DRAFT REPORT

The Effects of Nitrogen and Sediment Loading on Water Quality in the Virginia Western Shore Tributaries of Chesapeake Bay

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Prepared for

US EPA Chesapeake Bay Program
Ecosystem Processes Modeling Program
Annapolis, MD

March 1998

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Abstract

Water quality variables and sediment and nitrogen loading rates for the Rappahannock, York, and James Rivers were evaluated graphically and statistically for differences among estuaries and regions within estuaries. Interannual differences were examined to identify patterns in the water quality responses to nitrogen and sediment loading . The rivers were also compared with Patuxent River, a well studied Maryland tributary estuary for which similar data are available.

Substantial differences were noted in the yields of nitrogen and sediments from the watersheds of the three rivers. In particular, the Rappahannock watershed was found to yield much more nitrogen and sediment per area than the other watersheds in Virginia, but less nitrogen than Patuxent River's watershed.

Annual means of surface chlorophyll-a, surface nitrate plus nitrite and surface total suspended solids were related to annual mean nitrogen or sediment inputs in many cases; however, the strength and direction of the relationship (positive or negative) varied regionally within estuaries and among the corresponding regions of different estuaries. There was strong evidence in the James River for flow-independent changes in nitrate concentrations, which correspond temporally to a major BNR implementation.

Hypoxic volumes were calculated for each of the rivers using 3 mg $^{-1}$ as the DO threshold. Hypoxia was most severe in the Rappahannock River and virtually absent in the James River, but was not as severe in any of these estuaries as in the Patuxent River or Chesapeake Bay. A comparative analysis shows that the severity of hypoxia for 6 estuaries in the Chesapeake Bay system is predicted by TN loading rates. Interannual differences in hypoxia in the Rappahannock and York Rivers were also related to TN loading rates.

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Introduction

Nutrient management issues in the Rappahannock, York and James River watersheds has not received as much attention in the past as have the same issues in the Patuxent River, Potomac River, and the Maryland Chesapeake Bay watershed. This may be because the water quality problems associated with nutrient enrichment in the estuaries dowstream have been seen as less compelling and the pressures of land development less immediate. However, there is little reason to suspect that these estuaries are completely immune to the problems that have threatened these same habitats in Maryland waters. In fact, the some of the same types of problems, including hypoxia and loss of seagrasses have been well documented in these estuaries. Moreover, these estuaries are home to many important living resources which are important to the Virginia coast and Chesapeake Bay as a whole. These are among the reasons the scientific and management community has convened the Virginia Tributary Strategies Technical Synthsis Workshop this month.

From the perspective of an ecologist, Virginia's estuaries are a unique opportunity for comparative ecology. These estuaries share many common features such as their relatively narrow and deep bathymetry, yet also have important differences. In this study, we assemble, compare and contrast key properties describing these estuaries and their watersheds. Looking at the available water quality, freshwater input, nutrient input and sediment input data we investigate the responses of water quality in these estuaries to interannual variations in inputs, comparing the observed responses in each estuary with the other Virginia estuaries and with Patuxent River, a well-studied estuarine system. This same comparative approach could and should be applied to other aspects of the ecology of these estuaries besides basic water quality variables; however, water quality provides an important context within which other processes may be understood. Consequently, this study is a necessary first step.

Study Sites

The Rappahannock, York and James Rivers are three of the 6 major tributary rivers of Chesapeake Bay and the only major tributaries entering the Virginia portion of the Bay. The Rappahannock and York River watersheds lie entirely within the Virginia Tidewater and Piedmont Regions, while the larger James River watershed extends into the Appalachian Mountains

(Figure 1; Table 1). The York and Rappahannock watershed are small relative to the entire Chesapeake Bay watershed, each contributing about 4% to the total drainage area, while the James River watershed is larger, contributing 15% of the total watershed area. The James River estuary is also the largest of the three estuaries, while the Rappahannock and York River estuaries are smaller (Table 1). In comparison, the Patuxent River has a surface area of 1.11×10^8 m^2 and a volume of 6.51×10^8 m^3, about 2/3 the size of the York estuary, the smallest of the three Virginia rivers. Because of its large above-fall line area, the James River has more than twice the watershed area/surface area of the Rappahannock and Patuxent Rivers. The York has an intermediate value.

Table 1. The physical dimensions of the Rappahannock, York, James and Patuxent River estuaries. The areas and volumes are from Cronin and Pritchard (1975). Watershed areas are from Gutierrez-Magness et al. (1997).

Basin Name	Surface Area (10^6 m^2)	MLW Volume (10^6 m^3)	Mean Depth (m)	Watershed Area/ Surface Area
Rappahannock	342	1753	5.1	19
York	190	917	4.8	35
James	557	2393	4.3	45
Patuxent	111	651	5.9	21

Environmental Monitoring and Assessment Program (EMAP) land-use data were obtained from Langland et al. (1995). The gauged portions of the watersheds of the Rappahannock, York and James River watershed are at least 50-70% forested, with most of the remaining watershed in agriculture (Table 2). Less than 5% of any of the watersheds are "urban" or "herbaceous urban." Rural land uses dominate the watershed of all of these estuaries. In contrast, the gauged portion of Patuxent River watershed is 35% urban or herbaceous-urban, reflecting it's place in the highly developed Washington-Baltimore corridor. Relative to the Virginia watersheds, urban development in the Patuxent River basin has come at the expense of forested areas rather than agriculture.

Table 2. Land uses in gauged portions of the Rappahannock, York, James and Patuxent River watersheds. The land uses for the York River watershed are a weighted average of the land uses for the Pamunkey and Mattaponi watersheds. The land uses for the James River watershed are a weighted average of the land uses for the James and Appomattox River watersheds. The data are from Langland et al. (1995).

Basin	Agri-culture	Forest	Urban (%)	Herba-ceous Urban	Other
Rappahannock	44.4	50.3	1.9	3.0	0.4
York	32.5	62.6	1.8	1.3	1.8
James	25.5	69.2	3.4	1.1	0.7
Patuxent	45.9	18.9	25.8	9.3	0.1

Data Available

This analysis is based primarily upon the Chesapeake Bay Water Quality Monitoring Program (CBMP) water quality database and USGS estimates of river flow and nutrient loading. The nominal period of record for the CBMP data is 1985 to 1996, during which time 6 to 13 stations spanning the salinity gradient of each estuary (Figure 1) were visited approximately biweekly during the spring, summer and fall, and monthly during winter. There were numerous times when some or all variables were not available. This sometimes reduced the number of observations that could be included in these analyses (e.g. annual means) or required more complicated statistical analyses to accommodate irregular data (e.g. use of least-squares means).

Some concerns have been raised as to the reliability of an unknown (possibly all) number of the chlorophyll-a measurements from the Virginia tributaries (M. Olson, personal communication). A simple time-series plot of chlorophyll-a levels in the lower reaches of each estuary shows an apparent step decrease in chlorophyll-a concentrations following a brief gap in the the data at the end of 1991 (e.g. station LE3.2 in the lower Rappahannock, Figure 2). This pattern suggests a methods change rather than a major ecological change. For the present, it was decided to keep these potential problems in mind, but proceed with this analysis assuming that the chlorophyll-a measurements are correct.

An apparent method change for nitrate plus nitrite (NO23) occurred with the resumption of NO23 data in 1994, although this is not reflected in the method code variable, NO23_M. There was a decrease in the method detection limit (MBL) for NO23 after 1991. NO23 observations flagged below MDL were never below 0.05 mg N l^{-1} prior to 1992, when the minimum dropped to 0.006 mg N l^{-1}. Moreober, an analysis of the distribution of NO23 values at station LE3.2 indicates that prior to 1992 more than 10% of the values were exactly 0.5 mg N l^{-1}. These results conflict with EPA (1992), which indicates much lower method detection limits. It also appears that some kind of censoring of maximum values occurred, although this is difficult to demonstrate. For the purpose of this analysis, the effect of the MDL decrease was considered explicity, but there was no action taken to account for possible censoring of peak concentrations.

There was a change in the MDL for TSS near the end of 1988. According to the variable SOURCE all observations were from VA/VWCB, which according to EPA (1992) had an MDL for TSS of 4 mg l-1 though August 1988. It then dropped to 2 mg l^{-1}. According to observations flagged as below MDL, MDLs were 5 mg l^{-1} through most of 1988, dropped to 1 mg l^{-1}, then increased again to 3 mg l^{-1} in 1991. The effect of these changes in MDL have the potential to affect the results for areas with low TSS; however, the effects are not as severe as for NO23. Due to likely small effect of this MDL change, no explicit treatment of this problem was applied for these analyses.

