Dissolved Loads of Rivers and Surface Water Quantity/Quality Relationships
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Nutrient and sediment budgets for the tidal Potomac River and Estuary

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ABSTRACT Twice-weekly salt, suspended sediment, and nutrient species samples were collected during the 1979-1981 water years at six stations along the 101 nautical mile tidal reach of the Potomac River between Washington, DC, and Chesapeake Bay. The concentration data were used to continuously calibrate a hybrid one-layer, two-layer kinematic transport model. Monthly loads computed by the calibrated model were used together with point and nonpoint source data to compute nutrient and sediment budgets for three zones of the tidal Potomac. All of the 8.15×10^6 tons of sediment supplied during the study period were trapped in the study area; 13 000 tons were from Chesapeake Bay. 82% of the supplies of both total nitrogen and total phosphorus were trapped, but only 9% of dissolved silica. Most of nitrogen and phosphorus were retained in the estuarine zone, most of the sediment and silica in the tidal river.

Bilan des matières nutritives et des sédiments pour la rivière à marée du Potomac et son estuaire
RESUME Des prélèvements de sel, de sédiments en suspension et de matières nutritives ont été effectués deux fois par semaine d'octobre 1979 à septembre 1981 le long de 101 miles nautiques, bief affecté, par la marée de la rivière Potomac entre Washington, DC, et la Chesapeake Bay. Les données (substances dissoutes) ont été utilisées pour calibrer de facon continué un modèle de simulation hybride à une ou deux couches de transport cinématique. Les charges mensuelles calculées par le modèle ont été utilisées conjointement avec des données de sources ponctuelles et non ponctuelles afin de calculer les bilans de matières nutritives et de sédiment de trois zones situées sur la rivière à marée du Potomac. La totalité des 8.15×10^6 tonnes de sédiment produits pendant la période d'étude se sont déposés dans la région d'étude; 13 000 tonnes provenaient de la Chesapeake Bay. 82% de l'approvisionnement de l'azote total et du phosphate total, mais seulement 9% de la silice dissoute se sont déposés. La plupart de l'azote et du phosphate ont été retenus dans la zone de l'estuaire, la plupart des sédiments et de la silice ont été retenus dans la rivière à marée.

INTRODUCTION

During the period from 1977 to 1982, the US Geological Survey (USGS) conducted a major interdisciplinary study of the tidal Potomac River and Estuary. As part of this study, salt, suspended sediment, and nutrient species samples were collected at least twice weekly at three tidal river sampling stations during the 1979 to 1981 water years (October 1978-September 1981). During the 1980 and 1981 water years, one transition zone and two estuarine sampling stations were added. In addition to the station sampling, monthly longitudinal profiling cruises were conducted beginning mid-way through the 1979 water year and continuing through 1981. The station and longitudinal-profile salt and sediment concentration data were used to continuously calibrate a hybrid one-layer, two-layer box model. The calibrated model was in turn used to compute monthly loads of nutrient and suspended sediment passing the sampling stations. This paper discusses how these loads were computed and combines them with point and nonpoint source loading information to determine intermediate-range sediment and nutrient budgets for the tidal river, transition zone, and estuary.

BACKGROUND

Study area

The study area (Fig.1) consists of the 101 nautical mile (nm) tidally influenced portion of the Potomac River between its mouth on Chesapeake Bay and the head of tide at Chain Bridge near Washington, DC. The six sampling station locations are shown on Fig.1. The upstream boundary condition monitoring station is located at Chain Bridge. The next downstream tidal river station is at Alexandria, just downstream of the Blue Plains Advanced Waste Treatment (AWT) Plant which serves approximately two-thirds of the nearly three

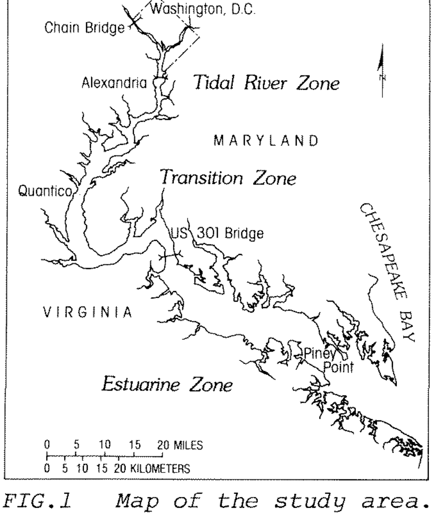

FIG.1 Map of the study area.

