplankton Flux (kg × 10^6 yr^{-1})
Nitrogen						
Maryland Mainstem Bay						
Upper	54	6.6	35.7	7.7	2.9	15.5
Lower	124	34.2	54.3	41.1	34.1	54.1
Potomac River						
Upper	147	13.6	58.7	3.7	1.5	6.6
Lower	173	10.2	35.3	15.9	3.4	11.6
Patuxent River						
Upper	189	21.3	71.8	0.6	0.2	0.7
Lower	106	16.5	42.5	1.4	0.7	1.7
Choptank River						
Upper	148	12.9	28.5	0.3	0.1	0.2
Lower	95	19.1	34.7	3.3	2.4	4.4
Phosphorus						
Maryland Mainstem Bay						
Upper	3.8	0.74	12.3	0.54	0.32	5.36
Lower	9.8	3.22	17.7	3.25	3.21	17.67
Potomac River						
Upper	2.2	2.29	20.4	0.06	0.26	2.29
Lower	13.4	1.34	11.5	1.23	0.44	3.77
Patuxent River						
Upper	17.3	1.87	27.2	0.05	0.02	0.26
Lower	10.8	1.68	12.7	0.15	0.07	0.51
Choptank River						
Upper	17.3	1.28	9.3	0.03	0.01	0.05
Lower	6.0	1.69	10.2	0.21	0.21	1.28

[a] Benthic nutrient flux data from Boynton et al. (1990).
[b] Macrozooplankton data are from Jacobs (1989).
[c] Microzooplankton data are from Sellner et al. (1989) and Brownlee (personal communication).

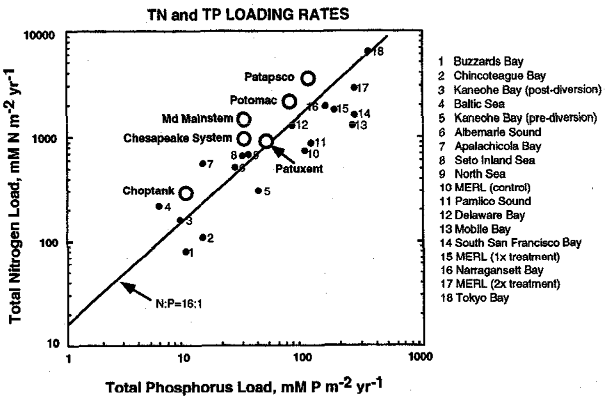


Fig. 6. Scatter diagram showing annual total nitrogen (TN) and total phosphorus (TP) loading rates to a sampling of estuarine and coastal systems. Data sources are as follows: National Oceanographic and Atmospheric Administration/United States Environmental Protection Agency (1989) for systems 1, 7, 13; Nixon et al. (1986b) for systems 6, 8, 9, 10, 11, 12, 14, 15, 16, 17, 18; Smith et al. (1981) for systems 3, 5; Wulff et al. (1990) for system 4; Boynton et al. (1992) for system 2; this study for systems labeled on the diagram except for the Patapsco River estuary which is from Stammerjohn et al. (1991). Data from National Oceanographic and Atmospheric Administration/ United States Environmental Protection Agency (1989), Nixon (1986b), and Smith et al. (1981) were adjusted to include TN and TP from point and diffuse landside sources and atmospheric inputs directly to surface waters of these systems (Kelly personal communication). The bold line represents the Redfield Ratio of inputs.

sediments and excreted by zooplankton is immediately available for phytoplanktonic uptake.

Discussion

Comparisons of Nutrient Inputs Among Coastal Systems

During the past few years nutrient loading rates for a diverse mixture of ecosystems have appeared in the literature. For example, the National Oceanographic and Atmospheric Administration and the Environmental Protection Agency have compiled estimates of loading rates for many coastal systems of the United States (National Oceanographic and Atmospheric Administration/ Environmental Protection Agency 1989). Nixon et al. (1986b) and Kelly (personal communication) have also assembled loading data for both aquatic and terrestrial systems. They concluded that coastal systems have become among the most heavily fertilized of ecosystems because of increasing anthropogenic additions of nitrogen and phosphorus.

To place our estimates of terrestrial and atmospheric nutrient inputs to Chesapeake Bay and its tributary systems in perspective, we compared reported TN and TP loading rates for other coastal and estuarine systems (Fig. 6). There is about a factor of 10 difference between the highest and lowest TN and TP loading rates for the Chesapeake systems and factors of about 80 for TN and 30 for TP for all systems shown in Fig. 6. Compared to other estuarine systems, loading rates to Chesapeake Bay are moderate to high for TN and low to moderate for TP. In the Chesapeake systems, except the Patuxent River, the nutrient input ratio (TN:TP) is well above the Redfield Ratio and higher than in most other systems surveyed. These differences appear to be related to the types of nutrient sources entering the system. Those in which diffuse sources predominate tend to have high TN:TP ratios while those in which point sources dominate have lower ratios. In the Chesapeake systems only the Patuxent has significant point-source nutrient inputs (Table 3) and a relatively low TN:TP input ratio. The pre-diversion and post-diversion sewage input rates for Kaneohe Bay (points 3 and 5 in Fig. 6) also indicate the importance of diffuse versus point sources in determining TN:TP input ratios.

However, it is also clear that comparable nutrient loading rates in different systems do not produce the same responses as those observed locally. For example, N loading rates for the Potomac River and Narragansett Bay are very similar but poor water-quality conditions extend throughout the mesohaline portion of the Potomac, whereas the analogous location is limited to a very restricted reach of upper Narragansett Bay (Nixon et al. 1986a; Magnien et al. 1990). On the other hand, loading rates to the Baltic Sea are much lower than those of most of the Chesapeake systems, but hypoxic and anoxic conditions are now characteristic of both (Larsson et al. 1985). Estuarine morphology, circulation, and regional climate conditions undoubtedly have strong influences on the relative impact of nutrient loading rates (Wulff et al. 1990).

Internal Nutrient Losses, Recycling, and Stocks Relative to Nutrient Input Rates

Responses of estuarine systems to elevated nutrient-loading rates include loss of submersed vascular plant communities (Kemp et al. 1983), development of hypoxic or anoxic conditions in bottom waters of stratified estuaries (Boicourt 1992), increases in primary production rates, and increased rates of nutrient recycling, but only slight enhancement of higher food-web production (Nixon et al. 1986b; Nowicki and Oviatt 1990). Recent investigations in the Chesapeake have also reported similar attenuated responses to loading rates. For example, we found a significant relationship between TN loading and primary production rates at one site in the mainstem bay (Fig. 7A) and between TN loading and sediment releases of am-