The USGS river flow record spanned the entire period of record of the CBMP data with the exception of the Mattaponi River, for which data for 1988 were missing. River discharge rate was measured continuously at USGS gauging stations on the Rappahannock River at Fredericksburg, VA, the Mattaponi River at Beulahville, VA, the Pamunkey River at Hanover, VA, the James River at Richmond, VA and the Appomattox River at Matoaca, VA. Information regarding these gauging stations and their watersheds is summarized in Table 3. Statistics for the York River were generated by adding the data for the Pamunkey and Mattaponi Rivers. The 1988 monthly mean discharge of the Mattaponi River and was estimated via a linear regression model. The monthly mean discharges for the Mattaponi River (1985-1996, excluding 1988) were well predicted (r^2=0.91) by the monthly mean discharge of the Pamunkey River, thereby allowing estimates of the missing data to be generated with a high degree of confidence.

The USGS nutrient loading estimates were only available for a few years, plus several partial years. Data from 1988 into 1993 were obtained from Belval et al. (1995), while data for part of 1995 through 1996 were obtained from H. Johnson (USGS, personal communication). The 1995-96 data are provisional and should be considered subject to change. For the remaining years, it was necessary to estimate the nutrient loading rates via the relationship between annual mean nutrient loading rates and annual mean river discharge rates. While such simple regressions are not adequate to predict daily nutrient loading rates, they appear more than adequate to predict the annual mean nutrient loads.

Interpolatation Procedures

For the purpose of calculating certain spatially averaged or totalled parameters, some water quality variables were interpolated to a regular grid covering each of the estuaries. This was accomplished using a linear spline as described in Hagy (1996). Interpolations were checked for gross errors by creating color-coded raster images of the interpolated field and scanning them visually.

Hypoxic Volumes

Hypoxic volumes were calculated by merging the interpolated dissolved oxygen (DO) profiles to the volume data of Cronin and Pritchard (1975), then summing the volumes of cells with DO less than the identified threshold. Annually integrated measures of hypoxia (i.e. hypoxic volume-days) were calculated by calculating the area under a linear spline fitted to the time series of hypoxic volumes.

Results and Discussion

Fall Line River Discharge, 1985-1996.

The long term mean (1985-1996) fall line discharge for the James River is much larger than for the other two rivers due to it's larger watershed; however, when normalized to area, the yield from the James watershed (0.39 m y^{-1}) and the Rappahannock watershed (0.38 m y^{-1}) are almost identical, while that of the York watershed (0.32 m y^{-1}) is somewhat less. Annual mean discharges from the Rappahannock and York Rivers both had a coefficient of variation (CV) of 39%, while the larger James River watershed was slightly less variable (CV=27%). The total range in annual mean flows was 300% for the Rappahannock and approximately 200% for the York and James Rivers. Over the period 1985-1996, three years were especially dry in all the basins (1986, 1988, 1991), while three years were especially wet (1993, 1995, 1996; Figure 3). In other years, departures from average hydrologic conditions occurred in some of the basins, but not all. Overall, the wettest years occurred in the 1990's, a pattern accentuated by the extraordinarily high river discharge in 1996. River flow in 1989 was unusual in that the peak discharge occurred later than in most years, a pattern observed throughout the Chesapeake Bay region.

The amount of variability in annual mean river flow for these rivers is about typical of what is found in many river basins. From an ecological perspective, the variations in flow are likely to be important. The prevalence of wet years during the middle 1990s and drier years in the earlier part of the data record makes it difficult or impossible to separate real trends that might have been observed under average hydroligic conditions from flow-driven ecological effects. An exception is that the low flow year in 1995 followed immediately by the high flow year in 1996 presents a unique opportunity to investigate flow effects separately from other changes in the estuary or its watershed.

Table 3. Statistics describing Virginia western shore tributary basins and their USGS flow gauging stations. The data are from the USGS WWW site (http://h2o-nwisw.er.usgs.gov/nwis-w/VA/). Ungauged watershed areas are from Gutierrez-Magness et al. (1997).

Basin Name	USGS Gauge Number	Gauged Area (km^2)	Ungauged Area (km^2)	Datum (m above NGVD*)	Mean Discharge ($m^3 s^{-1}$)
Rappahannock	01668000	4134	2533	16.8	50.8
York River	n/a	4357	2382	n/a	44.6
Mattaponi	01674500	1557		3.8	
Pamunkey	01673000	2800		4.5	
James	n/a	20984	4109	n/a	250.4
James	02037500	17503		30.1	
Appomattox	02041650	3481		20.8	

* National Geodetic Vertical Datum of 1929, an elevation very close to sea level.

Fall Line USGS-Estimated Sediment and Total Nitrogen Loading Rates

Where possible, calendar year means of sediment (TSS) and total nitrogen (TN) loading rates were calculated for each of the rivers (Table 4). For other years, annual mean loading rates were estimated on the basis of their correlation with annual mean river discharge. Annual mean TN loading rates were well correlated with annual mean river flow for all the rivers (Figure 4). The annual mean TSS loading rates were also well correlated with annual mean river flow for the Rappahannock and York Rivers, but not as well for the James River (Figure 5). The estimated regression parameters are summarized in Table 5, while the estimated annual mean loading rates for for each river are summarized in Table 6a,b.

Based on the USGS-estimated loads alone, there were clear differences in TN and TSS loading rates that were not related to watershed size. The York river had by far the lowest TN and TSS loading rates when scaled to watershed area, while the Rappahannock River had the highest loading rates. In particular, the Rappahannock TSS load per watershed area was 10 times the rate for the York River and more than 2.5 times the rate for the James River. The differences for TN loading were less dramatic but not trivial. In comparison, the area-scaled fall-line average TN loading rate for Patuxent River for the the same years (1990-1992, 1996), was 2.41 kg d^{-1} km^{-2}, much higher than for any of the Virginia rivers. This probably reflects the prevalence of urban land uses and point source nitrogen sources in the Patuxent River watershed relative to the Virginia rivers.

Table 4. Calendar year mean total nitrogen (TN) and total suspended solid (TSS) loads (kg d^{-1}) at the fall lines for the Rappahannock, York and James River. The data are from Belval et al. 1995. The York River loads are the sum of the Mattaponi and Pamunkey River loads, while the James River loads are the sum of the James River and the Appomattox River loads.

	Rappahannock		York		James	
Year	TN	TSS	TN	TSS	TN	TSS
1989	5,849	1,413,817				
1990	5,841	706,600	2,854	114,094	17,952	1,468,081
1991	3,441	248,969	1,374	58,906	14,539	1,047,636
1992	5,468	639,558	1,696	59,653	15,030	1,412,826
1996	11,451	2,386,701	4,129	179,495	27,874	3,923,034
Mean (kg d^{-1})	6,550*	995,457*	2,513	103,037	18,849	1,962,894
kg d^{-2} km^{-2}	1.58	240.8	0.58	23.65	0.90	93.54

*To make the means comparable, the Rappahannock River means do not include 1989.

Table 5. Estimated parameters for regressions relating annual mean fall line total suspended solids and total nitrogen loading rates to annual mean fall line river discharge rates. The regression models have the form $Y=\alpha+\beta x$.

Basin	Total Nitrogen		Total Suspended Solids	
	α (kg d^{-1})	β ((kg d^{-1}) (m^3 s^{-1})$^{-1}$)	α (kg d^{-1})	β ((kg d^{-1}) (m^3 s^{-1})$^{-1}$)
Rappahannock	-600	121	$-7.48(10^5)$	$3.16(10^4)$
York	202	53	-2496	2408
James	-5583	90	$-3.09(10^6)$	$1.87(10^4)$
Pamunkey	97	54	1622	2975

Table 6a. Annual mean fall line total nitrogen (TN) loading rates (kg N d^{-1}) for the Rappahannock, York, James Rivers and Pamunkey Rivers, estimated where not present in Table 4 using the linear regressions on river flow in Table 5. The York River loads are the sum of the Mattaponi and Pamunkey River loads, while the James River loads are the sum of the James River and the Appomattox River loads. The loading rates for 1986 and 1988 were not estimated for the James River because the regression model predicted negative loading rates. This indicates that extrapolation outside the range of the existing data may not be appropriate, but does not invalidate the model within the range of the data.

Year	Rappahannock	York	James	Pamunkey
1985	4654	2653	16835	1808.34
1986	2414	1638		1054.28
1987	4811	3102	20590	1901.68
1988	2737	1704		1095.93
1989	5849	2278	21886	1498.67
1990	5841	2854	17952	1957.17
1991	3441	1374	14539	1019.42
1992	5468	1696	15030	1168.17
1993	7588	3547	21618	2385.66
1994	6655	3687	19189	2490.35
1995	5629	2071	15210	1436.55
1996	11451	4129	27874	2977.43

Table 6b. Annual mean fall line total suspended solids (TSS) loading rates (kg d^{-1}) for the Rappahannock, York, James Rivers and Pamunkey Rivers, estimated where not present in Table 4 using the linear regressions on river flow in Table 5. The York River loads are the sum of the Mattaponi and Pamunkey River loads, while the James River loads are the sum of the James River and the Appomattox River loads. The loading rates for 1986 and 1988 were not estimated for the James River because the model predicted negative loading rates. This indicates that extrapolation outside the range of the existing data may not be appropriate, but does not invalidate the model within the range of the data.