million population of the Washington DC metropolitan area. The station between the tidal river and transition zone is at Quantico, where the sale concentration seldom reaches one part per thousand (ppt). The station at the seaward end of the transition zone is at Morgantown, Maryland, where salt concentrations ranged between 0.6 and 10.8 ppt. The estuarine sampling station was at Piney Point (nm 18.5), and the seaward boundary condition monitoring station was at Chesapeake Bay where the salt concentrations ranged from 7.0 to 23.8 ppt. The tide in the study area is of the mixed semi-diurnal type with a range of 1.3 ft at the mouth and 2.9 ft just upstream of Alexandria. The estuary seaward of Morgantown is generally classified as 2-b on the Hansen-Rattray (1966) diagram, a partially mixed coastal plain estuary.

Hydrology

The drainage area of the Potomac River at the Little Falls gauging station just upstream of Chain Bridge is 11 570 square miles (mi^2); there are another 3100 mi^2 tributary to the river between this gauge and the mouth. The 51-year annual average discharge of the river at Little Falls is 11 400 ft^3s^{-1}. The peak discharge was 484 000 ft^3s^{-1} and the minimum mean daily discharge was 601 ft^3s^{-1}. Yearly average discharges for the 1979 and 1980 water years were respectively 16 630 and 16 280 ft^3s^{-1}. These are both more than 40% greater than the annual average so both years are classed as extremely wet. Although the wet years have nearly identical average discharges, the hydrograph in 1979 was much more volatile. The maximum daily average flow during 1979 was 201 000 ft^3s^{-1} and there were six days on which the daily average exceeded 100 000 ft^3s^{-1}, while during 1980 the maximum daily average discharge was only 78 000 ft^3s^{-1}. In contrast to 1979, 1980's flow arrived during several extended moderately high discharge events. The yearly average discharge during 1981 on the other hand, was only 6905 ft^3s^{-1} which is 39% below the 51-year average, and 1981 is classed as extremely dry.

The variability in the input discharge hydrograph is reflected in the annual river input loads (given in the first row of each section of Table 2). The most striking difference is demonstrated between sediment loads for the 1979 and 1981 water years. Although the water discharge of 1979 was only 2.4 times that in 1981, the corresponding ratio of sediment loads was 6.6. Taking another view, the river-supplied total nitrogen during 1979 was 3.0 times that from the point sources in the Washington, DC area during 1979, while during 1981 the corresponding ratio was only 1.6. Such hydrological and loading differences can profoundly affect the annual nutrient and sediment budgets.

TRANSPORT COMPUTATIONS

Constituents considered

In computing nutrient and sediment budgets, seven constituents, salt, suspended sediment, dissolved silica, dissolved and particulate phosphorus (P), and dissolved and particulate nitrogen (N) were considered. The vertical and longitudinal distribution patterns of the conservative constituent salt were used mostly in calibrating the circulation components of the box model. Suspended sediment concentrations were considered most carefully in calibrating those components of the model dealing with the vertical structure of the circulation. Because of the volatility of the biological processes occurring within the study area, there is considerable cycling between the dissolved and particulate species of P and N. This cycling has been considered in computing separately the transport of the two phases of each nutrient. However, because of the spatial and temporal variations in the cycling it is difficult to deal rationally with segment budgets of the species separately so the discussion that follows will treat total P and total N.

Transport model

Even for a short period, direct measurement of nutrient or sediment transport through a tidal river or estuarine cross section is a major undertaking. The duration and spatial extent of the USGS study precluded such direct measurement so the concentration data at our sampling stations were collected to be used in continuously calibrating a kinematic transport model. The transport model (Fig.2) incorporates the characteristics of a number of the classes of models

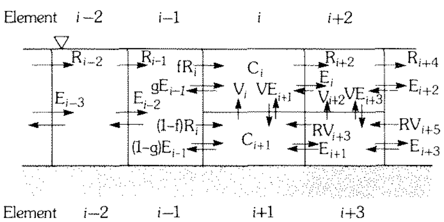

FIG.2 Hybrid box model.

