Technical Analysis of Response of Chesapeake Bay Water Quality Model to Loading Scenarios

A Report of the
Modeling Subcommittee
Chesapeake Bay Program Office
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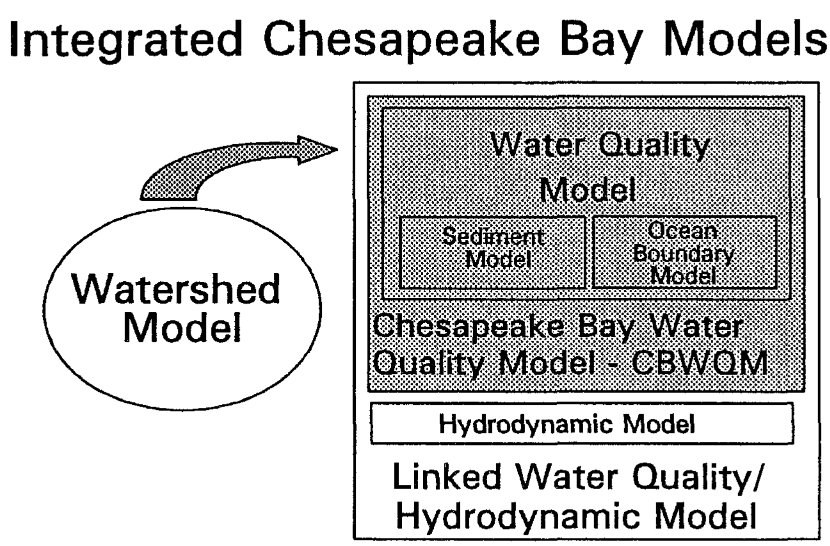
PREFACE

In 1983, the Chesapeake Bay Program identified excess nutrients, or eutrophication, as the primary reason for water quality decline in the Chesapeake[1]. To quantify the nutrients contributing to eutrophication and the nutrient reductions necessary to restore Chesapeake Bay resources, several water quality models have been developed and applied.

The first model application was the Watershed Model. The first phase of that model, completed in 1982, documented the magnitude and source of the point and nonpoint nutrient loads to the Bay for wet, dry, and average hydrology years[1].

To examine the impact of nutrient loads on the mainstem Bay, a steady state water quality model of the Bay was completed in 1987. Using simplified loading estimates and simulation procedures, this model calculated the average or steady state summer (June - September) conditions in the mainstem Bay . Results from the steady-state model indicated that a 40% reduction in nutrient loads would eliminate anoxia (dissolved oxygen concentrations less than 1.0 mg/l) in the mainstem.

To confirm the estimates of anoxia reduction, and to refine estimates of the improvements in Bay water quality in response to nutrient load reductions, work began on an integrated set of Chesapeake Bay models in 1987 (shown below). The linked watershed, hydrodynamic, water quality, and sediment models were completed in 1992. This report documents the findings from the application of these integrated models to evaluating the technical aspects of various load reduction scenarios.



The following model refinements were made in the development of the integrated models.

WATERSHED MODEL

The Watershed Model was updated to provide greater detail of atmospheric and agricultural sources[2]. This model was used to 1) determine the distribution of the point and nonpoint source loads and the controllable and uncontrollable portions of the loads; 2) determine the quantity of loads reduced under different management actions; 3) determine the nutrient loads to the Bay under different Clean Air Act scenarios; and 4) quantify the loads under future (year 2000 conditions). These loads were used as input conditions for the Chesapeake Bay Water Quality Model.

CHESAPEAKE BAY WATER QUALITY MODEL (CBWQM)

The CBWQM is a time variable, three dimensional water quality model coupled with a model of sediment processes. The CBWQM is driven by a hydrodynamic model simulating the hourly movement of Bay waters over the three year (1984 - 1986) simulation period. The sediment model provides simulation of sediment nutrient sources and sinks. An ocean boundary submodel simulates the expected coastal input of loads under different nutrient management conditions. The details of model development, structure, calibration, and sensitivity are given in separate reports[3,4,5].

This report is divided into seven sections. Section I briefly describes the Chesapeake Bay Water Quality Model and introduces the scenarios analyzed. Section II describes the scenarios and associated nutrient and sediment loads in detail. The third section provides background for the more detailed analysis of Bay water quality response that follows. Sections IV and V summarize aspects of Bay circulation and its influence on water quality. Section VI surveys the nutrient, phytoplankton, and sediment response to loading reductions. Section VI also examines the overall nutrient budget and the exchange among the tributaries and mainstem. Section VII concludes the report with a detailed examination of the mainstem dissolved oxygen response to the interactions among nutrient loads, transport, sediment processes, and phytoplankton processes examined in the previous sections. A summary of major findings is included in each section and an overview of these findings is provided in the Technical Summary.

The report is designed to be a resource for a diverse technical and managerial audience. With this eclectic readership in mind, the following suggestions are made.

1) The harried reader may want to review the Technical Summary only.
2) A reader with more time may include the major conclusions on pages II-10, VI-11 through VI-12, and VII-6, with reference to areas of interest within the appropriate sections.
3) The determined reader who persists in the completion of the entire report will be rewarded with a more complete analysis of Bay water quality response to nutrient loading reductions, and will have a greater understanding of how Bay water quality is expected to respond under different loading conditions.

The work described in this report is by no means complete. Scenarios have been applied to develop the tributary loading allocations of a 40% reduction of controllable nitrogen and phosphorus. Other scenarios annually track the loads to compare annual reductions with the year 2000 goal.

Further model refinements are now under way. These refinements will examine the relationship among air deposition, water quality, and key living resource areas including SAV, benthos, and phytoplankton/zooplankton. The refined model analysis of air deposition, and water quality/living resource interaction will be completed in 1997.

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ENDNOTES

1. M.E. Gillelan et al., 1983. Chesapeake Bay: A Framework for Action U.S. EPA Chesapeake Bay Program. Annapolis, MD.

2. A.S. Donigian et al., 1991. Watershed Model Application to calculate Bay Nutrient Loads: Phase II Findings and Recommendations U.S. EPA Chesapeake Bay Program. Annapolis, MD

3. C.F. Cerco and T. Cole, 1993. Application of the Three-Dimensional Eutrophication Model CE-QUAL-ICM to Chesapeake Bay U.S. Corps of Engineers Waterways Experiment Station. Vicksburg, MS.

4. D.M. Di Toto and J.J. Fitzpatrick, 1993. Chesapeake Bay Sediment Flux Model U.S. Corps of Engineers Waterways Experiment Station. Vicksburg, MS

5. B.H. Johnson et al., 1991. Users Guide for a Three-Dimensional Numerical Hydrodynamic, Salinity, and Temperature Model of Chesapeake Bay U.S. Corps of Engineers Waterways Experiment Station. Vicksburg, MS.

TECHNICAL SUMMARY

INTRODUCTION

A modeling framework was constructed for the Chesapeake Bay system to provide a credible basis to assist the decision-making process and to further the understanding of Bay water quality processes and the sensitivity of such processes to external nutrient loading. The modeling structure consists of a Watershed Model to generate nutrient loads from the Bay sub-basins; a three-dimensional, time variable hydrodynamic model; and a three-dimensional, time variable model of water quality coupled to a model of sediment chemistry.

Extensive calibration analyses of the entire modeling structure was conducted using data collected primarily during a three year period from 1984-1986. The Chesapeake Bay Program Modeling Subcommittee completed its initial review of the Chesapeake Bay Water Quality Model (CBWQM) calibration in May 1991 and concluded the model could provide useful information to the Bay community, especially with respect to dissolved oxygen problems in the deep water of the main Bay. Final calibration of the CBWQM was completed in January 1992.

After completion of the model calibration, the models were used to address management issues such as: (1) What impact do reductions or increases in nutrient loads from point and nonpoint sources delivered by the Bay's major tributaries have on Chesapeake's water quality? and (2) How much of the nutrient loads to the Bay is natural and how much is related to man-made sources, and to what extent can loads be controlled?

The CBWQM provides projections of the expected water quality responses (including dissolved oxygen concentrations) in the main Bay under a variety of proposed management scenarios. The purposes of this report are therefore to (a) document the results of a full set of loading scenario computations, (b) analyze the scenario results across different loading conditions and (c) interpret the results in the light of the sensitivity of the Bay model to various loading conditions.

A total of 21 scenarios were run for this work and a summary description of the 11 scenarios that formed the basis for the analysis herein is given in the Table below.

Scenario Number	Scenario Tag	Scenario Description
1	BASE	1984-1986 Conditions
2	40% CONT	40% Reduction of controllable load ("Agreement" states only)
3	40% +CAA	Scenario #2 + Clean Air Act atmospheric reductions
4	40%CAA+BASIN	40% + CAA for entire basin
5	LOT	Limit of technology (LOT) for nutrient reductions
6	LOT -UPPER	Limit of technology for "Upper Bay" only, others at BASE
7	LOT - MID	Limit of technology for "Middle Bay" only, others at BASE
8	LOT - LOWER	Limit of technology for "Lower Bay" only, others at BASE
10	LOT - N ONLY	LOT for nitrogen only, phosphorus as incidental by N reduction
11	LOT - P ONLY	LOT for phosphorus only, nitrogen as incidental by P reduction
16	90% RED	90% reduction in total N & P loading from BASE

SCENARIO NUTRIENT LOADS

This report is focused on the response of the main Bay to various nutrient loading scenarios. The "external" loads are comprised of (1) fall line watershed loading, (2) below fall line watershed load, (3) point source loads, (4) atmospheric loads direct to the water surface of the Bay, and (5) ocean loading. The "internal" loadings from tidal tributaries to the Bay are calculated by the CBWQM and are given at the interface of the tributary with the main Bay. Fall line loadings and below fall line loadings are calculated from the Watershed Model (WSM). Point source loads were obtained from inventories. Atmospheric loads were estimated based on available data, and ocean boundary loads were estimated using shelf nutrient data and a simple exchange model at the mouth of the Bay.

The three principal reference loadings that established the extent of feasible reductions, are:

1. Base Case Load,
2. Controllable Load, and
3. Limit of Technology (LOT) Load.

a. Base Case. The Base Case loading represents the 1984 -1986 loading as a reference time period. This is the same period as used for the calibration of the CBWQM.

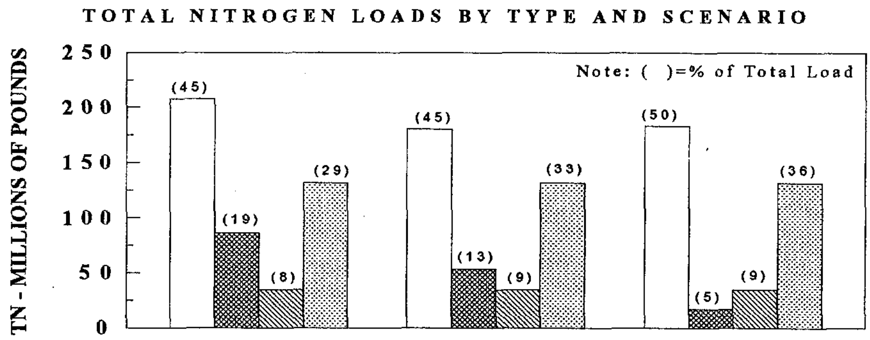
b. Controllable Load. Controllable loads are defined as the difference between Base Case loads and a WSM run using an all forested basin (excluding NY, WV & DE) with no point sources. 40% Controllable loads are those agreed to in the Bay agreements.

c. LOT Load. Limit of Technology loads for Non-Point Source (NPS) inputs were determined by evaluation of Best Management Practices (BMP) and implemented in the WSM. Point source (PS) LOT loads were assumed as follows: 3.0 mg/L for TN, 0.075 mg/L for TP, and 1.0 mg/L for BOD.

In order to represent year to year variation in hydrology, the scenario runs were conducted over a ten year period with flows representative of the interval from 1979 to 1988. Wet, dry and average years during this period were assigned the 1984, 1985 and 1986 hydrologies, respectively. The total river flows to the Bay for 1984 to 1986 are 487,300 cfs (13,800 m^3/s), 459,100 cfs (13,000 m^3/s), and 476,700 cfs (13,500 m^3/s), respectively. The CBWQM was run for these ten years in sequence and the final five years were output. In this report, the emphasis is on year #9, the average hydrologic year.

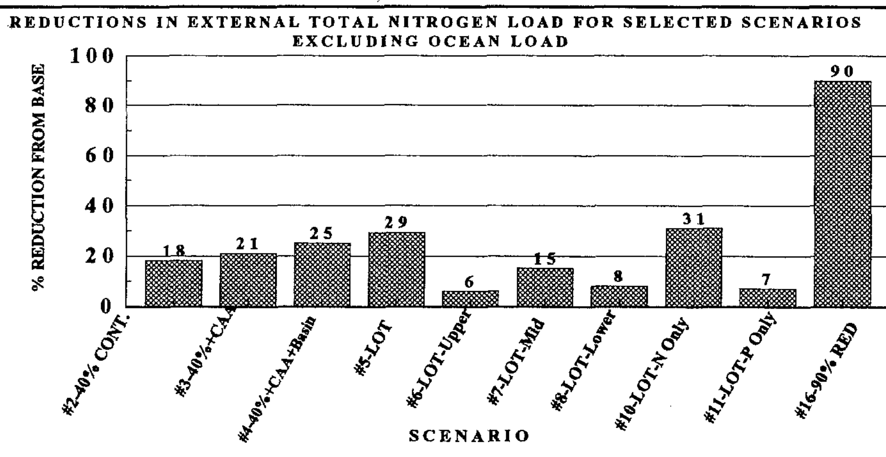
TOTAL NITROGEN LOADS

The Figure below shows the total annual nitrogen (TN) loads used for three of the principal scenarios: Base Case, 40% Controllable and the Limit of Technology (LOT). Base and LOT runs provide an approximate bounding of the feasible range of load reductions. As shown in this Figure, the major source of nitrogen is from the nonpoint sources making up more than 45% of the total for all three scenarios. The point sources decline from 19% of total at Base to 5% at LOT illustrating the greater possible reduction of point source loading relative to nonpoint source reduction. Atmospheric loading directly to the tidal waters is about 9% of total. Ocean loading of TN is a significant component of the total load to the Bay and is estimated to range from 29% to 36% of the TN loading for Base to LOT.



	#1-Base	#2-40% Cont	#5 LOT
NPS	207.5	180.4	183.0
PS	86.8	53.4	17.0
ATMOS.	34.6	34.6	34.6
OCEAN	131.8	131.8	131.8
TOTAL	460.7	400.2	366.4

The Figure below indicates the percent reduction of external TN loading (excluding ocean input) from the Base Case for selected scenarios. The increase in % reduction across the variations of the 40% Controllable (#2) through scenario #4 can be noted. Clean Air Act controls (CAA) on a basin-wide scale and including the non-basin states increase the percent reduction from 18% to 25%. It can also be seen that scenario #4 is approaching the LOT scenario #5. The LOT-Mid (#7) run removes almost as much TN as the 40% Controllable case.

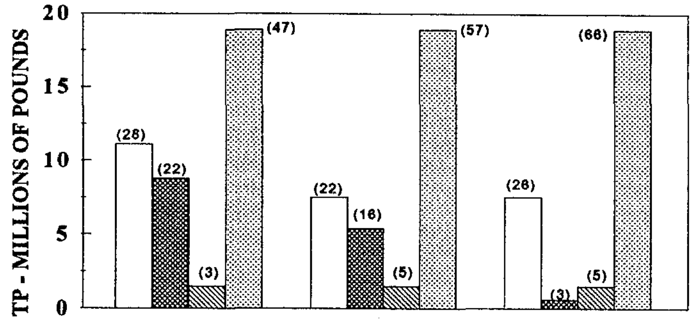


The relative reduction of TN loading due to point and nonpoint sources indicates that the point source loading is reduced considerably more than the nonpoint loading in the LOT scenario. In LOT, the point source loading is reduced about 85% from Base case while the nonpoint source loading is reduced 14-23% from Base. This is a reflection of the relative technological difficulty in reducing nonpoint TN loading as opposed to point TN inputs. It should be noted that location of such reductions is also important. The Upper Bay region is dominated by the nonpoint input of the Susquehanna River so that the contribution from point sources in that region is small while the middle Bay region is responsible for about 50% of the load reductions (Scenario #5 vs. #7).

TOTAL PHOSPHORUS LOADS

The accompanying Figure shows an important difference between TP and TN sources. As shown, the ocean loading of TP dominates the loading inputs accounting for as much as 66% of the TP load at the LOT scenario. It can also be noted that the nonpoint and point source loading are closer in magnitude than for TN, but for LOT the nonpoint load is about the same as for the 40% Controllable case. This is a reflection of the fact that most of the TP is considered controllable.

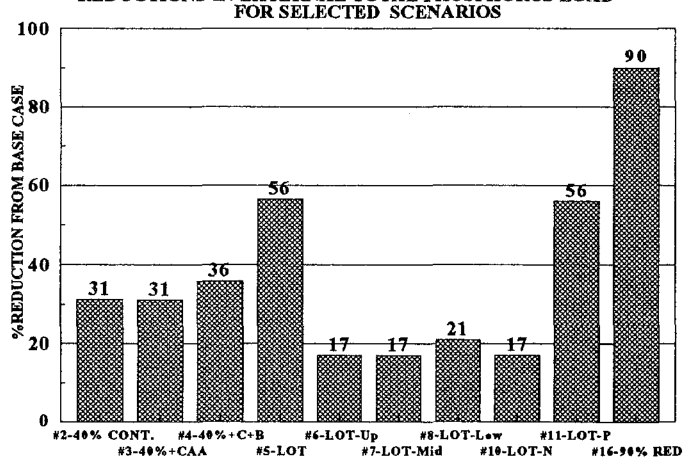
TOTAL PHOSPHORUS LOADS BY TYPE AND SCENARIO



	#1-Base	#2-40% Cont	#5 LOT
NPS	11.1	7.5	7.5
PS	8.8	5.4	0.6
ATMOS.	1.5	1.5	1.5
OCEAN	18.9	18.9	18.9
TOTAL	40.3	33.3	28.5

The percent reduction of TP from Base for a series of scenarios is given in the Figure to the left. The reductions are higher than for TN reflecting the greater technological control for TP over TN. For LOT, a 56% reduction is calculated although it should be recognized that if the ocean load were included, the net percent reduction of TP for LOT due to all loads drops to 29%.

REDUCTIONS IN EXTERNAL TOTAL PHOSPHORUS LOAD FOR SELECTED SCENARIOS



The following principal conclusions are drawn from this analysis of the TN and TP loads.

1. The upper limit of overall total nitrogen reduction from the base case is from about 20 - 30% of the total input load (excluding input from the ocean), with PS being more controllable than NPS.

2. The upper limit of overall total phosphorus reduction from the Base case is from about 30-55% of the total input load (excluding input from the ocean).

3. The calculated ocean nutrient input load (which is independent of scenario) is estimated to contribute about 30-35% of the total input nitrogen load and about 45-65% of the total input phosphorus load.

4. Deposition of atmospheric nitrogen directly to the Bay waters is about 10% of the Base case loading.

5. 40% reduction of controllable nitrogen for nonpoint sources is approximately equal to the Limit of Technology reduction of nitrogen nonpoint sources.

6. The application of LOT results in significantly larger percentage reductions in point source nutrient loadings to the Bay than nonpoint source loadings.

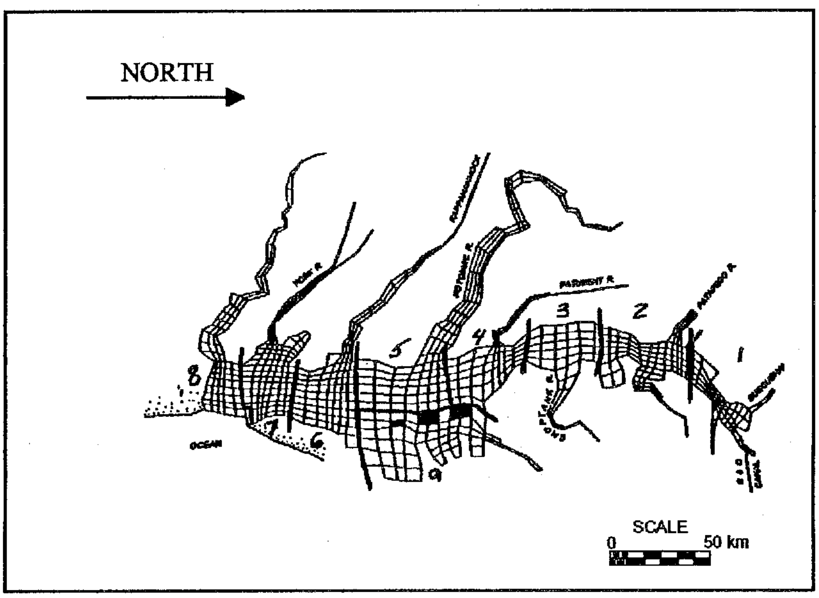
7. The loading to the Upper Bay is primarily from the Susquehanna River while the remainder of the Bay accounts for more than 50% of the load reductions.

CBWQM RESPONSE - GENERAL CONSIDERATIONS

Since model output for all state variables, time and locations is voluminous, some averaging of model results over time and space is necessary. Although the CBWQM calculates state variable concentrations at a time scale of hours, such calculations are for computational stability only. Input information is provided on a week to week basis and the kinetics that are incorporated in the model are representative of longer time behavior. The model is considered to represent processes on a time scale of months, seasons and longer. Therefore, some of the model output results were averaged over months while other results were averaged over seasons according to the Table below.

TEMPORAL PERIODS USED IN AVERAGING MODEL OUTPUT

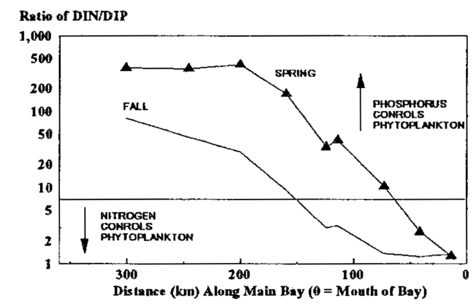
SEASON	DESCRIPTION	JULIAN DAY	APPROX. MONTHS
I	"Winter"	0 - 60	Jan.- Feb.
II	"Spring"	61 - 150	Mar. - May
III	"Summer"	151 - 270	June - Sept.
IV	"Fall"	271 - 365	Oct. - Dec.



The Bay spatial grid scale horizontally is about 10 km by 5 km by 1.7m and includes from two to fifteen cells in the vertical direction for a total of 4029 cells. Two sediment segments (aerobic and anaerobic) are incorporated under the water column segments. Again, in order to provide tractable output, water column model results are averaged spatially according to the zones indicated in the Figure below.

NUTRIENT, PHYTOPLANKTON, CARBON & SOD RESPONSE

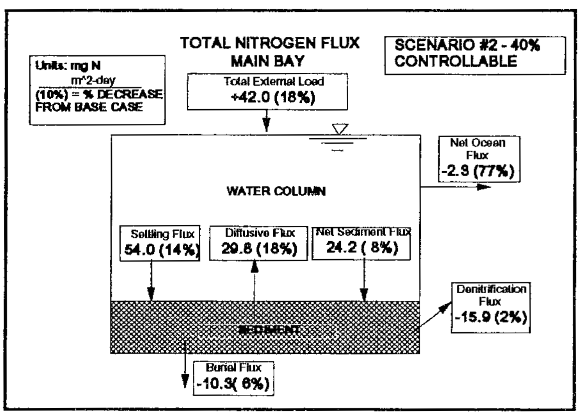
An important consideration in the behavior of nutrients in the Bay is the degree to which nitrogen and/or phosphorus limits phytoplankton growth. One measure of which nutrient is important is the ratio of Dissolved Inorganic Nitrogen (DIN) to Dissolved Inorganic Phosphorus (DIP). Ratios significantly greater than about 7-10 on a mass basis indicate a tendency toward phosphorus limitation while ratios significantly less than that range tend to indicate nitrogen limitation.

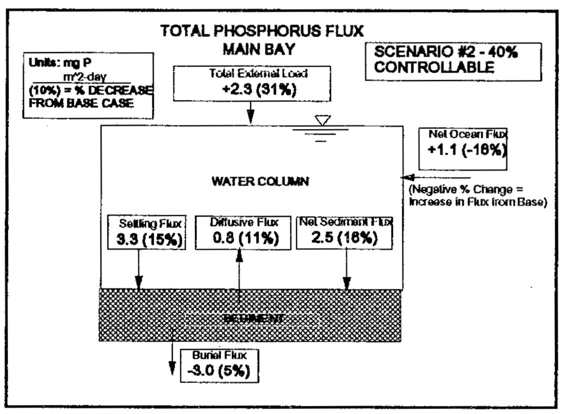


Longitudinal variation of surface DIN/DIP ratio for BASE case. Average over zone over season for average year.

As shown in the accompanying figure, for the base case averaged over zone over the spring, the Bay is calculated to be phosphorus limited from the head to about 75 km from the mouth. During the summer, more of the lower Bay becomes nitrogen limited and during the fall average conditions, more than half of the Bay is nitrogen limited. For the load reduction scenarios, the general tendency is for the LOT N&P and LOT N Only scenarios to increase the region of the Bay that is nitrogen limited. The LOT P Only however, decreases the region of nitrogen limitation because of an apparent increased nitrogen transport to the lower Bay.

<u>Nitrogen and Phosphorus Fluxes</u> The Figures below shows the calculated annual nitrogen and phosphorus fluxes for the main Bay 40% Controllable scenario. Total external load is the load from fall lines, below fall lines, point sources and direct atmospheric deposition to the Bay. Net ocean flux is the net exchange at the mouth of the Bay. The settling flux is the gross settling to the sediment of the Bay. Diffusive flux is the net exchange of dissolved nutrient forms across the sediment-water interface. Net sediment flux is the difference between gross settling and diffusive flux. Denitrification flux is the loss of nitrogen due to the conversion to nitrogen gas, primarily in the sediments. Finally, the burial flux is the net loss of nitrogen or phosphorus from the bottom sediment segment of the model. All fluxes are given in areal units. It should also be noted that these fluxes are for the average year (year #9) of the variable hydrology sequence and

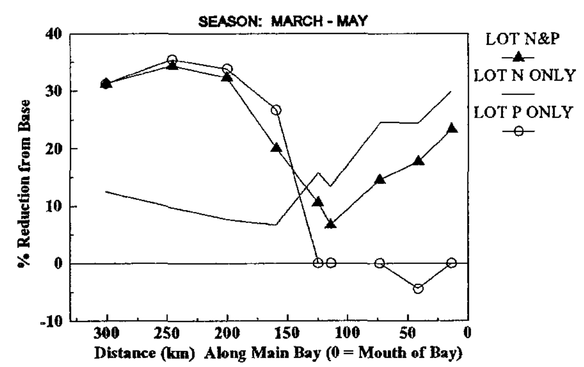




as such reflect a flux "snapshot". It can readily be observed that all fluxes do not necessarily add up to zero because of the dynamic non-steady state nature of the computation.

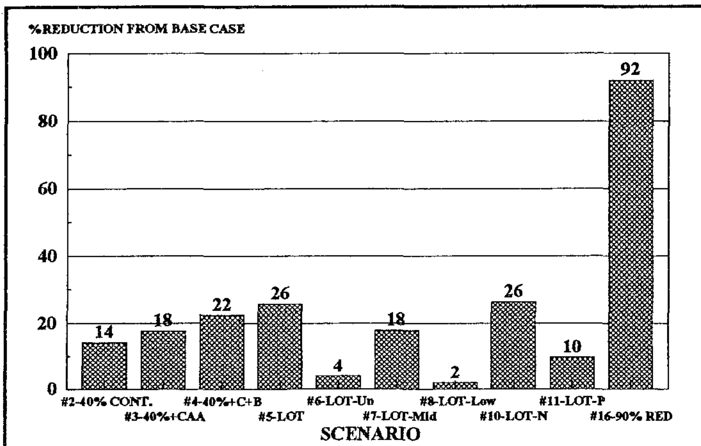
The calculated export of nitrogen and import of phosphorus can be noted. For this scenario, a significant reduction in nitrogen exiting the Bay is estimated while for phosphorus, the influx of phosphorus from the ocean is calculated to increase over the Base case condition. The burial loss of phosphorus is significant and is about equal to the total external load to the Bay.

Phytoplankton Response Several significant insights were obtained by examining the model response of phytoplankton biomass and primary production as a function of nutrient reduction. For the 40% Controllable scenario, phytoplankton biomass is reduced about 10% in the spring (with a minimum percent reduction from Base of zero at about 125 km from the mouth) and about 15% during the summer. As shown in the Figure below, the response of phytoplankton biomass to LOT, LOT-N Only and LOT-P Only reflected the nitrogen - phosphorus limitation regions discussed above. For the spring (similar results occur for the summer), the biomass in the upper 100 km is reduced almost entirely by reductions in phosphorus while the biomass in the lower 100 km is reduced by controlling nitrogen. The increase in percent reduction for LOT- N Only over LOT for both N & P in the lower 100 km is interpreted to result from a down-Bay transport of nitrogen when phytoplankton are reduced in the upper Bay because of control of phosphorus. Because of biomass reduction in the upper Bay by phosphorus control, light penetration is estimated to increase in that region, while for the lower Bay, light penetration will increase because of nitrogen removal.

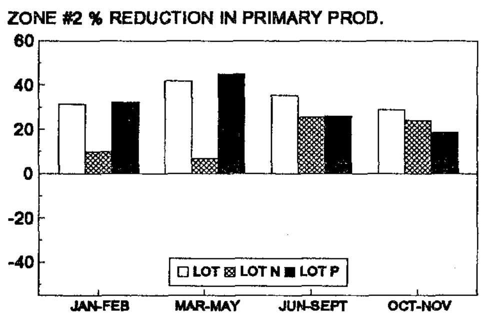


Longitudinal variation of percent reduction of surface chlorophyll on g/m^2 basis. Average over zone over season for average year.

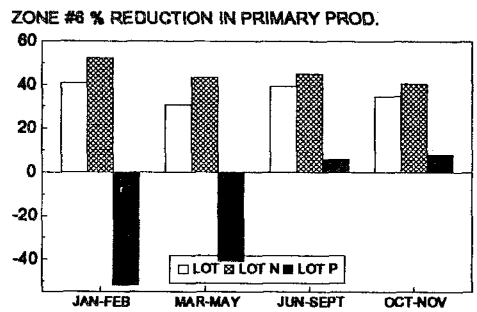
The response in terms of primary production across scenarios is summarized in the next Figure. For the 40 % Controllable scenarios (#2 - #4), it is seen that as the load is increasingly reduced for these scenarios, the impact on the primary production approaches the LOT case. The reductions in the mid Bay areas (LOT-Mid) is also shown to be a significant part of the overall reduction. The annual averages, however tend to mask the actual seasonal dynamics of primary production and the spatial variability of reductions in primary production as a function of which nutrient is reduced. Thus, the LOT P Only annual average reduction is only 10% whereas the spring reduction is over 40%. The responses for two



Reductions in Primary Production for Selected Scenarios. Average Year zones over season and for the three LOT scenarios helps explain these results and are shown in the following two Figures. For Zone 2, the reduction is controlled entirely by phosphorus in the winter and spring whereas in the summer, the production is controlled equally by nitrogen and



Variation of % reduction from Base of phytoplankton primary production. Zone #2. Average over zone over season for average year.

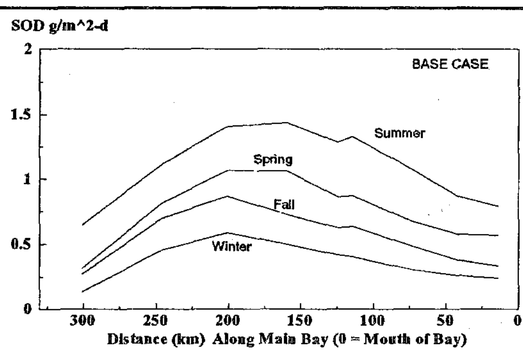


Variation of % reduction from Base of phytoplankton primary production. Zone #6. Average over zone over season for average year.

phosphorus. In the fall, nitrogen is more controlling than phosphorus. For the mid-Bay Zone 4 (not shown), phosphorus controls in the winter and spring whereas nitrogen is the controlling nutrient for the other two seasons. For the summer in Zone 4, LOT P Only results in virtually no change in production over Base case. For Zone 6, the impact of downstream transport of nitrogen to the nitrogen poor regions of the Bay is immediately apparent. For the winter and spring seasons, LOT P Only results in an increase in production over Base case due to this down Bay transport of nitrogen. In the summer and fall, this effect is less pronounced because of the relatively lesser impact of phosphorus reductions in the upper Bay regions during these periods.