Year	Rappahannock	York	James	Pamunkey
1985	624119	108880	1568002	95163
1986	39014	62728		53954
1987	665000	129264	2348184	100263
1988	123455	65742		56230
1989	1413817	91818	2617521	100582
1990	706600	114094	1468081	97225
1991	248969	58906	1047636	51909
1992	639558	59653	1412826	52018
1993	1390227	149475	2561813	126712
1994	1146578	155849	2057025	132434
1995	878781	82400	1230298	74845
1996	2386701	179495	3923034	151082

Annual Mean Surface Water Quality in the Virginia Tributaries

Annual means of chlorophyll-a, total suspended solids (TSS) and nitrate plus nitrite (NO23) were calculated for surface water at several stations along the salinity gradient of the three Virginia rivers. These were then related to total nitrogen (TN) loading rate (chlorophyll-a, NO23) or total suspended solids (TSS) loading rate (TSS concentration), and to each other. For the purpose of making a fair comparison of annual mean NO23 when the method detection limit changed, an adjustment was made to 1994-96 observations. A new variable was defined in which 1994-96 nitrate observations below the 1985-1990 detection limit were increased to that level. Both the new variable and the original values were retained for the analysis.

Known processes in estuarine circulation, biogeochemistry, and ecology offer several alternative mechanisms to explain each of the possible responses to inputs of freshwater, nitrogen and sediments. Experience with water quality patterns in Patuxent River suggests that different responses will be observed in different regions of the estuary, and that each relationship may very likely be punctuated by a few outlier observations resulting from unique convergences of circumstance. Thus, the initial objective is to characterize the direction and predictability of the response of water quality to fall line water, nitrogen and sediment inputs. Where possible, we may speculate which mechanisms probably dominated the response. A few of the typical types of responses are discussed briefly below.

Hagy (1996) concluded that in the tidal fresh reaches of Patuxent River, chlorophyll-a concentrations decrease when river flow increases, even though net production of phytoplankton apparently increases. This was attributed to the dilution effect of higher river flow. In contrast, the same study found that increased river flow and TN loading accelerated phytoplankton net production in the lower Patuxent estuary, probably by increasing the nutrient supply to the lower estuary, and was associated with high chlorophyll-a concentrations. Since residence times for the lower estuary were barely affected by increases in Patuxent River discharge (Hagy 1996), the flow-induced flushing that appeared to dominate water quality patterns in the tidal fresh region did not dominate the lower Patuxent. These two types of water quality patterns and the associated mechanisms serve as a point of departure for an analysis of the same relationships in the Rappahannock, York, and James Rivers. In addition, it should be noted that additional mechanisms are possible and are likely to be important at some times and in some places. For example, light limitation of phytoplankton production can occur in a relatively deeply mixed and turbid body of water (e.g. Hudson River, Howarth et al. 1996), resulting in a lack of nutrient-driven effects, but leaving the possibility of other flow effects related to mixing depth or suspended sediment concentrations.

Table 7. The mean surface water concentrations of chlorophyll-a (Chla-a), nitrate plus nitrite (NO23) and total suspended solids (TSS) along the salinity gradients of the Patuxent River and the three major Virginia Rivers over the period of record. The arrows in parentheses indicate the effect of TN loading (Chl-a and NO23) or TSS loading (TSS). The means were calculated using an additive linear model (model effects include station, year, month, station*year, station*month) to prevent bias resulting from missing values and inconsistent sampling frequency. Station TF4.2 is in the Pamunkey River and the responses indicated are relative to Pamunkey River loadings. Nitrate plus nitrite concentrations for the Virignia rivers that were below 4.28 µM were adjusted upward to that level to ensure comparability of annual means after a decrease in the detection limit.

Basin	Tidal Fresh	Transition	Lower Estuary
Patuxent	PXT0402	XED4892	XDE5339
Chla (µg l^{-1})	31.4 (↓)	18.2 (nc)	11.9 (↑)
NO23 (µM)	69.3 (↑)	38.2 (↑)	8.4 (↑)
TSS (mg l^{-1})	36.1 (nc)	38.8 (nc)	10.4 (↑)
Rappahannock	TF3.3	RET3.2	LE3.2
Chla (µg l^{-1})	7.86 (↑)	12.8 (↓)	9.2 (nc)
NO23 (µM)	25.5 (nc)	11.0 (↑)	6.6 (↑)
TSS (mg l^{-1})	37.1 (↓)	20.9 (↓)	8.4 (↓)
York	TF4.2	RET4.3	LE4.2
Chla (µg l^{-1})	4.5 (↓)	11.1 (nc)	10.3 (↑)
NO23 (µM)	19.0 (nc)	10.7 (nc)	5.7 (↑)
TSS (mg l^{-1})	16.8 (nc)	37.4 (↑)	17.3 (↑)
James	TF5.6	RET5.2	LE5.3
Chla (µg l^{-1})	12.6 (nc)	12.1 (↑)	10.3 (nc)
NO23 (µM)	37.2 (↓)	25.4 (↓)	13.0 (↑)
TSS (mg l^{-1})	25.4 (↑)	41.0 (↑)	17.6 (↓)

Nitrogen, Chlorophyll-a and TSS in the the Rappahannock River, 1985-1996

Relative to the other estuarine areas considered, the tidal fresh Rappahannock River (TF3.3) is a low chlorophyll-a, high nitrate, high suspended solids environment (Table 7). This may be related to the high nitrogen and sediment yield per watershed area for the Rappahannock watershed compared to the other Virginia tributaries (Table 4). However, nitrate levels were 50-75% less than in the tidal fresh Patuxent River. As river flow, TN loading, and TSS loading increased, TSS concentrations tended to decrease slightly while chlorophyll-a increased (Figure 6). The highest TSS concentrations were associated with the lowest chlorophyll-a concentrations. This suggests that light limitation was the major factor controlling phytoplankton production and biomass in the upper Rappahannock River. Moreover, it is reasonable to hypothesize that increased flow diluted the suspended sediment load, or otherwise reduced the light limitation, allowing higher phytoplankton production and biomass.

The highest chlorophyll-a concentrations in the Rappahannock River were found in the middle portion of the estuary (RET3.2; Table 7). When river flow, TN loading and TSS loading increased, chlorophyll-a and TSS in this area of the estuary tended to decrease, while nitrate concentrations increased. This also suggests that nutrient limitation was not the principal control on phytoplankton production and biomass. Increased flushing may be responsible for the decrease in both chlorophyll-a and TSS under higher flow conditions. The increase in nitrate concentration with river flow is probably associated with both higher nutrient delivery and lower nitrogen uptake by phytoplankton. Figure 6 illustrates the uncertainty imposed by the previously method detection limits. Since more observations are probably affected by the detection limit in years with low TN loading than in other years, the increase in NO23 with TN loading may be greater than is indicated by the data.

TSS, and nitrate concentrations were much lower in the lower Rappahannock River estuary (LE3.2) than in the tidal fresh region, but chlorophyll-a was slightly higher. There was no clear relationship between TN loading and chlorophyl-a or between TSS loading and TSS concentrations. However, there was a broadly expressed increase in nitrate concentrations as TN loading rate increased. This suggests that higher TN loading and river flow at the Rappahannock River fall line increased nutrient delivery to the lower estuary, but that a range of competing mechanisms precluded a strong response by the phytoplankton community. Additionally, the effect of interactions with Chesapeake Bay may be strong in the lower Rappahannock. These interactions could mimic a response to Rappahannock River TN loading since river discharge rates in different basins are correlated. More specific conclusions will require ana analysis directed at evaluating specific mechanisms. An example of such a detailed analysis would include estimating the flushing processes accross the mouth of the estuary. This could be approached with a salt and water balance model (i.e. "box" model).

Nitrogen, Phytoplankton and TSS in the York River, 1985-1996

Because the York River divides into the Mattaponi and Pamunkey River before becoming tidal fresh, we focused on the Pamunkey River (TF4.2) branch for analysis of the tidal fresh portion of the York River. The tidal fresh Pamunkey river had lower concentrations of chlorophyll-a, nitrate, and TSS than the tidal portions of the other rivers. Chlorophyl-a was lower than at any location in any of the rivers examined. Moreover, as flow increased, chlorophyll-a decreased linearly to extremely low levels for an estuary (Figure 7), even as nitrate and TSS remained unchanged (Table 7).