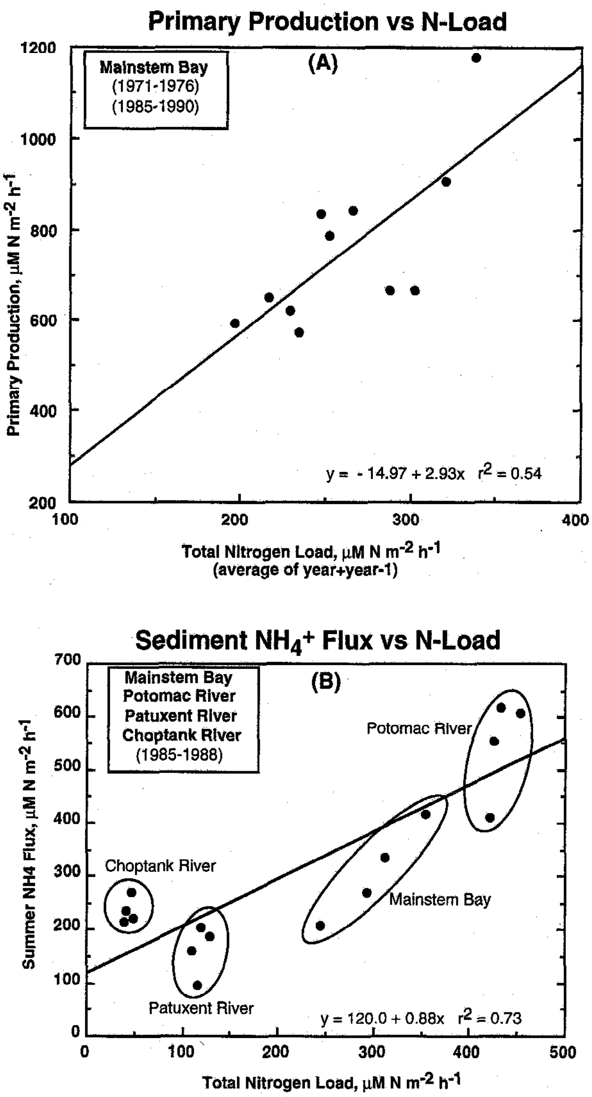


Fig. 7. Scatter plots of (A) annual TN loading rates versus annual phytoplankton primary production rates for several years (1971–1976 and 1985–1990) at a station in the mesohaline portion of Chesapeake Bay and (B) annual TN loading rates versus summer sediment releases of ammonium from several areas of Chesapeake Bay. Data are from Boynton et al. (1990) and Boynton et al. (1991).

monium (Fig. 7B). These results suggest that the coupling between nutrient loading, water-column production of organic matter and recycling of nutrients from sediments occurs over time scales of about several years or less. In addition to laboratory work that supports this view of nutrient dynamics, our attempts to find significant correlations in our field data suceeded only when the system-level responses (i.e., productivity, benthic recycling) were linked to nutrient loads that occurred within small time scales.

Nutrient budgets constructed here for different systems also allow for comparative analysis of how nutrients are processed and partitioned. Nutrient losses, recycling rates, and storages estimated for each of the Chesapeake systems were expressed on an areal basis (g m^{-2} or g m^{-2} yr^{-1}) and plotted versus annual TN and TP loading rates from terrestrial and atmospheric sources (Fig. 8). Nitrogen and phosphorus burial and, to a lesser extent, denitrification rates and fisheries yields were qualitatively directly proportional to loading rates (Fig. 8A, B). Sediment releases of nitrogen and phosphorus were also proportional to loading rates (Fig. 8C, D). However, water-column recycling rates (mainly from microzooplankton excretion) were moderate at the highest loading rates (Potomac River), highest at intermediate loading levels, and successively lower at lower loading rates. Water-column stocks of TN and, to a lesser extent TP, were also proportional to loading rates (Fig. 8E, F). However, areal estimates of sediment TN and TP stocks indicated that the Maryland mainstem site was enriched, for reasons which are not clear, in both TN and TP stocks relative to loading rates; other sites exhibited a general increase in sediment stocks proportional to loading rates.

Several tentative conclusions emerge from this analysis. First, most features that responded to loading rates exhibited an attenuated response: unit increases or decreases in loading rates were not matched by equivalent change in a rate or stock. For example, there was a factor of eight difference in nutrient loading rates between the Potomac and Choptank rivers but only a factor of two difference in sediment N recycling rates. Similar attenuated responses were found for a variety of variables measured in a set of marine mesocosms exposed to a range of nutrient enrichment rates (Nixon et al. 1986b).

Although field data from different estuaries have indicated that denitrification removes a relatively constant proportion (40–50%) of nitrogen inputs (Seitzinger 1988), this process was decreasingly important with increasing N loading rates in mesocosm experiments (Seitzinger et al. 1984). Denitrification removed only about 25% of N inputs to Chesapeake estuaries. The relationship between TN loading and denitrification rates reported by Seitzinger (1988) may in part be explained by the fact that in those systems a large percentage of TN inputs were in the form of nitrate, the nitrogen species required for denitrification. In fact, some of the very highest denitrification rates reported (5,000 µM Nm^{-2} h^{-1}) were measured in systems that were characterized by extremely high nitrate concentrations (~500 µM) in overlying waters (Billen et al. 1985). At relatively low TN loading rates, denitrification rates may be low because both ni-

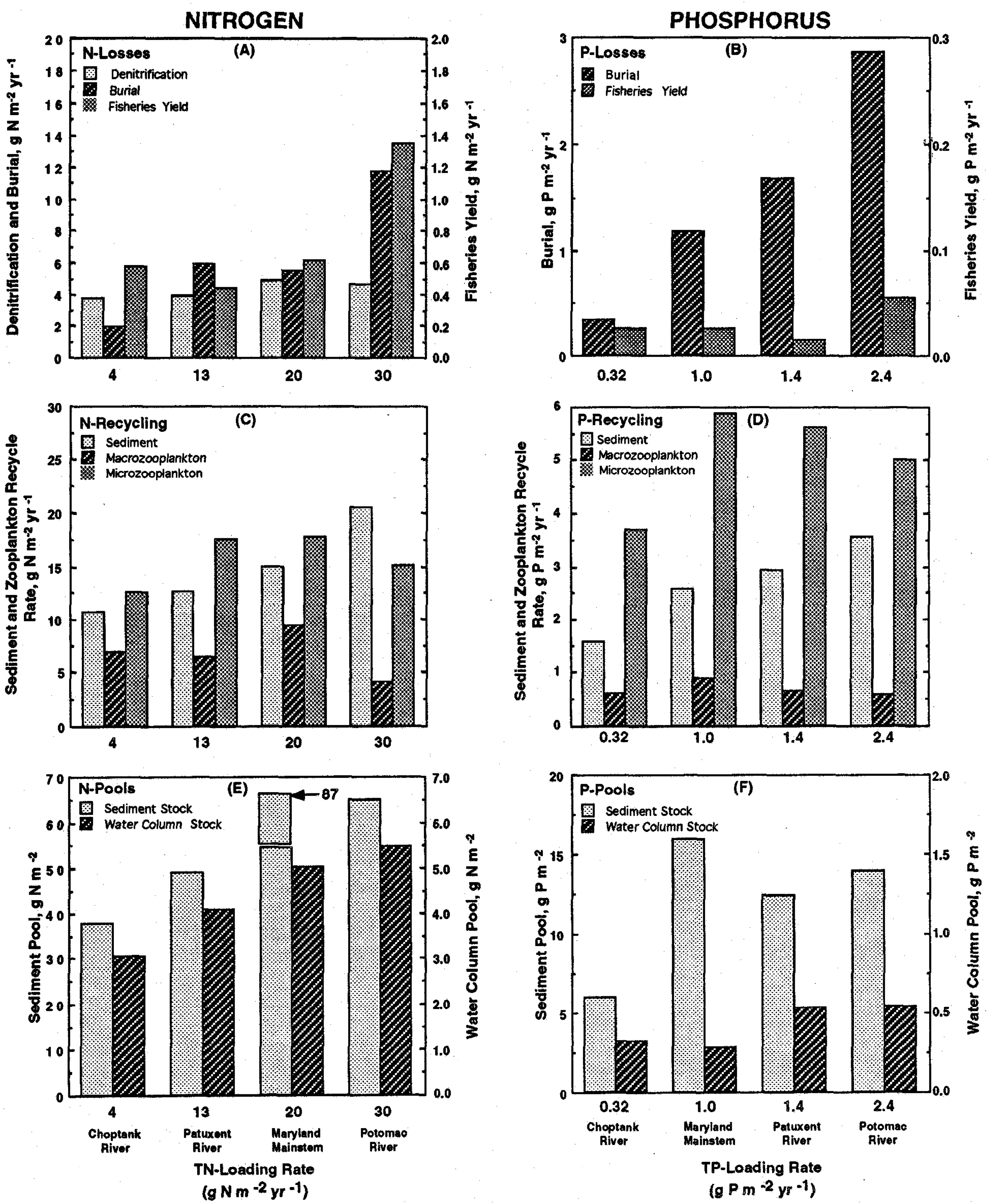


Fig. 8. Bar graph showing annual average areal nutrient loss rates (denitrification, burial in sediments and fisheries yield), recycle rates (sediments and zooplankton), and stocks (sediments and water column) of nitrogen and phosphorus plotted against average annual areal loading rates of TN and TP.

trate availability from overlying waters and labile organic matter needed as substrate for the process are in short supply. Rates increase as N loading increases up to the point when organic matter supplies are sufficient to cause sediments and overlying waters to become hypoxic or anoxic, inhibiting nitrification and hence limiting an important nitrate source (Kemp et al. 1990).