introduced by Officer (1980) but the formulation has been generalized to allow unsteady-state transport. The model also differs from the usual formulation in that a non-advective exchange or exchange flow, E, is used in place of the gradient diffusion-term to simulate the dispersion due to tidal action and other processes. A functional relationship between E and the Fickian dispersion coefficient can be demonstrated. As shown in Fig.2, the model is a hybrid, incorporating two-layer elements in the estuarine zone where the reverse flow, RV, simulates the effect of non-tidal circulation. Both layers may have non-advective exchange, E, and a vertical non-advective exchange, VE, may be specified. The vertical advective flow, V, is simply the difference between the leaving and entering components of the upstream-flowing net non-tidal circulation, RV.

In applying the hybrid conceptual model to the study area, nm 61.4 (six nm seaward of Quantico) was chosen as the dividing line between the one-layer and two-layer sections. This was because nm 61.4 was the furthest point up-river at which significant salinity stratification was observed at any time during the study period.

This agrees with Elliott's (1976) observation that the upstream limit of two-layer flow occurred near nm 63. The single-layer segment upstream of nm 61.4 contains 19 main channel elements and 10 embayment elements. Below nm 61.4 there are 20 two-layer elements and seven more single-layer embayment elements, so that the model contained 76 elements. The dividing line between the one- and two-layer elements was fixed at nm 61.4 primarily as a programming convenience. Seemingly this would also fix the location of the turbidity maximum but not in this case because by varying such transport model parameters as VE, the fractions of RV going to the next upstream element or to V, and the relative volumes in the two layers, the turbidity maximum can be moved to any desired spot in the two-layer segment. In practice the turbidity maximum was usually located between Morgantown and nm 61.4.

Because the purpose of the model is load computation and not process simulation, and because the model is continuously calibrated, the formulation of the source-sink terms in the individual constituent concentration computation sub-models can be relatively unsophisticated. Distributed source terms (which represent such processes as the resuspension of sediment particles or the percolation of dissolved nutrients from bottom sediment pore waters) are specified as supply rates per unit of element bottom area. Bennett & Nordin (1977) have shown how the settling of sediment in flowing water can be treated as a first-order decay process where the decay rate is dependent on both sediment and flow properties. Michaelis-Menton kinetics governing the uptake of dissolved nutrients by phytoplankton can be represented as a first-order process. Thus, processes which represent the loss of a particular species from the water column are expressed as linear reaction terms. The amount of dissolved nutrient lost by phytoplankton uptake is incorporated in the particulate nutrient component equation as a source function. The rate coefficient of the linear reaction term in the particulate nutrient models represents the lysing of the particulate nutrient to the dissolved state. Particulate nutrients are also lost by sedimentation at the same rate as the inorganic sediments. For N and P, the latter is the only mechanism by which there can be a net nutrient loss from the water column. The model contains 17 major parameters, five dealing with the various aspects of the circulation, and a source term and a reaction rate coefficient for each of the six non-conservative constituents.

In solving the mass balance differential equations for each of the constituent concentrations, the source-sink terms are expressed explicitly, and the exact integral method of Kremer & Nixon (1979) is used for obtaining the contribution of these terms to the mass balance. Because the differential equations are solved sequentially, the concentrations in the source-sink terms must be expressed explicitly to guarantee mass conservation during nutrient phase changes. The differential equations themselves are analytically intractable and therefore must be solved numerically. An implicit finite difference technique was used because of its inherent stability. Because of the two layered elements and the embayment elements, the resulting coefficient matrix is not tri-diagonal. However, it is banded so that it can be inverted efficiently.

CALIBRATION PROCEDURE

The circulation and constituent transport sub-models were calibrated using monthly data sets, each of which consisted of all data collected during the month at each of the four internal measuring stations plus the data collected during the monthly longitudinal profiling cruise. Four different criteria were considered in obtaining best-fit parameter sets for the individual months. The first was the root mean square (RMS) error of the predictions of the concentrations of the particular constituent at all of the four measuring stations. The second was the RMS error for all observations of that constituent along the longitudinal cruise profile. Third and fourth were respectively the average arithmetic errors at each of the individual stations and the individual arithmetic errors for each of the major segments covered during the longitudinal profile. Each of the two-layer stations or two-layer segments yielded two of these error values.