The middle estuary of the York River (RET4.3), just downstream from West Point, is characterized by levels of chlorophyll-a, TSS and nitrate in the same range as the middle reaches of the Rappannock River. Average chlorophyll-a and nitrate were 50-75% less than the Patuxent River. There was no monotonic relationship between TN loading rate and chlorophyll-a, although the data suggested a hypobolic relationship where the highest chlorophyll-a was associated with intermediate loading levels. This may indicate the potential for nutrient limitation at low loading levels and flushing effects or light limitation at the highest river flow and loading levels. This is supported by a clear increase in TSS concentration with TSS loading, a pattern observed in the middle Patuxent River, but not observed in the middle Rappahannock River.

The lower York river had low annual mean chlorophyll-a, moderate TSS levels, and especially low nitrate levels. Chlorophyll-a increased with TN loading rate, as did TSS with TSS loading. There is also an increase in nitrate with TN loading (Figure 7), although the pattern would be invisible were is not for the 1992 decrease in the detection limit. Chlorophyll-a and TSS are positively correlated, as in the middle York River and the lower Patuxent River. These patterns strongly suggest nutrient-driven patterns in water quality, rather than light-limitation or control by flushing processes.

Nitrogen, Phytoplankton and TSS in the James River, 1985-1996

The tidal fresh James River (TF5.6) had lower chlorophyll-a, NO23 and TSS concentrations than the tidal fresh Patuxent River, but higher levels tham the other two Virginia tributaries (Table 7). Chlorophyll-a and TSS increased slightly or did not change with increasing river flow, while nitrate clearly decreased as river flow increased (Figure 8). Additionally, a marked decrease in NO23 concentrations, potentially related to management actions, was observed for the 1994-96 observations.

Chlorophyll-a and TSS in the middle portion of the James River (RET5.2) increased with flow to a greater extent than in the tidal fresh portion of the river. In contrast, NO23 concentrations decreased with increaseing river flow, but not in as pronounced a way as in the tidal fresh portion of the river. Moreover, in 1994-96, NO23 concentrations were slightly lower and did not decrease further as river flow and TN loading rate increased.

In the lower James River (LE5.3), there was a positive relationship between chlorophyll-a and TN loading rate. NO23 concentrations also increased strongly with increasing river flow, opposing the trend observed in the tidal fresh region of the estuary (Figure 8). NO23 concentrations increased with TN loading rates between 1994 and 1996 at a similar rate as earlier in the record, but with lower concentrations on average. This may be a direst result of implementation of biological nitrogen removal at the 37.2 MGD Hampton Roads Sanitation District-VIP sewage treatment plant, which occurred in June 1991 (A. Butt, personal communication).

Hypoxia in the Virginia Rivers

Seasonal depletion of dissolved oxygen from waters below the pycnocline (hypoxia), is a feature of Rappahannock River and York River, but not the James River (Figure 9). However, the predicability, duration and intensity of hypoxia is lower in the Virginia Rivers than in Patuxent River and the Maryland Mainstem of Chesapeake Bay. The lack of any hypoxia during 1991 in any of the Virginia estuaries underscores this observation.

To make a first-order comparison of hypoxia in the 3 Virginia Rivers, Patuxent River and Chesapeake Bay, an index was created that expressed the observed hypoxia as a fraction of the maximum amount of hypoxia possible. Although a more rigorous analysis is possible, for the present time is was assumed that the surface mixed layer has 3 times the volume of the bottom layer mixed. Therefore, only 25% of the total volume could potentially be hypoxic. Additionally, even in the most hypoxia-prone areas, hypoxia is rarely observed outside of June through August, about 90 days. Hence, the theoretical maximum postulated here is that hypoxia could affect 25% of the total estuarine volume for a period of 90 days. For each basin, we scaled the the 1986-1995 average hypoxic volume-days to the number of volume-days available in the respective basin under this assumption (Table 8). This comparison indicates that Rappahannock River had nearly 2.5 times the hypoxia of York River, but only half the hypoxia of Patuxent River and one third that of Chesapeake Bay.

These differences in the hypoxia index are predicted by the whole-watershed TN loading rates for the estuaries scaled to the surface area of the estuary (Figure 12). The whole-watershed TN loading rate were estimated for each of the Virginia estuaries by dividing the average fall line TN loading rate by the fraction of the watershed that is above the fall line. More rigorous estimates of TN loading for the Maryland portion of Chesapeake Bay, Choptank River and Patuxent River were obtained from Boynton et al. (1995). This relationship indicates that across basins with similar geomorphology and estuarine circulation (with the exception of the Choptank River), the severity of seasonal dissolved oxygen problems can be predicted to some extent by the TN loading rate. The James River is anamalous in that hypoxia is lower than expected from the TN loading rate. One potential explanation is that the source for the water exchanged with Chesapeake Bay is very close to the Atlantic Ocean and potentially less metabolically active. Hypoxia in Patuxent River may be exacerbated by its exchange with Chesapeake Bay.

Table 8. Relative hypoxia in several tributary estuaries in the Chesapeake Bay Region. To compare basins of different size, the annual mean hypoxia was scaled to total volume-days per year.

Basin	Annual Mean Hypoxia, DO<3 mg l^{-1} (10^9 m^3 d)	Hypoxia Index (%)
Rappahannock	12.34	31
York	2.67	13
James	0	0
Patuxent	8.69	59
Chesapeake Bay	1,050	91

Year to year variations in hypoxia can also be related to water year mean TN loading or river discharge. While these two variables are often well correlated, changes in watershed and management actions lead to departures from the correlations. As a consequence, the regressions predicting hypoxia are not necessarily equivalent. In the case of Patuxent River, water year river discharge predicts hypoxia better than water year TN loading rate (Figure 11). This is somewhat surprising considering that Hagy (1996) found evidence that bottom water oxygen demand increased in Patuxent River with river flow, while vertical diffisive exchange did not appear to change dramatically. One possibility is that the hydrological factors that drive river flow changes also affect Susquehanna River discharge, a potentially important factor in Patuxent River hypoxia. In contrast, basin-specific changes in Patuxent River TN loading apart from those caused by flow are not necessarily correlated with loading to Chesapeake Bay loading.

Hypoxia in both Rappahannock and York Rivers was predicted by both water year river flow and water year TN loading. TN loading estimates for this analysis were derived from the CBP HSPF watershed. Rappahannock River hypoxia was variable at TN loading rates less than 6000 kg d^{-1}, but became relatively more predicable at higher loading rates. Prediction limits indicate that hypoxia may be absent in years with less than 5000 kg d^{-1} average TN load. In contrast, hypoxia in York River was highly variable at all levels of loading, and a lack of hypoxia was a likely possibility at any of the observed levels of TN loading. This may be due to the fact that hypoxia is always low in the York River compared to the Rappahannock and Patuxent Rivers. York

River hypoxia in 1993 was much higher than predicted by the regression, perhaps because hypoxia was very severe in Chesapeake Bay in that year.

Summary

The Rappahannock, York and James Rivers each exhibit responses in their estuarine receiving waters to inputs at their fall lines. However, these responses are not identical in each of the rivers, nor are they identical to Patuxent River in their responses. Chlorophyll-a in the tidal fresh portions of both the York and James Rivers exhibited the same decline with increased river flow and TN loading as was obsered in the tidal fresh Patuxent River. Similarly, NO23 concentrations in these rivers increased with TN loading, indicating the potential for nutrient-driven increases in phytoplankton production and biomass. However, these increases were not obvious as in the case of Patuxent River. Nutrient management action appears to have reduced the NO23 concentration observed in the lower James River at any given TN loading rate at the fall line. Some of the water quality patterns in these estuaries are very remarkable and merit further investigation. In particular, it would be worthwhile to investigate the extent of light-limitation of phytoplankton growth rates and the role of flushing processes in regulating water quality in these estuaries.

The average severity of hypoxia within sub-estuaries in the Chesapeake Bay system is related to the average TN loading rates. Moreover, hypoxia in Patuxent River, Rappahannock River, and York River in any one year is positively correlated with TN loading in that year. This suggests that although hypoxia in the York and Rappahannock Rivers is relatively mild under current TN loading regimes, it will probably worsen if TN loading rates are allowed to increase significantly. Moreover, the extent of change may be readily predicable.

References

Belval, D. L., J. P. Campbell, S. W. Phillips, and C. F. Bell. 1995. Water-quality characteristics of five tributaries to the Chesapeake Bay at the fall line, Virginia, July 1988 through June 1993. U.S. Geological Survey. Water-Resources Investigations Report 95-4258.

Boynton, W. R., J. H. Garber, R. Summers, and W. M. Kemp. 1995. Inputs, transformations, and transport of nitrogen and phosphorus in Chesapeake Bay and selected tributaries. *Estuaries*. 18(1B): 285-314.