Nutrient burial rates proportional to loading rates may result because sediment loading rates and deposition rates are also highest in the most heavily loaded systems (Table 6). In fact, most of TP enters these systems as inorganic particulates and as such is particularly susceptible to burial (Summers 1989). Water-column TN and TP stocks were generally proportional to loading rates, but the response was very attenuated. This is not surprising given the relatively short water columns (<15 m) characteristic of these systems. It appears that systems must be much deeper (e.g., Baltic Sea) before water-column increases in nutrient concentrations represent significant new storage (Nixon 1987; Wulff et al. 1990).

Reasons for the more complex response of zooplankton recycling to loading rates are not apparent other than that microzooplankton standing stocks were lower at the highest loading rates than at more intermediate levels. Finally, fish yields were not consistently related to loading rates as might be expected on theoretical grounds and from the results of large-scale experimental studies (e.g., Cooper and Steven 1948). Since fishing effort information was not available, it is uncertain whether fish yields represented stocks or were more a reflection of traditional fishing patterns (e.g., low fishing effort for menhaden in tributary rivers) and local fishing regulations (e.g., no purse seining allowed in Maryland waters). It is frustrating to find that one of the prime reasons for initiating the expensive and difficult task of rehabilitating eutrophicated systems is also among the least certain of terms in these evaluations.

These analyses are obviously limited; the number of sites is small and the range in TN and TP loading is also small compared with loading rates observed in a larger selection of estuarine systems (Fig. 6). We have avoided a statistical treatment of these data for these reasons; a broader examination and more rigorous treatment of these processes relative to loading rates and other system-size features is needed.

Nutrient Exchanges at the Seaward Boundaries

In this section we expand discussion of exchange processes to include both the four sites previously discussed (Maryland mainstem, Potomac, Patuxent, and Choptank rivers) as well as results of simplified budget calculations for the full Chesapeake system which includes the entire mainstem, all tributary rivers and has a seaward boundary between Cape Henry and Cape Charles (Fig. 2). Estimates of nutrient exchanges at the downstream boundaries of these systems suggest a remarkably consistent pattern (Table 7). Between 12% and 45% of terrestrial plus atmospheric sources of TN are exported at the downstream end for all systems except the Choptank, while TP is imported at the seaward boundary at rates equivalent to 9–37% of terrestrial plus atmospheric inputs. Although the general pattern observed here for nutrient exchange at downstream boundaries is relatively consistent, the one exception is the net import of TN at the Choptank mouth (Table 7). Seliger et al. (1985) and Sanford and Boicourt (1990) have reported intrusions of deep water into the Choptank system. Because these deep waters are characterized by high concentrations of dissolved N and P (Magnien et al. 1992), intrusions would result in nutrient importation.

In this analysis, nutrient exchanges at the seaward boundary were estimated by subtraction, assuming steady-state conditions (i.e., ignoring temporal changes in nutrient pool sizes). While these internal nutrient pools appear to turnover at seasonal to annual time-scales (Tables 3 and 8), interannual changes in size appear to be small relative to annual input and output terms in respective budgets (Boynton et al. 1982). Our results for TN and TP exchanges at the seaward end of the entire Chesapeake Bay system differ markedly from two previous estimates derived from budget analyses (Table 10). The present estimates of TN exchange are intermediate between the previous reports, while, in contrast to our calculations, both previous studies concluded that TP was exported from the bay. While these previous studies provided useful initial perspectives on the question of nutrient sources and sinks, key assumptions in both were probably incorrect. Dynamic computations of nutrient exchanges at the seaward boundaries of the bay and three tributaries are now also available from numerical simulations (Table 11; Cerco and Cole 1992). Although these numerical estimates are subject to scaling errors associated with spatial and/or temporal variabilities in nutrient concentrations and water velocities occurring outside the computational domain, the model has been well calibrated with extensive nutrient data. Indeed, the model results compare remarkably well with our budget estimates of seaward nutrient exchanges for several of the tributaries and for the full Chesapeake system (Table 11).

Vertical gradients of nutrient distributions at the

TABLE 10. A comparison of results of three nutrient budget studies completed for the full Chesapeake Bay system. All entries in the table are expressed as percentages of total inputs.

	Inputs						Losses						
	Atmospheric (wet-fall)		Diffuse		Point		Denitrification	Sediment Burial		Fish Harvest		Ocean Export	
Study	N	P	N	P	N	P	N	N	P	N	P	N	P
Smullen et al. (1982)	15	8	66	45	19	47	0	99	99	0	0	1	1
Nixon (1987)	15	8	66	45	19	47	—[a]	5	14	2	1	93	85
This study (see Fig. 11)	12	7	60	58	28	35	26	35	129	9	5	30	−37

[a] Nixon combined losses due to ocean export and denitrification.

mouth of the bay (Fig. 2; between Cape Henry and Cape Charles) offer further support for the strength of budget estimates of net exchange. In Chesapeake Bay and most of its major tributaries, hydrodynamics are characterized by two-layer gravitational circulation, with net seaward transport in the upper layer and net landward transport in the lower layer (Pritchard 1967). If, as is indicated in the present analysis, TN is exported and TP imported at the seaward end of the Chesapeake Bay system, we would expect surface water concentrations of TN and TP to be greater than and less than, respectively, those in bottom waters at the bay mouth. Although there is considerable temporal variability in a 4-yr composite annual cycle of fortnightly TN and TP measurements at bay mouth stations, patterns are completely consistent with the computed net oceanic exchanges (Fig. 9). The consistent importation of phosphorus (mostly as PP) at the mouth of the bay and its tributaries corresponds with previous conclusions that coastal plain estuaries, such as Chesapeake Bay, act as net sinks for oceanic sediments, which are delivered in landward-directed near-bottom fluxes (Meade 1969).

Comparing net exchanges at the seaward boundaries with landside nutrient loading for the Chesapeake Bay study sites, as well as for a selection of other estuarine systems, reveals several interesting patterns (Fig. 10). There is a suggestion of an asymptotic relation for nitrogen, with increasing positive exchange (export) with increasing landside loading. This implies that these estuaries have a general assimilative capacity for nitrogen inputs from landside sources. At low N loading rates, most of the inputs are buried or denitrified, while at high input rates, these estuaries approximate a conduit for seaward transport. The substantial variations around this general pattern probably arises from differences in circulation patterns (water residence time) and estuarine morphologies (e.g., ratio of shoal to channel area, relative sill height) among these systems. The relations for phosphorus appear more complex. Chesapeake Bay systems suggest an inverse relation between seaward exchange and landside loading, while other systems exhibit a direct relation similar to that observed for nitrogen. For the partially stratified Chesapeake Bay systems, the relative rate of P import is roughly proportional to the strength of stratification. Increased stratification is associated with stronger gravitational circulation, which would drive the bottom layer influx of particulate P (Pritchard 1967). If the rate of terrestrial P loading is related to areal rates of freshwater input (e.g., diffuse sources dominate), the direct relation between P loading and P import at the mouth would result from the same freshwater input that drives the gravitational circulation. For better-mixed estuarine systems like Narragansett and Delaware bays (Fig. 10), net water velocities are more often directed seaward at all depths (Weisburg and Sturges 1976; Wong and Garvine 1984). Thus, in these systems increasing concentrations of TP with depth would not induce as much importation.

TABLE 11. Comparisons of annual net TN and TP exchange at seaward boundaries of Chesapeake Bay systems based on nutrient budget calculations (this study) and hydrodynamic water quality model simulations (Cerco and Cole 1992). Entries in the table have units of kg × 10^6 TN or TP per year and represent results of budgets and simulations based on averages of 1985 and 1986 data.