These results from the LOT scenarios provide further evidence of the calculated down Bay transport of nitrogen by LOT phosphorus load reduction. Such increases in nitrogen increase primary production in the lower nitrogen limited regions of the Bay and as will be discussed shortly, have a proportionally smaller impact on the DO of the bottom waters of the Bay. On the other hand, phosphorus load reductions have a positive impact in the upper Bay zones where the system is phosphorus limited.

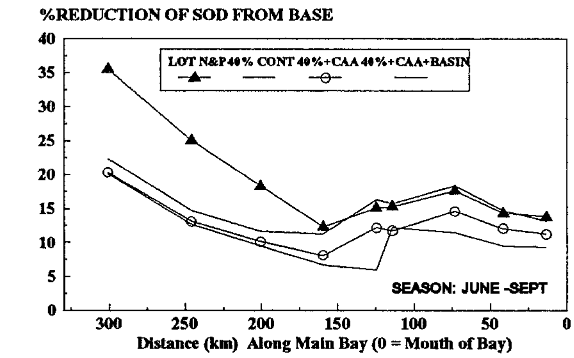
Sediment Oxygen Demand Response The demand of the sediment for oxygen is calculated by the sediment sub-model of the CBWQM. The water column is coupled to the sediment model through the settling of particulate nutrients. The sediment oxygen demand (SOD) is calculated using the net carbon flux to the sediment as the primary input loading. Maximum loading of carbon to the sediment is during the summer months and is the highest in the upper Bay zones. Peak values in this region are about 0.8 gC/m^2-d. The Figure shows the variation in the SOD for the Base case across the zones and for the four seasons. Maximum SOD is calculated to occur in the summer and in Zones 3 to 6. This is in contrast to the carbon flux to the sediment which is maximum in the upper



Longitudinal variation of sediment oxygen demand for BASE case. Average over zone over season for average year.

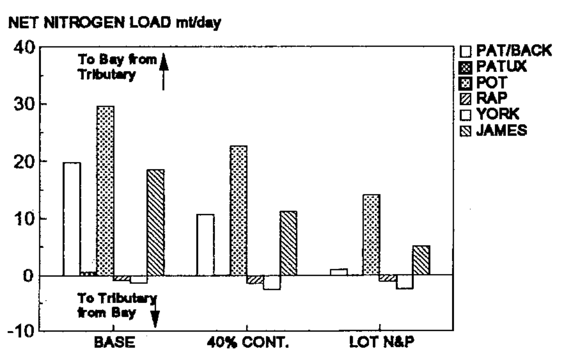
during which there is zero SOD thereby lowering the overall average. On the other hand, the difference may be related to the labile and refractory components of the carbon used in the model. The fall line particulate loadings are considered to be all refractory while the point sources are assumed to be 70% labile and particulate carbon produced from phytoplankton is assumed to be 55% labile. Thus, while the sediment of the upper zones receive more carbon, the nature of the carbon is largely refractory in contrast to the middle and lower zones where the carbon results from primary production and is considerably more labile. Since the calculated diagenesis rate in Zones 3 and 4 is higher than in Zone 2, one concludes that the variable carbon fractions has an effect on the SOD in Zone 2 and together with the periods of zero DO is contributing to the lower calculated SOD in that Zone.

The percent reductions in SOD for the 40% Controllable scenarios (#2 - #4) in comparison to the LOT N&P scenario is displayed in the Figure to the right. The upper Bay reductions in SOD are higher under this latter scenario due presumably to the higher degree of phosphorus removal in the LOT than in the 40% controllable. The differences in nitrogen loading are not as great. For the middle and lower regions of the Bay, the 40% controllable scenarios approach the LOT N&P loading in reducing SOD. In fact, the 40% + CAA + Basin control is at the LOT level of reduction for zones 4 through the rest of the Bay.



Longitudinal variation of percent reduction of SOD from Base case. Average over zone over season for average year.

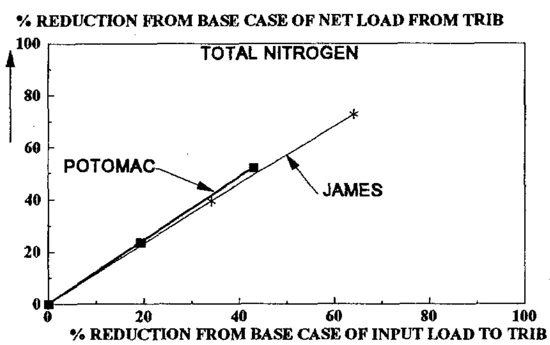
<u>Tidal Tributary Interface Nutrient Loading</u> The net input of the tidal tributaries to the main Bay is of particular interest since such loadings represent actual contributions to the Bay proper. As part of the Bay model calculations, mass balances were conducted around the principal tributaries and the exchange of load across the interfaces of the tributaries was calculated for each of the scenarios.



Variation of annual net nitrogen load from tributaries for Base, 40% controllable and LOT N & P scenarios. Average year.

The net flux of nitrogen across the interfaces of the major tidal tributaries is indicated in the Figure. The three largest inputs are the Patapsco/Back, Potomac and James estuaries. The Patuxent contributes a small input, while the remaining two lower Bay tributaries receive a net input from the Bay. An interesting point of these runs is that the Rappahannock and York rivers are calculated to receive nitrogen from the Bay as opposed to these tributaries providing nitrogen to the Bay. Indeed, under several removal programs (including the 40% Cont. and LOT N&P that are shown) the input net nitrogen load increases from the Bay to the tributary. This is undoubtedly a result of a complex interaction of transport and nutrient concentration where the gradient from the Bay to these tributaries is increased under various removal programs. A similar behavior is calculated for the net phosphorus loadings from the tributaries.

An important linearity in the net interfacial load of both TN and TP from the Potomac and James over the range of loadings from the base to the LOT (not including the geographical runs) is shown in the Figure to the left. As seen for TN , if the total input load of TN to the Potomac or James is reduced by, say, 30% from the base case load, then the net load of TN exiting from the Potomac or James is reduced about 35% from the base case net load. Therefore, in spite of the rather complex nonlinear interactions that exist in the overall model framework, and the apparent interactions between the Bay and the tributaries, the relationship of net load from these two tributaries to the Bay is directly proportional to the reduction in external load to the tributary. However, as noted previously, loads from the James influence only the lower Bay and mouth region, while load reductions from the middle Bay including the Potomac provide significant improvements in the main Bay water quality.



Relationship between % reduction of input load to tributary and net load exiting tributary to Bay for TN.

The ability to examine the behavior of the Bay with the calibrated CBWQM under different removal levels of nutrients in combination is a particularly important use of the model. Such behavior is not directly observable in the Bay and can only be predicted by a credible model. The degree to which phosphorus and nitrogen load reductions have an impact on the water quality of the Bay is of course an important consideration in the decision making process.

In general, the Bay can be divided into three broad regions: the upper approximately 100 km of the Bay where control of phytoplankton growth is by phosphorus, the approximately 100 km of the lower Bay where the phytoplankton production is controlled by nitrogen and a middle Bay region of about 100 km where a transition takes place. The extent of nitrogen control proceeds up the estuary during the summer and fall and is a function of fresh water hydrology and resulting circulation. This general conclusion is consistent with interpretations of observations made on the Bay by a variety of investigators. Modeling shows that as phosphorus loadings to the Bay are reduced (with nitrogen loadings remaining at approximately Base levels), excess nitrogen is transported down the Bay in the surface waters. This transported nitrogen then stimulates phytoplankton production in this nitrogen limited region of the Bay. This "additional" relatively labile biomass then settles in the downstream region and contributes to higher SOD in that area. Phosphorus removal however has a distinctly positive effect in the surface waters of the upper Bay where spring and summer phytoplankton biomass are reduced considerably more than if only nitrogen were removed. Such reductions of biomass of 20-30% have an impact on light penetration, with a 20% increase in light calculated for the 2 m depth at LOT levels.

Reductions in nitrogen have of course a direct effect on phytoplankton production in the nitrogen limited areas and subsequently on the carbon fluxes and the SOD. In addition, the nitrogen load reductions result in improvement in meeting the DIN habitat requirements for the SAV.

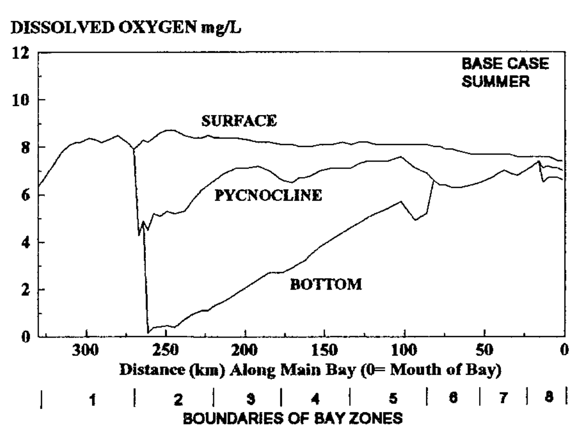
It is concluded from the analyses reviewed here, that load reductions of both phosphorus and nitrogen are necessary to result in reductions in the nutrients, phytoplankton biomass, (with increases in light penetration) and sediment oxygen demand. Phosphorus load reductions are most effective in achieving improvement in these measures of water quality in the upper Bay. Nitrogen removal is required throughout the Bay: in the upper Bay to reduce nitrogen loads that would be transported down Bay under the phosphorus reduction and in the middle and lower Bay to directly reduce biomass and hence SOD.

The Susquehanna River, a non-tidal tributary to the Bay accounts for a majority of the nutrient input on an average annual basis (about 42% of the TN and 31% of the TP loads). The net input of nutrients on an annual average basis from the principal tidal tributaries to the Bay is exclusively from the Patapsco/Back, Potomac and James estuaries. The Rappahannock and York estuaries are calculated to receive a net input of nitrogen and phosphorus from the Bay. For the Potomac and James estuaries, the net nutrient load exiting the tributary to the Bay is approximately linear to the external load of nutrient to the tributary. Nutrient loads from the Potomac enter the middle Bay region where water quality impacts persist while nutrient impacts from the James are limited to the lower Bay and Bay mouth region.

DISSOLVED OXYGEN RESPONSE

The calculated response of the dissolved oxygen (DO) of the Bay assumes particular importance in analyzing the effects of scenario nutrient load reductions. The dissolved oxygen focus in this Section is twofold: (1) evaluation of the seasonal (specifically summer) average DO response, and (2) analysis of the response of the DO concentrations below 1 mg/L, the working definition of anoxia. The latter quantity is determined by calculating the volumetric extent and temporal extent of DO below 1 mg/L. These "anoxic volume-days" have units of m^3 - days.

The summer average longitudinal DO profile for the Base case loading condition and for the average hydrology flow year is shown here. The summer profile is the basis for comparison of assessing the effect of nutrient reduction scenarios. The rapid drop of the minimum bottom DO between the spring level of greater than 5 mg/L to the minimum summer average level of 0.1 mg/l can be noted. The steep increase in the bottom DO beyond the upper limit of the deep trench at approximately 260 km is due to a rapid decrease in depth. The marked vertical gradient in DO during the summer can also be seen where average

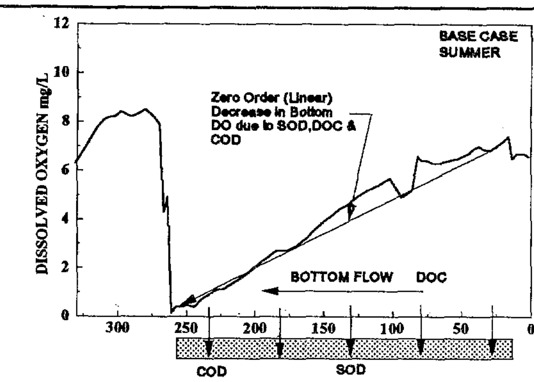


Calculated longitudinal variation of DO for Base case averaged over SUMMER for average year.

surface DO is generally supersaturated due to algal productivity and the bottom DO is responding to deep water sinks of oxygen. The marked difference in the longitudinal profiles between the surface and pycnocline levels and the bottom level can also be noted. Examination of the bottom DO longitudinal summer profile indicates an approximate linear decrease in DO as one progresses up the Bay. A simple analysis of the behavior of the DO in the bottom waters can be made to help understand this behavior.

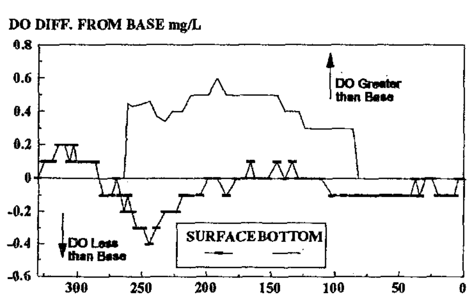
The principal sinks of oxygen in the bottom water are the sediment oxygen demand (SOD), the oxidation of the dissolved organic carbon (DOC) and the immediate uptake of oxygen to satisfy the chemical oxygen demand (COD) of reduced substances released from the sediment. Phytoplankton respiration is neglected since during the summer the bottom layer phytoplankton biomass is small. In the CBWQM, the sediment and water column are interactive and not separated. However, since the output from the sediment model is computed as equivalent SOD and COD, an analysis can be made considering these processes as external sinks of DO. The rates of utilization of oxygen in the model are oxygen dependent, but this complication is not considered here in this simple analysis. Also, vertical mixing of oxygen is not included which simplifies the analysis considerably. The DO concentration is thus given by a linear equation

The accompanying Figure illustrates this behavior. At the head end of the trench after the approximately 17 days of total travel time, the total DO decline is then about 6.5 mg/L or for an initial bottom DO at the mouth of the Bay of about 7 mg/L, a DO of about 0. 5 mg/L is calculated. The analysis represents a general process of bottom water moving up the Bay, losing oxygen during the time of travel of the parcel (due principally to a constant withdrawal of oxygen to satisfy the SOD) and arriving at the head end of the trench at anoxic levels.

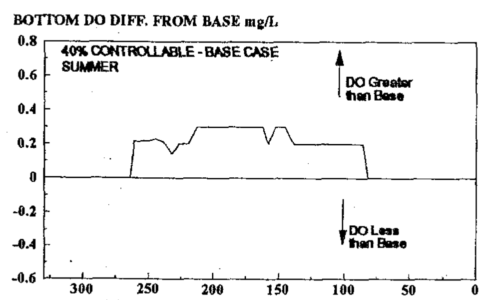


Showing approximate zero order (linear) decrease in bottom DO, Base case, Summer, average year.

The Figures below show the summer average DO for the LOT N&P and the 40% Controllable scenarios. For the LOT N&P, the bottom DO is improved, but not to the point of raising the DO above anoxia (i.e., DO < 1 mg/L) on a summer average basis. Analysis of the



Longitudinal variation of DO difference between LOT and Base case averaged over summer for average year.

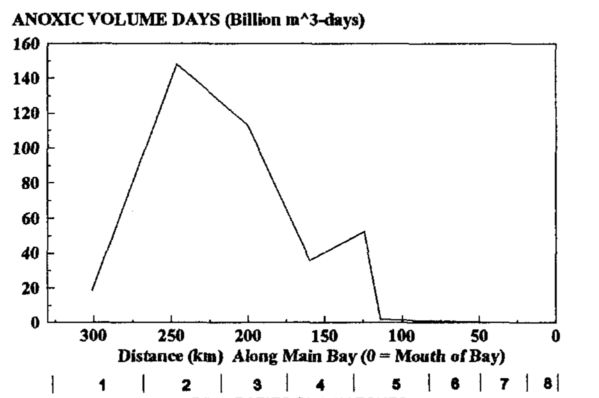


Longitudinal variation of bottom DO difference between 40% Controllable scenario and Base case averaged over summer for average year.

range of load reduction indicates that only when the incoming loads are reduced by at least 50% of the external load is the summer average bottom DO calculated to be greater than 1.0 mg/L. The 40% controllable scenario improves the bottom DO by about a constant 0.2 mg/L on a summer average basis which is about half of the LOT N&P scenario.

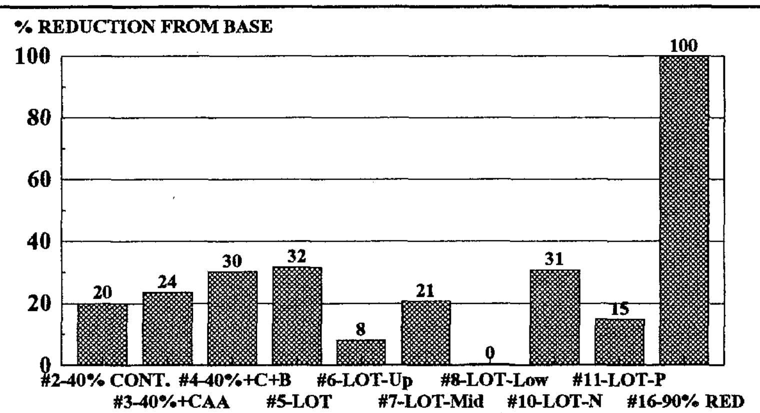
Anoxic Volume Days Response As noted above, a useful measure of the degree of anoxia is the total volume •days where the DO was calculated to be less than 1 mg/L. That is, anoxia is tracked on a volume basis over time and a sum is tabulated for each scenario. Maximum anoxia occurs in the summer with about 16% occurring in the spring and fall and none in the winter. The longitudinal variation of the anoxia as shown to the left indicates peak regions in zones 2 and 3 where about 70% of the annual total occurs. An additional 24% occurs in Zones 4 and 9 (Eastern Shore).

The percent reductions in total annual anoxic volume days from the Base case for selected scenarios is shown below. Complete elimination occurs at 90% N&P removal (Scenario #16). The upper limit of anoxia reduction provided by the best technology (LOT) is about 30%. Note that 40% controllable +CAA+Basin control (Scenario #4) approaches the improvement from LOT N&P (#5).



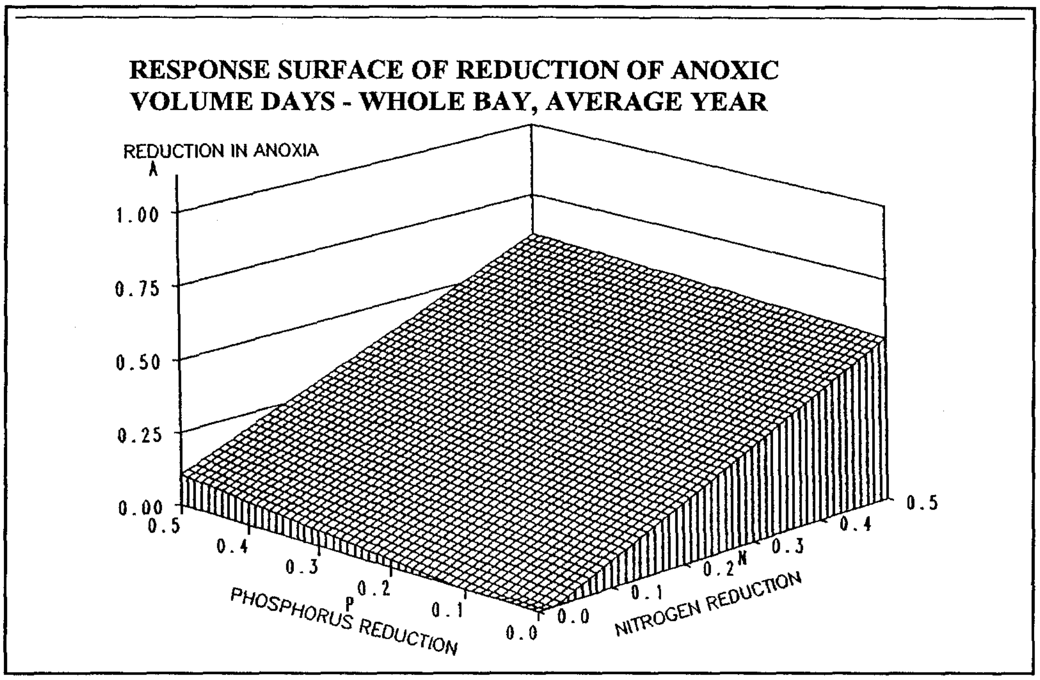
Longitudinal variation of anoxic volume days for Base case total over zone for average year.

The relative impact of nitrogen and phosphorus is seen by comparing #10 and #11 with



Percent reductions in anoxic - volume - days from Base case for selected scenarios. Average Year

#5. As noted above, LOT P Only has less of an impact on the bottom DO and as shown in Figure VII - 12, only a 15% improvement in anoxia is calculated which is half that from LOT N Only. The relationship between nitrogen and phosphorus loadings and the response in terms of anoxic volume •days is further described by the use of response surface analysis. Combining scenario runs in a single plot of Bay wide anoxia reduction versus TN and TP load reductions allows the visualization of the change in DO improvement as a function of nutrient reductions. Such a surface is shown below.



As seen from this Figure, reductions in TN improve the DO conditions more than reductions of TP of the same magnitude. It should also be noted that LOT N Only has a greater reduction in primary production during the summer months in the mid to lower Bay regions. Since maximum anoxia occurs during the summer, LOT N Only can be expected to also have a relatively larger impact on summer anoxia than LOT P Only.

In addition to this hypothesized effect, two other effects may also contribute to the reduced effect on anoxic volume-day response to the LOT - P Only scenario. As noted previously, reduced phosphorus loading reduces primary production in the surface waters of the upper Bay. Such a reduction has the following two consequences:

(1) the reduced algal growth at the surface decreases surface water DO which in turn decreases the vertical concentration gradient thereby reducing the exchange of DO and replenishment of bottom DO in the upper Bay, and

(2) the reduced algal growth will not assimilate as much ammonium with the result that nitrification will increase in the surface waters, decreasing the DO and again decreasing the vertical transport of oxygen to bottom waters of the upper Bay.

It can also be noted that the location of where LOT load reductions are applied is also significant. Thus, comparing Scenarios #6,#7 and #8 indicates that maximum impact on bottom anoxia is from load reductions in the mid-Bay region. That is, as Figure VII - 12 indicates, there is a negligible percent reduction in anoxic volume days under Scenario #8 (LOT - Lower Bay) as compared to 8% for Scenario #6 (LOT - Upper Bay) and 21% for Scenario #7 (LOT - Middle Bay). The minimum impact on anoxia for LOT in the lower Bay only is apparently a consequence of (a) no net input of nutrients from the Rappahannock and York estuaries (but an input from the

Bay into these tributaries), and (b) transport of nutrient input from the James out through the mouth of the Bay more than transport of nutrients up the Bay proper.

Conclusions The results presented in this Section indicate the following:

1. Bottom DO concentrations under Base case conditions reach minimum summer average levels of less than 1 mg/L. The approximate linear decline in oxygen with distance as one proceeds up the Bay in the direction of the bottom flows is a result of the distributed sink of oxygen occasioned principally by the sediment oxygen demand. As such, the minimum bottom DO at the head end of the trench reflects the accumulated DO depletion of a bottom water parcel since it entered the Bay. All SOD along the path of bottom water contributes to the DO depletion.

2. Feasible reductions in nutrient loadings of about 20 -30% N & P (i.e., LOT and "40% controllable" scenarios) result in improvement in bottom DO over Base by about 0.2 - 0.4 mg/L as a summer average.

3. Load reductions of about 50% or greater result in minimum summer average DO concentrations above 1 mg/L.

4. 90% N & P reductions are calculated after the ten year simulation to result in average summer DO of greater than 5 mg/L.

5. A measure of anoxia as given by the volumetric and temporal extent of DO less than 1 mg/L (the anoxic volume days) is a maximum in the summer and in Zones 2-4 under Base case. The feasible load reduction scenarios result in a range of reduction in anoxic volume days of about 20 - 30% from Base. This reduction in anoxia is directly proportional to the load reduction of nitrogen of about 20-30%.

6. Response surface analysis of anoxic volume days on a Bay wide basis indicates a generally linear response in anoxia reduction as a function of nitrogen with little effect due to phosphorus reductions. The maximum effect of phosphorus is in Zone 4, a region that contributes a relatively smaller fraction to the Bay wide total anoxia.

7. Even though the upper Bay is phosphorus limited, reductions of phosphorus do not have as significant an effect on anoxic volume days as do nitrogen reductions. The reasons for this response are complex . Phosphorus controls primary production in the winter and spring while nitrogen controls primary production in the summer, the period of maximum anoxia. Also, when only phosphorus is removed there is a calculated increased nitrogen transport to down Bay nitrogen limited regions which increased downstream SOD. This effect is apparently coupled with reduced primary production in the surface waters of the upper Bay resulting in a reduced vertical DO gradient and less oxygen transferred to the bottom waters of the upper Bay.

8. The location of where LOT load reductions are applied is also significant. Thus, the scenarios where LOT reduction were selectively applied by Bay regions (Upper, Mid and Lower) indicate that maximum impact on bottom anoxia is from load reductions in the mid-Bay region. A negligible percent reduction in anoxic volume days is calculated for LOT in the Lower Bay only as compared to 8% for LOT for the Upper Bay and 21% for LOT in the Middle Bay. The minimum impact on anoxia for LOT in the lower Bay only is apparently a consequence of (a) no annual net input of nutrients from the Rappahannock and York estuaries (but rather an input from the Bay into these tributaries) and (b) possible transport of nutrient input from the James out through the mouth of the Bay more than transport of nutrients up the Bay proper.

TECHNICAL ANALYSIS OF RESPONSE OF CHESAPEAKE BAY WATER QUALITY MODEL TO LOADING SCENARIOS

I. INTRODUCTION

A. BACKGROUND

A modeling framework was constructed for the Chesapeake Bay system (Figure I-1) to provide a credible basis to assist the decision-making process and to further the understanding of Bay water quality processes and the sensitivity of such processes to external nutrient loading. The structure includes a Watershed Model, (WSM), (Donigian et al., 1991) to generate nutrient loads from the Bay sub-basins, a three-dimensional , time variable hydrodynamic model (Johnson et al., 1991a, 1991b; Dortch, 1990, Blumberg et al., 1991) and a three-dimensional, time variable model of water quality (Cerco and Cole, 1992) coupled to a model of sediment processes (Di Toro and Fitzpatrick, 1993). The integrated latter two models herein designated as the Chesapeake Bay Water Quality Model (CBWQM) are driven by the hydrodynamic model and loadings generated by the WSM.

Extensive calibration analyses of the entire modeling structure was conducted using data collected primarily during a three year period from 1984-1986. The Chesapeake Bay Program Modeling Subcommittee completed its review of the CBWQM calibration in May 1991 and concluded the model could provide useful information to the Bay community. However, additional calibration efforts continued during 1991 to improve overall model performance. Although no significant changes in the model calibration resulted from this continuing effort, the final calibration did smooth out some spatial variability allowing for a much better match between observed and predicted values. Final calibration of the CBWQM was completed in January 1992.

A full documentation of this calibration effort is given in the aforementioned reports. After completion of the development and calibration of the water quality model of the Bay, a series of runs were conducted to test and explore model response to loading outside of the calibration conditions and to provide input into the decision-making process. The preliminary results from seven initial runs to test overall model behavior were summarized in a progress report by the Nutrient Reevaluation Workgroup of the Chesapeake Bay study (Nutrient Reevaluation Workgroup, 1992). As stated in that report, the models are to address the following management issues:

What impact do nutrient loads from point and nonpoint sources delivered by the Bay's major tributaries have on Chesapeake's water quality?

How do these impacts change with reductions or increases in these sources?

How are these impacts distributed across the Bay's habitats?

How much of the nutrient loads to the Bay is natural and how much is related to man-made sources, and to what extent can loads be controlled?

How long will it take the water quality in the Bay to improve once nutrient controls are fully implemented?

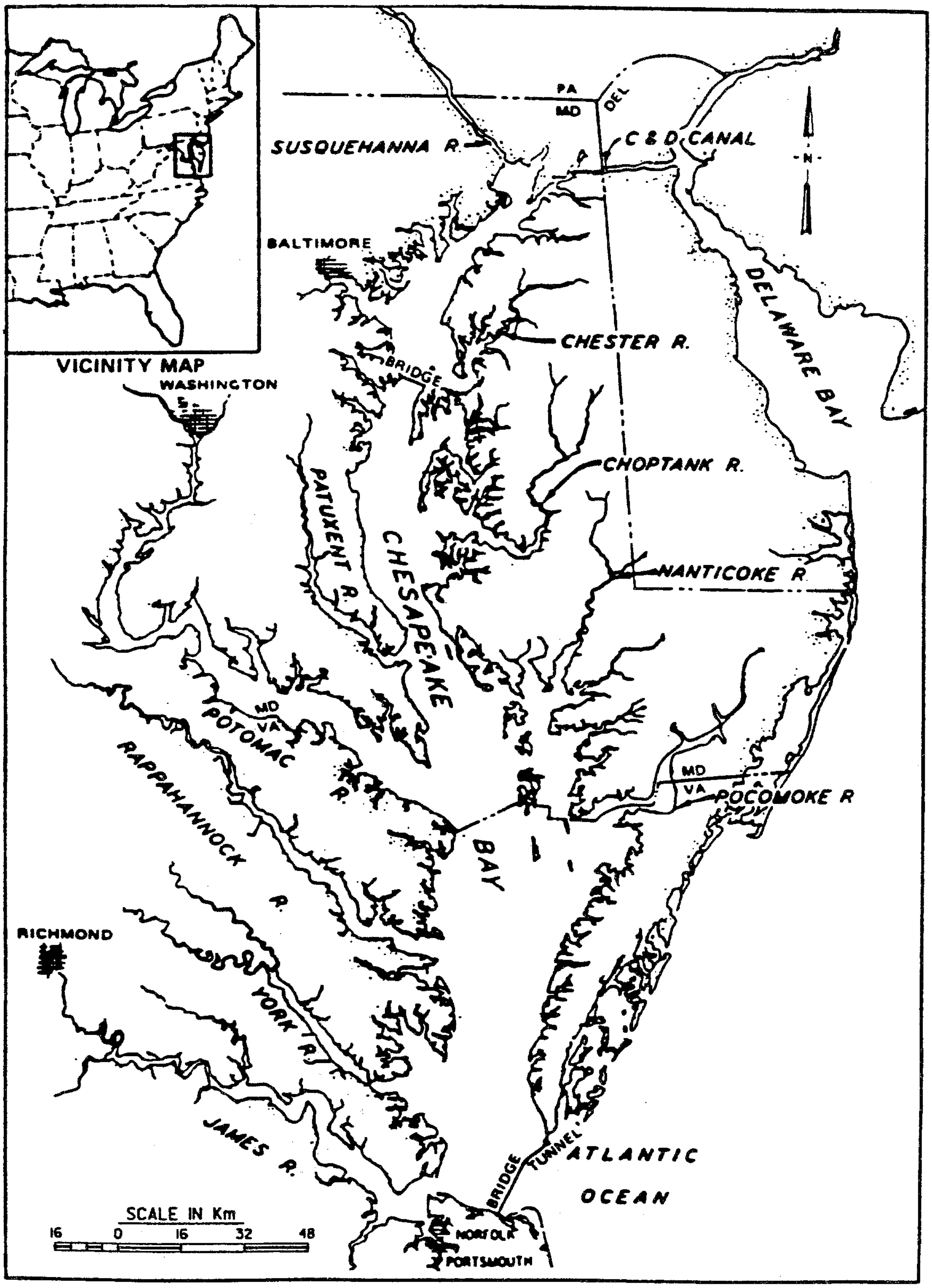


Figure I - 1 The Chesapeake Bay

One of the key questions answered during the reevaluation was whether meeting the 40 percent nutrient reduction goal would translate into a significant improvements to the Bay's anoxic problems. The CBWQM provides projections of the expected water quality responses including dissolved oxygen concentrations in the main Bay under a variety of proposed management actions (e.g., point and nonpoint source controls). A number of scenarios were run simulating water quality conditions under varying reductions of point (PS) and nonpoint source (NPS) loads.