Cronin, W. B. and D. W. Pritchard. 1974. Additional statistics on the dimensions of the Chesapeake Bay and its tributaries: Cross-section widths and segment volumes per meter depth. Chesapeake Bay Institute. The Johns Hopkins University. Reference 75-3. Special Report 42. April 1975.

EPA. 1992. Guide to Using Chesapeake Bay Program Water Quality Monitoring Data. US EPA Chesapeake Bay Program. Annapolis, MD.

Guiterrez-Magness, A. L., J. E. Hannawald, L. C. Linker, and K. J. Hopkins. 1997. Chesapeake Bay Watershed Model Application & Calculation of Nutrient & Sediment Loadings. Appendix E: Phase IV Watershed Land Use & Model Linkages to the Airshed & Estuarine Models. Modeling Subcommittee of the Chesapeake Bay Program. US EPA Chesapeake Bay Program. Annapolis, MD.

Hagy, J. D. 1996. Residence times and net ecosystem processes in Patuxent River estuary. M.S. Thesis. University of Maryland College Park. College Park, MD.

Howarth, R. W., R. Schneider, and D. Swaney. 1996. Metabolism and organic carbon fluxes in the tidal freshwater Hudson River. *Estuaries*. 19(4): 848-865.

Langland, M. J., P. L. Lietman, S. Hoffman. 1995. Synthesis of nutrient and sediment data for watersheds within the Chesapeake Bay drainage basin. U. S. Geological Survey. Water-Resources Investigations Report 95-4233.

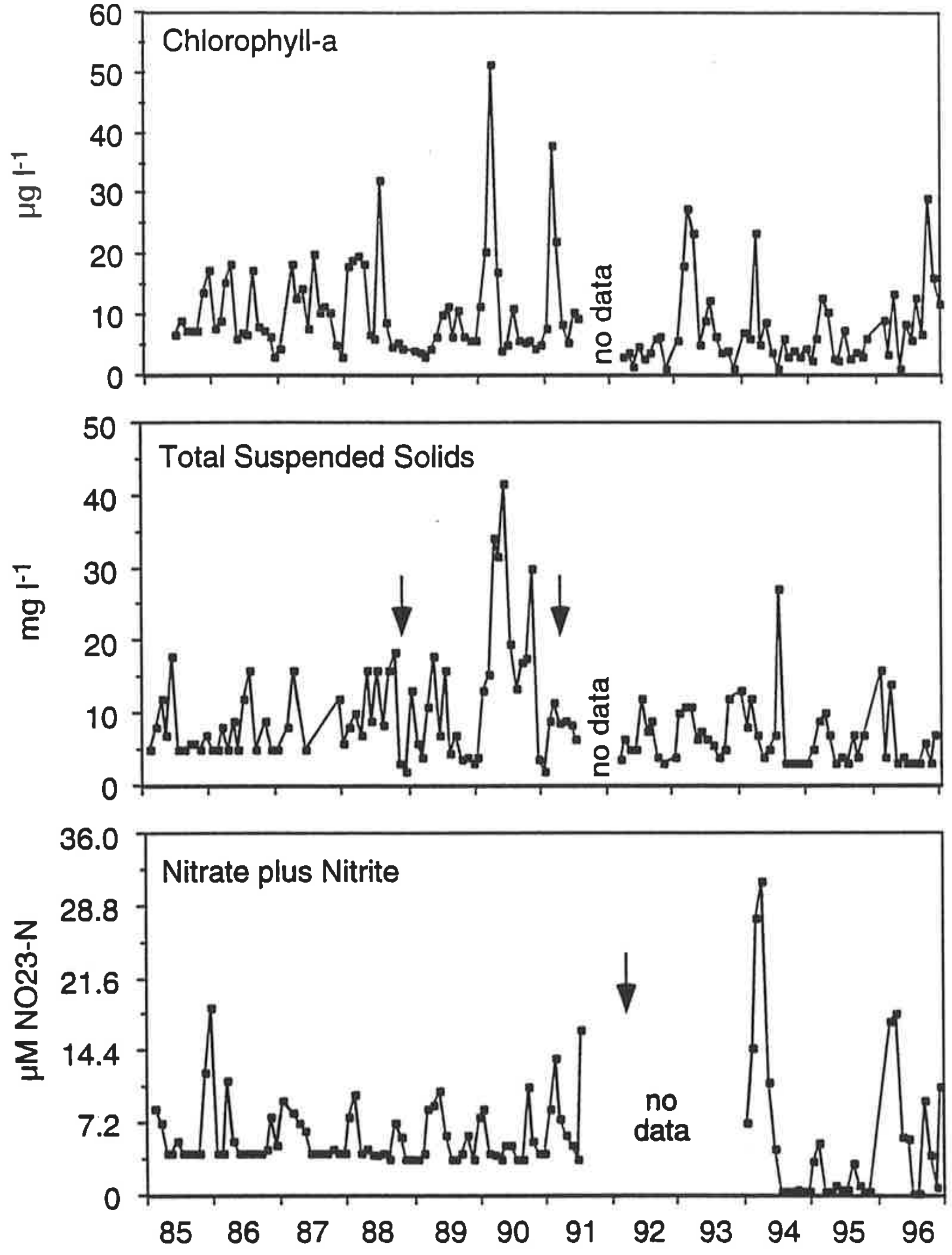


Figure 2. A time series of Chlorophyll-a, total suspended solids (TSS) and nitrate plus nitrite (NO23) in surface water at station LE3.2 in the lower Rappahannock River. Method detection limit changes were documented for TSS and NO23 where indicated by arrows. No method changes were indicated for chlorophyll-a.

FiG 1 IS A MAP OF VA TRIBS.

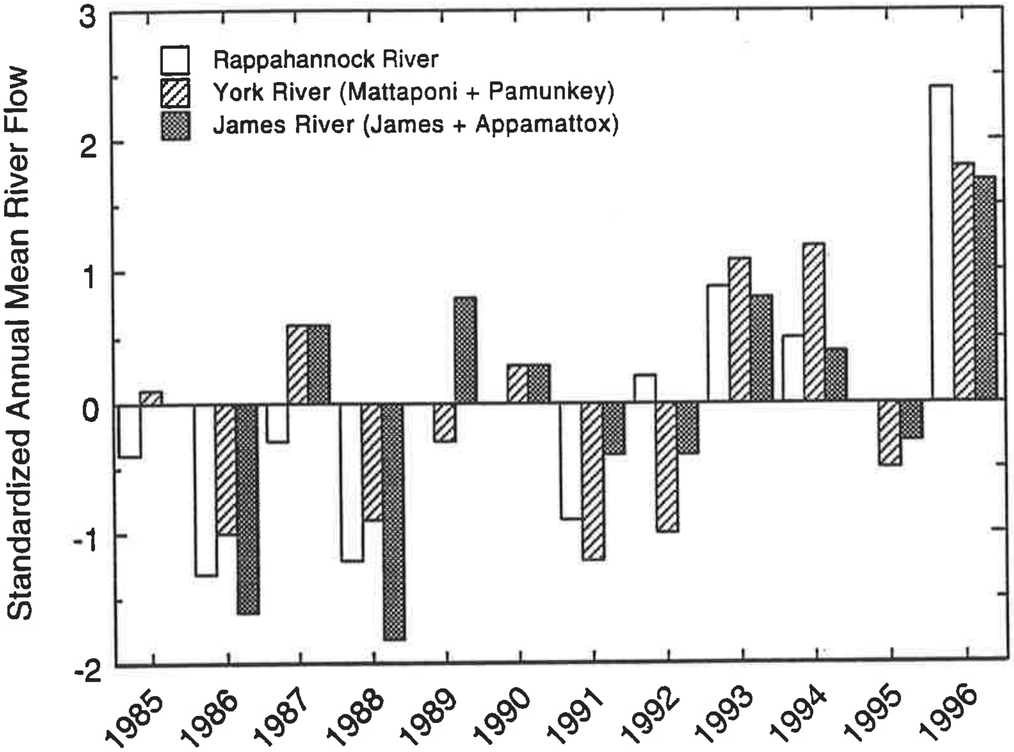


Figure 3. The stardized fall line river discharge from the Rappahannock River, York River, and James Rivers from 1985-1996. The discharge from the York is calculated as the sum of the Pamunkey and Mattaponi Rivers, while the James River flow is the sum of the James River at Richmond and the Appamattox River. Because there are no flow data for the Mattaponi River during 1988, that component of the York River flow was estimated from a regression of monthly mean Mattaponi River flow on monthly mean Pamunkey River flow. The standarized values are calculated using $z = (x - \bar{x})/s$