	Nutrient Budget Calculations		Simulation Model Predictions	
Location	TN	TP	TN	TP
Potomac River	14.07	−0.59	14.36	0.62
Patuxent River	0.21	−0.06	0.33	0.02
Chesapeake Bay system	45.88	−4.11	31.28	−2.21

Variations in TN and TP Inputs

Inputs of TN and TP to estuaries such as Chesapeake Bay fluctuate significantly at time scales from hours to centuries. It is of interest to know how the fate of these nutrient inputs might also vary on equivalent time scales. By examining such temporal variations in nutrient loading, especially in relation to contemporaneous variations in ecological processes, we can begin to gain perspective on the fate and effects of these nutrients and on what sort of responses should be anticipated to anthropogenic changes in nutrient loading.

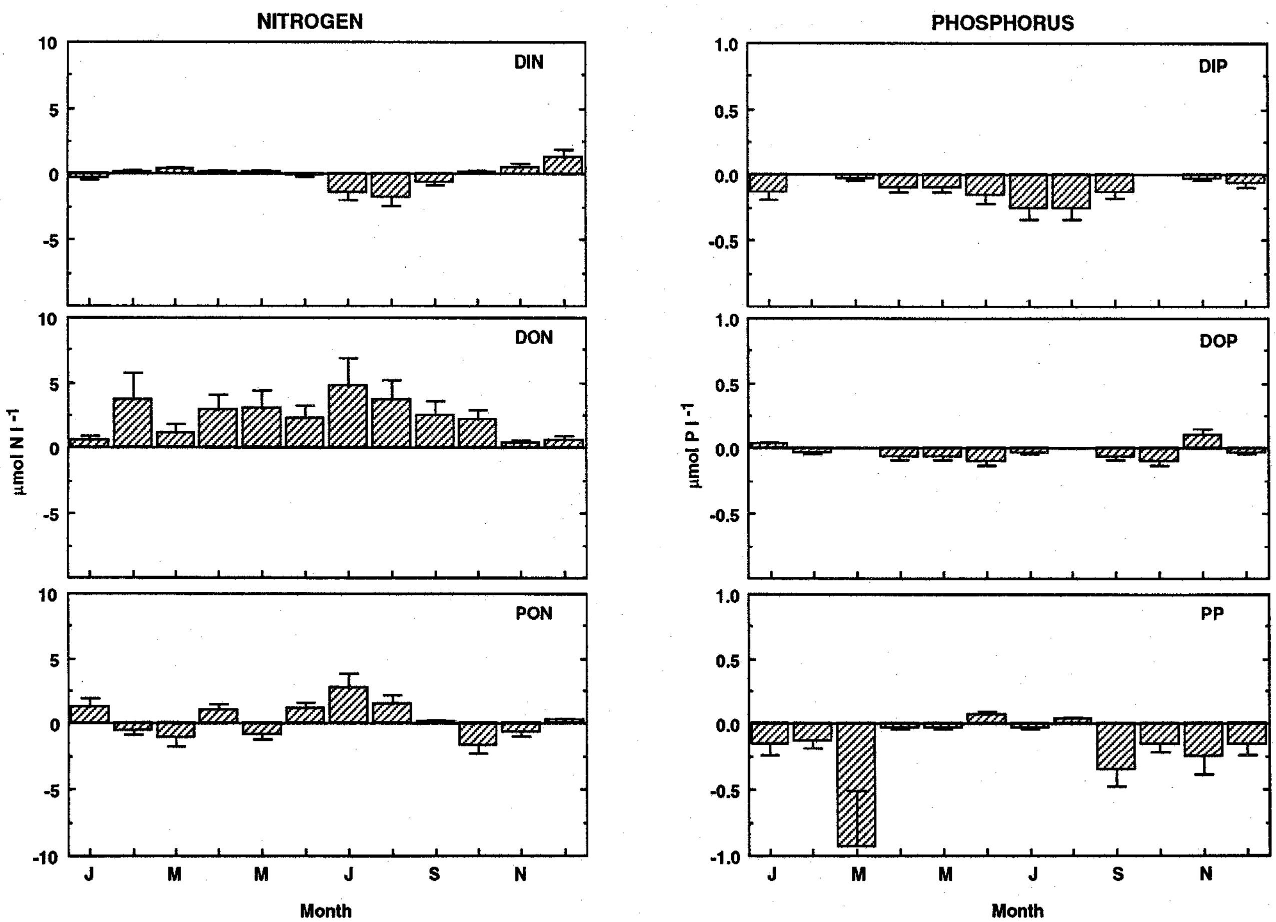


Fig. 9. Plots of monthly differences (mean and standard deviation) between surface and bottom water concentrations of nitrogen and phosphorus compounds at a station at the mouth of Chesapeake Bay located between Cape Charles and Cape Henry. Monthly averages were computed using data from 1988 to 1991.

An 11-yr record (1978–1988) of nitrogen and phosphorus loading to the mainstem bay from the Susquehanna River illustrates a marked pattern of interannual variability (Fig. 3). For both nutrients, there is a strong seasonality, which essentially follows the annual hydrograph of riverflow. Annual inputs of TN (primarily as nitrate) and TP (primarily as particulate P) varied by a factor of two and four, respectively, during this period, with maximum loadings in 1984 and minimum values in 1985 and 1988. No secular trend in nutrient loading rate was evident in this data record. In contrast, concentrations of total nitrogen and total phosphorus did exhibit general trends over the course of this data record (Fig. 4). TN concentrations significantly increased over the first 8 yr of this period (at a rate of about 4 μM yr^{-1}), followed by a slight decline during the last 4 yr. Annual mean concentrations of TP showed a slight, but statistically significant, decline over the period (at approximately -0.06 μM yr^{-1}), which has been attributed to a recent removal of phosphate from detergents throughout the watershed and better controls on sediment erosion in the uplands (Summers et al. 1991; Magnien et al. 1992). Whereas TN concentration exhibits a marked seasonal pattern driven largely by changes in nitrate levels, which peak from December through February, annual cycles for TP concentration are more erratic but typically include an annual maximum coinciding with the riverflow maximum in February through April. These changes in nutrient concentration have resulted in a substantial increase in the TN:TP loading ratio from approximately 20 mg mg^{-1} to 35 mg mg^{-1} over the period of record (Fig. 4). Such changes in nutrient loading may be contributing to a transition from N-limited to P-limited algal growth during certain times of the year in the upper bay (Magnien et al. 1992; Fisher et al. 1994). This rate of increase in TN concentration is on the same order as the general trend reported for many North American rivers during recent years (Smith