The purposes of this report are therefore to address these questions by (a) documenting the results of a full set of loading scenario computations, (b) analyzing the scenario results across different loading conditions and (c) interpreting the results in the light of the sensitivity of the Bay model to various loading conditions.

B. WATER QUALITY GOALS AND REQUIREMENTS FOR INTERPRETATION OF SCENARIOS

Several water quality goals and requirements can be utilized as guidelines in interpreting scenario results and in comparing results between scenarios. These water quality goals and requirements are considered from the point of view of the maintenance, protection and improvement of the aquatic ecosystem habitat. The focus is on the Bay fisheries, and supporting aquatic life communities, including the benthic community and the submerged aquatic vegetation (SAV). Details for the assessment and determination of water quality requirements are given in Chesapeake Bay Program (1993), Dennison et al (1993), Batuik et al (1992), Jordan et al (1992) and Funderbuck et al (1991). The principle water quality parameters are: dissolved oxygen (DO), dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), phytoplankton chlorophyll *a*, light attenuation coefficient and total suspended solids.

For further reference in later sections of this report, the DO goals are summarized in Table I-1 and the SAV requirements are summarized in Table I-2.

TABLE I-1 SUMMARY OF DISSOLVED OXYGEN GOALS[1]

Dissolved Oxygen Goal	Location & Other Specifications
At least 1.0 mg/L at all times	Throughout Bay & tidal tributaries, including subpycnocline waters
Between 1-3 mg/L for less than 12 hrs and interval between 1-3 mg/L longer than 48 hrs.	Throughout Bay & tidal tributaries, including subpycnocline waters
Monthly mean at least 5 mg/L	Throughout above-pycnocline waters of Bay & tidal tributaries
At least 5 mg/L at all times	Throughout above-pycnocline waters of anadromous fish spawning reaches, rivers and nursery areas
[1]See CBP (1993) and Jordan et al (1992) for details.	

TABLE I - 2 SUMMARY OF SAV HABITAT REQUIREMENTS[1]

SAV Habitat Requirements for One Meter Restoration		
Water Quality Parameter	Value	Other Specifications
Light Attenuation Coefficient (m^{-1})	<2 <1.5	For TF[2] & OL[2] regions, April-October CLP[3] For ME[2], April-October CLP and for PO[2], March-Nov. CLP
Total Suspended Solids (mg/L)	<15	ForTF,OL & ME, April-October CLP and for PO, March-Nov. CLP
Chlorophyll *a* (μg/L)	<15	For TF,OL & ME, April-October CLP and for PO, March-Nov. CLP
Dissolved Inorganic Nitrogen (mg/L)	<0.15	For ME , April-Oct. CLP and for PO, March-Nov. CLP
Dissolved Inorganic Phosphorus (mg/L)	<0.02 <0.01	For TF & OL, April-Oct. CLP and for PO, March-Nov. CLP For ME, April-Oct. CLP
SAV Habitat Requirements for Two Meter Restoration		
Light Attenuation Coefficient (m^{-1})	<0.8	For TF,OL & ME, April-October CLP and for PO, March-Nov. CLP

[1] See Batuik et al (1992) and CBP (1993) for details.
[2] TF = Tidal Fresh (<0.5 ppt salinity), OL = Oligohaline (<5-5 ppt), ME = Mesohaline (>5-18 ppt) and PO = Polyhaline (>18 ppt).
[3] Critical Life Period

C. RATIONALE FOR SCENARIO CHOICES

The loading scenarios included four groupings of conditions representing the need to examine model response over a range of conditions, permit assessment of scenario responses relative to water quality goals and requirements and provide input for management purposes.

1. Loads within the "feasible" loading reductions representing controllable loads and limit of technology loading conditions[1],
2. Load reductions to levels beyond the feasible range to low values to test the sensitivity and stability of the model,
3. Loading to "pristine" levels to test model response under pre-European settlement conditions, and
4. Load scenarios for allocation and management purposes.

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[1] See Section II. Model Loads and Scenarios for specifications of "controllable" and "Limit of Technology" loading conditions.

D. SUMMARY LISTING OF SCENARIOS

Table I-3 below summarizes the scenarios completed for this report. A more complete description of the scenarios is given in the Appendix.

TABLE I-3 SUMMARY OF SCENARIOS

Scenario Number	Scenario Tag	Scenario Description
1	BASE	1984-1986 Loading
2	40% CONT	40% Reduction of controllable load ("Agreement" states only)
3	40% +CAA	Scenario #2 + Clean Air Act atmospheric reductions
4	40%CAA+BASIN	40% + CAA for entire basin
5	LOT	Limit of technology
6	LOT -UPPER	Limit of technology for "Upper Bay" only, others at Base
7	LOT - MID	Limit of technology for "Middle Bay" only, others at Base
8	LOT - LOWER	Limit of technology for "Lower Bay" only, others at Base
9	LOT - MID (A)	Same as #7 except Potomac River basin loads at Base
10	LOT - N ONLY	LOT for nitrogen only, phosphorus at Base
11	LOT - P ONLY	LOT for phosphorus only, nitrogen at Base
12	65% LOT	Loads at 65% of LOT
13	BNR	Point sources at seasonal BNR
14	ALLOCATION 2	Variable loading by Bay region
15	50% N & P	50% reduction in total N & P loading from Base
16	90% RED	90% reduction in total N & P loading from Base
17	90% N ONLY	90% reduction in total N loading only from Base
18	90% P ONLY	90% reduction in total P loading only from Base
19	31%N -18%P	31% & 18% reduction in total N & P, respectively
20	10%N - 49%P	10% & 49% reduction in total N & P, respectively
21	SUS. REGR.	Same as Base case (#1), with regression loads for Sus. R. load

The 21 scenario runs cover a wide range of loading conditions and hence water quality response in the Bay. Using the "Base" run #1 as a reference loading condition, other scenarios include the feasible range (#2-#11), responses beyond feasible load reductions (#15-#20) including an estimate of pristine loading (approximated by run #16) and several management runs (#12-#14). Run #21 is a comparison run with run #1 but using regression estimates of loading from the Susquehanna River rather than loadings as generated by the Watershed Model. Details of the loading into the model are given in Section II.

In addition to the scenario runs listed above, a series of "tracer" calculations were also made. These runs included release of conservative and non-conservative constituents in various portions of the Bay model in order to track the behavior of such variables and to provide additional information for interpreting the more complex water quality runs.

II. MODEL LOADS AND SCENARIOS

A. LOADING CONSIDERATIONS

1. Introduction

This report is focused on the response of the main Bay to various loading scenarios. As such, the loadings from tributaries to the Bay (as well as the exchange with the ocean) are evaluated at the interface of the tributary with the main Bay. Also, loadings external to the water column and loadings interacting with the sediment are compiled. Figure II -1 shows a schematic of the external loadings together with the delineation of the Bay into the three large regions of Upper - Bay, Mid-Bay and Lower Bay as used in Scenarios #6 through #9 and #14.

As indicated, the external loads are comprised of (1) fall line loading, (2) below fall line load, (3) point source loads, (4) atmospheric loads direct to the water surface of the Bay, and (5) ocean loading.

Fall line loadings and below fall line loadings are calculated from the Watershed Model (WM). Point source loads were obtained from inventories. Atmospheric loads were estimated based on available data and ocean boundary loads were estimated using shelf nutrient data and a simple exchange model at the mouth of the Bay. Cerco and Cole (1992) describe the procedure in detail.

Tidal tributary interface loadings are the result of fall line loadings, point source inputs and below fall line loadings together with the within-tributary processes of transport, kinetic and sediment interactions. The net tributary loads are discussed in some detail in Section VI - F of this report.

2. Reference Loadings

The three principal reference loadings that established the extent of feasible reductions, are:

1. Base Case Load,
2. Controllable Load, and
3. Limit of Technology (LOT) Load.

As noted in the Introduction, in addition to these loading "boundaries", a series of other loading patterns were used in the scenarios to determine Bay response over a wider range of loading reductions.

a. Base Case. The Base Case loading represents the calculated response from the 1984 -1986 loading as a reference time period. This is the same period used for the calibration of the CBWQM.

b. Controllable Load. Controllable loads are defined as the difference between Base Case loads and a WSM run using an all forested (excluding NY, WV & DE) basin with no point sources.

c. LOT Load. Limit of Technology loads for NPS inputs were determined by evaluation of Best Management Practices (BMP) and implemented in the WSM. The basic LOT NPS reduction components include:

1. Conventional tillage was placed into conservation tillage together with simulation of the retirement of highly erodible land by placing additional conservation tillage and hay land into pasture,

2. Animal waste control where 75% of animal waste acres were converted to pasture land,

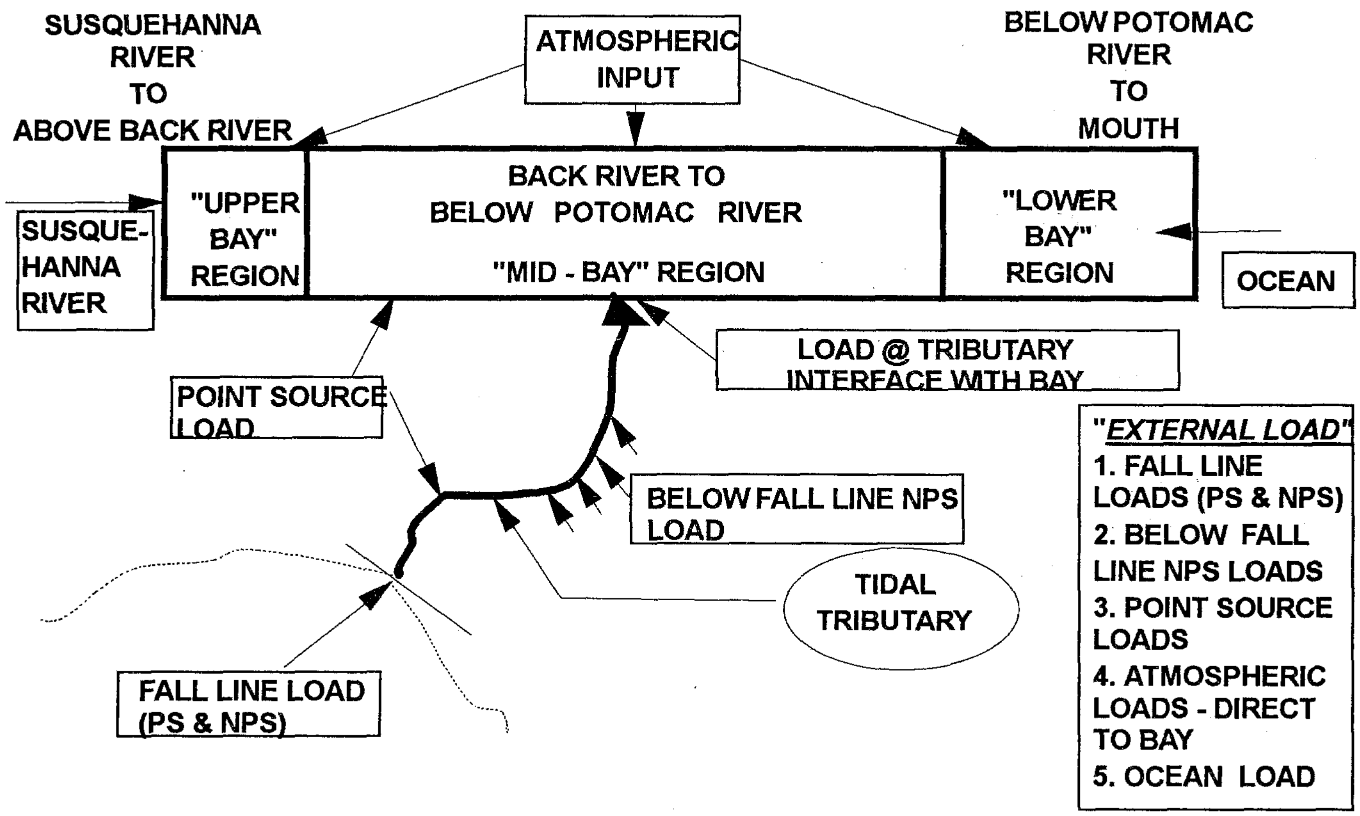


Figure II-1. Load Categories and Bay Regions for "Geographical" Scenarios

3. Nutrient management controls where all cropland and hay land had reduced manure and fertilized inputs as recommended by state NPS programs,

4. Pasture controls, such as grazing load stabilization systems, stream protection systems or spring development, where reductions of 4%, 8% and 8% were taken for TN, TP and BOD, respectively,

5. Urban controls, such as wet and dry ponds or infiltration trenches, where a 20% reduction of TN and TP is assumed,

6. Structural BMP's on farmland including any physical or constructed practice such as vegetated filter strips or waterways implemented on cropland, where 4%,8% and 8% reductions in TN, TP and BOD, respectively, are assumed, and

7. Forest controls where NH4, PO4 and BOD loads were reduced by State to account for LOT controls of silviculture, (5%, 7.5% and 10% for PA, MD and VA, respectively).

Point source (PS) LOT loads were assumed as follows: 3.0 mg/L for TN, 0.075 mg/L for TP, and 1.0 mg/L for BOD.

B. HYDROLOGICAL SEQUENCE

In order to represent year to year variation in hydrology, the scenario runs were conducted over a ten year period with flows representative of the interval from 1979 to 1988. Wet, average and dry years during this period were assigned the 1984, 1986 and 1985 hydrologies, respectively together with the associated transport for those years as calculated by the hydrodynamic model. The total river flows to the Bay for 1984 to 1986 are 487,300 cfs (13,800 m^3/s), 459,100 cfs (13,000 m^3/s), and 476,700 cfs (13,500 m^3/s), respectively. Figure II - 2 shows the seasonal flow variation for the average year for three of the major tributaries to the Bay as generated by the WSM and as used for load generation at the fall lines.

Table II-1 shows the flows and sequence used in the scenarios.

TABLE II - 1
HYDROLOGICAL SEQUENCE USED IN SCENARIOS

YEAR	HYDROLOGY ASSIGNED
#1 - 1979	Wet (1984)
#2 - 1980	Dry (1985)
#3 - 1981	Dry (1985)
#4 - 1982	Average (1986)
#5 - 1983	Average (1986)
#6 - 1984	Wet (1984)
#7 - 1985	Dry (1985)
#8 - 1986	Average (1986)
#9 - 1987	Average (1986)
#10 -1988	Dry (1985)

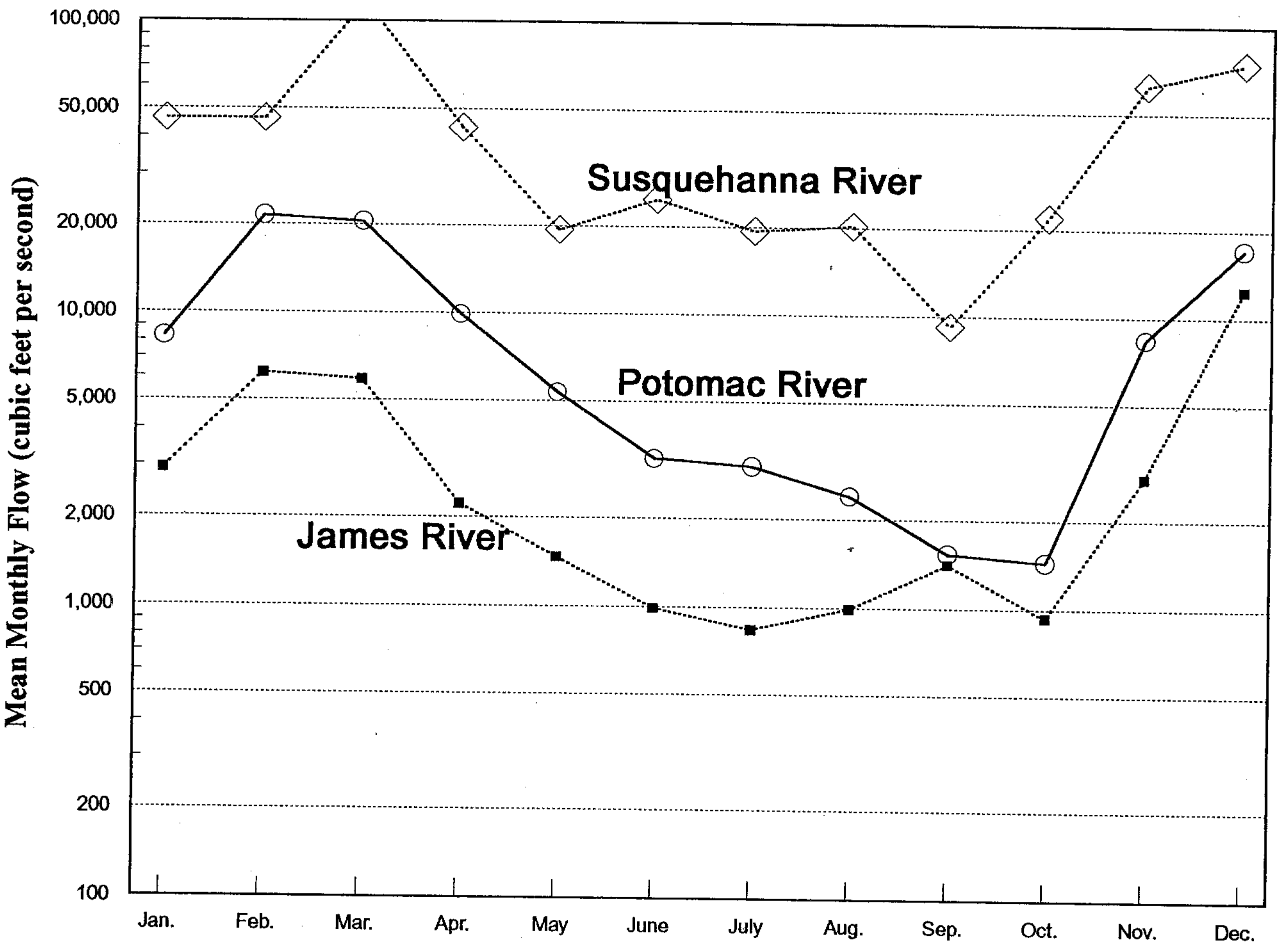


Figure II-2. Susquehenna, Potomac and James Rivers Mean Monthly Flows from Watershed Model. Average Year, 1986.

The CBWQM was run for these ten years in sequence and the final five years were output. In this report, the emphasis is on year #9, the average year. This choice is dictated by the time to a dynamic steady state. The water quality response for the average year is the closest to this dynamic equilibrium.

C. DESCRIPTIONS OF SCENARIOS

The scenarios discussed in this report are summarized in Table II-2. A complete tabulation of the input nitrogen and phosphorus loads for each scenario run is presented in Appendix A.

D. SCENARIO NITROGEN LOADS

Figure II-3 shows the total nitrogen (TN) loads used for three of the principal scenarios: Base Case, 40% Controllable and the Limit of Technology (LOT). These three runs provide an approximate bounding of the feasible range of load reductions. As shown in this Figure, the major source of nitrogen is from the nonpoint sources making up more than 45% of the total for all three scenarios. The point sources directly to the Bay or it's tidal tributaries decline from 19% of total at Base to 5% at LOT indicating a significant reduction of point source loading relative to nonpoint source reduction. This is discussed further below. Atmospheric loading directly to the tidal waters is about 9% of total. Ocean loading of TN is a significant component of the total load to the Bay and is estimated to range from 29% to 36% of the TN loading for Base to LOT.

Figure II-4 indicates the % reduction of external TN loading (excluding ocean input) from the Base Case for selected scenarios. The increase in % reduction across the variations of the 40% Controllable (#2) through scenario #4 can be noted. Clean Air Act controls (CAA) on a basin-wide scale and including the non-basin states increase the % reduction from 18% to 25%. It can also be seen that scenario #4 is approaching the LOT scenario #5. The LOT-Mid (#7) run removes almost as much TN as the 40% Controllable case.

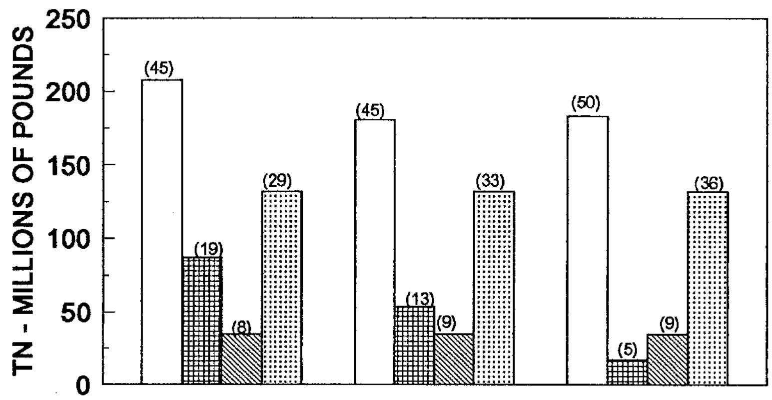
The distribution of TN loads by tributary and Bay shore area is plotted in Figure II-5 for three scenarios. The Susquehanna River input is the largest and makes up about 47-60% of the total load over the three scenarios. The reduction in the Susquehanna load from the Base Case to LOT is about 14% while for the Potomac, the reduction from Base Case to LOT is about 43%. It can also be noted that the contributions from the smaller tributaries in the Bay shore areas (i.e., West shore MD , West shore VA and East shore MD/VA) together make up about 15% of the total TN load.

The variation of the nitrogen components for the Base Case and the Susquehanna River is shown in Figure II-6. The NO_3 -N form is shown as the principal component to the TN load with some additional contribution from the organic-N form. This contribution of nitrogen species is approximately representative of the other tributaries.

TABLE II-2
LIST OF SCENARIOS

NO.	TAG	DESCRIPTION/OBJECTIVE
1	BASE	Establishes the existing conditions against which load reductions will be applied or compared. This scenario simulates the water quality conditions with 1984-86 loads.
2	40% CONT.	This run represents the Bay Agreement Goal. The 40% reduction applies to the "controllable" load, not the total load to the Bay.
3	40% + CAA	The 40% reduction of controllable loads from the Bay Agreement States is combined with the basin-wide reductions in delivered deposition loads expected from implementation of the 1990 Clean Air Act (CAA). This run, compared with the 40% reduction (Scenario 2), provides an estimate of the additional Bay load reductions brought about by the CAA.
4	40% CAA+ BASIN	The 40% reduction of controllable loads from all states in the basin is combined with the basin-wide reductions in delivered deposition loads expected from implementation of the Clean Air Act (CAA). This run provides an estimate of the additional Bay load reductions attributed to the CAA and by expanding the participation of the nonagreement states (Delaware, New York and West Virginia).
5	LOT	This run establishes the upper boundary of load reductions using a combination of point source controls at the Limit of Technology (LOT) and the most comprehensive best management practices for NPS controls.
6	LOT-UPPER	This run examines the influence of load reductions to the tidal fresh portions of the Bay. In this run, loads from the Susquehanna basin and upper Bay below the fall line segment down to, but not including Back River, are reduced using a combination of point source controls at the Limit of Technology (LOT) and the most comprehensive best management practices for NPS controls. All other areas of the basin are at base loads.
7	LOT -MID	This run examines the influence of load reductions to the lower salinity mid-region of the Bay. In this run, loads from the Potomac basin and mid-Bay below the fall line segments from Back River down to, but not including the Rappahannock River, are reduced using a combination of point source controls at the Limit of Technology (LOT) and the most comprehensive best management practices for NPS controls. All other areas of the basin are at base loads .
8	LOT -LOWER	This run examines the influence of load reductions to the higher salinity lower-region of the Bay. In this run, loads from the James basin and lower-Bay below the fall line segments from Rappahannock down to the Bay mouth are reduced using a combination of point source controls at the Limit of Technology (LOT) and the most comprehensive best management practices for NPS controls. All other areas of the basin are at base loads.
9	LOT- MID (A)	This run holds the Potomac River basin at Base conditions. It is a variant of the Geographic 2 scenario (Scenario 7) and investigates the relative impact of the Potomac River basin on anoxia in the Bay. Fall line and below fall line PS and NPS loads from the Potomac River and its basin were left at Base Case levels while Limit of Technology N and P controls were applied from Back River to just above Potomac River. Geo-regions 1 and 3 are held at base case loads.
10	LOT - N ONLY	LOT for nitrogen only with phosphorus held at Base conditions. Nitrogen PS effluent levels were at 3.0 mg/L with the most comprehensive best management practices employed for NPS controls in the Bay Agreement States.

11	LOT - P ONLY	LOT for phosphorus only with nitrogen held at Base conditions. Phosphorus PS effluent levels were held at 0.075 mg/l with the most comprehensive best management practices employed for NPS controls in the Bay Agreement States.
12	65% LOT	This run used a load reduction from the Base Case equivalent to 65% of the difference between limit of technology loads and Base Case loads. Additionally, segment dependent reductions in atmospheric loads of nitrate over the land surface and non-tidal portion of the water surface in the watershed were applied.
13	BNR	The run is with point sources (PS) at season biological nutrient removal (BNR) with NPS loads at limit of technology (LOT). PS loads at three-stage BNR for the months of May through November.
14	ALLOCA-TION 2	This scenario is based on variable loadings by Bay regions. Geo-region 1 & 2 N controls correspond to 72% of LOT with P load reductions equal to 40% of the controllable P load. Geo-region 3 maintains N & P load reductions equal to 40% of controllable loads.
15	50% N& P	This run establishes a mid-range for a response curve testing the main Bay's response to both nitrogen and phosphorus reduction.
16	90% RED	The run is a 90% reduction of N & P loadings from Base conditions and was used to determine if the sediment model refinements were correct.
17	90% N ONLY	This run establishes the upper boundary for a response curve testing the main Bay's response to nitrogen removal alone.
18	90% P ONLY	This run establishes the upper boundary for a response curve testing the main Bay's response to phosphorus removal alone.
19	31% N &18% P	An incremental nutrient reduction with N point source at LOT, P point source at Base Case and the most comprehensive NPS reductions are made. Used for response surface analysis. Analogous to LOT N.
20	10% N &49% P	An incremental nutrient reduction with P point source at LOT, N point source at Base Case and the most comprehensive NPS reductions are made. Used for response surface analysis. Analogous to LOT P.
21	SUS. REGR.	Effect of Susquehanna load estimated by regression model in contrast to watershed model load.



	#1-Base	#2-40% Cont	#5 LOT
NPS	207.5	180.4	183.0
PS	86.8	53.4	17.0
ATMOS.	34.6	34.6	34.6
OCEAN	131.8	131.8	131.8
TOTAL	460.7	400.2	366.4

Figure II-3. Total Nitrogen Loads by Type and Scenario, Average Year. (Numbers in parentheses = % of total load)

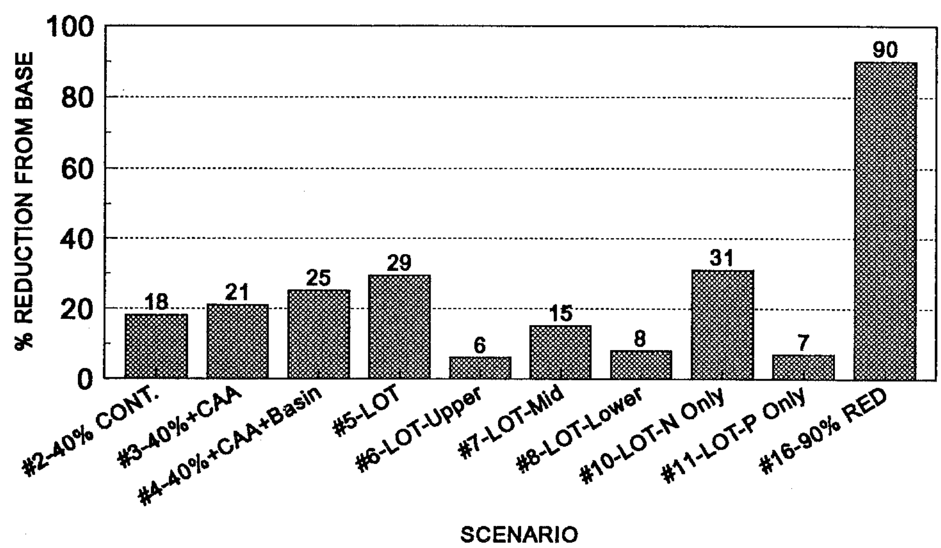


Figure II-4. Reductions in External Total Nitrogen Load for Selected Scenarios. Average Year

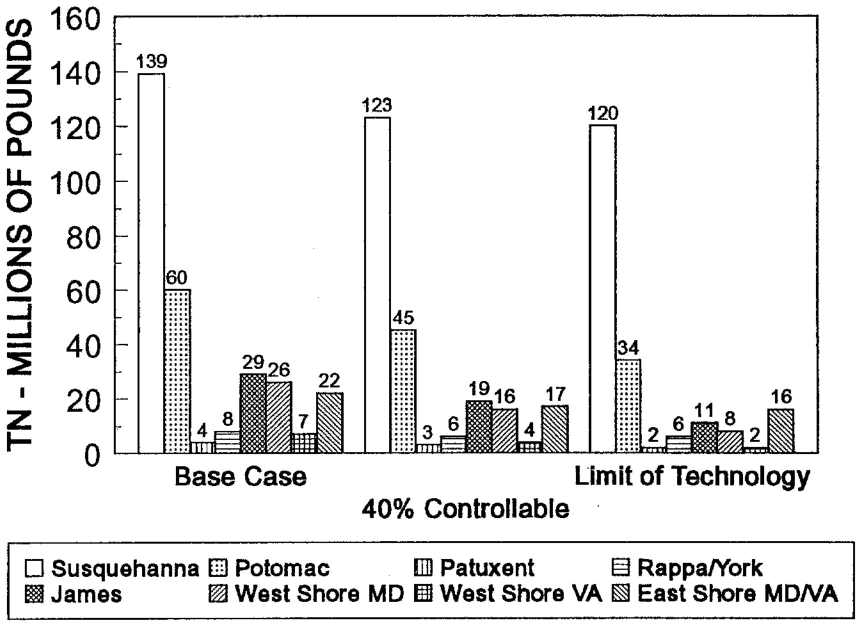


Figure II-5. Total Nitrogen Loads Into Major Tributaries by Scenario - Average Year

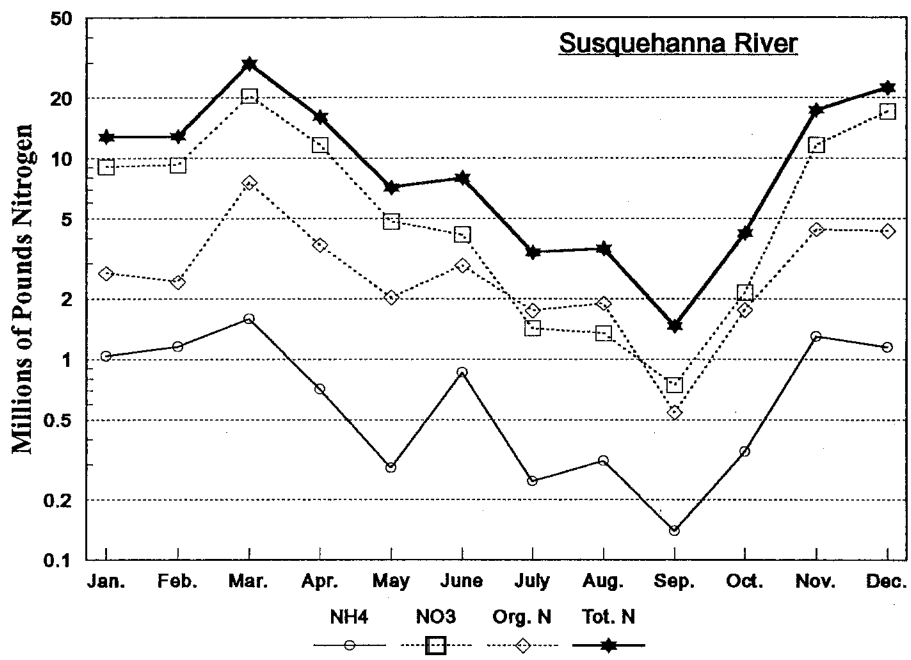


Figure II-6. Base Case Nitrogen Loads from Susquehanna River. Average Year

The monthly variation in TN loading for the average year and Base loading is shown in Figure II-7 for three major tributaries. As indicated, the within-year variation is approximately similar for the three tributaries. It can also be noted that, for the Susquehanna, the range from the peak loading in March to the lowest loading (which occurs in September) is considerable and declines about 95% during this period. Minimum loading for the James is estimated to be during the June-July period while for the Potomac and Susquehanna rivers, the minimum occurs in September.