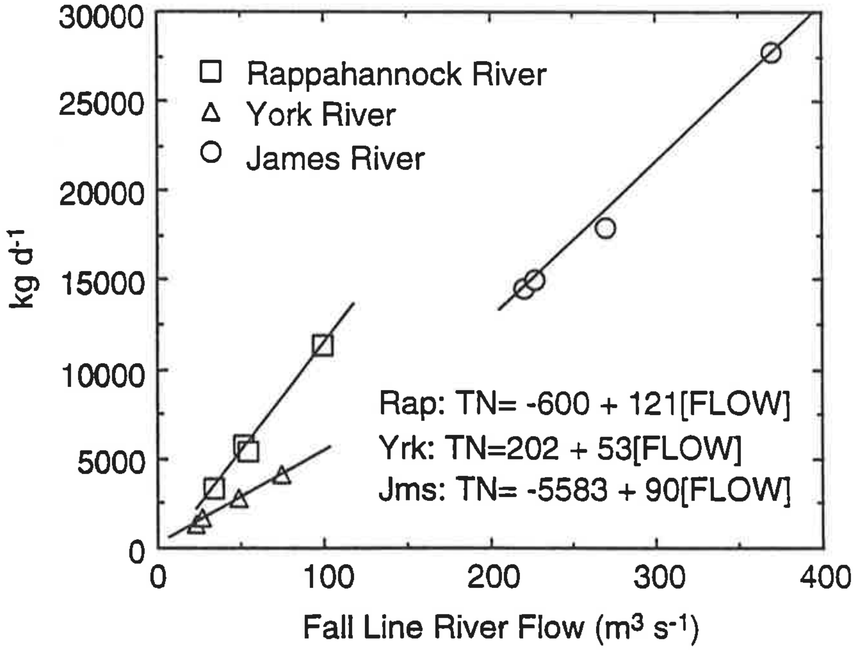
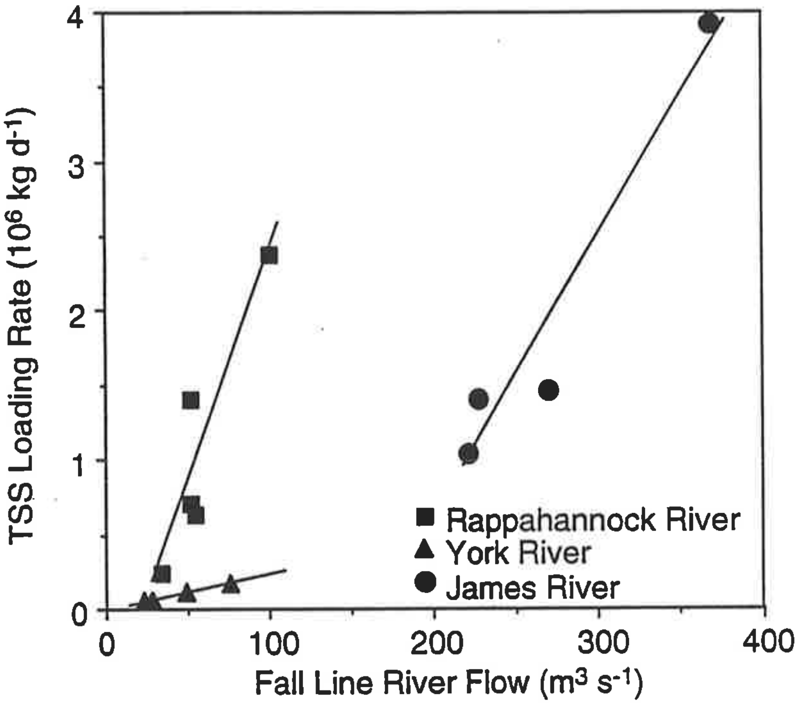


Figure 4. The relationships between annual (calendar year) mean fall line river discharge and the annual mean fall line total nitrogen (TN) loading rate as estimated by the USGS for the three major Virginia western shore tributary estuaries. The loads and flows for the York River are the sum of the loads and flows for the Pamunkey and Mattaponi Rivers, while the same for the James River is the sum of the James River and Appamattox Rivers. In each case, the r^2 for the model is greater than 0.99.



R: $TSS = -7.48(10^5) + 3.16e(10^4)(FLOW) \quad r^2 = 0.85$

Y: $TSS = -2496 + 2408(FLOW) \quad r^2 = 0.99$

J: $TSS = -3.09(10^6) + 1.87(10^4)(FLOW)$

Figure 5. The relationships between annual (calendar year) mean total suspended solids (TSS) loading rate and annual mean fall line river flow for the Rappahannock, York and James Rivers. The coefficient of determination (r^2) has been omitted for the James River because the estimate is invalidly dominated by the 1996 observation.

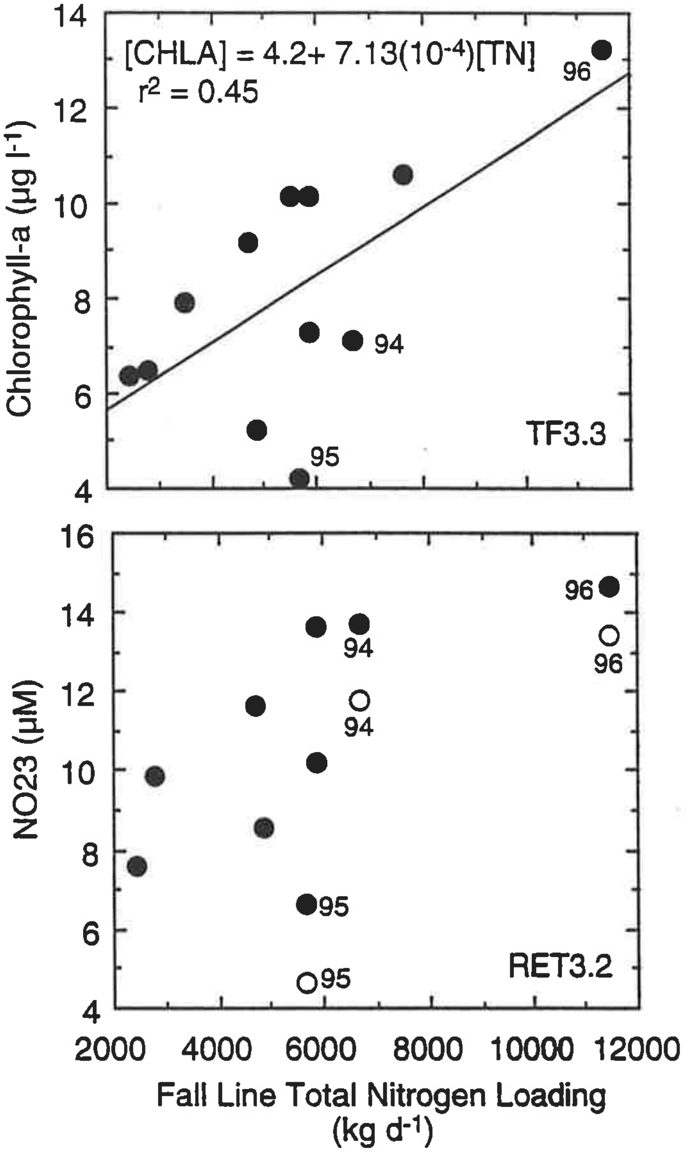


Figure 6. Annual mean surface chlorophyll-a at TF3.3 in the tidal fresh Rappahannock River (upper panel) and annual mean surface NO23 at RET3.2 in the middle Rappahannock (lower panel) related to Rappahannock River fall line TN loading rates for 1985-1996. The 1994-96 NO23 observations have been adjusted upward to correct for the decrease in detection limit that occurred in 1992. The open circles show the unadjusted concentrations for 1994-96.