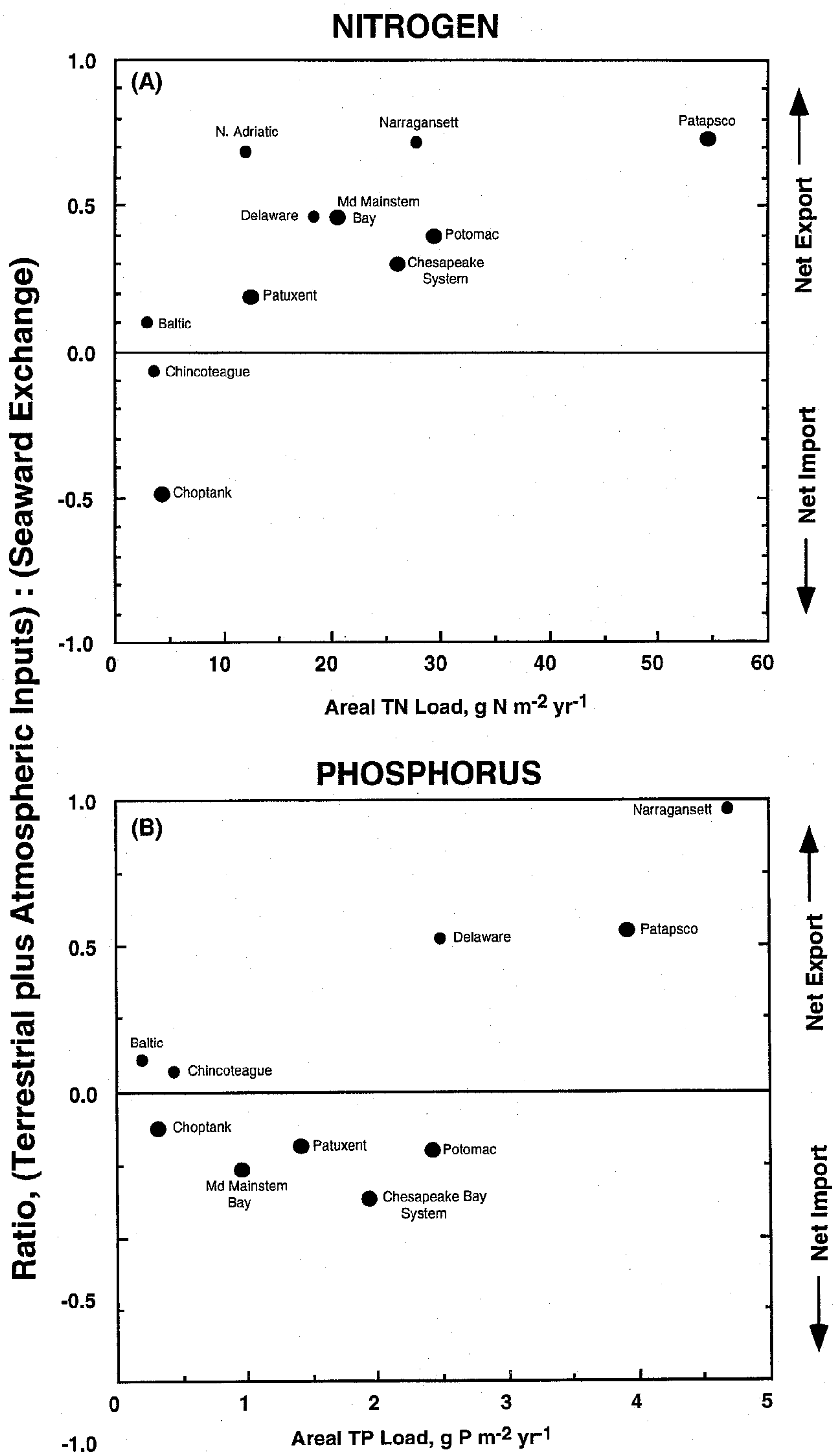
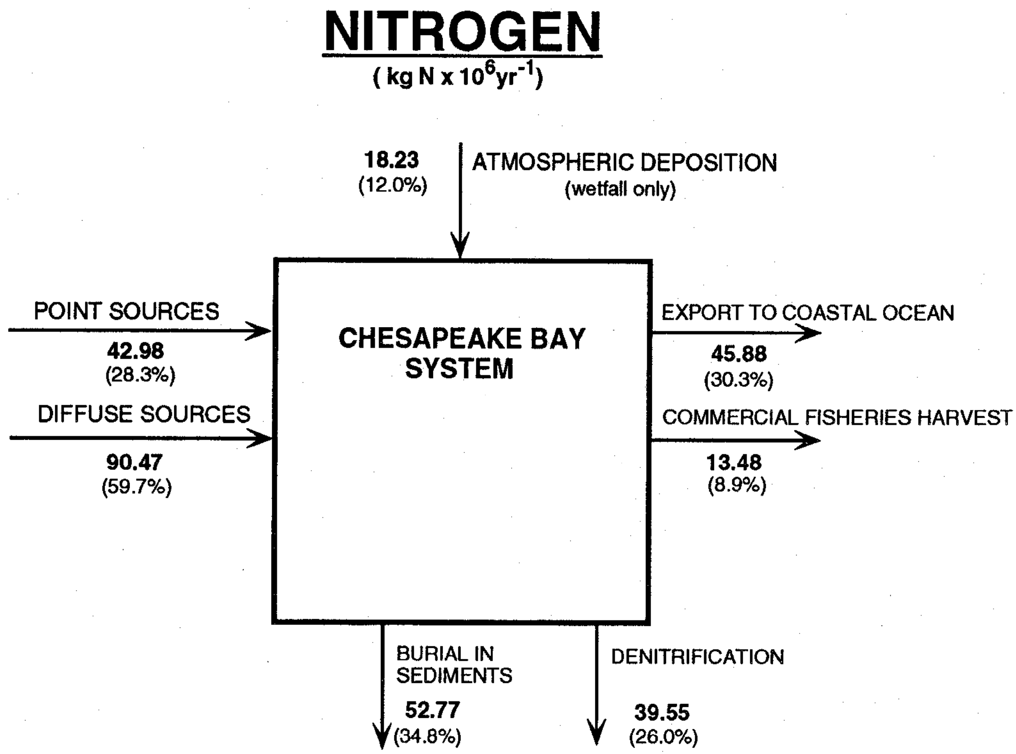


Fig. 10. Scatter plots of annual areal loading rates of (A) nitrogen and (B) phosphorus versus annual areal export:import ratio for Chesapeake Bay study sites and several other sites where appropriate information was available. Data sources are as given in Fig. 6 except for the Northern Adratic, which is from Degobbis et al. (1986).



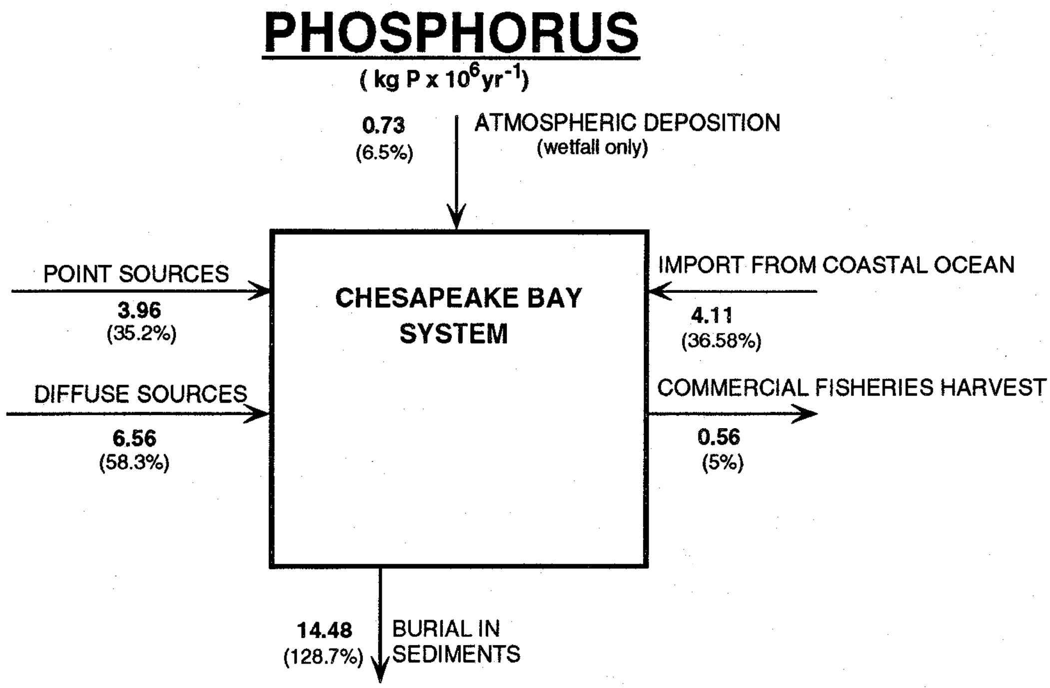


Fig. 11 Simplified annual TN and TP budgets for the entire Chesapeake Bay system. Point sources are from Macknis (1988); diffuse sources are from the United States Environmental Protection Agency Chesapeake Bay: Framework for Action Appendix B (1983); direct atmospheric deposition (wet-fall) of TN and TP to surface waters of the bay is from Smullen et al. (1982); surface areas of the mainstem bay and tributaries are from Cronin and Pritchard (1975); denitrification rates for the mainstem bay and tributaries are from Kemp et al. (1990); the depositional area of the Virginia mainstem is 50% of the total area (Kerhin et al. 1983); the depositional

TABLE 12. A comparison of current (mid 1980s) and reconstructed historical (pre-European settlement) nutrient loading rates to four subsystems of the Chesapeake and for the entire Chesapeake Bay system.