The relative reduction of TN loading due to point and nonpoint sources indicates that the point source loading is reduced considerably more than the nonpoint loading between the Base Case and LOT. This is illustrated in Figure II-8 where the loading across the three Bay regions (see Figure II-1) is shown. As shown, in progressing from Base to LOT, the point source loading is reduced about 85% while the nonpoint source loading is reduced from 14-23% in proceeding from Base to LOT. This is a reflection of the relative technological difficulty in reducing nonpoint TN loading as opposed to point TN inputs. Also, it should be noted that the Upper Bay region is dominated by the nonpoint input of the Susquehanna River so that the contribution from point sources in that region is small.

Further insight into the relative reduction of the TN loading across scenarios and between point and nonpoint loading is given in Figure II-9 and II-10. For the former Figure, the % reduction of the point source for the 40% Controllable case is 40% by definition. For the nonpoint loading for that scenarios, however, the % reduction is only 14% leading to a net 18% reduction as indicated in Figure II-4. Also, as shown the % reduction for the nonpoint inputs for the 40% Cont. scenario is about equal to the nonpoint reduction for the LOT case (14% vs. 16%).

Finally, the relative contribution to the reduction from Base case from three categories of TN loading and across several scenarios is shown in Figure II-10. In this Figure, "Fall Line" includes the NPS and PS entering the Bay and tidal tributaries, "Below Fall Line" is the NPS loading entering the tidal tributaries and Bay and "Point Source" represents the input loading of point sources below the Fall Line (see also Figure II-1). Again, the significant contribution from point source reductions is shown for all scenarios except the LOT-Upper run which, as noted earlier, is dominated by the Susquehanna input.

E. SCENARIO PHOSPHORUS LOADS

Figures II-11 through II-18 parallel the previous figures for nitrogen but focus on the phosphorus loading, reductions in loading and distribution of phosphorus loads.

Figure II-11 shows an important difference from the TN plot (contrast to Figure II-3). As shown, the ocean loading of TP dominates the loading inputs accounting for as much as 66% of the TP load at the LOT scenario. (Reference should be made to Cerco and Cole, 1992 for a detailed discussion of the ocean boundary condition that gives rise to this significant TP input.) It can also be noted that the nonpoint and point source loading are closer in magnitude than for TN, but for LOT the nonpoint load is about the same as for the 40% Controllable case.

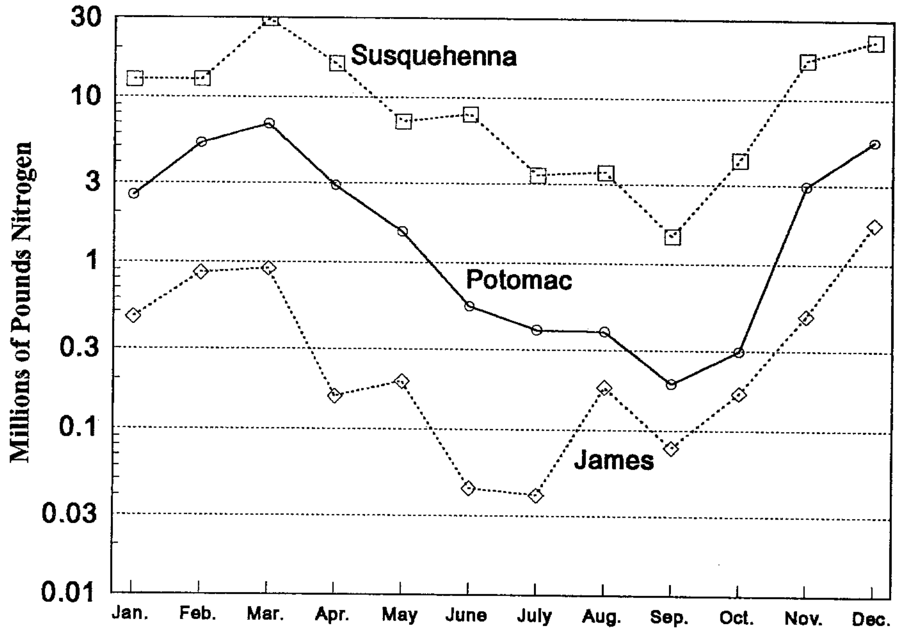


Figure II-7. Base Case Nitrogen Loads from Three Principal Rivers. Average Year

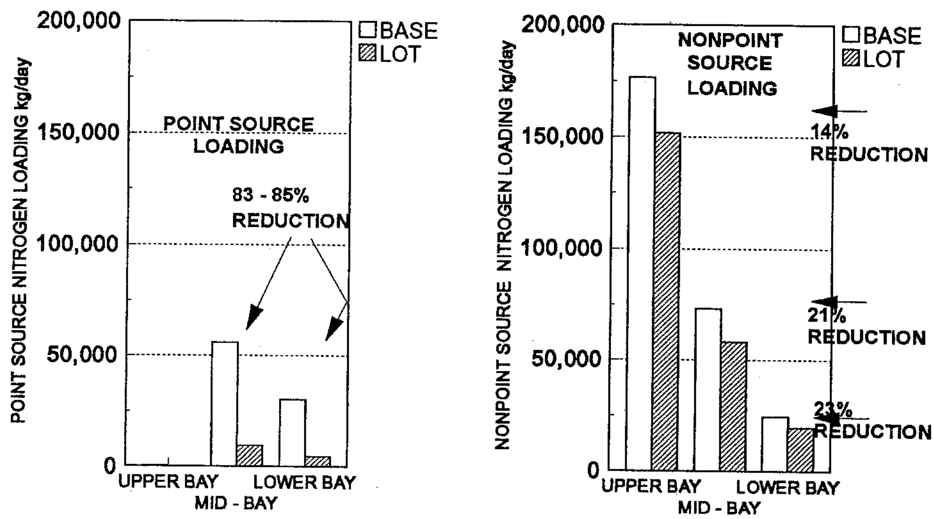


Figure II-8. Longitudinal Distribution of Total Nitrogen Point & Nonpoint Loads for Base Case and Limit of Technology (Nonpoint = Fall Line + Below Fall Line Loads)

Figure II-9. Reductions in Point and Nonpoint Nitrogen Loading.
Average Year

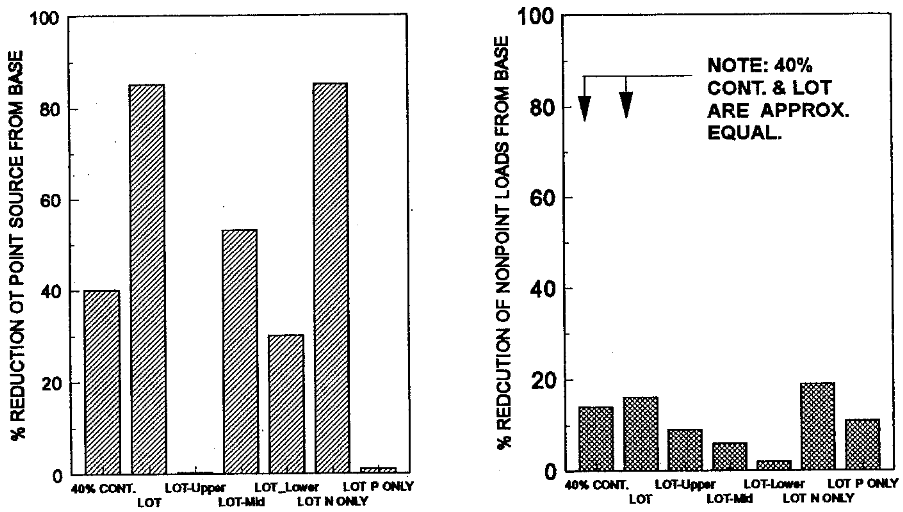
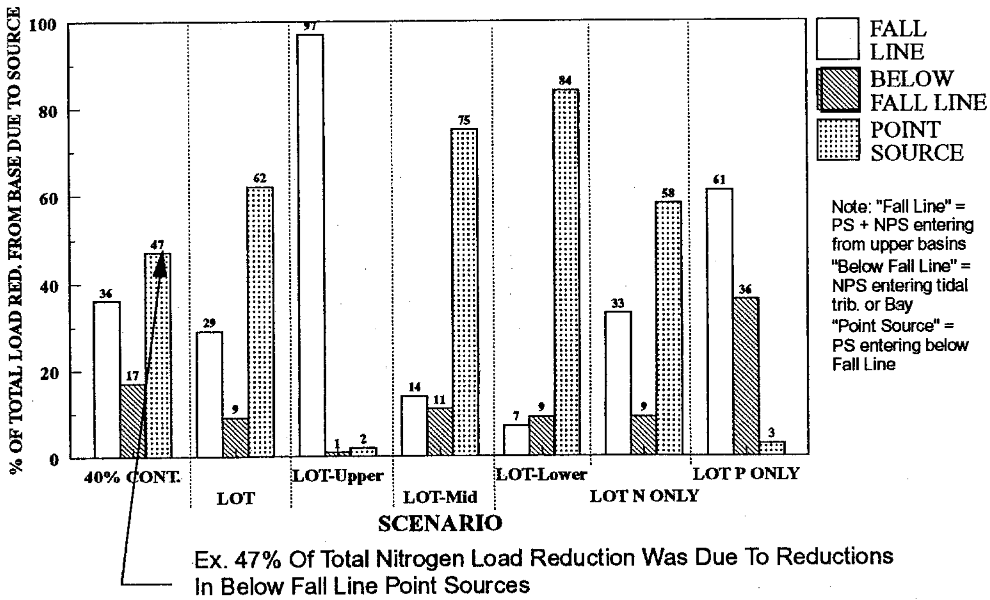


Figure II - 10. % OF Total Nitrogen Reduction Due to Fall Line, Below Fall Line and Below Fall Line Point Source Loads.
Average Year



The % reduction of TP from Base for a series of scenarios is given in Figure II-12. For TP, the reductions are higher than for TN reflecting the relative increase in technological control for TP over TN. For LOT, a 56% reduction is calculated although it should be recognized that if the ocean load were included, the net % reduction of TP from Base due to all loads drops to 29%.

Figure II-13 (for TP) is similar to Figure II-5 (for TN) except that the contribution from the James river is significantly greater in TP than TN. The relative input of TP from the Susquehanna river is less than TN ranging from 33% at Base to 41% at LOT (as opposed to 47-60% for TN). Figure II-14 shows that the principal phosphorus species calculated for the Susquehanna is the organic-P form, considered a less available form for phytoplankton uptake in the CBWQM. The seasonal variation in TP load for the average flow year is shown in Figure II-15 and shows a pattern similar to that for TN. (A discussion of the ratio of the TN/TP for the input loads is given below.)

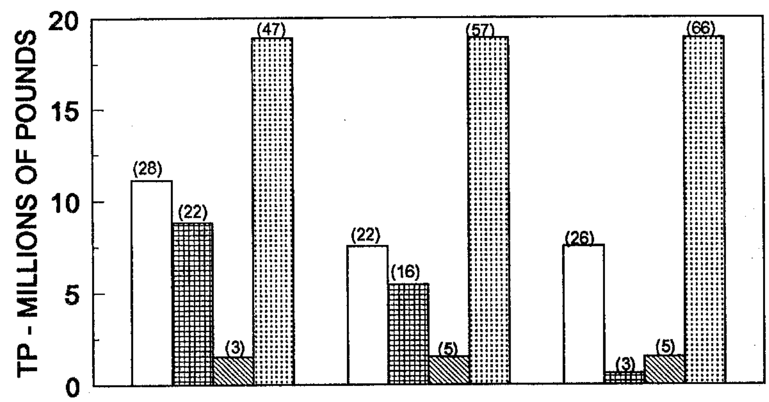
Figures II-16 through II-18 differ from comparable figures for TN (Figures II-8 to II-10) in the increased reduction of TP from nonpoint sources. Figures II-16 and 17 indicate that although PS reductions from Base to LOT are about 96%, NPS reductions are about 45% or twice the reductions for NPS TN. Figure 18 illustrates this further by showing that the relative contribution to the total reduction from point sources is 36% for the 40% Cont. case. (Figure II-18 is similar to Figure II-10 where "Fall Line" represents both NPS and PS loadings from above the Fall line, "Below Fall Line" are the NPS loads entering below the Fall line and "Point Source" are the direct inputs of PS below the Fall Line.)

In contrasting these TN and TP load estimates, relative to PS reductions, decreases in the NPS TN loading are calculated to be more difficult technologically than NPS TP loading. This is presumably a reflection of the assumptions made throughout the general process of load generation.

F. TN/TP RATIO FOR INPUT LOADS

The ratio of the TN/TP loading provides a guideline for determining which nutrient may be limiting in the control of phytoplankton biomass. A TN/TP ratio of 7 (by mass) represents the "Redfield Ratio", i.e., the elemental stoichiometry of oceanic algal cells. In general, TN/TP values significantly less than about 7-10 indicates potential nitrogen limitation while TN/TP ratios significantly greater than 7-10 indicates potential phosphorus limitation. Figure II-19 shows the TN/TP ratio for the input loads as described earlier. Several points can be noted. For the average year shown in this figure, the overall TN/TP ratio is close to the range where nitrogen or phosphorus may be limiting. Ocean TN/TP is at the Redfield ratio (an assumed shelf water TN of 0.37 mg/L and TP of 0.053 mg/L was used). The NPS loading TN/TP is significantly above 7-10 indicating potential phosphorus limitation from that source, but because the ocean load is a significant portion of the total load to the Bay, the overall TN/TP is decreased. It should also be recalled that these values are for the entire year and monthly variations are to be expected as shown in the next Figure.

Figure 20 shows these monthly variations in TN/TP for three significant tributaries. The Susquehanna river TN/TP is always significantly above 7-10 while the Potomac and James tributary loading is in the region of 7-10 during several important months of the year.



	#1-Base	#2-40% Cont	#5 LOT
NPS	11.1	7.5	7.5
PS	8.8	5.4	0.6
ATMOS.	1.5	1.5	1.5
OCEAN	18.9	18.9	18.9
TOTAL	40.3	33.3	28.5

Figure II-11. Total Phosphorus Loads by Type and Scenario, Average Year.
(Numbers in parentheses = % of total load)

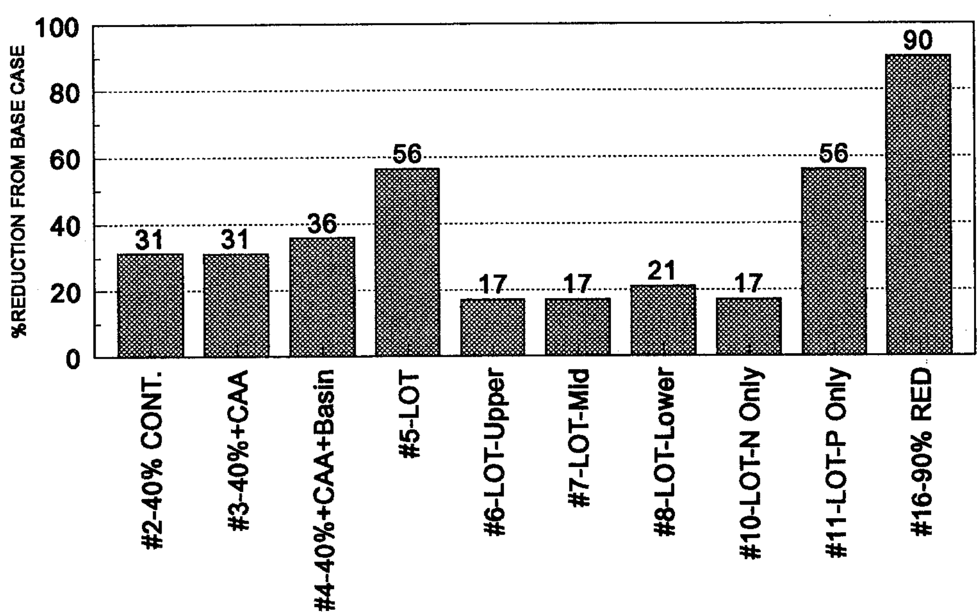


Figure II-12. Reductions in External Total Phosphorus Load for Selected Scenarios.
Average Year

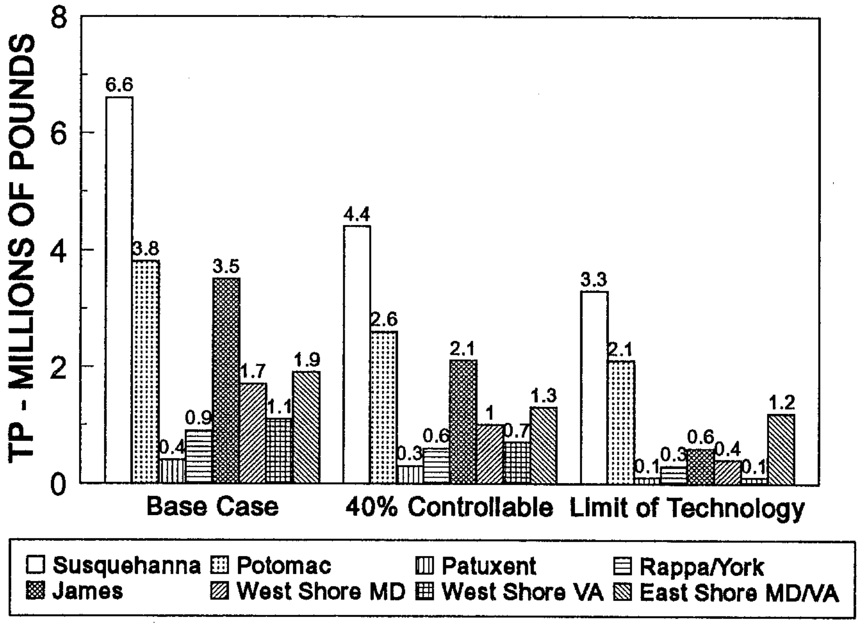


Figure II-13. Total Phosphorus Loads Into Major Tributaries by Scenario - Average Year

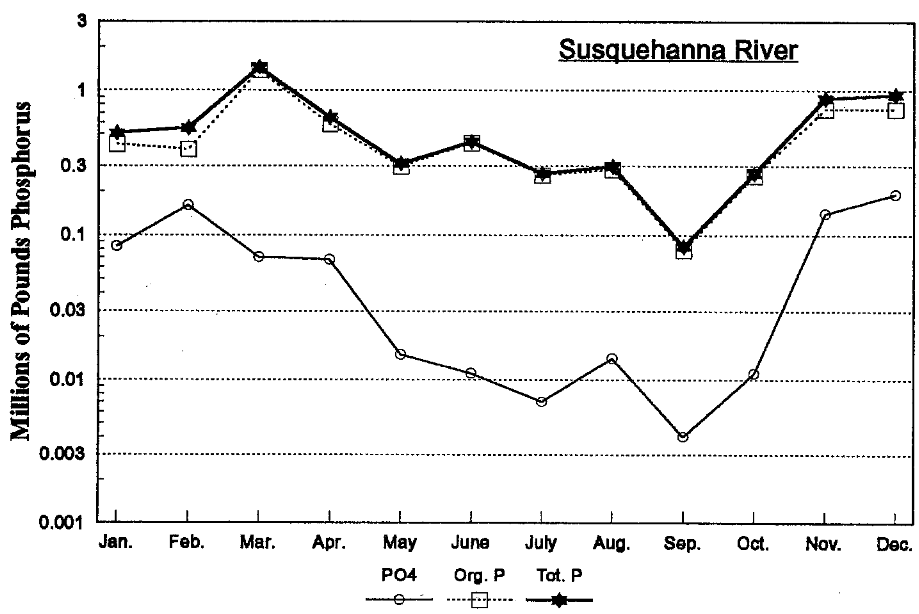


Figure II-14. Base Case Phosphorus Loads from Susquehanna River. Average Year

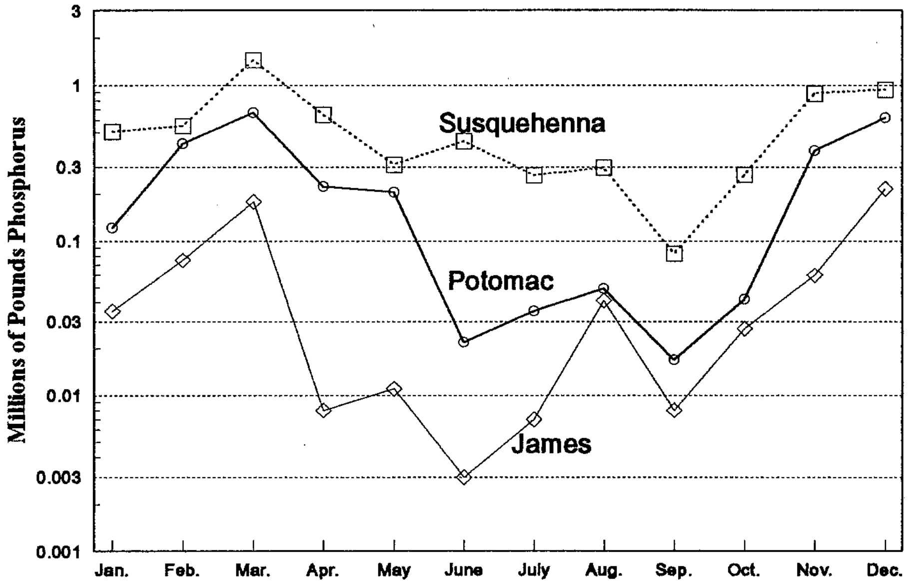


Figure II-15. Base Case Phosphorus Loads from Three Principal Rivers. Average Year

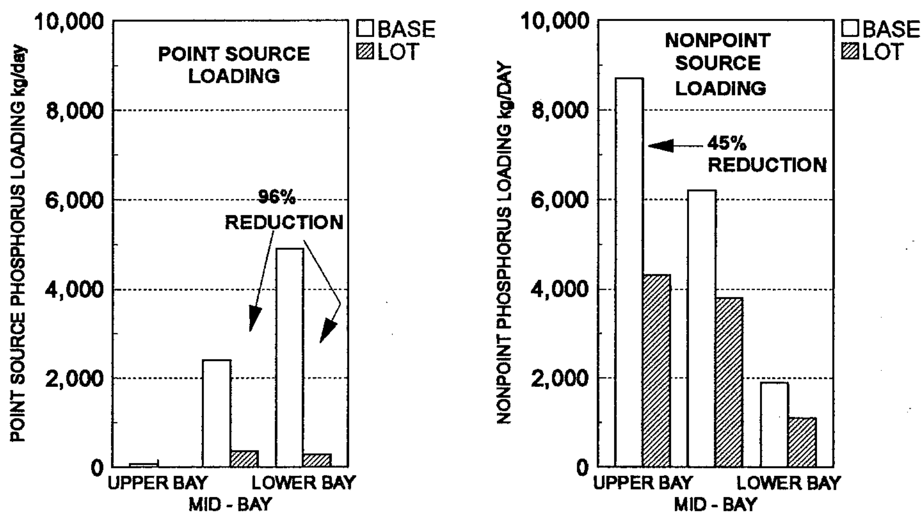


Figure II-16. Longitudinal Distribution of Total Phosphorus Point & Nonpoint Loads for Base Case and Limit of Technology (Nonpoint = Fall Line + Below Fall Line Loads)

Figure II-17. Reductions in Point and Nonpoint Phosphorus Loading.
Average Year

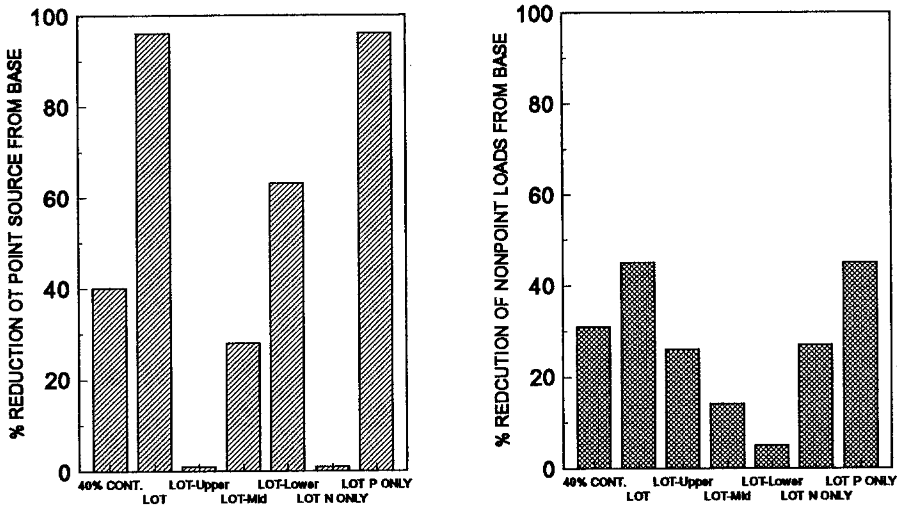
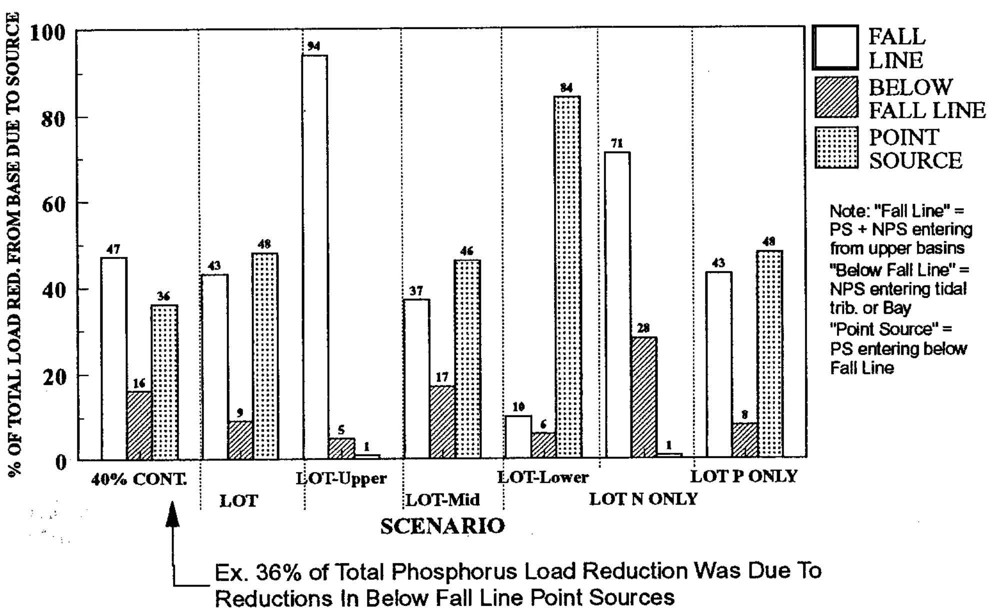
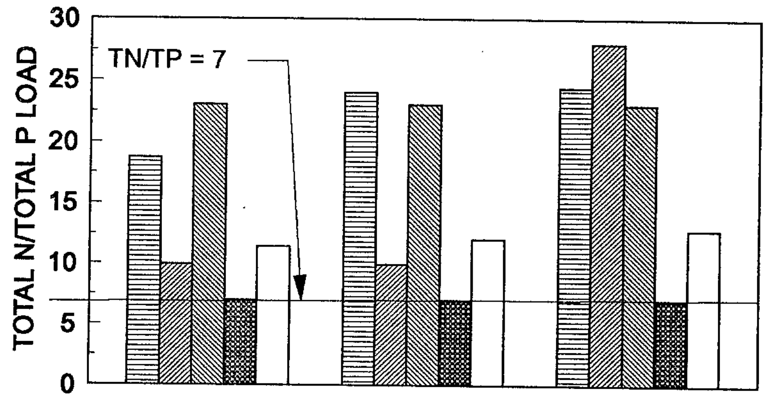


Figure II - 18. % OF Total Phosphorus Reduction Due to Fall Line, Below Fall Line and Point Source Loads.
Average Year





	#1-Base	#2-40% Cont	#5 LOT
NPS	18.7	24.0	24.4
PS	9.9	9.9	28.0
ATMOS.	23.0	23.0	23.0
OCEAN	7.0	7.0	7.0
TOTAL	11.4	12.0	12.8

Figure II-19. TN/TP Ratio by Load Type and Scenario, Average Year.

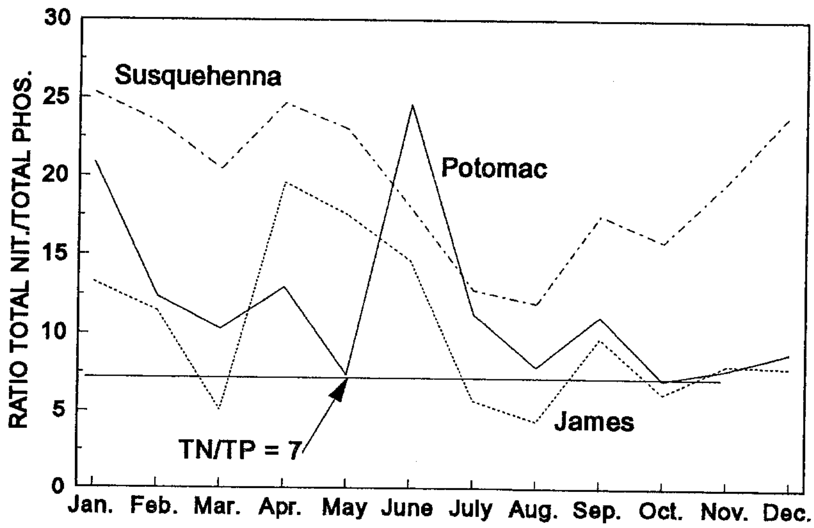


Figure II-20. TN/TP Ratio of Loads for Three Tributaries, Base Case Average Year.

G. SCENARIO CARBON LOADS

Total incoming carbon loads were estimated from point source inventories and from Watershed model runs. Table II-3 is a summary of the allochthonous (external) carbon loads for the Base, 40% controllable and LOT scenarios. Figure II-21 shows the organic carbon loading by basin and scenario.

TABLE II - 3
ORGANIC CARBON LOADINGS
(Average Year)

SCENARIO	CARBON LOAD (10^6 lbs/yr)	% REDUCTION FROM BASE
#1 - Base	484	
#2 - 40% Controllable	327	32
#5 - LOT	300	38

In contrast to nitrogen and phosphorus loads, a significant source of organic carbon is also generated internally by phytoplankton primary production. As will be seen later in this report, the principal carbon loading to the Bay is from this autochthonous (internal) source. Therefore the external carbon sources assume a reduced role in terms of the impact of controlling these sources. Table II -3 indicates an overall reduction from the Base case of about 32% for Scenario #2 and a relatively small improvement to 38% for LOT. Figure II - 21 shows the principal external carbon source to be the Susquehanna River followed by the Potomac River. These results also indicate that the 40% controllable scenario is close to the Limit of Technology for organic carbon loading.

H. SCENARIO SOLIDS LOADS

The suspended solids in the Bay are of importance in determining the extent of light extinction and penetration and hence influence the production of plant biomass. The CBWQM does not model the fate and transport of suspended solids. As currently configured, the CBWQM calculates changes in light penetration or extinction by tracking changes in phytoplankton chlorophyll. The concentration of suspended inorganic solids (as empirically linked to incoming river flows) is therefore not changed across scenario runs. However, an examination of input solids loading as generated by the Watershed Model is of interest to qualitatively determine the potential impact of nonpoint nutrient controls on light penetration.