The RMS error criterion is the best overall measure of goodness of fit for all of the stations and is a good index of the percentage error of the prediction. The individual average arithmetic errors are used to ensure overall balance in calibration and because of their immense usefulness in the continuing process of refinement of the parameter set. The relative magnitudes of the individual arithmetic errors indicates where the greatest improvement can be obtained in adjusting the parameters, and the sign of the error tells whether the chosen parameter should be increased or decreased. Parameter set adjustment was continued for a particular monthly simulation period until the arithmetic errors were less than 10% of the corresponding average constituent concentration or until it was demonstrated that this goal could not be achieved.

Although calibration was conducted in monthly increments, the basic time-step size for model simulation was one day, and all boundary condition inputs and parameter values could change daily if necessary. During the early simulation trials for a particular month, the circulation parameters were fine-tuned by minimizing the error criteria dealing with salt concentration. As calibration of the circulation parameters proceeded, sediment data were used, with particular attention being paid to the differences in concentration between the upper and lower layers at the estuarine sampling stations. Finally, the sediment transport model was fine-tuned using the distributed source term and the sedimentation rate parameter. The dissolved nutrient sub-models were calibrated next, and finally the particulate nutrient transport components. Because of the feedback mechanism between the dissolved and particulate nutrients the last two steps were often repeated several times.

RESULTS

Concentrations and loads

The final product of the calibration process is a parameter set which when combined in the model with the various input boundary conditions produced computed daily constituent concentrations at any desired location. According to the criteria discussed earlier, these computed concentrations are best-fit to the time series of observed concentrations at the four internal sampling stations. As an example, a time history of the river input sediment concentration at Chain Bridge and the computed and observed sediment concentrations at the Alexandria and Quantico stations are given in Fig.3 for the

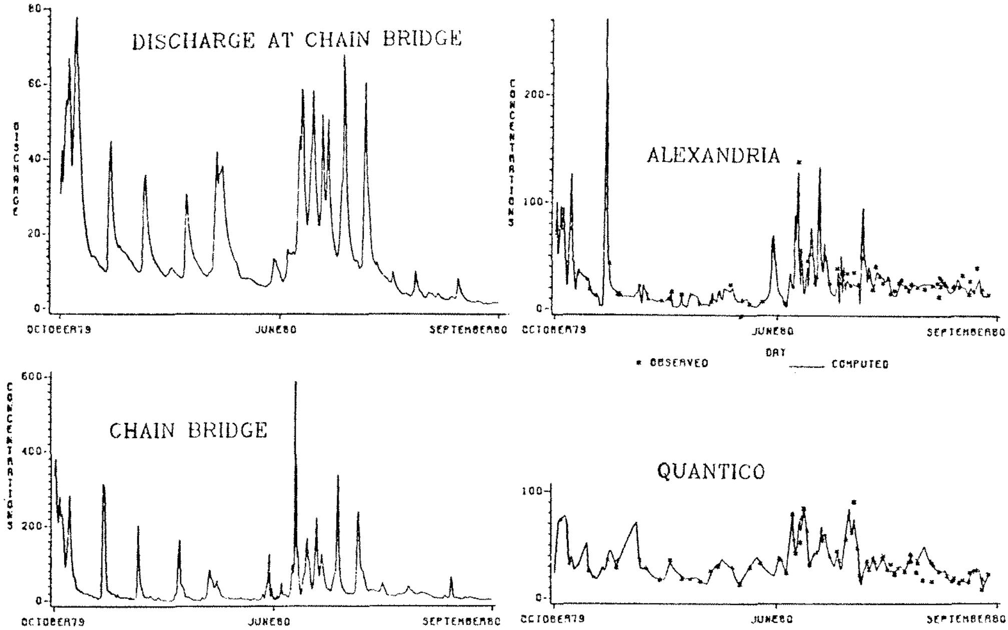

FIG.3 Examples of computed and observed sediment concentrations (mg l^{-1}) during the 1980 water year.