Location	Basin Area ($m^2 \times 10^6$)	Current Loading Rates[a] ($kg \times 10^6$ N or P yr^{-1})		Historical Loading Rates[b] ($kg \times 10^6$ N or P yr^{-1})		Relative Change (Current/Historical Loading)	
		TN	TP	TN	TP	TN	TP
Maryland Mainstem Bay	70,189	80.60	3.752	10.53	0.281	7.7	13.3
Potomac River	29,940	35.49	2.927	4.49	0.120	7.9	24.4
Patuxent River	2,392	1.73	0.195	0.36	0.010	4.8	19.5
Choptank River	1,779	1.54	0.115	0.27	0.007	5.7	15.8
Chesapeake system	164,183	151.68	11.250	24.63	0.657	6.2	17.1

[a] See Table 3 for details concerning current loading rates.

[b] Annual rates of release from forested watersheds were obtained from the literature and ranged from 0.1 to 0.63 g m^{-2} yr^{-1} for total nitrogen and 0.002 to 0.09 g m^{-2} yr^{-1} for total phosphorus. Rates of 0.15 and 0.004 g m^{-2} yr^{-1} of N and P, respectively, were used in these calculations. Data were from Beaulac and Reckhow (1982), Kauppi (1979), Watson et al. (1979), National Eutrophication Survey (1974), Uttormark et al. (1974), United States Environmental Protection Agency (1976), Bormann et al. (1977), Duffy et al. (1978), Schreiber et al. (1976), and Johnson (1992). The load estimates from forested lands for the pre-European period were based on data collected from forests currently exposed to very low levels of atmospheric deposition.

et al. 1987) but is lower than that reported for North American and European rivers during the decades of the 1960s and 1970s (Walsh et al. 1981; Meybeck et al. 1989). The small decline in TN concentration in the most recent years (Fig. 4) may indicate a general decline in nitrate losses from the Susquehanna watershed, or simply a short-term pause in the continuing pattern of increasing human population densities and associated TN loading from coastal watersheds (Peierls et al. 1991).

Although it is widely accepted that estuaries such as Chesapeake Bay and its tributary systems have experienced significant increases in nutrient loadings throughout this century, and especially since the 1950s (e.g., Officer et al. 1982; Cooper and Brush 1991), there is surprisingly little direct documentation. Estimates of nutrient inputs to the Patuxent River and Potomac River estuaries, based on historical data on human population densities and land uses, suggest that TN and TP loadings have increased at rates of 2–5% yr^{-1} and 10% yr^{-1}, respectively during the 1960s and 1970s (Table 5). For the Potomac estuary, TP loadings declined sharply in the 1970s with the introduction of advanced treatment of sewage wastes. TN and TP inputs increased at substantially smaller rates (0.5% yr^{-1} and 3.1% yr^{-1}, respectively) in this bay tributary during the period from 1913 to 1954 (Table 5). Similar data are evidently not available for the mainstem bay.

To provide a long-term perspective on these temporal changes in bay nutrient budgets, we have estimated what the nutrient inputs might have been under pristine conditions prior to European settlement of the Chesapeake basin (Table 12). This estimate is based on nutrient loading rates associated with mature forested lands and it assumes that atmospheric and point sources were negligible prior to European settlement. These computations indicate historical increases in TP and TN loading rates of 13-fold to 24-fold and 4.8-fold to 7.9-fold, respectively. The explanation for the relative differences in calculated historical increases in nitrogen versus phosphorus loadings to all of these systems lies in the much larger difference in TN versus TP loss rates from developed versus forested lands. Relatively large losses of TP from agricultural lands are associated with soil erosion (National Eutrophication Survey 1974). One caveat in the calculated changes in TN losses from these watershed is that loss rates used for forested lands are based on relatively recent measurements of present-day systems rather than from pristine areas. Because of the long-term atmospheric loading of nitrogen to forests around the world, present-day estimates of TN loss rates may be higher than those occurring four centuries ago (Aber et al. 1991). Although the relatively young forests of present-day may have higher rates (compared to pristine forests) of incorporation in accruing plant tissue, forests disturbed by human activities are generally characterized by relatively high nitrogen loss rates (Vitousek et al. 1979).

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area of tributaries is 80% of the total tributary area (Halka personal communication); sediment deposition rates in the mainstem and tributaries are from Officer et al. (1984), Dibbs (1988), and Brush (1984a, b), respectively; sediment TN and TP composition for the mainstem were from Boynton and Kemp (1985) and Cornwell (personal communication); sediment TN and TP content of Virginia tributaries were assumed to be the same as those in the Potomac (Table 6); fishery yields are from the National Marine Fisheries Service (1991) and conversions of fish biomass to TN and TP are as given in Table 6; exchanges of TN and TP with the coastal ocean were calculated as the difference between landside plus atmospheric inputs and internal losses.

Comparisons With Earlier Chesapeake Bay Nutrient Budgets

Our estimates of TN and TP budgets for the whole Chesapeake Bay system can be compared with two previous reports (Smullen et al. 1982; Nixon 1987) that used different approaches and reached very different conclusions (Table 11).

We developed TN and TP budgets for the full Chesapeake Bay system (Fig. 11) that included consideration of all mainstem bay areas and tributary rivers to the head of tide. In the Chesapeake Bay system budget, nutrient stocks in the water column and sediments and the recycle terms were not included and above and below fall-line TN and TP sources were combined. Sources of TN and TP ranked as follows; diffuse > point ≫ direct atmospheric inputs. Both burial in sediments (53%) and sediment denitrification (26%) were important internal losses of TN; fisheries yields were less important (9%). Subtraction of internal sinks from terrestrial plus atmospheric inputs indicates that about 30% of annual TN inputs are exported to the coastal ocean. Fisheries losses of TP were relatively small (5%) but burial of PP in sediments was very large and exceeded terrestrial plus atmospheric inputs (129%), indicating a net annual flux of TP from the coastal ocean or some other source to the bay. The major finding of this budgeting exercise is that substantial amounts of TN appear to be exported from the bay to the coastal ocean while the opposite appears to be the case for TP. Both previous budgets used input data that were averaged for the period 1979–1981 (Table 5); input data for the present study were averaged for the period 1985–1986. In general there is reasonably good agreement among studies both for the magnitude of inputs and the distribution of inputs among specific sources (Table 10). However, there are extreme differences in conclusions regarding the fate of TN and TP inputs. Smullen et al. (1982) concluded that virtually all TN and TP were retained within bay system sediments. Using the same input data but a different approach to determine fate of nutrients, Nixon (1987) concluded that about 93% of TN and 85% of TP were either lost to the atmosphere (denitrification) or exported to the coastal ocean. Our work indicates that a substantial amount of the annual input of TN is exported to the coastal ocean (30%), similar to the conclusion of Nixon, but that TP is imported, a conclusion even more extreme than that of Smullen et al. (1982).