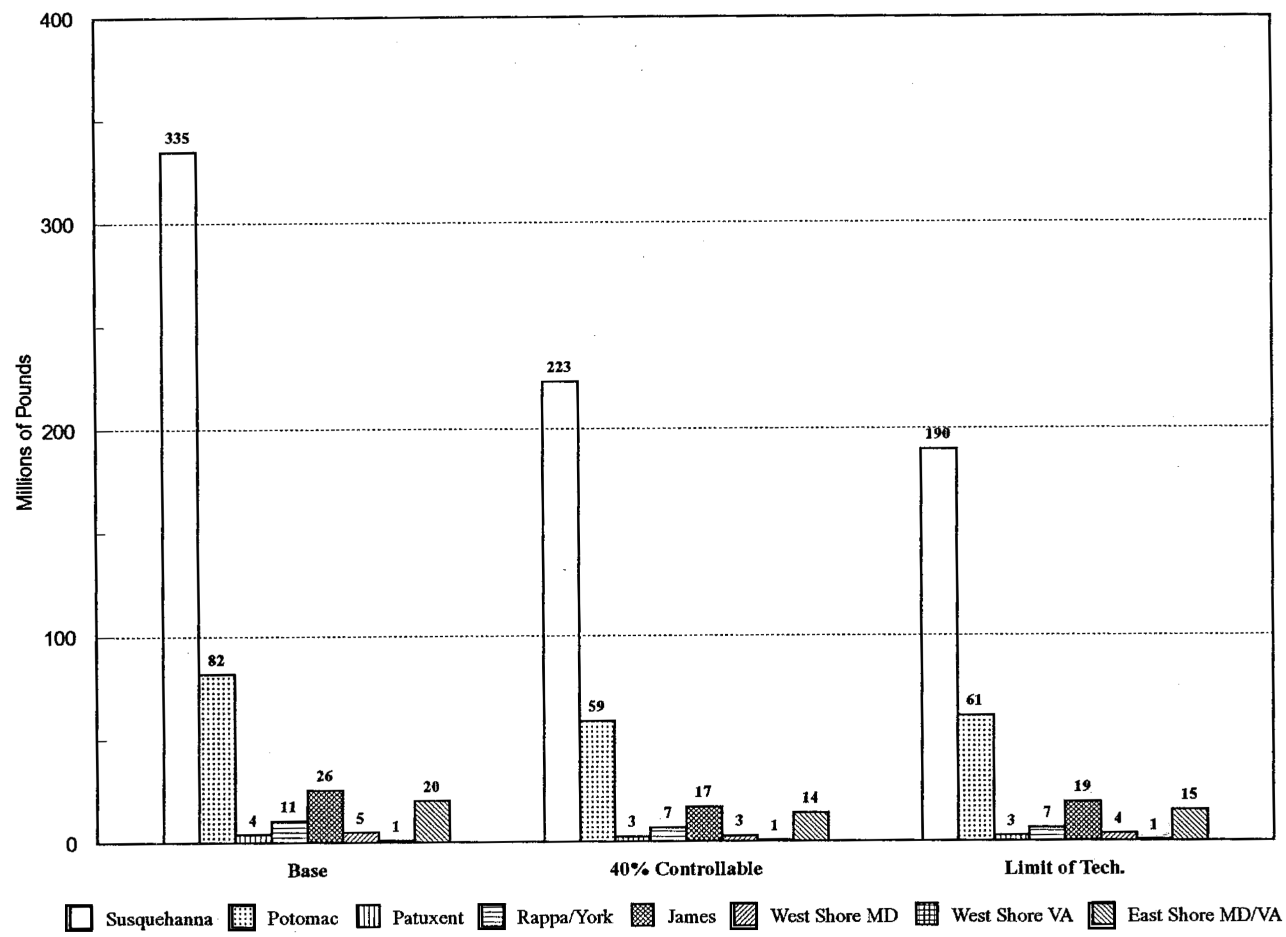


Figure II-21. Total Organic Carbon Loading by Scenario and Basin. Average Year

Briefly, the Watershed Model calculates sediment delivery based on the following scheme:

Land Processes			River Processes	
Erosion ----> Rate	Sediment -----> Storage	Transport -----> Factors	Deposition & ------> Scour	Suspended Sediment

The simulated erosion rate is dependent on rainfall, energy, antecedent soil moisture, and percentage of exposed soil. These values are largely input as data sets or are simulated internally.

Sediment storage is considered to be sediment dislodged by rainfall or plowing and available for transport. Sediment in storage is calculated at each time step as a balance of sediment detachment and re-attachment. Sediment storage for each land use is consistent throughout the model.

Transport factors move the field storage sediment to the river. These parameters are selected to match calculations of annual erosion for crop, pasture, and forest land based on National Resource Inventory (NRI) data. (The NRI is a national data base of land use and characteristics such as cover, slope and estimated erosion rates.) Gross erosion estimates are reduced by a delivery ratio to represent deposition within smaller sub-watersheds. The NRI data are at a county level.

Deposition velocities are user supplied parameters. Critical shear stresses are adjusted to simulate observed sediment concentrations at USGS river monitoring stations.

Suspended sediment is a Watershed Model state variable which is directly comparable with observed suspended sediment at monitoring stations.

Figure II-22 shows the calculated suspended solids loading for two principal inputs for the base case and over several years. The Potomac River sediment load is about an order of magnitude higher than that of the Susquehanna River. This is due to the reservoirs at the terminus of the Susquehanna River which act as sedimentation systems. Also, for the Potomac, the sediment load did not drop during the 1985 dry year, as would be expected and as calculated for the Susquehanna. The reason for the similar solids loading for the Potomac during the dry year is a large storm in November 1985 which crossed the upper Potomac. The WSM calculated significant bed load scour from this storm and subsequently transported this sediment load downstream. It can also be seen that the load for the Susquehanna can vary by about one order of magnitude between differing hydrologic years.

Currently, only two controls/scenarios result in reduced sediment loads:

1. conversions of conventional to conservation tillage; and
2. other LOT land use changes (crop land use into pasture land use).

These controls therefore reduce sediment loading through land use changes. It is important to note that no changes were made to account for sediment reduction from farm practices in the LOT scenario. The delivered LOT sediment reductions should therefore be considered extremely conservative.

Figures II-23 and II-24 show the WSM calculated sediment loads for differing scenario and controls. The "3-state forest" loading is considered to be the level of uncontrollable sediment loads delivered from Bay program states. As in the case of nutrients, New York in the Susquehanna basin, and West Virginia in the Potomac basin are left at base case land use (and base case sediment loads).

It is clear from these figures that the reduction in sediment load from base to LOT is small, but the previously mentioned important caveat should be noted. The year to year variation in solids

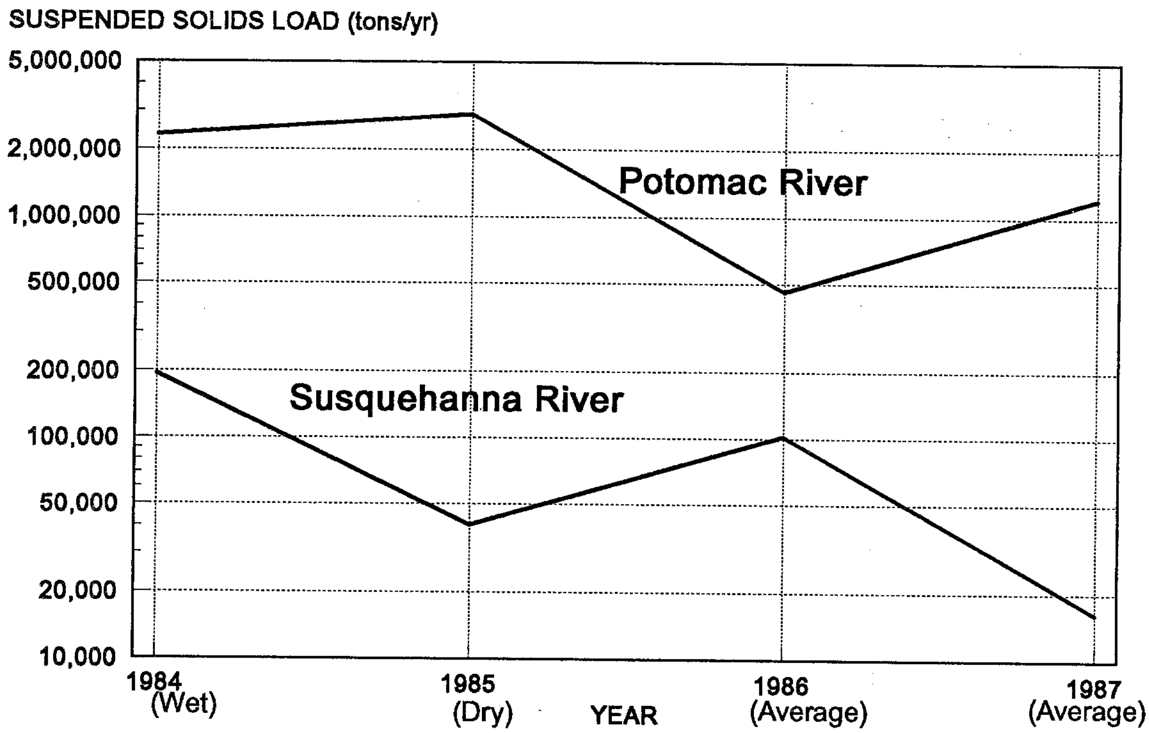
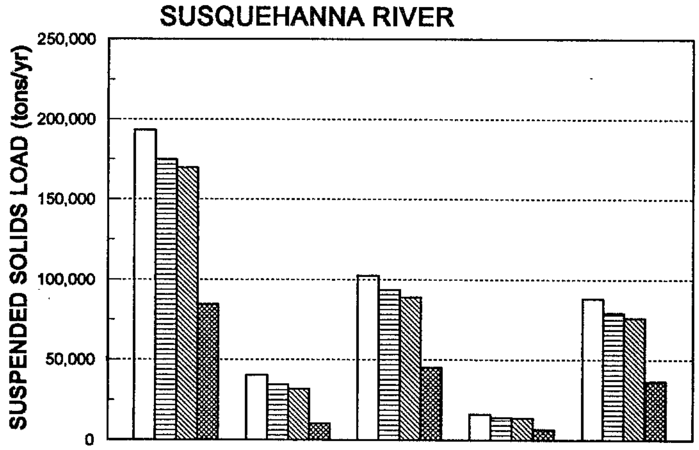
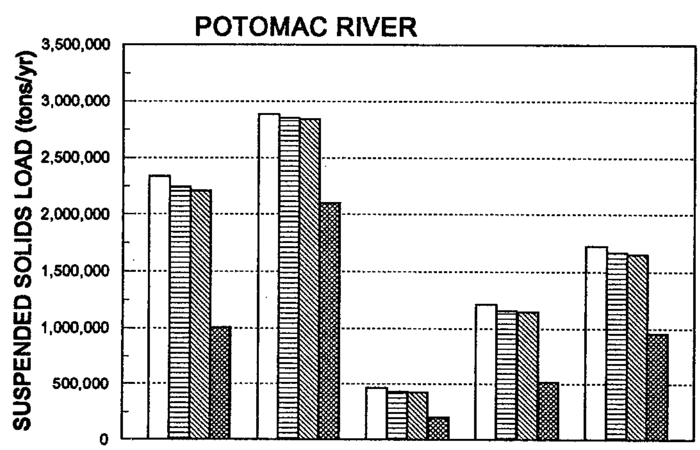


Figure II-22. Variation of Suspended Sediment Loads from Susquehanna and Potomac Rivers for Different Years



Scenario/Control	1984	1985	1986	1987	Mean
Base Case	1.9E+5	4.0E+4	1.0E+5	1.6E+4	8.7E+4
Cons Till	1.7E+5	3.4E+4	9.3E+4	1.4E+4	7.9E+4
LOT	1.6E+5	3.1E+4	8.8E+4	1.3E+4	7.5E+4
3-State Forest	8.4E+4	1.0E+4	4.4E+4	6.7E+3	3.6E+4

Figure II-23. Variation of Suspended Sediment Loads from Susquehanna River for Different Years and Controls



Scenario	1984	1985	1986	1987	Mean
Base Case	2.3E+6	2.8E+6	4.6E+5	1.2E+6	1.7E+6
Cons Till	2.2E+6	2.8E+6	4.2E+5	1.1E+6	1.6E+6
LOT	2.2E+6	2.8E+6	4.2E+5	1.1E+6	1.6E+6
3-State Forest	1.0E+6	2.0E+6	2.0E+5	5.2E+5	9.5E+5

Figure II-24. Variation of Suspended Sediment Loads from Potomac River for Different Years and Controls

loading is considerable and will tend to reduce the effectiveness of sediment control measures. For the Potomac, compared to other years, 1985 has less spread in the differences of load among the scenarios, particularly between base and forest. This is attributed to the previously mentioned November 1985 storm.

Generally, sediment loads of basins can be characterized as transport dominated processes in large basins and source dominated sediment loads predominate in small basins (Walling, 1983). This may explain to some extent the little difference among the few sediment reduction scenarios, i.e., the basin is not yet in steady state between sediment input from the land and transport of stored loads in the river. This is, a least, entirely consistent with the literature, which generally finds little immediate effect of Best Management Practice (BMP) on discharged sediment load (Illinois EPA, 1983; Walling, 1983). Additional runs would be desirable to further characterize the extent of sediment control, but these large basin are "in-stream process" dominated with respect to sediment loads. As indicated, it is known that the response of such system in the short run to sediment BMP's is not as great as it would be if the sediment loading were dominated by edge of stream loads.

I. SECTION II - CONCLUSIONS

The following principal conclusions are drawn from the loads given in this section.

1. The "feasible" range of overall total nitrogen reduction from the base case is from about 20 - 30% of the total input load (excluding input from the ocean),

2. The "feasible" range of overall total phosphorus reduction from the Base case is from about 30-55% of the total input load (excluding input from the ocean),

3. The calculated ocean nutrient input load (which is independent of scenario) is estimated to contribute about 30-35% of the total input nitrogen load and about 45-65% of the total input phosphorus load,

4. Deposition of atmospheric nitrogen directly to the Bay waters is about 10% of the Base case loading,

5. 40% reduction of controllable nitrogen for nonpoint sources is approximately equal to the Limit of Technology reduction of nitrogen nonpoint sources,

6. The application of LOT results in significantly larger percentage reductions in point source nutrient loadings to the Bay than nonpoint source loadings,

7. The TN/TP ratio for total input load is calculated at about 12 across scenarios, indicating an input load situation that depending on season and Bay location, may result in either nitrogen or phosphorus controlling phytoplankton production,

8. Reductions in suspended solids between Base and LOT are conservatively estimated at about 6-14% for the Potomac and Susquehanna Rivers, but would be considerably higher if reductions would include decreases in sediment due to farm plans.

III. CBWQM RESPONSE TO SCENARIO LOADS - GENERAL CONSIDERATIONS

A. TEMPORAL AND SPATIAL AVERAGING

Since model output is very large for all state variables, time and locations, some averaging of model results over time and space is necessary. Cerco and Cole, 1992 discuss this averaging in the context of model calibration and present the details of the averaging used therein. The same averaging is used for the scenario output. Although the CBWQM calculates state variable concentrations at a time scale of hours, such calculations are for computational stability only. Input information is provided on a week to week basis and the kinetics that are incorporated in the model are representative of longer time behavior. The model is considered to represent processes on a time scale of months, seasons and longer. Therefore, some of the model output results were averaged over months while other results were averaged over seasons according to the Table below.

TABLE III - 1. TEMPORAL PERIODS USED IN AVERAGING MODEL OUTPUT

SEASON	DESCRIPTION	JULIAN DAY	APPROX. MONTHS
I	"Winter"	0 - 60	Jan.- Feb.
II	"Spring"	61 - 150	Mar. - May
III	"Summer"	151 - 270	June - Sept.
IV	"Fall"	270 - 365	Oct. - Dec.

The Bay spatial grid scale horizontally is about 10 km by 5 km by 1.7m and includes from two to fifteen cells in the vertical direction. Two sediment segments (aerobic and anaerobic) are incorporated under the water column segments. Again, in order to provide tractable output, water column model results are averaged spatially according to the zones indicated in Figure III - 1 and described in Table III - 2 below.

The water surface areas for each zone and for the entire Bay are also shown in this Table and are used to compute areal loading and responses of various constituents as detailed later in this report.

The principal Bay tributaries are also divided into zones for calibration analysis (see Cerco and Cole, 1992). The areas for the tributaries are also indicated in Table III - 2.

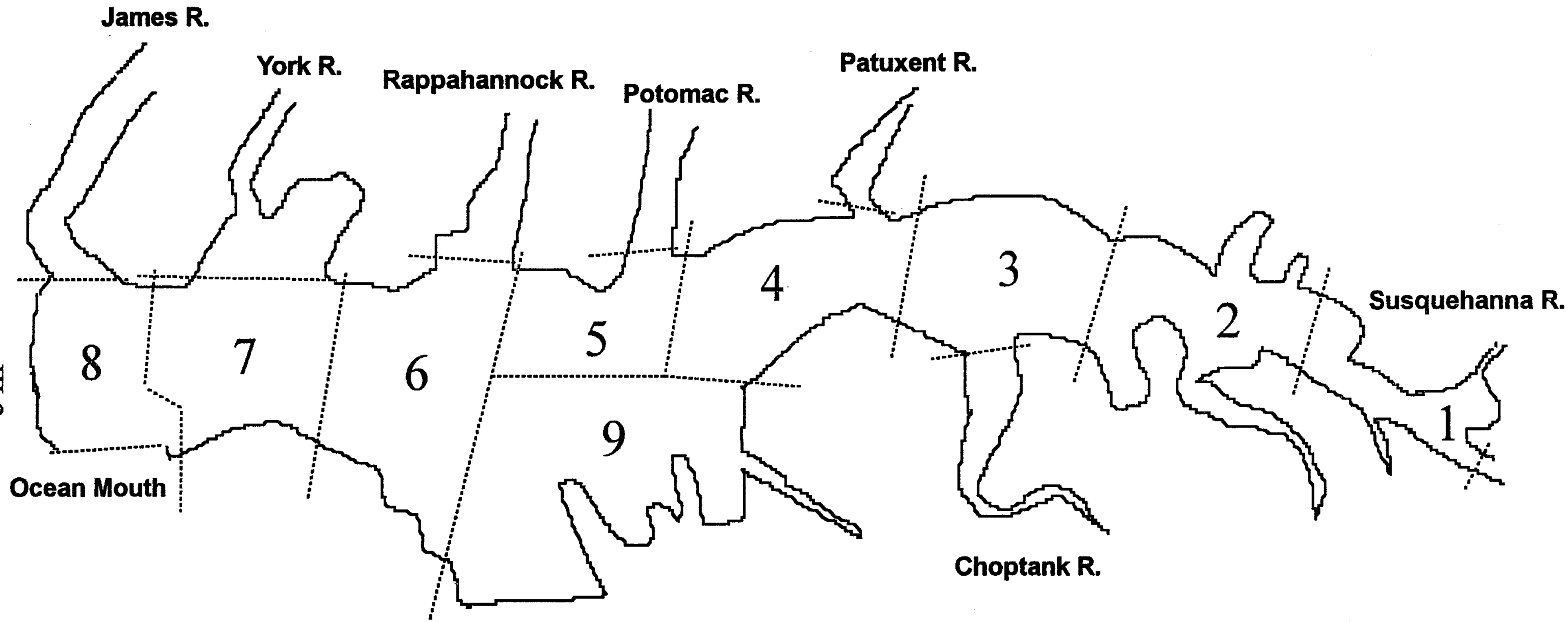


Figure III -1. Zones used for averaging of model output.

TABLE III - 2. ZONES USED FOR SPATIAL AVERAGING OF MODEL OUTPUT

ZONE	DESCRIPTION	RANGE-km (0 km = mouth)	ZONE LENGTH (km)	ZONE SURFACE AREA (10^9 m^2)
1	Conowingo to Back R.	330 - 272	58	0.502
2	Back R. to Choptank R.	272 - 220	52	0.977
3	Choptank R. to Patuxent R.	220 - 181	39	0.94
4	Patuxent R. to Potomac R.	181 - 138	43	0.859
5	Pot.R. to Rappahannock R.	138 - 90	48	1.04
6	Rapp. R. to York R.	90 - 56	34	1.03
7	York R. to James R.	56 - 27	29	0.617
8	James R. to Mouth	27 - 0	27	0.462
9	Eastern Shore	159 - 90	69	1.44
TOTAL BAY AREA				7.87
TRIBUTARY SURFACE AREAS				
Patapsco R.				0.1
Patuxent R.				0.114
Potomac R.				0.951
Rappahannock R.				0.365
York R.				0.465
James R.				0.511

Averaging over depth is accomplished by dividing the water column into three layers: the "surface" well-mixed layer (0 - 6.7 m), the "pycnocline" layer (6.7 - 12.8 m) and the "bottom" layer (>12.8 m), as shown in Figure III-2.

Table III - 3 shows volumes of the Zones by the three levels. Figure III - 3 shows the cumulative surface and bottom volumes.

geometry. The fluxes of constituents from the tributaries to the main Bay are calculated by summing all flows "into" the Bay with associated concentrations and all flows "from" the Bay. Fluxes are therefore not always necessarily associated with surface flows and bottom flows, but rather with tributary flows into the Bay and with flows from the Bay to the tributary. The tributary flows are further discussed below in Section IV.

C. FUNDAMENTALS OF RESPONSE SURFACE ANALYSIS

Time and cost constraints precluded exhaustive running of the Bay Model to explore the infinite N and P reduction options. A statistical technique called *response surface analysis* was used to enhance and interpret the information contained in the limited number of model runs. Response surface analysis was used to make and validate generalizations about how the Bay responds to nutrient reduction, to interpolate between model runs, and to compare the levels of achievement of different Bay water quality goals under a range of N and P inputs. In this technique groups of model runs are considered together so that trends in the model results can be appreciated. These trends are approximated by a mathematical function, the response surface. In the following discussion it may help to think of the following response surface analysis simply as an application of interpolation in two dimensions, the dimensions being reductions in nitrogen and phosphorus load to the Bay.

The outcome of any Bay model run can be considered to be some function of the nitrogen and phosphorus loading of that run:

$$y_j = f(N_j, P_j) + e_j$$

where, for $j = 1, 2, \ldots, m$, j stands for each one of m different model runs. The residual e_j is the error of the jth observation. y_j is some measurement of Bay response to different levels of nutrient loadings, such as the reduction in anoxia from scenario j or the level of SAV habitat improvement associated with that scenario predicted by the model. The function f is called the *response surface*. This function represents the workings of the model plus the process of condensing the model output. It has no precise mathematical form. f summarizes the trends in the model runs and enables the prediction (within the region covered by the data) of the Bay response for combinations of N and P loads which were not tested explicitly in a model run.

When the exact mathematical form of the response surface is unknown, or as in this case, does not exist, f can be approximated by a quadratic polynomial in N and P

$$y_j = b_1 + b_2N_j + b_3P_j + b_4N^2_j + b_5P^2_j + b_6N_jP_j + e_j$$

This is a very adaptable form. If the true response surface is flat, the second degree terms drop out in ordinary least squares regression. If the response surface is curved, the squared terms are significant. If multiplicative interactions between N and P are important, that shows up in the cross product term.

A prerequisite to response surface analysis is that there must be a unique relationship between settings of N and P and the response y. That means that the function must return a unique y_j for a unique choice of N_j and P_j. Therefore the definitions of N, P and y must be chosen carefully, and only model runs that conform to those definitions must be used to fit the polynomial.

Model scenarios where N and P reductions are defined as bay-wide same-percent reductions fit this requirement. Also the 40% controllable N and P reduction scenarios (runs 2, 3, and 4) approximately fulfill this requirement. Runs 2, 3, and 4 were included even though they weren't entirely free of geographic loading influence because of the desire to have a few more data than parameters to be fit. There are 6 constants in equation 2, and the regressions were more significant using 10 data than 7. The 10 runs chosen to fit the polynomial were:

Scenario 1	Base Case
Scenario 2	40% controllable N and P reduction from Agreement States
Scenario 3	Scenario 2 with N reductions from Clean Air Act implementation
Scenario 4	40% controllable N and P reduction from all Bay basin states plus Clean Air Act N reductions
Scenario 15	50% N and P reduction from base case
Scenario 16	90% N and P reduction from base case
Scenario 17	90% N reduction from base case
Scenario 18	90% P reduction from base case
Scenario 19	31% N 18% P reduction from base case
Scenario 20	10% N 49% P reduction from base case.

The other runs were not used because of the possibility of unequal geographic loadings violating the prerequisite.[1]

N and P were expressed in one of three sets of units in different regression analyses: (1) percent reductions from base case (with base case being 0% reduction of N and P), (2) daily loads of N and P to the Bay (kg/day), and (3) annual loads (million pounds per year). Changing the units of the independent variables has no effect on the shape of the surface. Only the scaling of the axes changes. For simplicity, all results will be reported using the first units only.

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[1] An attempt to construct a regression which could use all the runs was made; however, there were insufficient model runs to fit all the variables. Three N and three P variables were defined, one set of N and P loadings for each of the 3 geographic regions of the Bay. This made a total of 6 independent variable linear terms, 6 squared terms and 15 cross product terms. Preliminary results were very promising (with high R^2's) and showed that N and P loads from regions 1 and 2 dominate the production of anoxia in the Bay, but at least 2 more model runs would have been necessary to finalize the analysis.

The predicted response y also assumed various forms, all expressed as percent improvement over base case for an average year. Using the same 10 scenarios, unique response surfaces (presented here for the average flow year #9) can be generated for each of these responses.

(1) whole Bay anoxia (anoxia defined as DO < 1 mg/L)
(2) single zone anoxia for each of the 9 Bay zones
(3) summer, fall, or spring anoxia for the whole Bay
(4) summer, fall, or spring anoxia for each of the 9 zones
(5) whole Bay dissolved oxygen habitat goal achievement (see Table I-1 of Section I)
(6) whole Bay dissolved inorganic nitrogen goal achievement (see Table I-2 of Section I).

Since there was no violation of the dissolved inorganic phosphorus habitat goal in the base case run, this goal was not analyzed further.

Presentation of the results of the response surface analysis for DIN is given in Section VI - B - 4 and for anoxia in Section VII - E.

IV. BAY HYDRODYNAMIC TRANSPORT USED IN SCENARIOS

A. INTRODUCTION

The purpose of this section is to briefly review the principal aspects of the hydrodynamic transport as calculated by the hydrodynamic model of the Bay and which formed the underlying flow transport used in the scenarios. A general understanding of the flow transport is necessary in order to more fully interpret the scenario results. A complete description of the hydrodynamic model is given in Johnson et al, 1991.

B. MAIN BAY FLOWS

In general, the hydrodynamic flows of the Bay are a complicated function of ocean boundary condition, winds, river inflows and Bay geometry and bathymetry. Flows vary over the tide, over days, weeks, and seasons. Surface Bay flows are generally down the Bay toward the ocean while a return flow along the bottom layers of the Bay occurs from the ocean into the Bay. The apparent force of the earth's rotation further adds to the circulation by deflecting currents to the right in the direction of the flow. The simple two layer flow is therefore further impacted and inflows up the Bay may occur at mid-depth or surface layers as well as bottom layers.

In order to provide at least a preliminary understanding of the transport of the Bay, average annual flows have been computed across the interfaces of each of the zonal boundaries. Inflows are not always in a bottom layer. Similarly, "Outflows" are average flows for each cell that are leaving an interface. Outflows are not always in the surface layers.

Table IV - 1 is a compilation of the average annual interfacial flows. (See Figure III -1 for a map of the zones.) As shown in this Table, for the main Bay, the volume of flows entering and leaving an interface are large and the net difference between the flows is relatively small. Also, there is a relatively complicated transport structure in the vicinity of Zone 9, the Eastern Shore zone. Flows enter and leave this zone from Zones 4 and 5. Since Zone 5 receives the inflow from the Potomac estuary, the exchanges between that zone and Zone 9 is large. A flow balance around zone 5 indicates a significant transport into the Eastern Shore which then exits into Zone 6. Net interfacial flows from the tributaries to the main Bay are also the differences of two large inflows and outflows. The tributary flows are discussed more fully below.

Figure IV - 1 shows the longitudinal profile of the main Bay zonal interfacial flows and the general increase in the inflows and outflows as one proceeds down the Bay can be observed. Also, shown in this Figure is the net outflow across the interfaces where the exchange from 5 to 6 incorporates the exchange with zone 9. Except for the Eastern Shore region with its more complicated transport regime, the increase in the net outflow is relatively small and reflects primarily the net inflows from the tributaries.

Figure VI - 2 is a plot of the longitudinal variation in the net outflow from a zone interface as a percent of the total inflow to the interface. A high of 60% net outflow/inflow occurs at the head end of the Bay and declines to less than 10% in the lower half of the Bay. The net transport in the lower Bay is therefore not a significant component of the overall transport which is governed by the large multi-level Bay circulation.

TABLE IV - 1
AVERAGE ANNUAL INTERFACIAL FLOWS (m^3/s) FOR AVERAGE YEAR

INTERFACE	FLOW (From Zone # to Zone #)	FLOW (From Zone # to Zone #)	NET FLOW (From Zone # to Zone #)
Zone 1 & 2	2047 (2 to 1)	3252 (1 to 2)	1204 (1 to 2)
Zone 2 & 3	9619 (3 to 2)	10838 (2 to 3)	1218 (2 to 3)
Zone 3 & 4	10042 (4 to 3)	11273 (3 to 4)	1230 (3 to 4)
Zone 4 & 5	14048 (5 to 4)	13875 (4 to 5)	173 (5 to 4)
Zone 4 & 9	1041 (9 to 4)	2436 (4 to 9)	1395 (4 to 9)
Zone 5 & 6	10457 (6 to 5)	10408 (5 to 6)	49 (6 to 5)
Zone 5 & 9	6213 (9 to 5)	6309 (5 to 9)	96 (5 to 9)
Zone 9 & 6	6238 (6 to 9)	7697 (9 to 6)	1459 (9 to 6)
Zone 6 & 7	15949 (7 to 6)	17370 (6 to 7)	1421 (6 to 7)
Zone 7 & 8	17962 (8 to 7)	19414 (7 to 8)	1451 (7 to 8)
Zone 8 & Ocean	26020 (Ocean to 8)	27630 (8 to Ocean)	1610 (8 to Ocean)
James & Bay	2594 (B to J)	2750 (J to B)	156 (J to B)
York & Bay	4794 (B to Y)	4825 (Y to B)	31 (Y to B)
Rapp. & Bay	1615 (B to R)	1640 (R to B)	25 (R to B)
Pot. & Bay	4258 (B to Pot)	4498 (Pot to B)	240 (Pot to B)
Patux. & Bay	1108 (B to Ptx)	1115 (Ptx to B)	7 (Ptx to B)
Patap.& Bay	1,866 (B to Ptp)	1871 (Ptp to B)	5 (Ptp to B)

1. Estimate of Hydraulic Residence Time of Bottom and Surface Waters

An estimate can be made of the hydraulic residence time of the Bay zones by assuming a two layer Bay where the "Inflows" to a zone are primarily in the bottom layer and a fraction of the mid-layer volume and the "Outflows" from a zone are primarily in the surface layer and a fraction of the mid-layer volume. The hydraulic residence time for the bottom layer is estimated for each zone using the zone volume and the flow rate into the zone (inflow > outflow in most of the zones). For the surface layer, the residence time is estimated using the flow rate leaving each zone (inflow < outflow in most of the zones). The volumes of Table III - 3 are distributed into the two levels by assigning 50% of the mid-layer volume to the surface and to the bottom, respectively. The complicated transport in Zone 9 is ignored in this analysis. The hydraulic residence times for the two layers computed with these rules are shown in Table IV - 2.