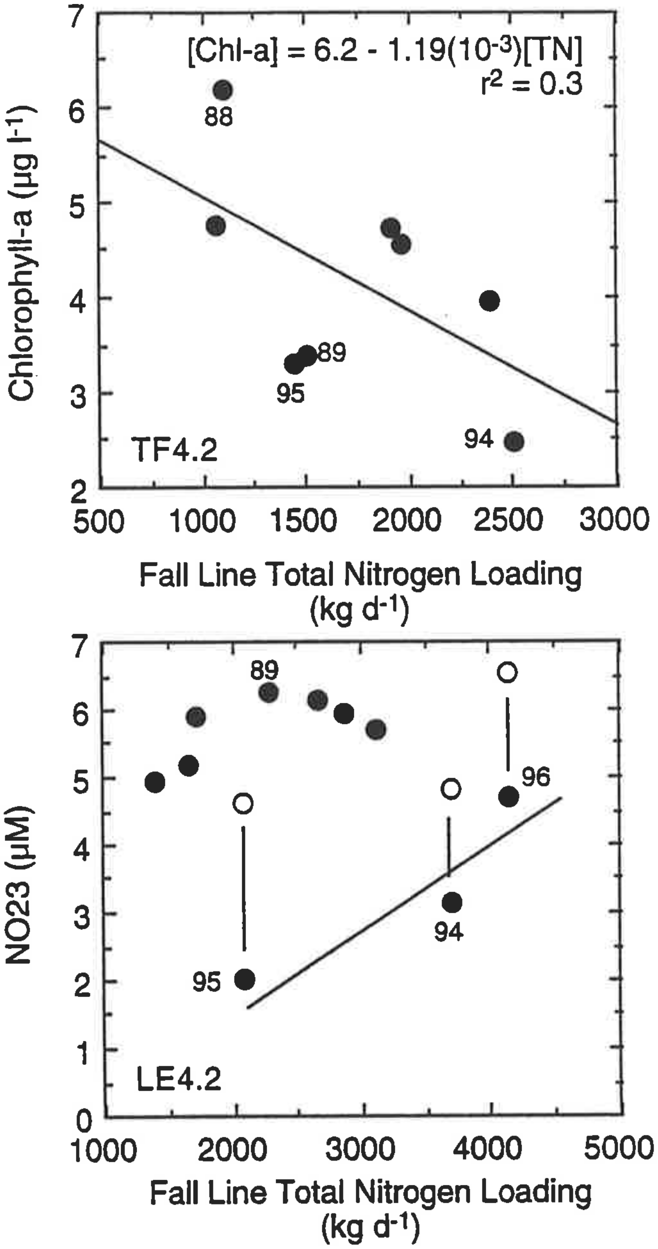


Figure 7. Annual mean surface chlorophyll-a at TF4.2 in the tidal fresh Pamunkey River (upper panel) and annual mean surface NO23 at LE4.2 in the lower York River(lower panel) related to York River fall line TN loading rates for 1985-1996. The 1994-96 NO23 observations have been adjusted upward to correct for the decrease in detection limit that occurred in 1992. The open circles show the unadjusted concentrations for 1994-96. The trend line is hand-drawn.

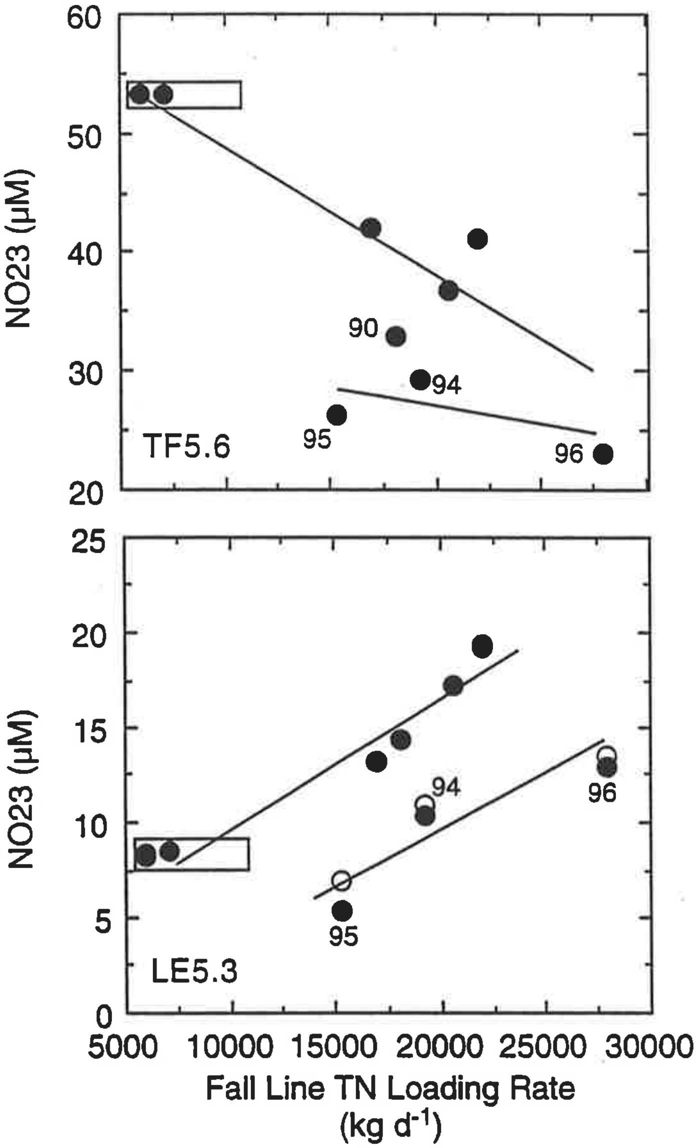


Figure 8. Annual mean surface nitrate plus nitrite (NO23) in the tidal fresh James River (TF5.6; upper panel) and the lower James River (LE5.3; lower panel) related to annual mean fall line total nitrogen loading rates. Because river flow in 1986 and 1988 was outside the range of flow rates for which TN loading rates were estimated (Figure 4), it is possible that the loading rates were higher than shown, but within the rectangle indicated. The open circules in the lower panel indicate the NO23 concentrations that would have been reported in 1994-96 had the detection limits not decreased in 1992. The regression lines are for either 1985-1992 or 1994-96 observations.

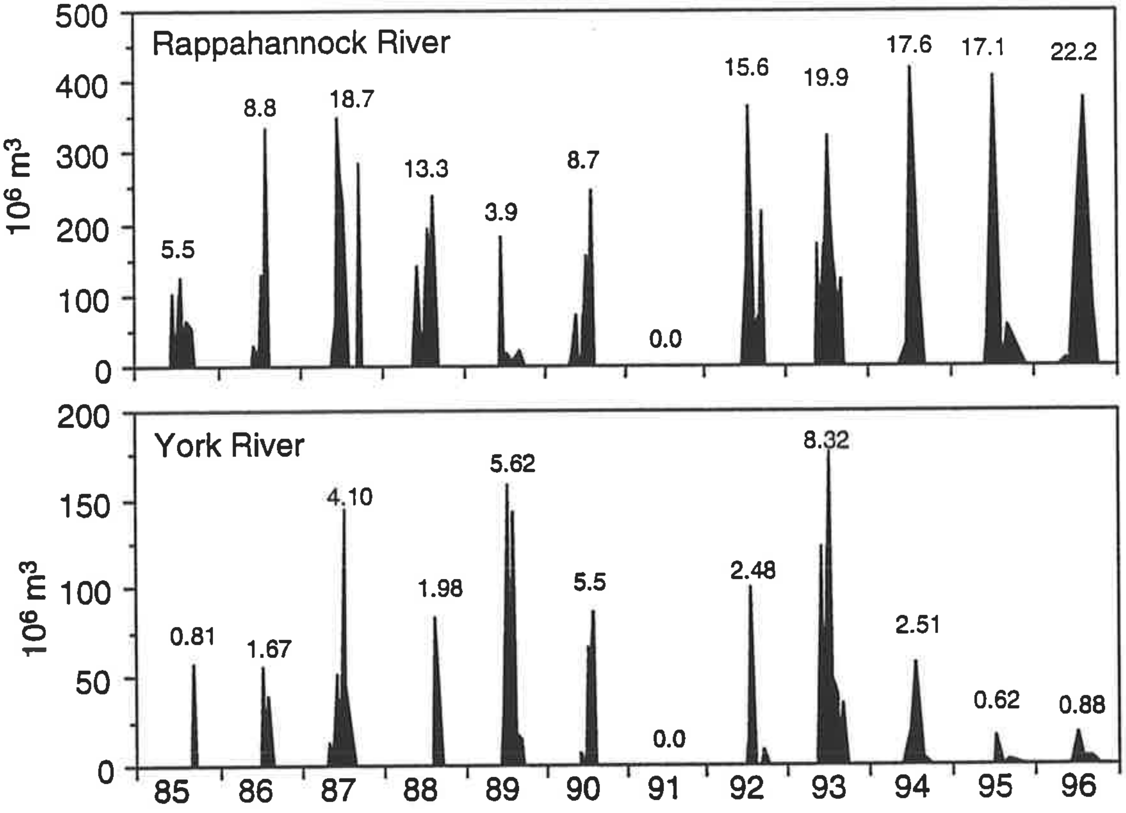


Figure 9. Hypoxic volume, the volume of water with dissolved oxygen less than 3 mg l^{-1}, in Rappahannock and York Rivers during 1985-1996. The value labels for each year are the annual integrals in 10^9 m^3d. Hypoxic volume (3 mg l^{-1}) did not occur in the James River with the exception of several isolated and small observations.