Given the large differences reported for the fate of nutrients entering the bay, it is of interest to attempt a reconciliation of results based in part on differences in approaches used and in part on the availability of new information. Smullen et al. (1982) simply assumed (without evidence) that nutrient losses due to denitrification and fisheries were negligible. The key calculation used in that study involved directly estimating losses at the bay mouth. They based their conclusion about exchange at the bay mouth on a 2-wk survey in summer of water current and nutrient concentration data. Results indicated a very small net flux of nutrients to the coastal ocean and this was taken to represent annual conditions. As a result, the authors concluded that nutrients were efficiently sequestered in sediments of the bay. Estimating relatively small net fluxes at the lower ends of these systems from very large exchanges of water having small nutrient concentration differences is extremely difficult, even in much smaller systems (Nixon 1987; Kjerfve and Proehl 1979). More recent and direct measurements of denitrification and fishery yields indicate that these losses are not trivial. Furthermore, estimation of net fluxes at the bay mouth based on a small dataset is clearly inadequate for estimating annual fluxes, especially in view of the complex current patterns common in the bay (Chao and Boicourt 1986) and the small, time-variable gradients in nutrient concentrations characteristic of many areas of the bay (Fig. 9). At this point it seems reasonable to conclude that the nutrient input rates developed by Smullen et al. (1982) were accurate but that the conclusions relative to nutrient fate were not.

In an effort to understand the source of differences between our nutrient budget and the budget of Nixon (1987), we have reproduced the results reported by Nixon and added two alternative calculations (Table 13). The approach used by Nixon for determining nutrient fate was to take the annual inputs of TN and TP to the full bay system and divide this by the fluvial sediment input. He reasoned that if all nutrients were retained in the bay, nutrient concentrations observed in bay sediments would be equal to the ratio of nutrient input to sediment inputs. In fact, these ratios were much higher than observed sediment nutrient concentrations, suggesting that most TN and TP was not retained in the bay. Using the same approach, but with data from the 1985–1986 period, we also found the input ratios of TN and TP per unit of sediment to be higher than observed (Table 13), but values were about half of those reported by Nixon because the fluvial sediment input estimate we used was slightly more than double the one used by Nixon (see footnote c, Table 13 for observed sediment PN and PP concentrations). The United States Army Corps of Engineers (1990) completed a shoreline erosion study of the bay and reported that as much sediment entered the bay

TABLE 13. A comparison of several calculations estimating the mean potential concentrations of TN and TP in Chesapeake Bay system sediments. This type of calculation was first applied to the bay by Nixon (1987) and was used to infer the degree to which nutrients were retained within the bay.

	Inputs			Calculated Sediment Composition	
Calculation	Sediments (kg × 10^9 yr^{-1})	Nitrogen (kg × 10^6 yr^{-1})	Phosphorus (kg × 10^6 yr^{-1})	%N	%P
Nixon (1987)	3.01	123	10.30	4.09	0.34
Version 1[a]	6.27	152	11.25	2.42	0.18
Version 2[b,c]	13.18	152	12.25	1.15	0.09
Version 3[d]				0.75	0.088
Actual range				0.12–0.47	0.05–0.18

[a] Nutrient loads are the same as those developed for the full Chesapeake system reported in this paper. Sediment loads include only those from riverine sources as in Nixon (1987).

[b] Nutrient loads are the same as those developed for the full Chesapeake system reported in this paper. Sediment loads include sediments from riverine sources but also sediments and particulate phosphorus from "fastland" erosion of shorelines of the bay system (United States Army Corps of Engineers 1990).

[c] Average sediment PN and PP content (% dry weight) are as follows for various regions of the bay: Upper Maryland Mainstem, 0.27 and 0.081; Mid-Maryland Mainstem, 0.33 and 0.064; Virginia Mainstem, 0.12 and 0.049; Upper Potomac, 0.28 and 0.113; Lower Potomac, 0.47 and 0.085; Upper Choptank, 0.40 and 0.006; Lower Choptank, 0.22 and 0.05; Upper Patuxent, 0.47 and 0.180; Lower Patuxent, 0.34 and 0.090; Virginia Tributaries, 0.26 and 0.049.

[d] The percent sediment compositions were calculated as in Version 2 but with nutrient inputs reduced by the amount of N lost in denitrification plus fisheries yields and the amount of P lost to fishery yields.

from shoreline erosion as from fluvial sources. In fact, not all shoreline areas of the bay were included in this evaluation so available estimates of shoreline sediment inputs are low. Using this new information, we repeated this calculation but considered both fluvial and shore erosion sediment sources (Version 2, Table 13). In this case, calculated TN and TP sediment concentrations were found to be about 1.15% and 0.09%, respectively, much closer to observed values but still somewhat higher than most, especially for nitrogen. However, if TN losses due to denitrification and fishery yields are subtracted from inputs, because this TN is not available for burial, then calculated sediment TN concentrations are about 0.75%. Similarly, if TP removed via fishery yields is subtracted from inputs, calculated sediment TP concentrations are also reduced, but only slightly (0.088%). The discrepancy between our results and those of Nixon appear to be largely resolved for phosphorus. Calculated and observed sediment PP values are similar provided that all of the new sediment entering the bay is included in the calculation. These computations suggest, as did Nixon's (1987), that TN is exported from the bay to the coastal ocean. It appears to us that the remaining differences will not be satisfactorily resolved until sediments in the tributary rivers have been mapped to show the extent of depositional areas and sediment deposition rate measurements have been made throughout the bay using sampling techniques that avoid the problems of core shortening and that take into account the results of the sediment mapping.

Uncertainty in Nutrient Budgets

In this section we comment on the uncertainty of the basic data and assumptions used to compute budget terms and the significance of these errors in terms of the conclusions we have reached.

Nutrient Sources

Inputs of TN and TP measured at the fall-line and from point sources appear to be quite accurate. Considerable effort has been directed toward compiling records of point-source discharges from all sources by both federal and state agencies and these are in agreement (Macknis 1988; Legg 1991). Sensitivity analyses concerning methods for calculating fall-line inputs indicate a range of values differing by no more than 10–20% (Summers 1989). However, there are some land areas draining into the bay and tributaries below the fall-line for which no direct measurements of diffuse source loading are available. In these cases, an indirect estimate was generated based on area, land-uses, and rainfall (Summers 1989). For the entire bay system and the larger tributaries these areas are relatively small (<18% of drainage basin area) and even relatively large errors would not substantially change loading rate estimates.

There is less certainty concerning the magnitude of other sources of TN and TP. First, near-surface groundwater sources entering from beneath the surface of the bay or along tidal shorelines have not been included and there does not appear to be sufficient data available at this time to support even a preliminary calculation. These sources could appreciably increase loading rates to some eastern shore tributaries (e.g., Choptank River) because of the extensive marshland-creek complexes that drain directly to the tidal estuary and the high nitrate concentrations in near-surface groundwater (Staver and Brinsfield 1991).

Second, these budgets include only atmospheric wet-fall of TN and TP directly to surface waters. Loading from the atmosphere would be underestimated by whatever portion reaches surface waters as dry-fall. Fisher and Oppenheimer (1991) considered ammonium and nitrate concentrations in rainfall delivering rates of 0.20 g m^{-2} yr^{-1} and 0.37 g m^{-2} yr^{-1}, respectively, for wet-fall and doubled these rates to include dry-fall (1.14 g m^{-2} yr^{-1}). We used a rate of 1.59 g N m^{-2} yr^{-1}, which does not include dry-fall (Table 4). Our values were higher because organic nitrogen was included and this constituted a major fraction of TN in rainfall. Relative to the work of Fisher and Oppenheimer (1991) the values used here were high despite the fact that dry-fall was not included. If the values of Fisher and Oppenheimer (1991) were used our conclusions would not appreciably change. If, however, the rate used here was doubled to include dry-fall then atmospheric deposition of TN would become a more important term in three of the systems (10–22%) and the dominant source (54%) in the Choptank River.

Both nitrogen and phosphorus are associated with eroding shoreline sediments and represent an additional nutrient source that was not included in these budgets. The magnitude of this input has only been determined for the Virginia portion of the bay (0.62×10^6 kg yr^{-1} and 0.43×10^6 kg yr^{-1} of TN and TP; Ibison et al. 1990). It would appear that TN from this source is very small compared to other sources, even if the values from Virginia were doubled or tripled to include the whole bay (Table 5). However, TP from this source could be substantial (~10% of TP inputs to the bay system) and evaluations to include the whole bay should be made.