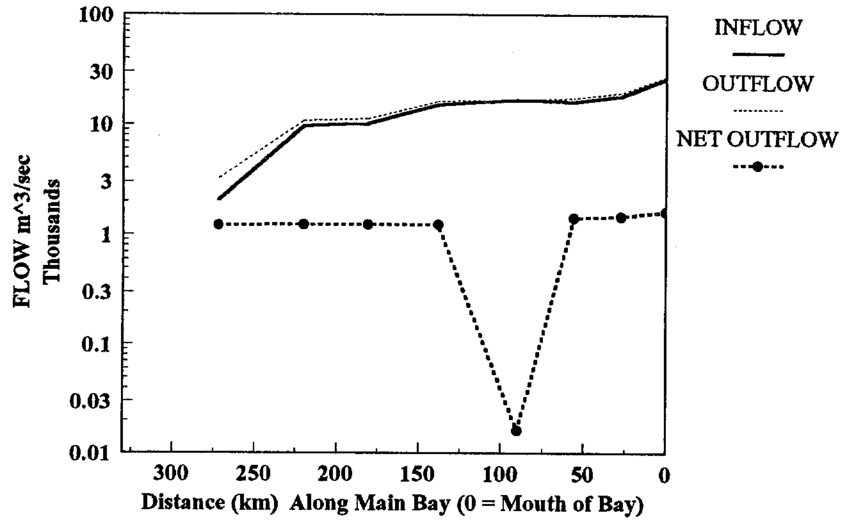


Figure IV - 1. Longitudinal variation of average annual inflows (from ocean direction) and outflows (to mouth of Bay)across zone interfaces. Average year.

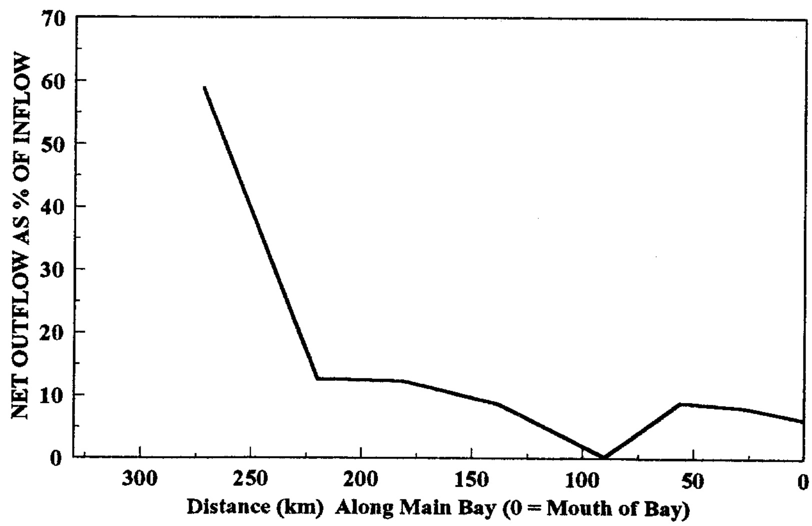


Figure IV - 2. Longitudinal variation of net outflow from zone interface as a percent of total inflow to interface.

TABLE IV - 2
HYDRAULIC RESIDENCE TIME ESTIMATES

"BOTTOM" LAYER

Zone/Interface	Volume[1] (10^9 m^3)	Inflow (m^3/s)	Residence Time[2] (days)	Cumulative Residence Time[3] (days)
Ocean - 8		26,020		
8	1.3		0.58	
7-8		17,962		0.58
7	1.91		1.23	
6-7		15,949		1.81
6	3.2		2.32	
5-6		10,457		4.13
5	4.28		4.74	
4-5		14,048		8.87
4	3.42		2.82	
3-4		10,042		11.69
3	3.27		3.77	
2-3		9,619		15.46
2	1.86		2.24	
1-2		2,047		17.7
1	0.22		1.23	
Upper end of Zone 1				18.93

"SURFACE" LAYER

Zone/Interface	Volume[1] (10^9 m^3)	Outflow (m^3/s)	Residence Time[2] (days)	Cumulative Residence Time[3] (days)
1	2.48		8.82	
1-2		3,252		8.82
2	6.7		7.15	
2-3		10,838		15.97
3	7.12		7.31	
3-4		11,273		23.28
4	7.07		5.9	
4-5		13,875		29.17
5	8.93		9.93	
5-6		10,408		39.11
6	8.88		5.91	
6-7		17,370		45.02
7	5.53		3.29	
7-8		19,414		48.31
8	3.86		1.61	
8-Ocean		27,630		49.93

1 Volumes are estimated using the data in Table III-3 after assigning 50% of the mid-layer volume to the bottom and surface layers.

2 Residence time is estimated for each zone by dividing the zone volume by the inflow into that zone for bottom and outflow from zone for surface. The zone 9 and all tributaries are ignored.

3 Cumulative residence time, which is equivalent to the time for bottom/surface water to travel from mouth/head to interface, is assigned to the interface.

As shown in this Table, the approximate cumulative residence time of assumed "Bottom" flows is about 19 days from the mouth to the head of the Bay and conversely, for the assumed "Surface" flows, the residence time is more than twice as long. It should be stressed that these are estimates only for the average year and assuming a simple two layer flow pattern. This approximate estimate of detention times is used later in analysis of scenario results.

C. MAIN BAY SALINITY - ZONAL AND SEASONAL AVERAGES

An important aspect of the Bay is the degree of vertical stratification resulting from the salinity and temperature distribution of the Bay waters. The average seasonal and zonal salinity values provide an additional overview of the Bay circulation. Figures IV - 3 and IV - 4 show the longitudinal distribution of the spring and summer average salinity for each zone. The marked longitudinal increase in salinity in the down-bay direction can be seen with an increase in salt from spring to summer, as of course would be expected. The vertical difference in salinity is also marked and increases in difference from the mouth of the Bay to the head.

D. TRIBUTARY INFLOWS, OUTFLOWS, NET FLOWS

As noted in the preceding Section III, the flows into and out of the tributary interfaces form an important basis for calculating the net input of nutrients from tributaries to the main Bay. Minor tributaries, such as the Patapsco, Rappahannock and York contribute less than the major tributaries and under several scenarios may experience a small but negative flux. Figure IV - 5 shows the flows at the interfaces of two major tributaries; the Potomac and James estuaries. For the Potomac, the principal flow into the tributary is in the deeper portion of the interface while the outflow is generally in the surface layers. For the James, however, there is a calculated inflow in the surface layers in the northern portion of the interface. Outflows are generally in the surface layers of the southern side of the James. The total inflows and outflows together with the net flows for each of the principal tributaries are shown in Figures IV- 6 and IV - 7. As seen, the total inflows and outflows are large for each tributary and the net flow represents the difference between two large estimates. Thus, for the Patapsco and Back Rivers, the net flow of 5 m^3/s represents the difference between total inflow and outflow of almost 900 m^3/s.

It should be recognized that these flow results are a function of the degree of spatial detail at the mouth of the tributary which is relatively coarse in some instances. A finer spatial detailing of the tributary and its interface with the Bay may result in a different interfacial distribution of flows, but the net flows, due to flow continuity are believed to be approximately correct.

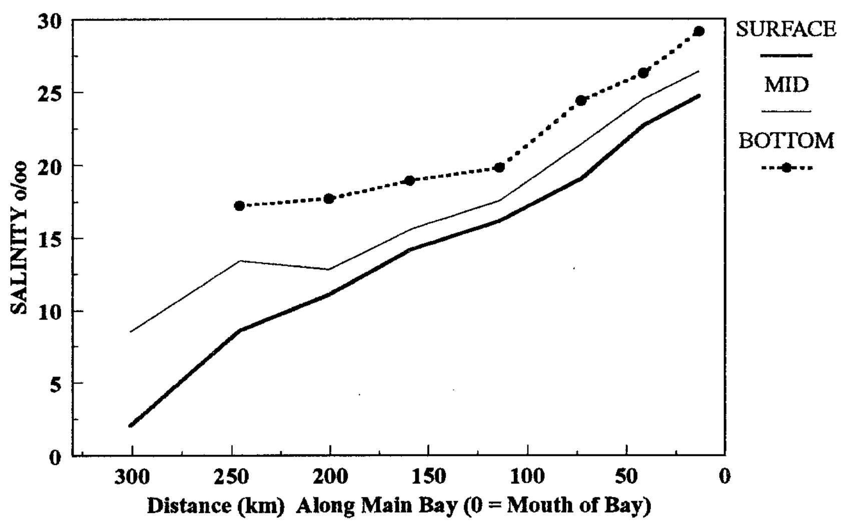


Figure IV -3. Longitudinal variation of SPRING salinity for Base case. Average over zone over season for average year.

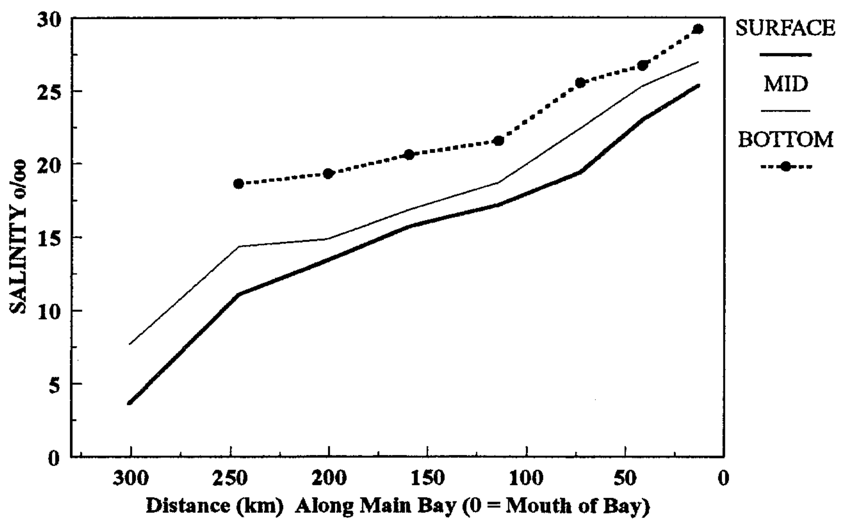


Figure IV -4. Longitudinal variation of SUMMER salinity for Base case. Average over zone over season for average year.

POTOMAC RIVER FLOWS (cubic meters/second)
INTERFACE WITH BAY

-752.4	-93.9	-95.7	-306.3
-368.5	-6.7	-27.1	-167.8
-270.7	48.3	-1.0	-131.1
-94.4	92.7	14.9	-100.7
	128.7	32.0	
	213.4	80.5	
	261.0	118.6	
	284.5	145.0	
	272.8	149.0	
	215.5	119.8	

Total Flow "IN"	-2416.3
Total Flow "OUT"	2176.7
Net Flow	-239.6

JAMES RIVER FLOWS (cubic meters/second)
INTERFACE WITH BAY

-554.1	-148.1	166.3
-245.4	-71.8	88.2
-143.4	-46.9	90.3
	-23.6	136.3
	54.9	
	62.6	
	82.1	
	126.9	
	134.4	
	137.3	

Total Flow "IN"	-1235.4
Total Flow "OUT"	1079.3
Net Flow	-156.1

AVERAGE FLOW YEAR

NOTE: NEGATIVE FLOWS = FLOW FROM TRIBUTARY TO BAY; POSITIVE FLOWS ARE FROM BAY TO TRIBUTARY

Figure IV-5. Tributary flows (cubic meteres/second) at Potomac and James River interfaces as calculated by Chesapeake Bay hydrodynamic model

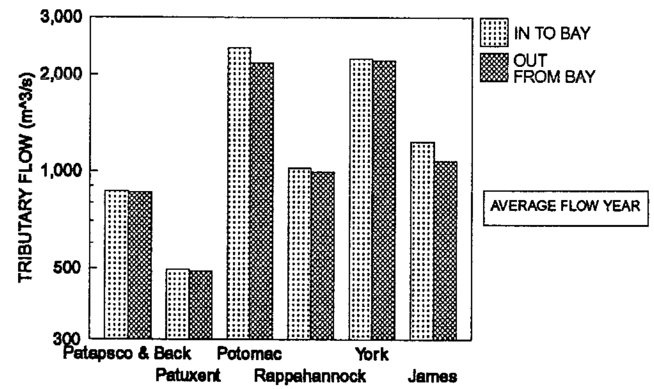


Figure IV - 6. Flows (m^3/s) Across Tributary Interfaces. ("IN" flows are from tributary to Bay; "OUT" flows are from Bay to tributary.)

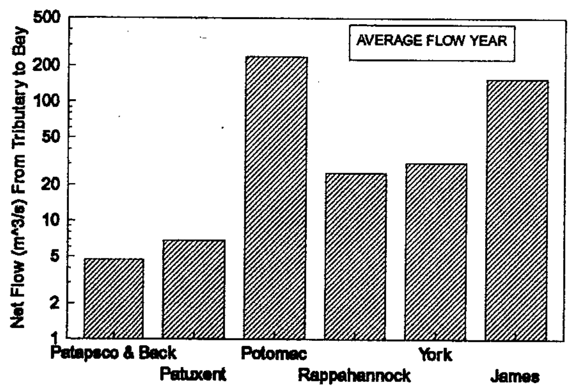


Figure IV - 7. Net Flows (m^3/s) Across Tributary Interfaces.

V. CBWQM RESPONSE TO UNIT LOADS OF "TRACER" VARIABLES

A. INTRODUCTION

In order to better understand the behavior of the CBWQM, a series of "tracer" runs were made. Since the hydrodynamic transport is complicated and recognizing the role of settling particulate nutrient forms, computations that assume a conservative variable or a non-conservative settling variable provide additional insight into Bay dynamics and help interpret the even more complicated interactions of various nutrient forms in the full CBWQM.

The CBWQM model was used with individual non-interacting state variables and was run for seven years using the "average" hydrology of the scenarios. The following procedure was used for the tracer variables:

1. Dissolved conservative tracers are input continuously into the model at the fall lines and ocean boundary of the nine Bay regions at an arbitrary concentration of 100 mg/L,
2. Conservative particles settling at the same rate as non-living particles in the calibrated model (1.0 m/d) are released continuously from the fall lines and ocean boundaries,
3. Conservative particles are released in the surface of the nine Bay regions at a constant rate (1 gm/m^2 - day) and at a settling rate of 1.0 m/d.

The results can then be examined to see the fraction of the released substance that is transported throughout the Bay or settled into the sediment. Normalizing the results by the input load of the tracer then provides 'unit responses" of these conservative substances. The range of the runs from dissolved conservative tracer to a tracer that is settling at a high rate provide "boundaries" to what would be expected for tracers that have other behavior. For example, algal settling in the model varies from 0- 0.25 m/d depending on the algal group and time of year. Also, for diatoms, in the spring bloom period (January - June), the net settling into the sediment is set equal to zero.

Table A - 2 in Appendix A provides a summary of the results in unit response matrix form. This matrix is termed the "steady state response matrix". In this form, the columns of the response matrix represent the water quality response in the Bay regions due to an input from a given fall line or ocean input. The rows represent the impact in a specific region of an input into all other regions.

B. RESPONSE TO CONSERVATIVE DISSOLVED TRACER

Figure V - 1 shows the steady state distribution of a conservative dissolved tracer discharged at various locations. The concentrations are the volume - averaged concentrations for a zone. The ordinate is the mg/m^3 concentration response in a zone per ton/day of input into the indicated location. Thus, for a dissolved input into the Bay at the Susquehanna River, the plot shows the volume averaged unit concentration response for each of the nine zones. Similarly, for the profile labeled "Pot." (Potomac), the plot shows the response in each of the nine zones for a dissolved input at the fall line of the Potomac River. The plots in Figure V - 1 are therefore the

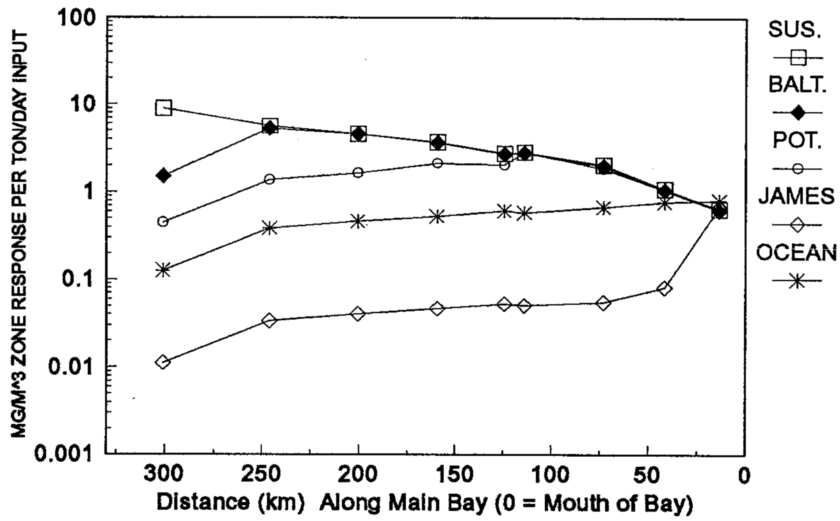


Figure V - 1. Longitudinal variation of steady state response to dissolved inputs at indicated locations. Dissolved input for tributaries is at fall lines.

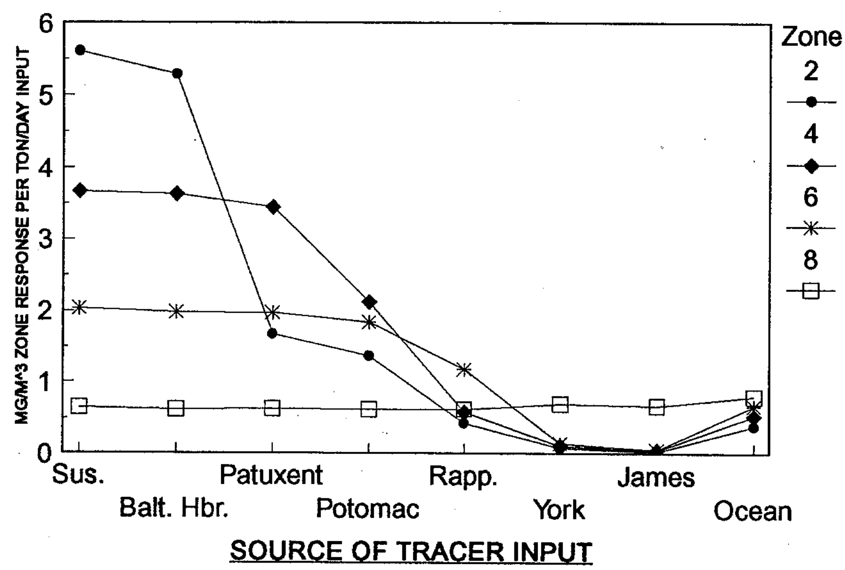


Figure V - 2. Steady state response in a given zone to dissolved inputs at indicated locations. Dissolved input for tributaries is at fall lines.

Bay columns of the first table in Table A - 2.

The general observation from this Figure is that dissolved inputs are distributed throughout the Bay in varying degrees, of course, depending on the location of the input. Dissolved input at the Susquehanna River results in concentration response that declines almost logarithmically down the Bay due to dilution and exchange with the ocean. It can also be seen that dissolved input at the ocean extends up into the Bay as of course is observed from the behavior of salinity, a conservative dissolved substance. Discharges of a dissolved conservative tracer at the fall lines of the tributaries has an equal effect on concentration from the tributary interface down the Bay. Thus, a conservative discharge at the fall line of the Potomac has a similar effect on the down Bay zone 6 as a dissolved conservative input from the Susquehanna. Of course, within the Potomac estuary itself, the concentrations are higher than for the main Bay. The concentration in the Potomac zone immediately below the fall line (see Table A - 2) is about 16.4 mg/m^3 per ton/d. At Zone 5, at the mouth of the Potomac, the concentration is about 17 % of this maximum concentration. The input from the Potomac is transported up the Bay by up-Bay flow so that at Zone 2, the concentration response is almost 50% of the response in Zone 5 where the Potomac enters.

Inputs of dissolved conservative tracer at the fall line of the James also impacts the entire Bay, but at a considerably smaller response. Thus, the response in Zone 8 where the James enters is only 3% of the maximum response immediately below the fall line in the James (23.9 mg/m^3 per ton/d). The response in Zone 2 is only about 5% of the response in Zone 8 where the James enters. This probably reflects the considerable dilution and exchange of the James inputs with the ocean boundary condition.

Figure V - 2 shows the response from the point of view of a given zone. That is, this figure shows selected rows of the first table of Table A - 2. The profile labeled "Zone 2" is the response in that zone due to inputs in the various indicated locations. Thus, for Zone 2, 5.3 mg/m^3 per ton/d is calculated to be the response in that zone due to a dissolved conservative tracer discharged into the Baltimore Harbor. Similarly, 1.4 mg/m^3 per ton/d is calculated in Zone 2 as the response from an input at the fall line of the Potomac. It is clear from this plot that inputs into the upper Bay to as far as at least the Potomac have an impact on Zone 2. Also, for Zone 6, as an example of a down Bay zone, inputs from all locations north of the Potomac have a similar effect on that zone. Inputs in the James have little effect on the main Bay except for Zone 8, the zone of exchange with the James. Finally, the response in Zone 8 is virtually identical from inputs into all locations.

C. RESPONSE TO CONSERVATIVE PARTICLE TRACERS

1. Inputs at Tributary Fall Lines

At the other extreme of the preceding tracer, where all material is dissolved and conservative and therefore tracks flows and reflects dilution, this tracer represents a conservative variable (in the kinetic, biodegradation sense) that settles with a velocity of 1.0 m/d. This settling velocity is the same as that used for non-living particles in the CBWQM.

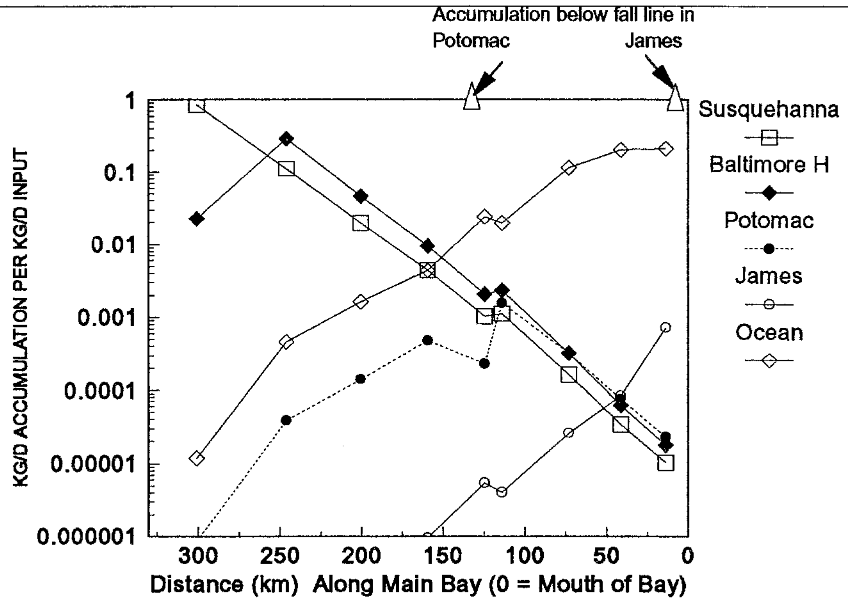


Figure V - 3. Longitudinal variation of steady state response of sediment acumulation flux in a zone due to particle inputs at indicated locations. Particle input for tributaries is at fall lines.

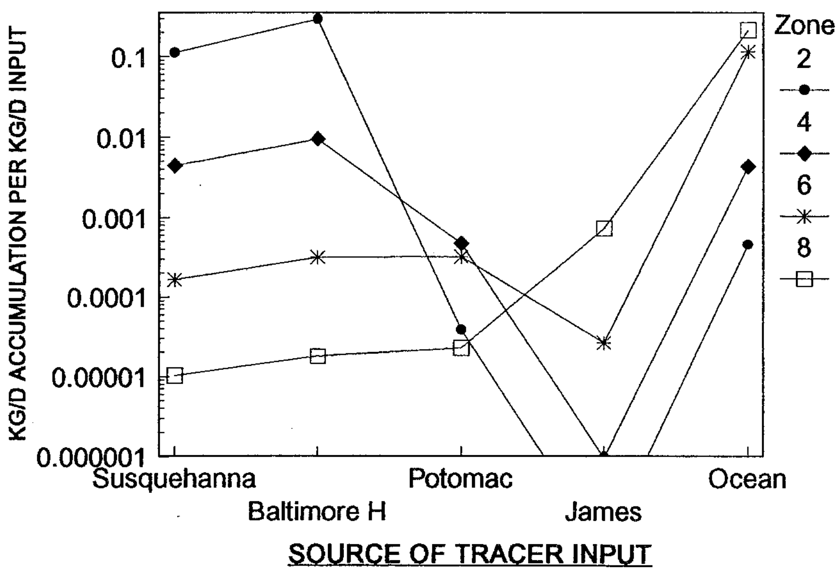


Figure V - 4. Steady state response in a given zone to particle inputs at indicated locations. Particle input for tributaries is at fall lines.

Figure V - 3 shows the response profiles in a manner similar to Figure V - 1. the difference is immediately apparent. The ordinate here however is the kg/d accumulated in the sediment of a given zone per kg/d input at the various indicated locations. For particle input from the Susquehanna, almost all the sediment accumulation is in Zones 1 and 2 immediately below the input. Virtually none of the particles on net reach the sediment in zones below these two upper zones. Also, in general, particle inputs at the fall lines do not significantly influence sediments in the main Bay. Thus, for the Potomac, the accumulation below the fall line in the estuary is about 1 kg/d per kg/d while in the main Bay Zone 5, is less than 0.1% of the peak below the fall line.

Figure V - 4 is the analog to Figure V - 2 and shows the sediment accumulation in a given Zone due to input at other locations. With the exception of the input from the Susquehanna, all other zones receive little accumulation from particle inputs at the fall lines of the indicated tributaries.

2. Inputs at Surface of Bay

The final set of tracer runs released particles at the surface of each of the zones at a fixed rate of 1 g/m^2-d and with a settling velocity of 1.0 m/d. The results are shown in Figures V - 5 and V - 6 and are analogous to Figures V- 3 and V - 4. In general, the maximum sediment accumulation is again in the zone into which the particles are released. For example, 45% of the particle load at the surface of Zone 6, settling at 1 m/d, accumulates in the sediment of zone 6. For Zone 2, the sediment accumulates only 0.2% of the particle load released in the surface of Zone 6.

D. CONCLUSIONS

Caution should of course be exercised in extending the results from these tracer runs too far. The recycling processes both in the water column, the non-steady state nature of the inputs and the dynamic nonlinear behavior that is inherent in the CBWQM preclude any extensive generalizations of the tracer runs to the variables in the model. However, some useful conclusions can be drawn.

1. Conservative Dissolved Substance

The tracer runs using a conservative dissolved substance indicate that the Susquehanna River and Baltimore Harbor have equivalent unit influences on Zones 2 and 3. Dissolved input into the Potomac at the fall line influences the Bay both up and down from the entrance of the Potomac but with major unit influence in Zone 4 and below. The unit influence of dissolved input at the fall line of the James is limited to Zone 8 where it is believed that most of the James dissolved loads to the Bay leave the system at the mouth. Although the unit influence of the ocean is small in the upper Bay, the actual effect may be significant due to the large oceanic load. Overall, as shown in Figure V-1, the Bay dissolved substance response is indifferent as to where load inputs occur upstream in the system.

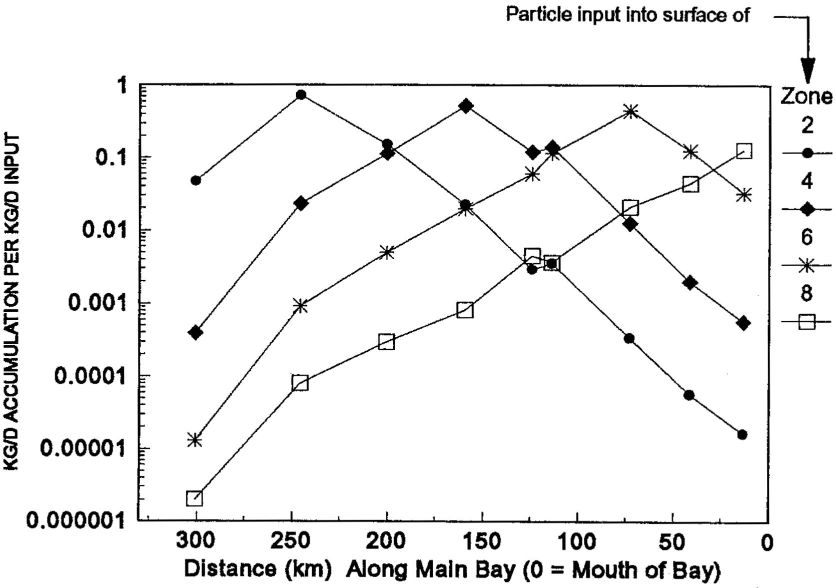


Figure V - 5. Longitudinal variation of steady state response of sediment acumulation flux in a zone due to particle inputs at the surface of the indicated zone.

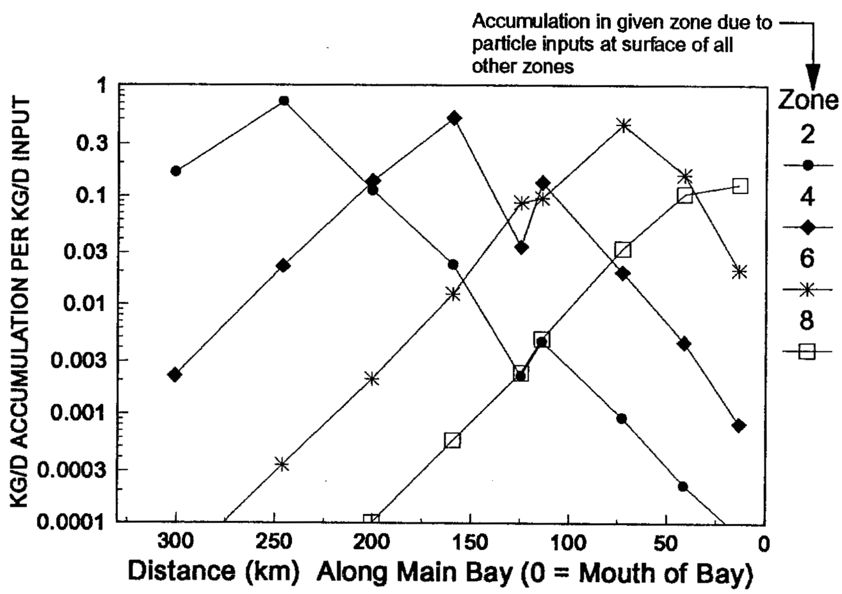


Figure V -6. Longitudinal variation of steady state response of sediment acumulation flux in a given zone due to particle inputs at the surface of all other zones.

2. Particle Inputs at Fall Lines

Overall, the results indicate that for the particle settling rates of 1.0 m/d used for the tracer, sediment accumulation occurs almost entirely in the immediate vicinity of the input. Thus sediment loads from the Susquehanna are mostly deposited immediately downstream. Some Baltimore Harbor sediments escape to the main Bay but virtually no sediment response is calculated outside of the tributaries into which the load was input (see Figure V-3). Particles imported from the ocean are distributed more widely than particles released at the fall lines. Roughly one third of the oceanic particles are exported from the Bay.

3. Particle Inputs at Surface of Bay

For the runs where particles were introduced into the surface of the zone and allowed to settle at 1 m/d, almost all of the particles in Zone 5 and above (including the Eastern Shore) are retained while some fraction of the particles formed in Zone 6 and below are lost. Particles input at the surface are transported upstream and downstream of the zone in which they are formed. The particle distribution is roughly bell shaped (see Figure V-5). In Zones 1 and 2, over 70% of the material formed in the zone is deposited within the zone. The fraction declines with distance downstream to only about 10% in Zone 8.

Particles with settling rates less than 1.0 m/d, such as the phytoplankton groups will of course be distributed more widely and impact sediments over a wider area, the upper bound of which is given by the dissolved tracer results. Since the algal group settling rates are considerably less than the 1.0 m/d (i.e., 0.1 - 0.25 m/d) and are set at zero during certain stages of the calculation, one can conclude from these tracer runs that algal particles are probably distributed widely throughout the Bay system and production in surface layers impact sediments in zones outside the immediate production zones.