1980 water year. For the months during the year with the highest and lowest average discharge, some of the corresponding error criteria are given in Table 1. Suspended sediment concentration is the most variable and difficult to predict of any of the constituents

TABLE 1 Example statistics and error criteria for suspended sediment during the 1980 water year

Month	*Discharge (ft^3s^{-1})*	*RMS error (mg l^{-1})*	*Alexandria: Mean concentrations (mg l^{-1})*	*Alexandria: Arithmetic error (mg l^{-1})*	*Quantico: Mean concentrations (mg l^{-1})*	*Quantico: Arithmetic error (mg l^{-1})*
October (1)	*33 700*	*27*	*44*	*0.14*	*47*	*-0.04*
September (12)	*1 600*	*8.8*	*17*	*4.6*	*23*	*0.20*

considered, so the error criteria listed in Table 1 are amongst the worst obtained. Despite what is shown in the table, the best agreement between observed and predicted concentrations for all constituents usually occurs during the relatively settled conditions of the low-flow months.

Combination of the computed concentrations in the elements adjacent to the sampling stations with the appropriate circulation flow quantities yields the corresponding fluxes or transport of the constituents through the cross section at which the station is located. Computed monthly loads of suspended sediment into and out of the study area and past the interior stations are shown in Fig.4.

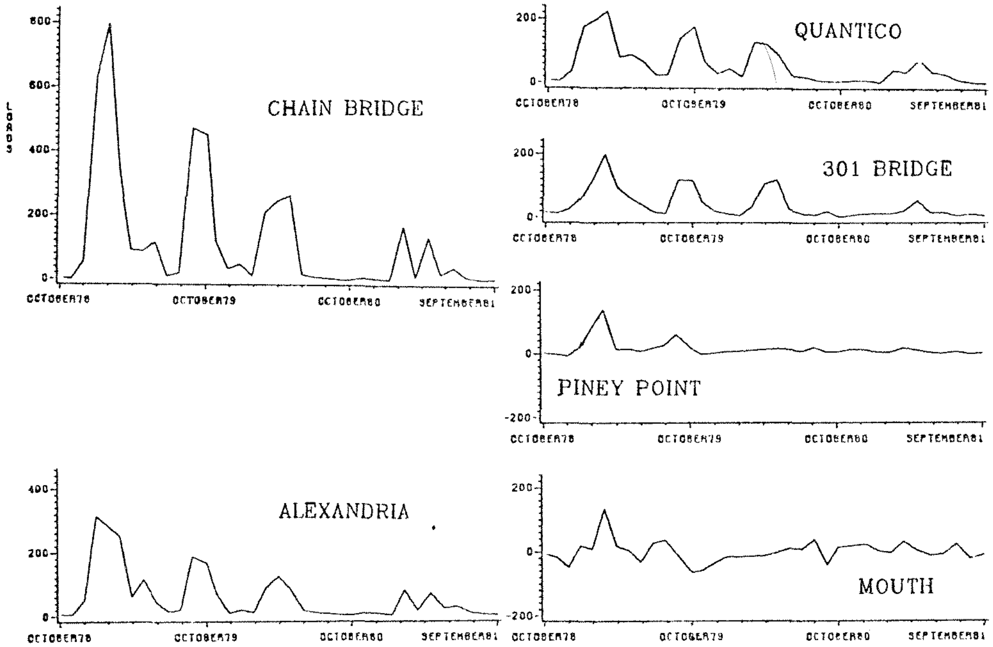

FIG.4 Monthly sediment loads (thousands of tons) passing the measuring stations during the 1979 to 1981 water years.

As expected, the extreme flow-induced variations in the input load are damped out as the sediment moves downstream, and the downstream reduction in the magnitude of the load due to deposition is obvious. The trapping is most pronounced for sediment but the nutrients are also retained. Monthly totals of daily loads of all the seven constituents are given by Bennett *et al.* (1984). Space permits only a brief summary here.