Finally, nutrient exchanges at the seaward boundaries of these systems were not directly evaluated but rather estimated by subtracting total internal losses from landside plus atmospheric inputs (Table 7). In stratified systems the net landward flow of deep water represents an additional source of nutrients. In fact, this type of input appears to be a source of TN and TP to the Choptank and of TP to all systems considered in this work. However, the magnitude of this type of input is not known and would require an intensive measurement effort to resolve.

Nutrient Losses

Denitrification rates in the Chesapeake area appear to be low relative to those reported for other coastal systems, and the fraction of TN input removed via denitrification is also less (15–30%) than in some aquatic systems (40–55%; Seitzinger 1988). This may be caused by low oxygen concentrations in deep water and reduced surficial sediments, which would limit sediment nitrification rates (Kemp et al. 1990). However, there appears to be agreement among measurements made in the bay region (Jenkins and Kemp 1984; Twilley and Kemp 1987). It does not seem likely that further measurements would change these estimates by a significant margin, assuming that insitu conditions do not change so as to favor increased denitrification rates.

The single most important source of uncertainty in these budgets concerns the burial term. Potential errors in one portion of the burial calculation appear to be of minor importance while the other could change some of the conclusions we have reached. First, depositional areas in the tributary systems have not been quantified as they have in the mainstem bay. In tributary areas we relied on qualitative estimates by investigators familiar with these systems (Halka personal communication) and used 80% of total area as the best available estimate of depositional areas. It is unlikely that depositional areas in the tributaries would be smaller than the mainstem because of the proximity of these areas to fluvial sediment sources. As a result, this error is probably less than 20%. A more important issue concerns estimates of annual sediment deposition rates. There have been quite a few deposition rate estimates made in the bay mainstem and in some tributary rivers. However, some of these exhibit large degrees of variability over relatively small spatial scales. Consequently, it is difficult to arrive at reasonable regional sediment deposition rates (e.g., Officer et al. 1984). In addition, some of these rates were determined from gravity core samples. Substantial core shortening can be associated with this methodology, leading to underestimates of deposition rates on the order of 2-fold to 3-fold (Nevissi et al. 1989; Blomqvist 1991; Crusius and Anderson 1991). Despite these important qualifications, we believe the deposition rates used in these budgets are reasonable for several reasons. First, we used measurements that were based on sediment cores collected either by a diver or by box corer so the core shortening problems are presumably reduced. Secondly, regional deposition rates were estimated based both on core samples (pollen, ^{210}Pb or ^{7}Be analyses) and by distributing sediments from fluvial plus shoreline erosion sources over areas of the bottom that are depositional. These estimates were in agreement and provided some confidence in the burial estimates that were used. However, the issue of error in burial calculations will not be satisfactorily resolved until there is a systematic evaluation of recent deposition rates throughout the bay system.

Finally, the fisheries yield term accounts for the TN and TP lost via commercial and recreational catches but not for the losses associated with growth and subsequent migration from the bay of very abundant fish species such as menhaden and anchovies. The migration term could represent a substantial loss because these species grow rapidly while in the bay during the warm seasons. Evaluation of a fish migration term would require estimates of stock size, age class, growth, and natural mortality characteristics. Although such a calculation is feasible, it would be difficult given the status of knowledge on stocks and population dynamics of these species.

Summary and Management Implications

In the past several years much new information has become available which has been essential for constructing the nutrient budgets presented here. These budgets provide an ecosystem-level framework to examine the manner in which nutrients are processed as they enter and leave these coastal systems and also to examine how the fate of nutrient inputs to these systems vary with different nutrient loading rates.

Diffuse sources of TN and TP were the dominant inputs, but both point and atmospheric sources were also quite important in some of these systems. The large range in nutrient loading rates and differences in the relative importance of the various sources indicate that basin-specific nutrient-control strategies are warranted. Compared to other estuarine systems, loading rates were moderate to high for TN and low to moderate for TP. However, it is also clear that different estuaries respond differently to similar loading rates and, in fact, it appears that nutrient uptake and recycling rates per unit nutrient input are relatively high in Chesapeake Bay and its tributaries compared to other systems (Kemp and Boynton 1992).

Some important nutrient stocks and processes considered in these budgets were proportional to nutrient loading rates. However, all responses to loading rates were attenuated. It appears that we should expect less than one-to-one responses in ecosystem nutrient processes as nutrient loads change via management actions. An attenuated response of dissolved oxygen in deep waters of the mainstem bay to nutrient load reductions has previously been indicated (Kemp and Boynton 1992).

At most sites, including the full Chesapeake Bay system, TN was exported to the next seaward system and the magnitude of the export was proportional to TN loading rates from terrestrial and atmospheric sources. TP was, however, imported from the next seaward system in all Chesapeake systems, and the degree of import increased as TP loading from terrestrial and atmospheric sources increased. Whatever the degree of export, all of these systems rapidly converted inorganic nutrients received from terrestrial and atmospheric sources to particulate and dissolved organic forms clearly indicating that these estuaries are not passive nutrient transport systems. Other coastal systems appear to export larger percentages of TN and TP inputs, but also as organic compounds (Degobbis et al. 1986; Nixon et al. 1986a; Nowicki and Oviatt 1990). The mechanisms that cause high retention rates and importation of TP in Chesapeake Bay are probably related to estuarine morphology and circulation patterns. The apparently large importation rate of TP from seaward sources may confound efforts to manage nutrient inputs to the mainstem bay. TP imports across the seaward boundary, however, represent a relatively small percentage of terrestrial plus atmospheric sources in the tributary rivers (9–31%) and only slightly more for the Maryland mainstem bay (34%). In addition, much of the TP stock in sediments and waters of the bay is not in a form directly available to phytoplankton and might not have much of an influence on water-quality conditions (Magnien et al. 1990; Keefe 1994). More understanding concerning the biological availability of phosphorus would clarify the importance of TP imports.

Many features of nutrient dynamics in these systems respond rapidly to changing loading rates, including primary production rates and sediment nutrient releases. This suggests that these systems have little "nutrient memory" beyond a year or so, despite large stocks of nutrients in sediments. It appears that much of the sediment nutrient stock is refractory and does not actively exchange with overlying waters. We speculate that internal TN losses would increase under lower loading rate conditions because hypoxic conditions in deep waters would not be so prevalent and would not inhibit nitrification-denitrification processes. Burial of TP would also increase because phosphorus would tend to remain bound to particles under oxic sediment conditions.

Calculations based on literature values indicate that current TN and TP loading rates are about 4.8–7.9 times and 13–24 times higher, respectively, than in the pre-colonial period. Since the base years upon which these budgets were calculated (1985–1986), TP loads have been greatly reduced in several major tributary rivers and TN loads have been reduced in one system. The differences in loading rates between pristine and current conditions are not so large as to preclude the possibility of reducing current loads to a point where the more damaging effects of eutrophication are diminished.

There is still uncertainty associated with these budget calculations despite a decade or more of effort. In particular, better estimates of atmospheric dry-fall and direct inputs of near-surface groundwater are needed. Sedimentation rates used in calculating nutrient burial appeared to be the most uncertain term associated with internal losses. Sediment mapping of the tributary rivers and a comprehensive survey of sedimentation rates would largely resolve this problem. A calculation concerning the role of migratory fish in TN and TP budgets would further refine these budgets and shed light on the role of migrations in estuarine nutrient cycling, especially under the lower nutrient-loading scenarios toward which management agencies are striving. Finally, the budgets developed here are all from moderately stratified coastal plain estuaries that share many common features but differ in rates of nutrient input. We have speculated as to how different types of coastal systems might process nutrients, but this is not a very satisfactory substitute for direct evaluations. We encourage others to develop budgets for estuarine and coastal systems having different characteristics of flushing and morphology and to use comparative analyses of all these systems as a means of furthering our understanding of ecosystem-scale nutrient dynamics.

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