VI. NUTRIENT, PHYTOPLANKTON, CARBON AND SOD RESPONSES

A. INTRODUCTION

The purpose of this chapter is to summarize the nitrogen, phosphorus, phytoplankton, carbon and sediment oxygen demand responses for the scenarios. The focus is two-fold: (a) How the nutrients and resulting carbon fluxes impact the DO under various scenarios, and, (b) How the reduction in nutrients impacts living resources habitat, as indicated by DIN, DIP, chlorophyll biomass and light penetration.

In order to set the stage for the subsequent analyses, Figure VI-1 shows the calculated longitudinal summer average DO for the Base case. As shown, the minimum bottom DO occurs at the head end of the deep trench in Zone #2. The principal reasons for this response under the Base case are explored in this chapter and the next as a means for assessing the impact of the nutrient reduction scenarios on the resulting DO.

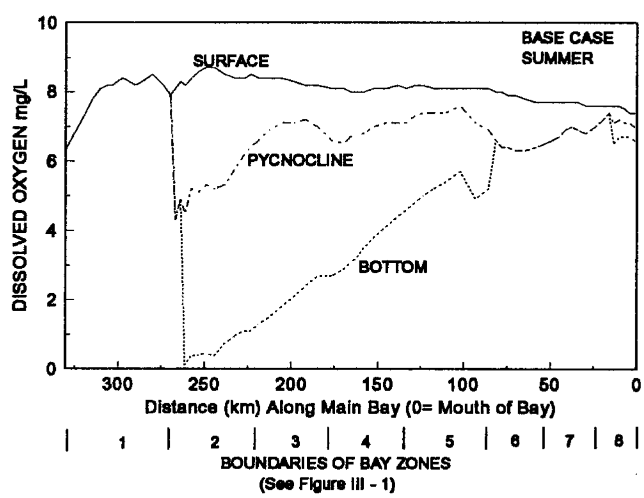


Figure VI - 1. Calculated longitudinal variation of DO for Base case averaged over summer for average year.

Comparisons are drawn in this section between the Base case nutrient and carbon conditions and a choice of several scenarios including the LOT scenarios (LOT N&P, LOT N only and LOT P Only) and the 40% Controllable scenarios. These comparisons provide a bounding of feasible responses and assist in examining the trade-off between nitrogen and phosphorus removals.

Throughout this section, Figures are presented as concentration profiles or other variables as a function of distance along the main axis of the Bay. In most cases, the points plotted represent the zonal averages for the particular case or season and are plotted at the mid-point of the zone. Zone 9, the Eastern Shore zone is plotted midway between Zones 4 and 5.

B. NITROGEN AND PHOSPHORUS RESPONSES

1. Nitrogen and Phosphorus Concentrations

Figures VI-2 and VI-3 show the longitudinal profiles for TN and TP averaged over zone and season for the Base case. The marked differences in the profiles can be noted, due principally to a significant input of phosphorus from the ocean boundary (see Cerco and Cole, 1992 for discussion of this boundary condition). For TN, spring concentrations exceed summer concentrations throughout the Bay with minimum values generally in the fall.

For TP, the variation longitudinally and seasonally is relatively small compared to TN since TP varies by about a factor of two while TN varies by about a factor of four. This is a consequence of the loading to the Bay from the Susquehanna and other rivers as well as the ocean (see Section II).

The spring nutrient conditions are important reference points for subsequent phytoplankton growth. The March-May profiles (which are similar to the winter) and June-September profiles for TN and DIN under Base and LOT cases are shown in Figures VI-4a,b. Figures VI-5a,b focus in on the DIN for a range of scenarios: Base, LOT (N&P), LOT for TN only and LOT for TP only. The differences between the spring and summer periods can be noted where the latter season generally has higher nutrient levels than in the spring. The reduction in the spring DIN from Base to LOT is most pronounced in the lower reaches of the Bay. It can also be noted that the DIN becomes a significant smaller proportion of the TN as one progresses down the Bay. This is partly a result of the ocean boundary condition for TN and DIN. The half saturation constant (a measure of the degree to which the phytoplankton growth rate is controlled by the nutrient) as used in the CBWQM is shown on the plot and indicates that in the upper Bay the DIN is significantly above this constant and approaches this constant as one proceeds down the Bay, showing potential nitrogen limitation in the mid to lower portion of the Bay.

Inspecting Figures VI-5a,b, it can be seen that the LOT P Only scenario increases the DIN in the upper and mid Bay over Base DIN levels and significantly over the LOT N Only DIN levels. As will be discussed again later, this is a result of reduced phytoplankton under LOT P only in the upper Bay allowing down-Bay transport of nitrogen which would otherwise have been taken up by the phytoplankton. The difference between LOT N&P and LOT N Only where the latter results in lower DIN is therefore another reflection of the Increased transport of nitrogen down the Bay under phosphorus reductions in the upper Bay.

Figures VI-6 a,b and VI-7a,b show similar plots for the TP and DIP. Again, summer DIP is higher than spring levels. For the spring, the upper Bay DIP is seen to be close to or below the half saturation constant for phosphorus indicating that the upper Bay is more phosphorus limited than nitrogen limited. The input of phosphorus from the ocean results in concentrations significantly above the half saturation constant for the lower Bay. For the summer, DIP is considerably above the half saturation constant. Figure VI-7a shows that for LOT N Only, the phosphorus is increased in the lower Bay over the Base case, apparently because of an analogous mechanism as noted above for DIN. That is, with reduced biomass in the mid Bay because of nitrogen reduction, more phosphorus is transported to the lower Bay, but because the lower Bay tends to be nitrogen limited, the impact of such phosphorus transport is negligible.

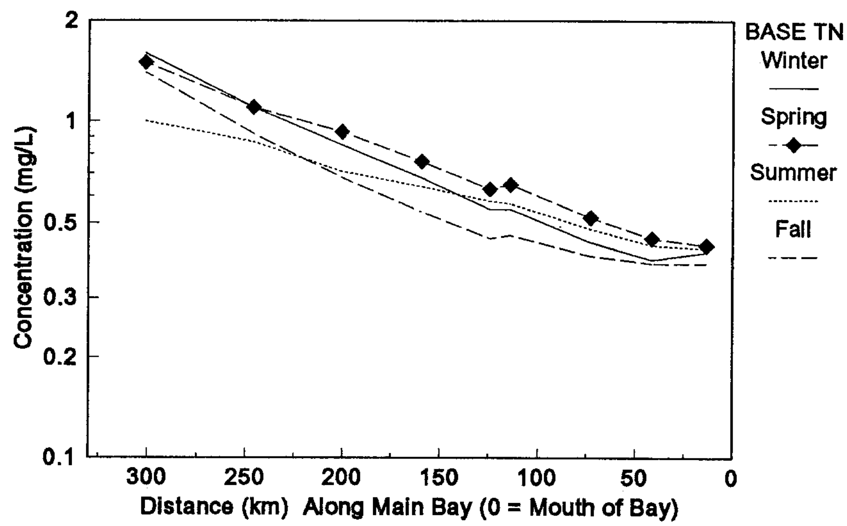


Figure VI - 2. Longitudinal variation of surface nitrogen. Average over zone over season for average year.

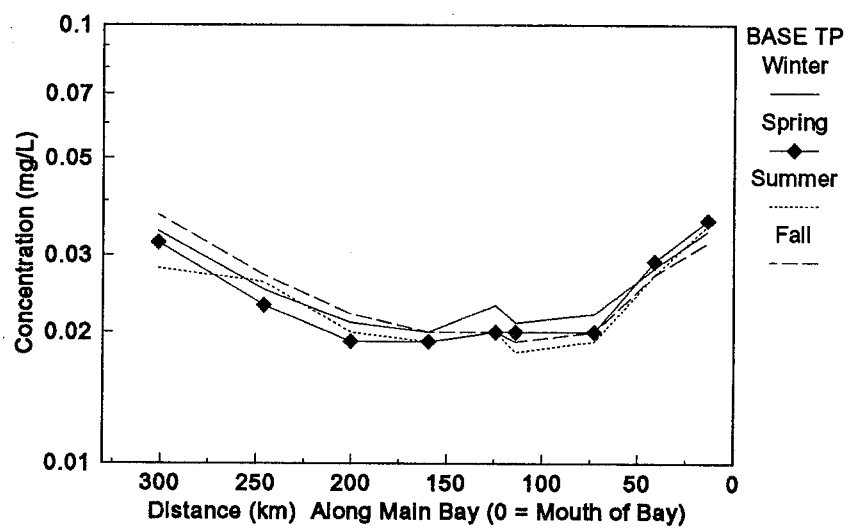


Figure VI - 3 . Longitudinal variation of surface phosphorus. Average over zone over season for average year.

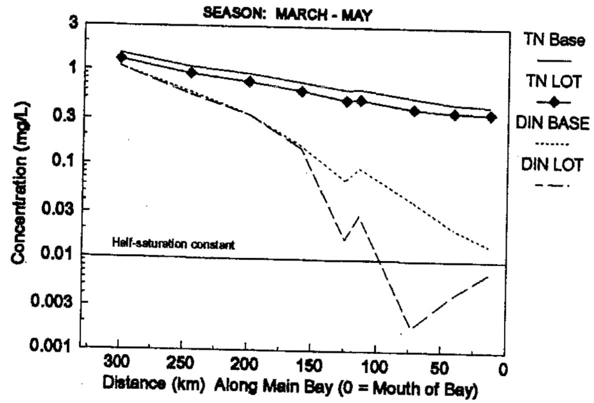


Figure VI - 4a. Longitudinal variation of surface nitrogen. Average over zone over spring for average year.

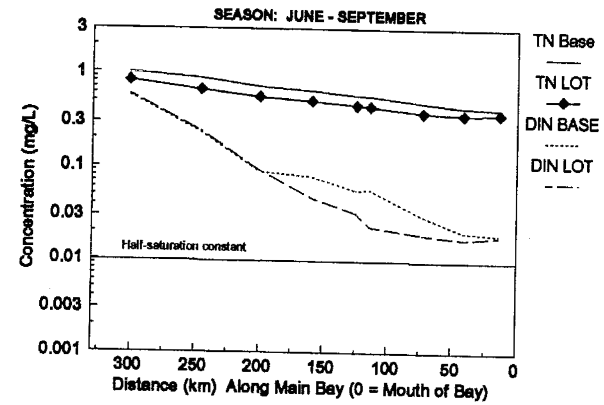


Figure VI - 4b . Longitudinal variation of surface nitrogen. Average over zone over summer for average year.

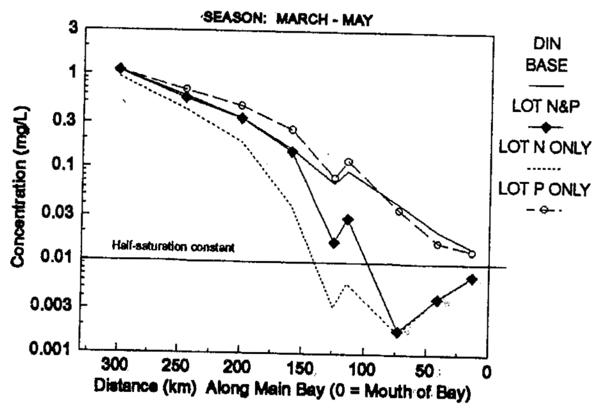


Figure VI - 5a . Longitudinal variation of surface DIN. Average over zone over spring for average year.

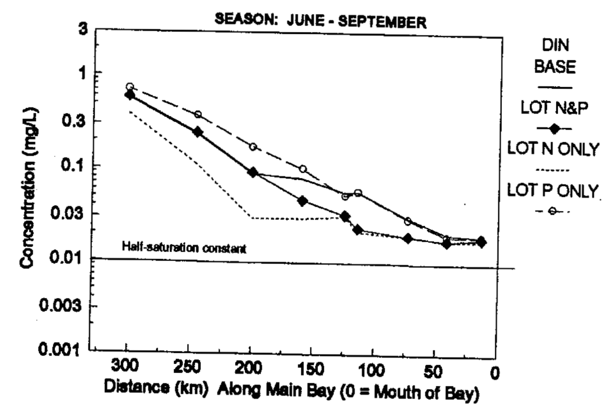


Figure VI - 5b . Longitudinal variation of surface DIN. Average over zone over summer for average year.

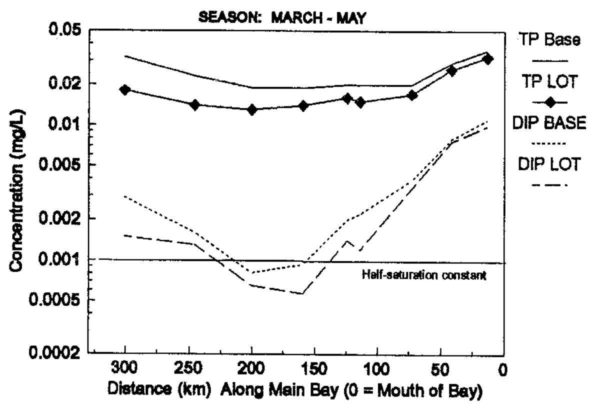


Figure VI - 6a. Longitudinal variation of surface phosphorus. Average over zone over spring for average year.

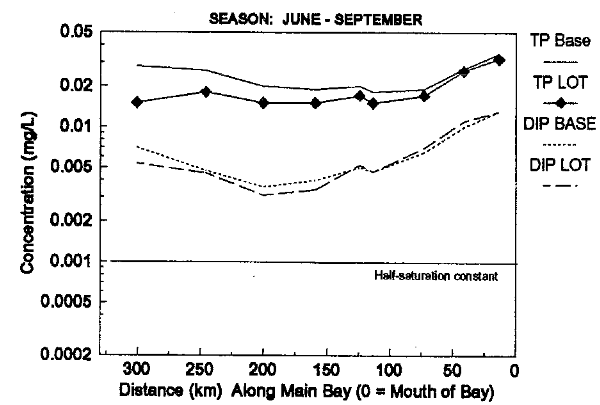


Figure VI - 6b. Longitudinal variation of surface phosphorus. Average over zone over summer for average year.

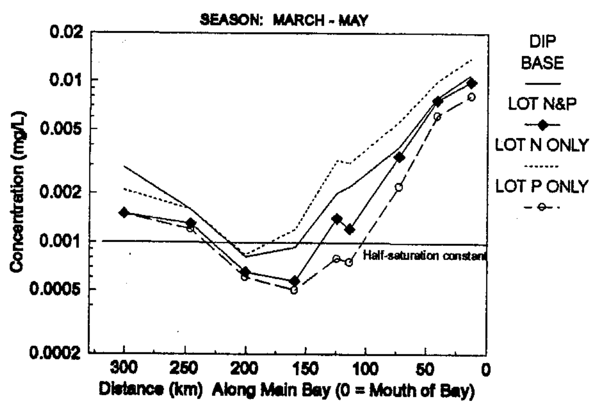


Figure VI - 7a. Longitudinal variation of surface DIP. Average over zone over spring for average year.

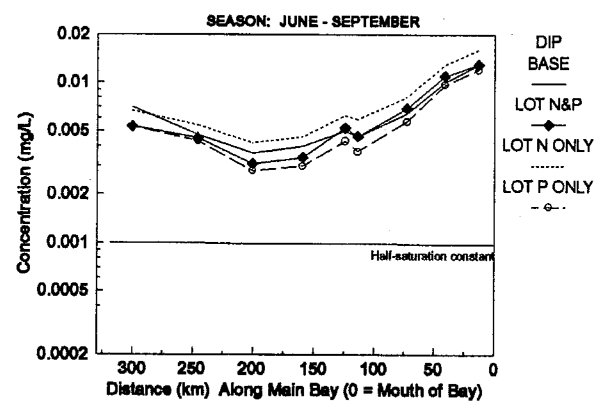


Figure VI - 7b. Longitudinal variation of surface DIP. Average over zone over summer for average year.

2. The DIN/DIP Ratio

The ratio of DIN to DIP is an important measure of whether nitrogen or phosphorus is important in controlling phytoplankton growth. Ratios significantly greater than about 7-10 on a mass basis indicate a tendency toward phosphorus limitation while ratios significantly less than that range tend to indicate nitrogen limitation. Figure VI-8 shows the DIN/DIP ratio for the base case averaged over zone over season. The "Redfield Ratio" of 7.2:1 on a mass basis is shown. During the average spring conditions for this average flow year, the Bay is phosphorus limited from the head to about 75 km from the mouth. During the summer, more of the lower Bay becomes nitrogen limited and during the fall average conditions, more than half of the Bay is nitrogen limited.

Figure VI-9 shows that the general tendency is for the LOT N&P and LOT N Only scenarios to increase the region of the Bay that is nitrogen limited. The LOT P Only however, decreases the region of nitrogen limitation because of increased nitrogen transport to the lower Bay.

Figure VI-10 displays the DIN/DIP ratio in a similar manner as the preceding figure but for the summer condition. Again, reducing the nutrient input increases the down-Bay region of nitrogen limitation and the effect of the LOT P Only is again to decrease nitrogen limitation while the LOT N Only increases N-limitation significantly over the LOT N&P case.

These results are in general agreement with the work of Fisher et al., 1992 who present data and analyses to support the hypothesis that during the spring, phosphorus (and silica) limit growth while N limits growth during the summer. Their data for August 1987 show a considerably larger region of the estuary being controlled by nitrogen than shown here for summer conditions. This is probably due to a combination of effects: e.g., the relatively long averaging period used here for "summer" (June - September), and the differing fresh water inflow hydrographs and associated nutrient loading.

3. Nitrogen and Phosphorus Fluxes

A second mode of interpreting the scenario results is to examine the changes in the fluxes of the principal processes of nutrient inputs, exchanges and sediment interactions. Figures VI-11 through VI- 16 show the nitrogen fluxes for the main Bay. Total external load is the load from fall lines, below fall lines, point sources and direct atmospheric deposition to the Bay (See also Figure II-1). Net ocean flux is the net exchange at the mouth of the Bay. The settling flux is the gross settling to the sediment of the Bay. Diffusive flux is the net exchange of dissolved nutrient forms across the sediment-water interface. Net sediment flux is the difference between gross settling and diffusive flux. Denitrification flux is the loss of nitrogen due to the conversion to nitrogen gas, primarily in the sediments. Finally, the burial flux is the net loss of nitrogen from the bottom sediment segment of the model. All fluxes are given in areal units. It should also be noted that these fluxes are for the average year (year #9) of the variable hydrology sequence and as such reflect a flux "snapshot". It can readily be observed that all fluxes do not necessarily add up to zero because of the dynamic non-steady state nature of the computation.

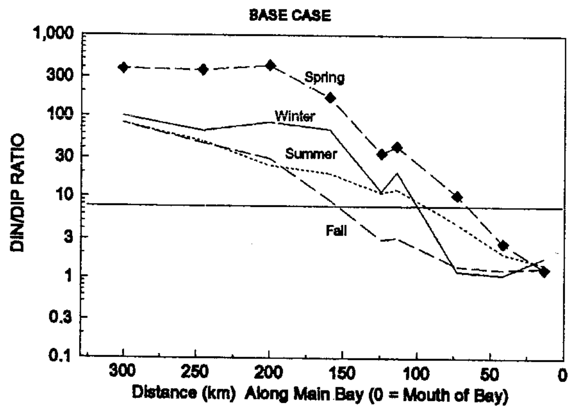


Figure VI - 8. Longitudinal variation of surface DIN/DIP ratio for BASE case. Average over zone over season for average year.

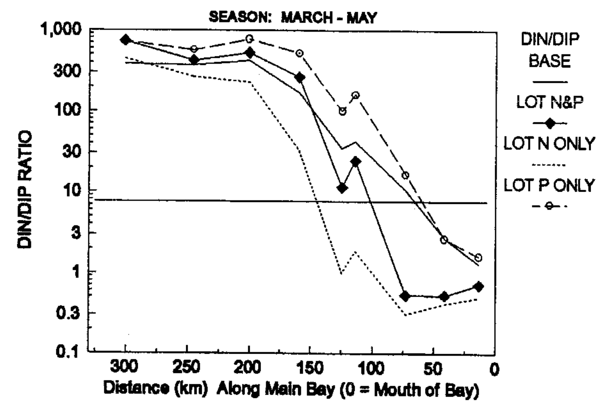


Figure VI - 9. Longitudinal variation of surface DIN/DIP ratio. Average over zone over season for average year.

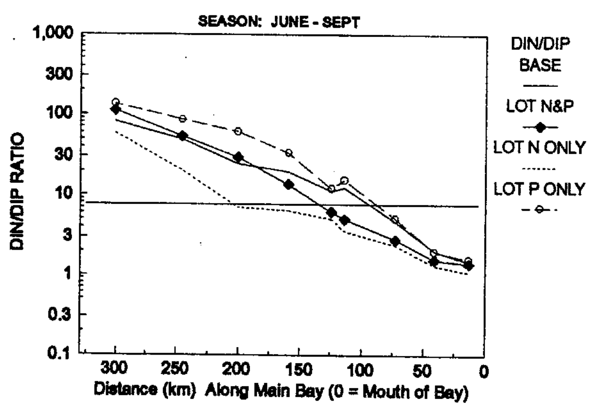


Figure VI - 10. Longitudinal variation of surface DIN/DIP ratio. Average over zone over season for average year.

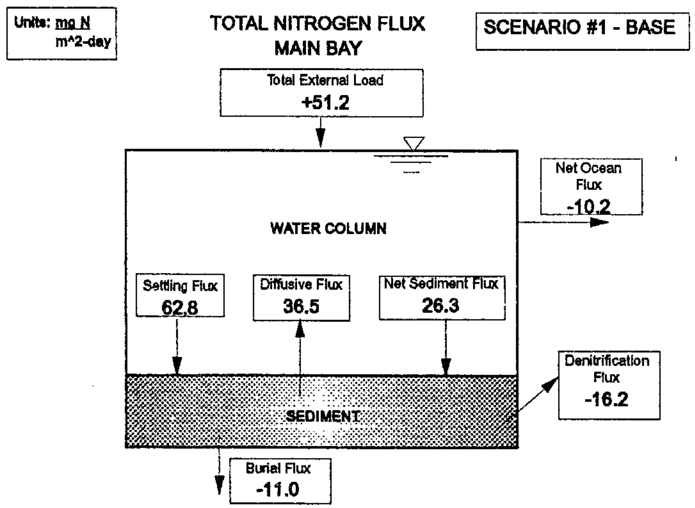


Figure VI - 11 Total Nitrogen Flux for Main Bay - Average Year

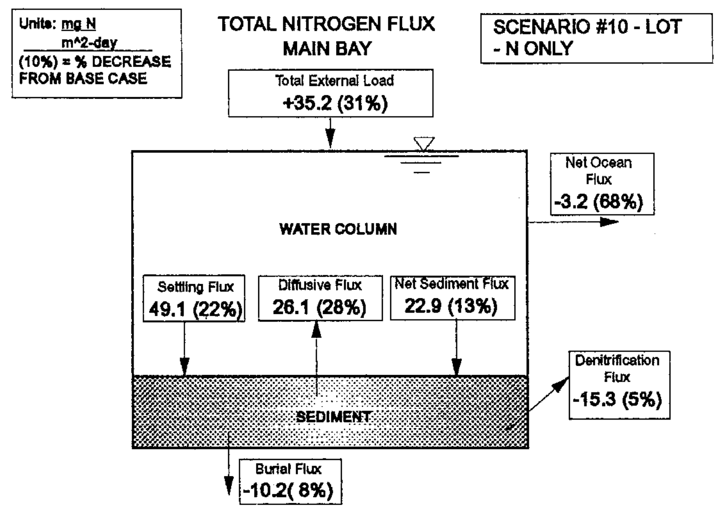


Figure VI - 12 Total Nitrogen Flux and % Decrease from Base Case for Main Bay - Average Year

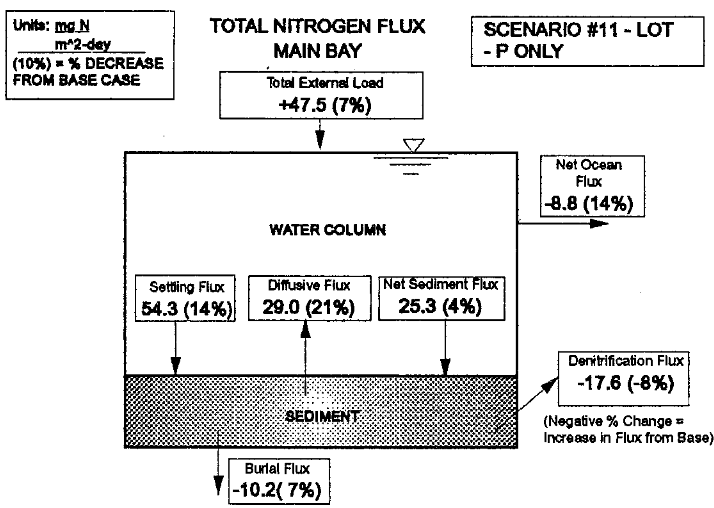


Figure VI - 13. Total Nitrogen Flux and % Decrease from Base Case for Main Bay - Average Year

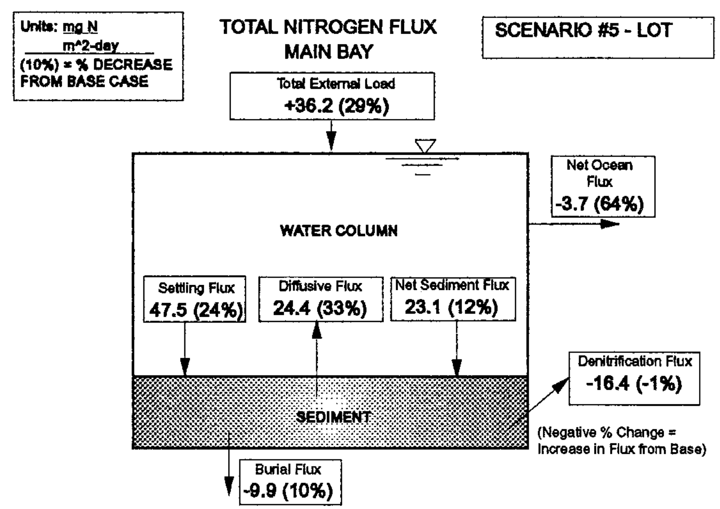


Figure VI - 14. Total Nitrogen Flux and % Decrease from Base Case for Main Bay - Average Year

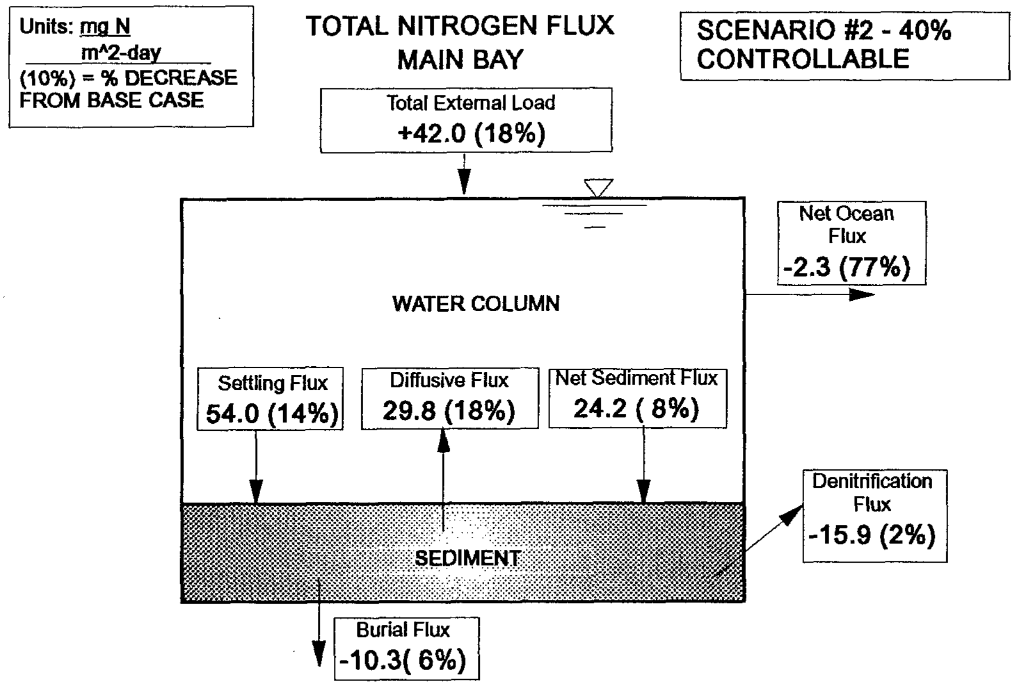


Figure VI - 15. Total Nitrogen Flux and % Decrease from Base Case for Main Bay - Average Year

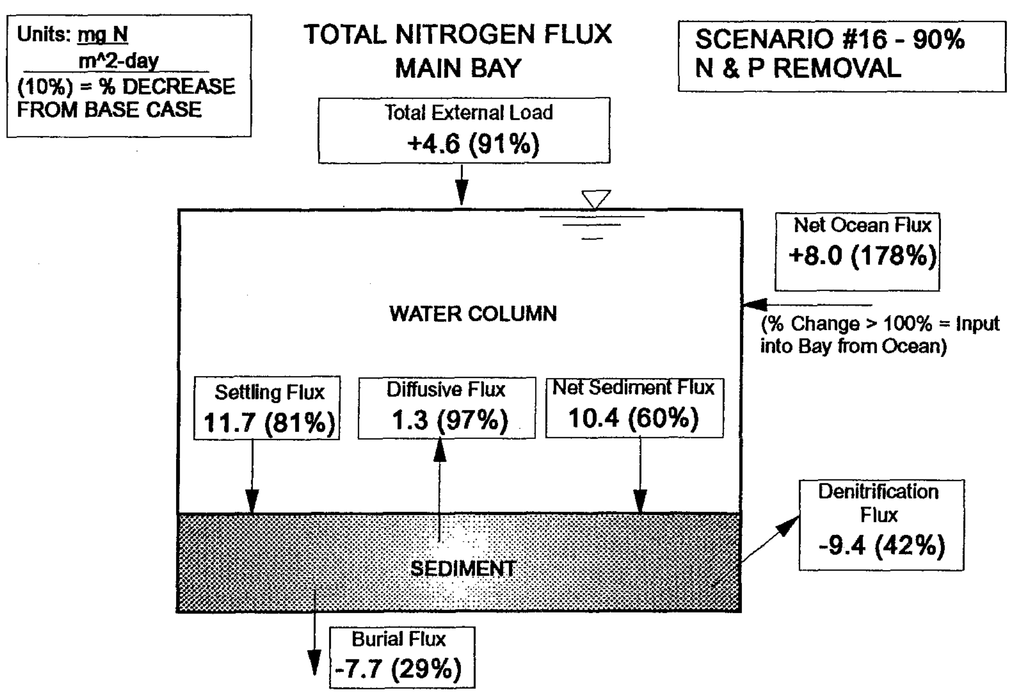


Figure VI - 16. Total Nitrogen Flux and % Decrease from Base Case for Main Bay - Average Year

The net nitrogen flux to the ocean occurs in all scenarios except the 90% N& P removal (Figure VI-16). For the feasible loading reduction scenarios, the net burial of nitrogen is approximately constant over the scenarios. An increase in denitrification flux over Base Case is calculated for both LOT N&P and LOT P Only.

For phosphorus, a net input from the ocean occurs, and for all the scenarios in Figures VI - 17 through VI-22, the ocean input flux is substantial and exceeds the Base case flux. Burial flux is again approximately constant across the scenarios. The influx of phosphorus from the ocean has a significant impact on the fluxes, which can be seen by comparing, for example, the net flux of nitrogen to the sediment with that of phosphorus. For nitrogen, the net sediment flux is about 50% of the external load while for phosphorus, the net flux to the sediment is about 100-150% of the external phosphorus loading. The extra phosphorus is calculated by the CBWQM to be fluxed into the Bay from the ocean.