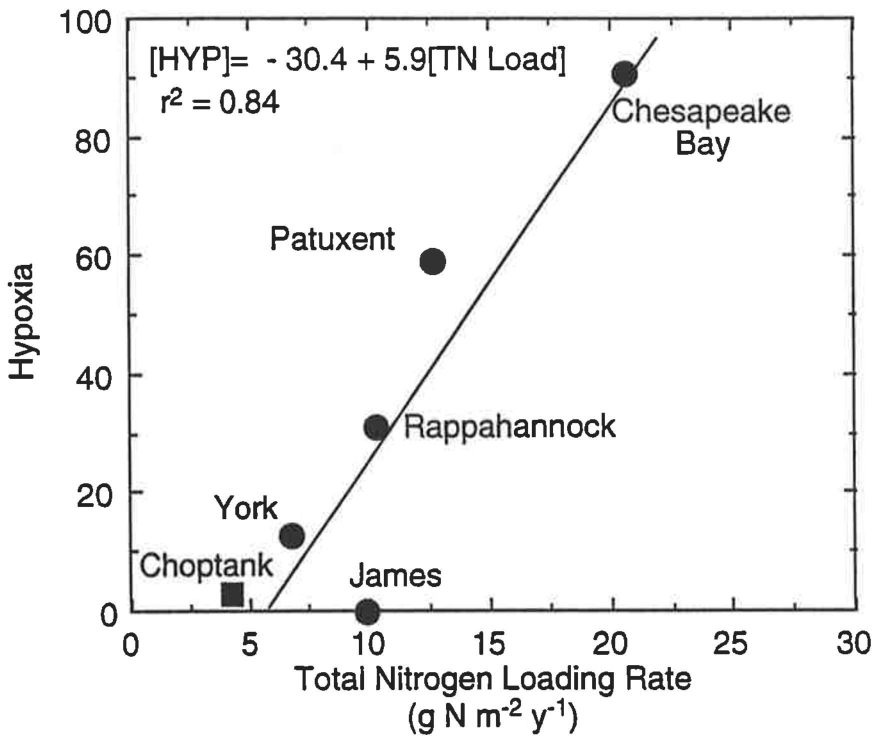


Figure 10. The relationship between the average values for the scaled hypoxia index and total nitrogen loading rates. Loads for the Virginia estuaries are estimated here. The loading rates for Chesapeake Bay, Choptank River, and Patuxent River are from Boynton et al. (1995). The Choptank River is indicated by a square because the hypoxia index value was not calculated as for the other estuary. However, the occurrence of hypoxia in Choptank River is known to be rare and limited, suggesting a value in the range indicated. It is nontheless possible that the actual hypoxia index value may be higher than indicated. The regression line was calculated using all the observations shown, including the Choptank River observation.

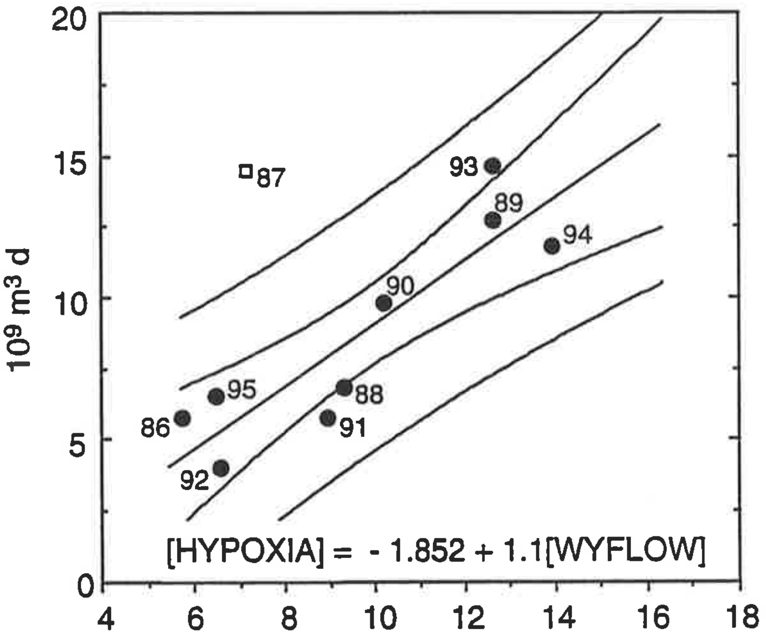


Figure 11. Annual hypoxia in Patuxent River (DO<3 mg l^{-1}) regressed on water-year river flow. The 1987 observation was omitted from the regression.

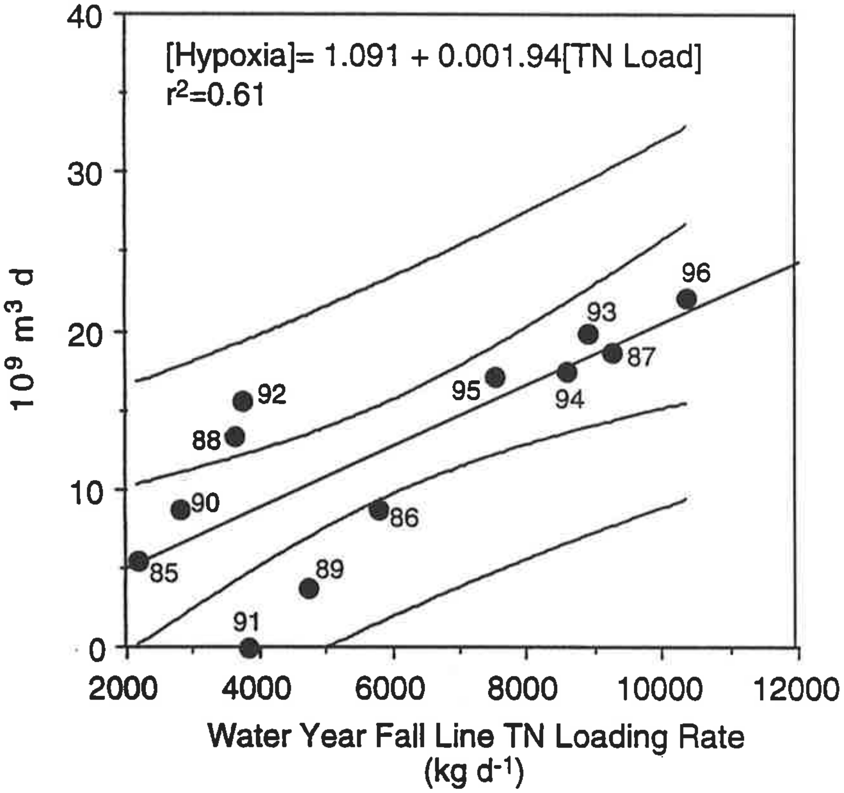


Figure 12. Hypoxia (hypoxic volume-days, DO<3 mg l^{-1}) in Rappahannock River related to water year fall line total nitrogen loading rates generated by the CBP watershed model. Because the 1996 estimate was not available from the model, a value was estimated via the relationship between water year river flow and water year TN loading rate. The outer bands are the 95% prediction intervals, while the inner bands are the the 95% confidence interval for the mean.

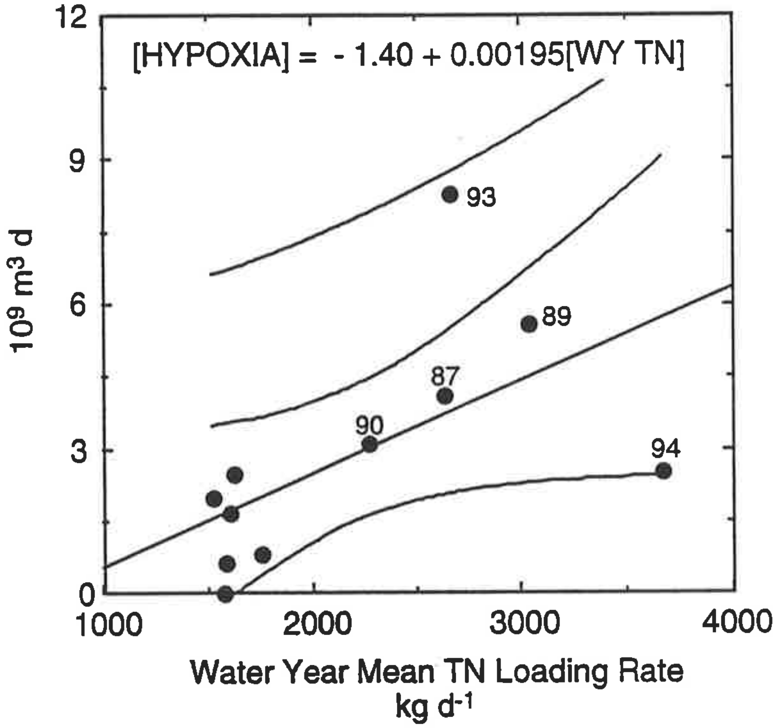


Figure 13. York River hypoxia (DO<3 mg -1) regressed on water year mean fall line TN loading rate estimated from the CBP Watershed Model. The top line is the upper 95% prediction limit. The curved bands show the 95% confidence interval for the hypoxia at any given loading rate.