Budgets

The computed loads of Bennett *et al.* (1984) are used in conjunction with Hickman's (1984) point and nonpoint sources to produce the individual water-year and three-year summary budgets given in Table 2. During the study period, 54% of incoming sediment was from the basin upstream of Washington, DC, 45% was from local sources and

TABLE 2 Annual and three-year summary constituent budgets for the tidal river (TR), transition zone (TZ), and estuary (E) (column 1 gives the upstream and downstream measuring stations delimiting the zones, column 2 lists point and nonpoint source loading to the zone and column 3 lists the amount of material retained in the zone

Zone	1979 River	Nonpoint	Trapped	1980 River	Point Nonpoint	Trapped	1981 River	Point Nonpoint	Trapped	3-year River	Point Nonpoint	Trapped
SEDIMENT (10^6 tons)												
	2.612	0.128		1.404	0.070		0.393	0.021		4.410	0.219	
TR		0.926	2.478		0.148	0.887		0.042	0.190		1.116	3.556
	1.072			0.736			0.265			2.073		
TZ		0.625	0.908		0.161	0.377		0.087	0.192		0.873	1.478
	0.788			0.520			0.160			1.468		
E		1.025	1.682		0.363	1.090		0.242	0.339		1.630	3.111
	0.131			-0.207			0.062			-0.013		
SILICA (SiO_2) (10^3 tons)												
	87.56			94.23			28.84			210.63		
TR		24.21	27.99		18.18	20.20		8.90	20.68		51.28	68.87
	83.78			92.20			17.04			193.01		
TZ		7.77	10.17		5.56	-3.31		2.11	-19.32		15.43	-12.46
	81.36			101.07			38.46			220.89		
E		12.41	-30.84		8.90	18.11		3.36	-16.50		24.67	-29.23
	124.60			91.85			58.30			274.76		
TOTAL PHOSPHORUS (10^3 tons)												
	2.691	1.054		1.414	0.699		0.756	0.525		4.861	2.278	
TR		0.831	1.876		0.195	0.089		0.095	0.499		1.121	2.464
	2.682			2.198			0.859			5.739		
TZ		0.762	0.095		0.148	0.459		0.038	-0.050		0.948	0.504
	3.335			1.880			0.933			6.148		
E		1.216	3.495		0.236	0.766		0.060	1.481		1.512	5.742
	1.035			1.329			-0.512			1.852		
TOTAL NITROGEN (10^3 tons)												
	29.16	9.79		28.20	8.11		10.45	6.76		67.82	24.66	
TR		5.49	4.43		2.71	2.52		1.04	3.45		9.23	10.40
	39.99			36.48			14.78			91.25		
TZ		2.09	5.81		0.94	1.32		0.38	6.86		3.41	13.99
	36.26			36.09			8.29			80.64		
E		3.80	37.23		1.68	20.26		0.82	9.36		6.30	66.85
	2.81			17.48			-0.26			20.03		

1% from Chesapeake Bay. For the nutrients of most concern to water quality managers, 44% of total P was from upstream of Washington, 24% was from Washington-area point sources, and 32% was from non-point sources. The corresponding figures for total N are 58%, 25%, and 17%. Because the net amount of sediment entering the study area from Chesapeake Bay was greater than that leaving, more than 100% of the sediment supplied from upland sources was retained in the study area during the study period. Although the temporal and spatial distributions of trapping were different, 82% of supplied quantities of both total N and total P were retained. On the other hand, only 9% of dissolved silica was trapped.

Using ^{210}Pb data, Knebel *et al.* (1981) estimate that 1.68 x 10^6 tons of sediment per year accumulate in the estuarine zone. This figure is somewhat in excess of the study-period average value of 1.04 x 10^6 tons obtained from Table 2. However, the former figure represents an average of approximately 60 to 120 years, a time period during which sediment supply rates probably were greater than at present. Therefore, the two figures are not in serious disagreement. Schubel & Carter (1977) have presented an annual sediment budget for Chesapeake Bay which shows that the Potomac receives approximately 44 000 tons per year from the Bay. This figures is an order of magnitude greater than the three-year average of 4300 tons obtained from Table 2. However, considering the uncertainties in the computation of both budgets, the agreement is acceptable. Discussions of estuarine nutrient budgets are even more scarce than are those of sediment budgets, however from the work of Taft *et al.* (1978) it can be interpreted that very little dissolved N escapes from Chesapeake Bay to the Atlantic Ocean. Because the Bay is generally believed to be a sink for sediment from the ocean, it is also reasonable to assume that little particulate N escapes. Therefore, if the Bay as a whole retains N, the conclusion that the Potomac retains more than 80% of the supplied total N, is also reasonable. Similar arguments can be applied to total P.

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