4. Nitrogen and Phosphorus Responses Interpreted in Terms of SAV Goals

The submerged aquatic vegetation (SAV) habitat requirements include a goal attaining of less than 0.15 mg/l dissolved inorganic nitrogen (DIN) for mesohaline and polyhaline present and potential locations of SAV colonization during the annual growth period of the vegetation (see Table I-2 of Section I). The extent of any model run in meeting the DIN goal can be tabulated, and then normalized to the base case scenario, so that all runs can be designated a percent improvement over base case (with base case as zero improvement, and complete compliance with the DIN goal as 1.00 = 100% improvement). For uniform baywide nutrient reductions the achievement of the DIN goal can be visualized as the response surface shown in Figure VI - 23 (See Section III - C for details on generation of response surfaces). This Figure shows DIN goal achievement (percent improvement over base case) on the vertical axis as a function of nitrogen and phosphorus load reductions (also expressed as percent improvement over base case) on the horizontal plane. As expected, the model predicts that the DIN goal responds strongly to nitrogen removals. Previous discussion of scenario results have indicated the downstream transport of nitrogen from phosphorus removal scenarios. The response surface DIN figure illustrates this result by indicating that phosphorus reductions caused the model to predict that DIN concentrations would increase somewhat in SAV habitat areas. DIN goal in this figure is for the cumulative effect during an average year for the entire Bay. Though seasonal and local effects in many cases are quite different from the overall total response, the total response indicates the dominant trend.

The dissolved inorganic phosphorus (DIP) goal for SAV is that for critical growing periods DIP concentrations must be less than 0.02 mg/l in actual and potential tidal fresh, oligohaline, and polyhaline SAV zones, and less than 0.01 mg/l in mesohaline SAV zones. (Table I-2). This goal was met 100% by the base case scenario.

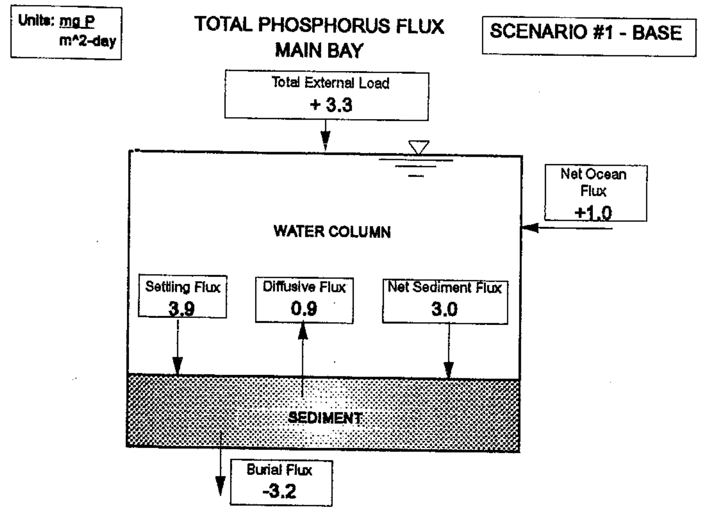


Figure VI - 17. Total Phosphorus Flux for Main Bay - Average Year

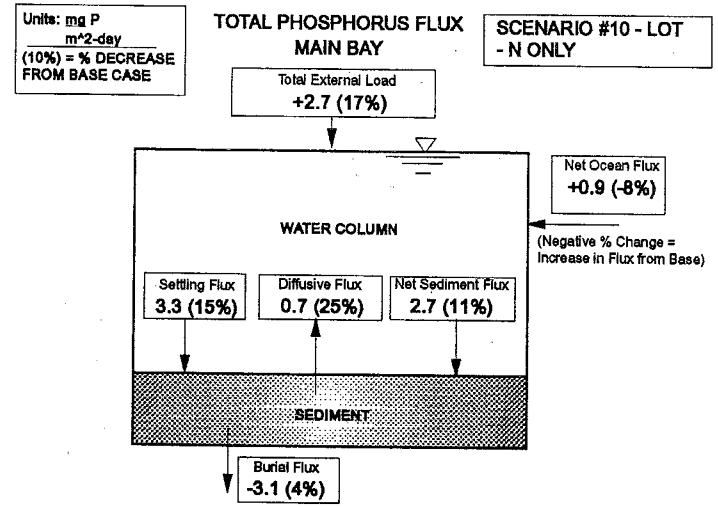


Figure VI - 18. Total Phosphorus Flux and % Decrease from Base Case for Main Bay - Average Year

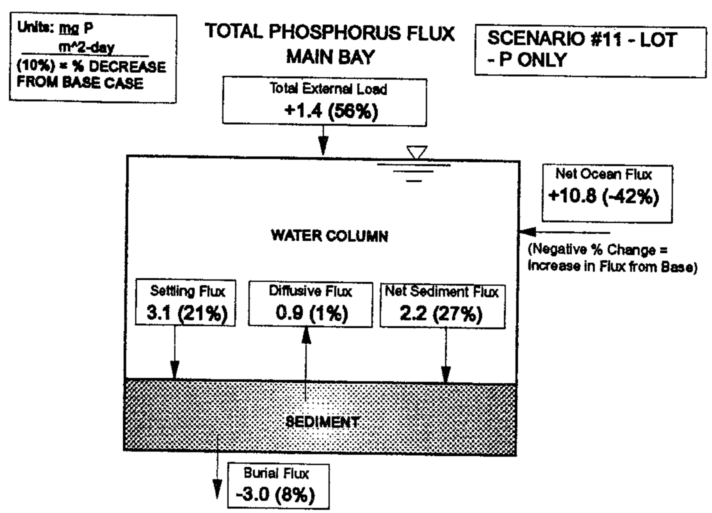


Figure VI - 19. Total Phosphorus Flux and % Decrease from Base Case for Main Bay - Average Year

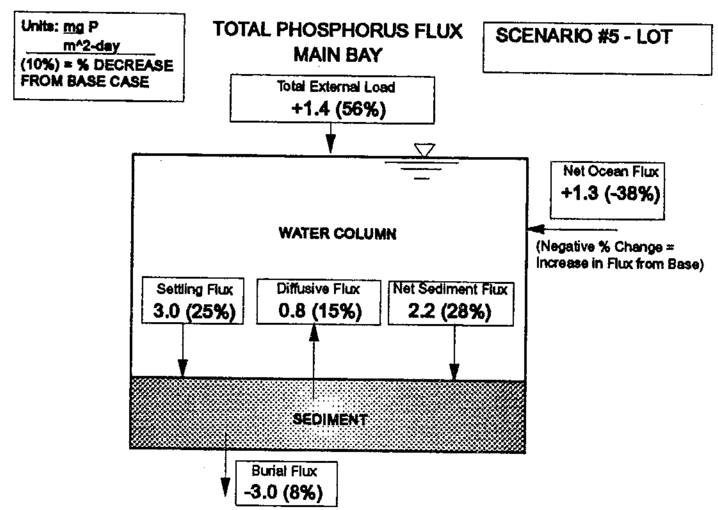


Figure VI - 20. Total Phosphorus Flux and % Decrease from Base Case for Main Bay - Average Year

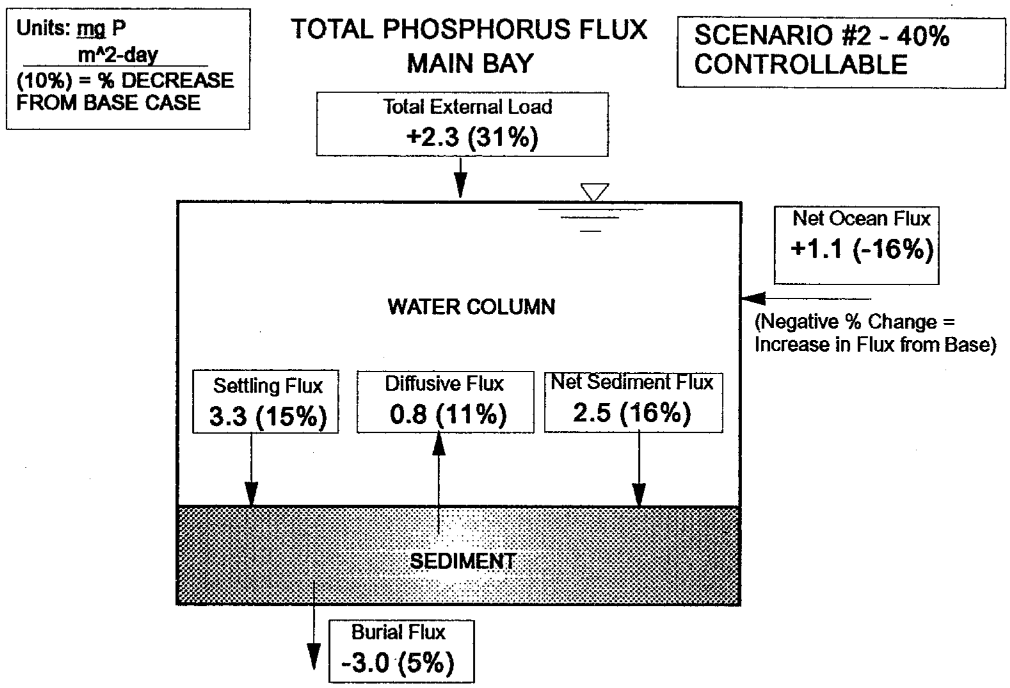


Figure VI - 21. Total Phosphorus Flux and % Decrease from Base Case for Main Bay - Average Year

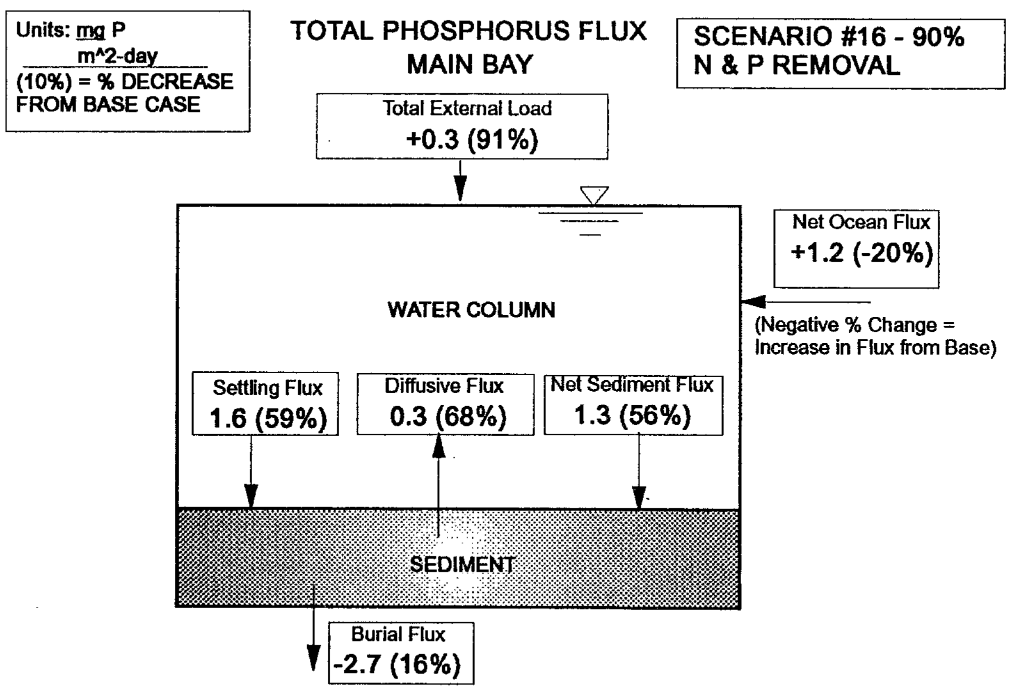


Figure VI - 22. Total Phosphorus Flux and % Decrease from Base Case for Main Bay - Average Year

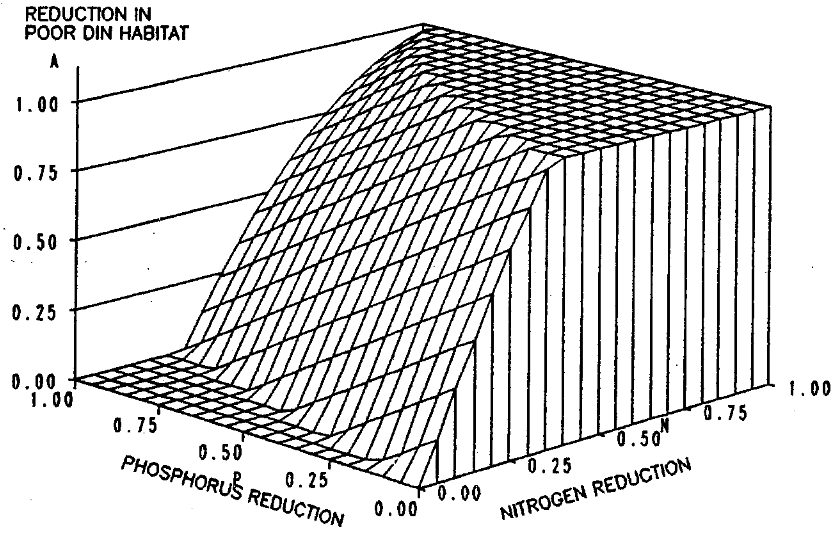


Figure VI - 23. Response surface analysis of dissolved inorganic nitrogen (DIN) over whole Bay, average year.

C. PHYTOPLANKTON RESPONSE

1. Base Case and Comparison to LOT Scenarios

Following the analysis of N and P behavior under the Base case and different scenarios, the response of the phytoplankton biomass can now be examined. Since it was concluded from the preceding analysis that the Bay is phosphorus limited in the upper reaches and nitrogen limited in the lower reaches, it is appropriate to check whether the phytoplankton response is calculated to be consistent with this nutrient behavior. First, Figure VI-24 shows the longitudinal and seasonal average phytoplankton for the Base case on a ug chlorophyll/L basis. Peak concentrations are calculated for the spring followed by a general decline in the summer and fall and an increase in the winter in preparation for the spring bloom. Figure VI-25 shows the chlorophyll biomass on a g chlorophyll/m^2 basis and indicates that peak areal biomass occurs in Zone #4 region (Patuxent to Potomac zone). Summer biomass is relatively constant with distance down the Bay. This is in contrast to the concentration plot which indicates peak concentrations of phytoplankton in Zone #2.

Figure VI-26 shows the distribution of spring surface chlorophyll on an areal basis for several scenarios consistent with the nutrient analyses. The impact of phosphorus removal or nitrogen removal is clear. LOT P Only results in biomass comparable to LOT N&P for the upper Bay but increases the biomass in the lower Bay above LOT N&P. Indeed, the LOT P Only results in chlorophyll biomass in the lower Bay at approximately the same levels as the Base case. On the other hand, LOT N Only has little effect in the upper Bay (recall that this scenario does include some P reduction) while in the lower Bay, LOT N Only is more effective in reducing biomass than LOT N&P. These results reflect the nutrient transport issues discussed above.

Figure VI-27 through 30 show the chlorophyll response as a percent reduction from the Base case for the four seasons. Beginning with the winter, the effect of P only and N only is seen clearly where the upper Bay reductions for P only are equivalent to LOT N&P while the lower Bay reductions are comparable to LOT N&P only when N is removed. Note LOT N&P is approximately constant along the Bay because of the effect of P in the upper Bay and N in the lower Bay. The next figure for spring shows a similar picture although here the LOT P only actually results in no change in biomass or a slight increase in biomass in the lower Bay.
The summer profile (Figure VI-29) shows a higher removal in the upper Bay for LOT N&P while the N only case is approximately constant throughout the Bay. The percent reductions for the fall season (Figure VI-30) show a dominance of N only behavior indicating that the LOT N&P response is due principally to N reduction except for the vicinity of Zone #2.

It is concluded from this analysis that chlorophyll biomass is controlled in the upper Bay by phosphorus and therefore reductions in phosphorus are necessary to reduce biomass in that region. The mid to lower portion of the Bay is controlled by nitrogen and nitrogen reductions are necessary to control biomass in that region. Control of either nutrient by itself at LOT levels would not be as effective as controlling both. Indeed, it is calculated that controlling only P at LOT levels would not result in any improvement in the lower Bay (and may degrade the lower Bay) because of increased nitrogen transport down to that area. Similarly, controlling only N at LOT levels has substantially less impact on the upper Bay biomass than P removal. Controlling both nutrients at LOT levels results in consistent overall biomass reductions.

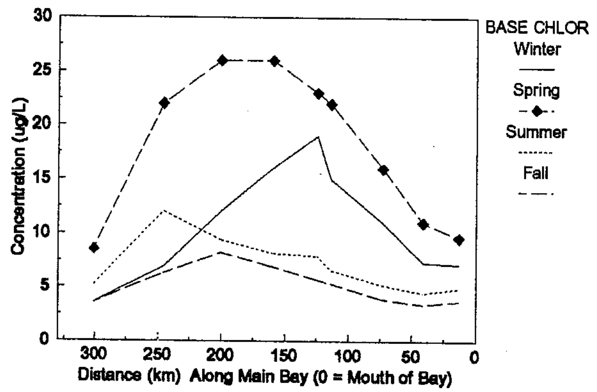


Figure VI - 24. Longitudinal variation of surface chlorophyll. Average over zone over season for average year. Base case.

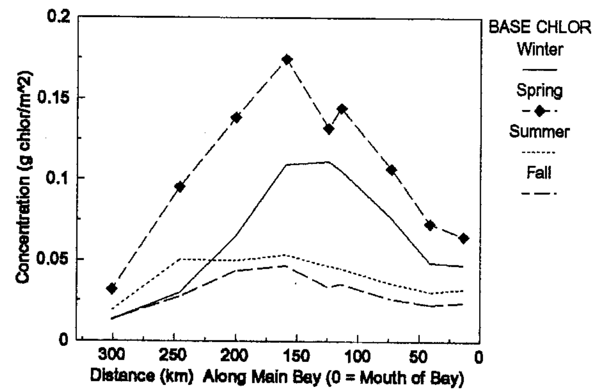


Figure VI - 25. Longitudinal variation of surface chlorophyll on a g/m^2 basis. Average over zone over season for average year. Base case.

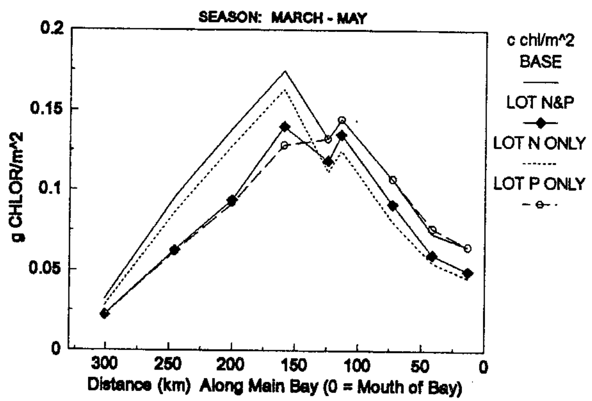


Figure VI - 26 . Longitudinal variation of surface chlorophyll on g/m^2 basis for various scenarios. Average over zone over season for average year.

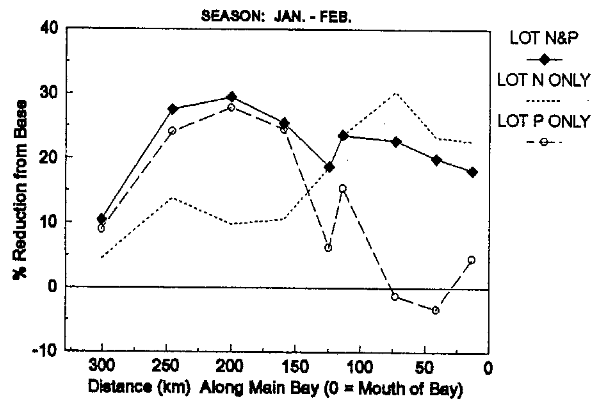


Figure VI - 27. Longitudinal variation of percent reduction of surface chlorophyll on g/m^2 basis. Average over zone over season for average year.

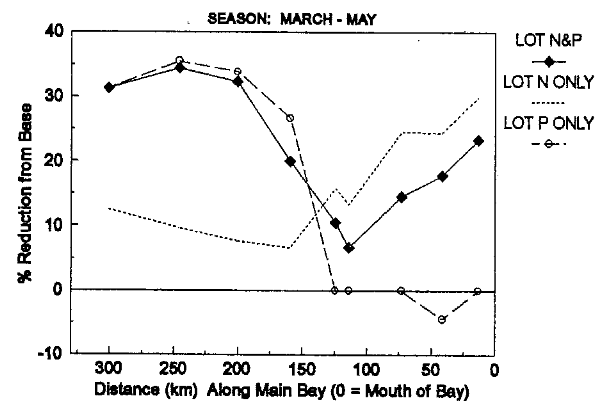


Figure VI - 28. Longitudinal variation of percent reduction of surface chlorophyll on g/m^2 basis. Average over zone over season for average year.

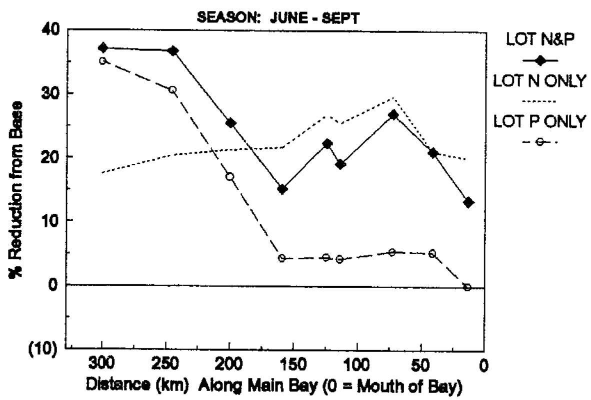


Figure VI - 29. Longitudinal variation of percent reduction of surface chlorophyll on g/m^2 basis. Average over zone over season for average year.

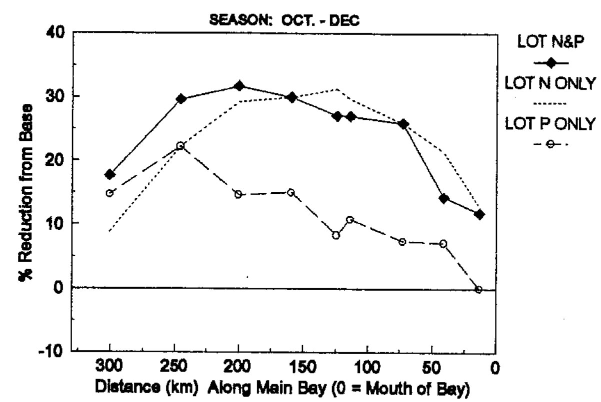


Figure VI - 30 . Longitudinal variation of percent reduction of surface chlorophyll on g/m^2 basis. Average over zone over season for average year.

2. Biomass Reduction Comparisons of "40% Controllable" Scenarios to LOT N&P

The preceding results can also be compared to the 40% Controllable scenarios (#2,#3 and #4). Figures VI-31 and 32 show the percent reduction of phytoplankton biomass by comparing these three scenarios to LOT N&P. For the spring period, 40% Controllable reductions in biomass are about two-thirds of those for LOT N&P and for Scenario #4 (40% Cont. +CAA + Basin) the mid to lower Bay response is comparable to LOT N&P. The upper Bay reductions are however about the same as 40% Controllable. For the summer reductions (Figure VI-32), similar responses are calculated.

The 40% Controllable scenario without CAA and all basin controls results in biomass reductions from Base from about 0-20% for the spring and from about 10-20% in the summer. Additional controls beyond the basic 40% Controllable have maximum impact in the mid to lower Bay with some further improvement (over Scenario #2) in the upper Bay.

3. Effect on Light Penetration

The effect of the preceding reductions in phytoplankton biomass on light penetration can also be evaluated. Such an effect is important for protection of the Submerged Aquatic Vegetation where the emphasis is on plants in the more shallow regions of the Bay. In the analysis that follows however, it should be stressed that responses in light intensity and light extinction are averaged over a zone and over a season. The results therefore do not necessarily refer directly to the shallows of the Bay but are only a zone wide indication of changes in light penetration.

The general equation for light penetration is given by

$$I = I_0 e^{-k_e z}$$

for I and I_o as the solar radiation at depth z and at the surface, respectively and for k_e as the extinction coefficient (1/m). The CBWQM calculates the light extinction coefficient as a function of incoming river flow (as an assumed relationship to incoming suspended solids), added to a background level and a linear relationship of extinction to phytoplankton chlorophyll concentration (see Cerco and Cole, 1992 for complete discussion). Briefly, the light extinction is composed of three components:

$$k_e = k_{eb} + k_{eQ} + k_{eC}$$

where k_{eb} is a minimum extinction coefficient (a function of Bay location), k_{eQ} is the extinction coefficient due to suspended solids as related to incoming river flows and k_{eC} is the extinction coefficient due to the phytoplankton. The latter coefficient is linearly related to the phytoplankton chlorophyll (ug/L), C_h, as

$$k_{eP} = 0.017 C_h$$

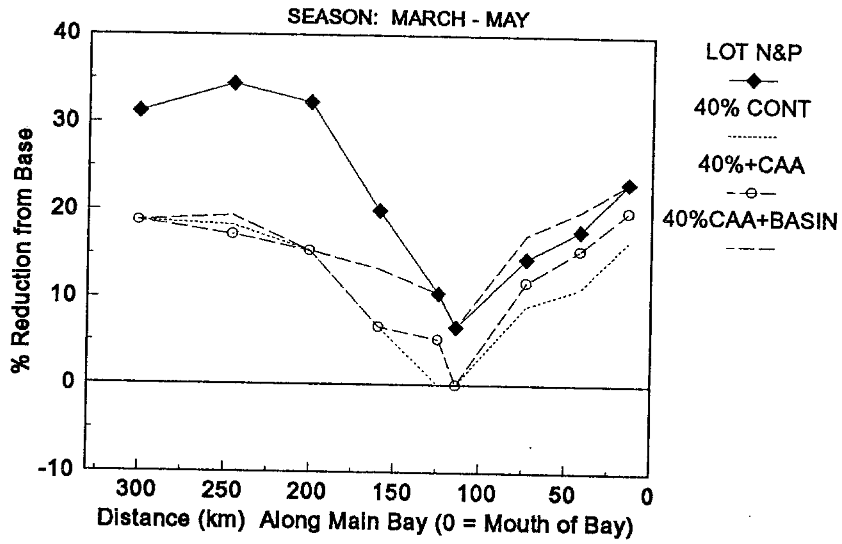


Figure VI - 31. Longitudinal variation of percent reduction of surface chlorophyll on g/m^2 basis. Average over zone over season for average year.

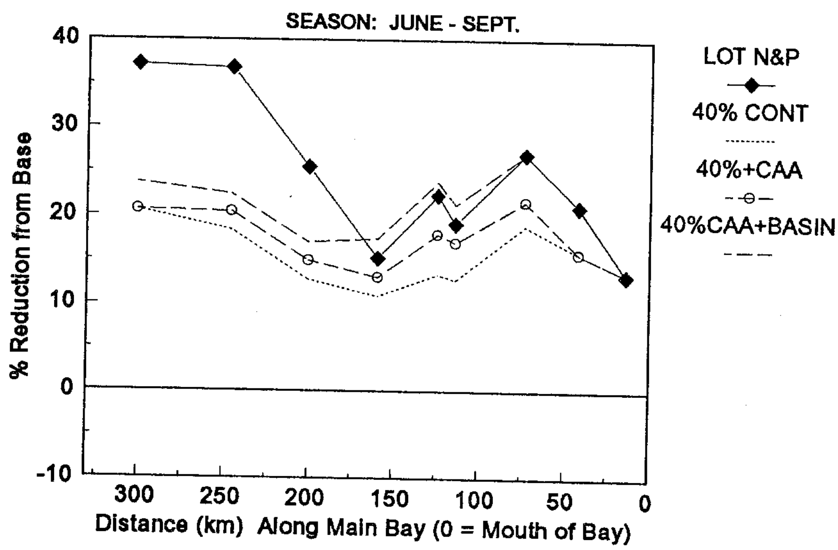


Figure VI - 32. Longitudinal variation of percent reduction of surface chlorophyll on g/m^2 basis. Average over zone over season for average year.

As incorporated in the CBWQM therefore, the part of the extinction coefficient that is controllable by nutrient reduction of phytoplankton is directly proportional to that biomass. The phytoplankton biomass reductions shown in Figures VI - 27 through 30 can therefore be interpreted as reductions in light extinction of that portion that is related to the phytoplankton.

Figure VI-33 shows the reduction in total light extinction coefficient for three reference scenarios. As seen, the LOT N&P case results in light extinction reductions of up to about 12%. This reduction as shown is entirely due to the reduction of phosphorus in the upper Bay as indicated by the result that the LOT P-only run is identical to the LOT N&P case. The small % reduction in the lower Bay is seen to be entirely a function of the nitrogen removal as shown by the LOT N Only. Note that the removal of phosphorus alone is calculated to result in no change in the light extinction or even a slight worsening of conditions in the lower Bay.

If attention is directed to the change in light intensity at a fixed depth, z, then the following equation is relevant:

$$\frac{I_2'}{I_1'} = e^{-z(k_{e2}-k_{e1})}$$

where I_1' and I_2' are, respectively, the ratio of light at depth z to surface light for a reference scenario (i.e. Base case) and a nutrient reduction scenario and similarly, k_{e1} and k_{e2} are the associated extinction coefficients for the respective scenarios. Figure VI - 34 shows the % increase in light intensity from Base case for a depth of 2m. Again, the strong influence of phosphorus removal in the upper Bay is evident while the importance of nitrogen removal for the lower Bay is also indicated.

4. Primary Production Response

Primary production of the phytoplankton is an important variable reflecting the net increase of the phytoplankton areal biomass per unit time. Figures VI-35 through VI-37 show the Base case seasonal variation of the primary production and chlorophyll for three zones of the Bay: Zone 2 in which the minimum bottom DO occurs, Zone 4, a transition region and Zone 6, representing a down-Bay area. Several interesting points emerge. For the upper Bay zone 2, peak biomass is in the spring whereas peak primary production occurs in the summer. Zones 4 and 6 indicate a similar pattern although less evident than for the upper Zone. The spatial gradient in production can also be noted where during the summer, Zone 2 production is at about 1 gC/m^2-d while for Zone 6, the production during the same season is about two-thirds less. Since the biomass is virtually constant over the three Zones, this would tend to indicate that the net growth rate of the phytoplankton is impacted in the lower Bay, presumably by limitations of nitrogen.

Figures VI-38 through VI- 40 show the percent reduction in primary production for the LOT, LOT N Only and LOT P Only scenarios. For Zone 2, the reduction is controlled entirely by phosphorus in the winter and spring whereas in the summer, the production is controlled equally by nitrogen and phosphorus. In the fall, nitrogen is more controlling than phosphorus. For the mid-Bay Zone 4, phosphorus controls in the winter and spring whereas nitrogen is the controlling nutrient for the other two seasons. Indeed, it can be noted that for the summer in Zone 4, LOT P

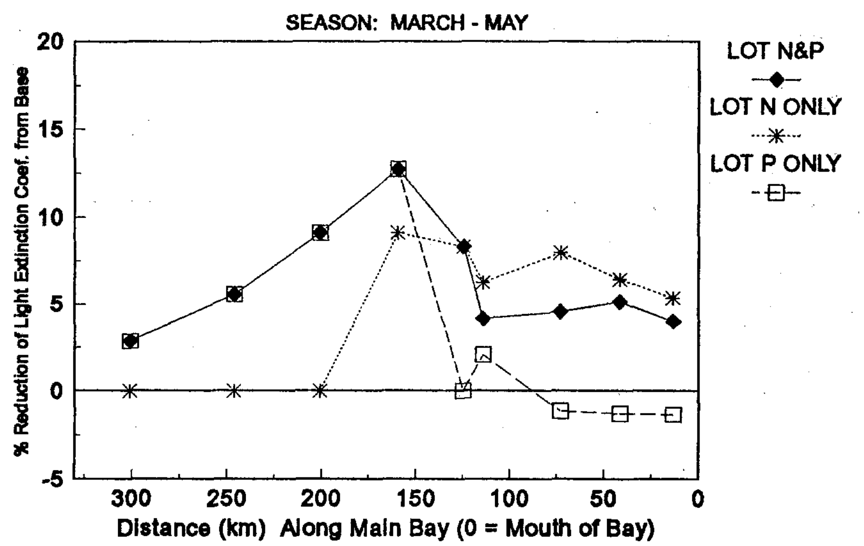


Figure VI - 33. Longitudinal variation of percent reduction of light extinction coefficient. Average over zone over season for average year.

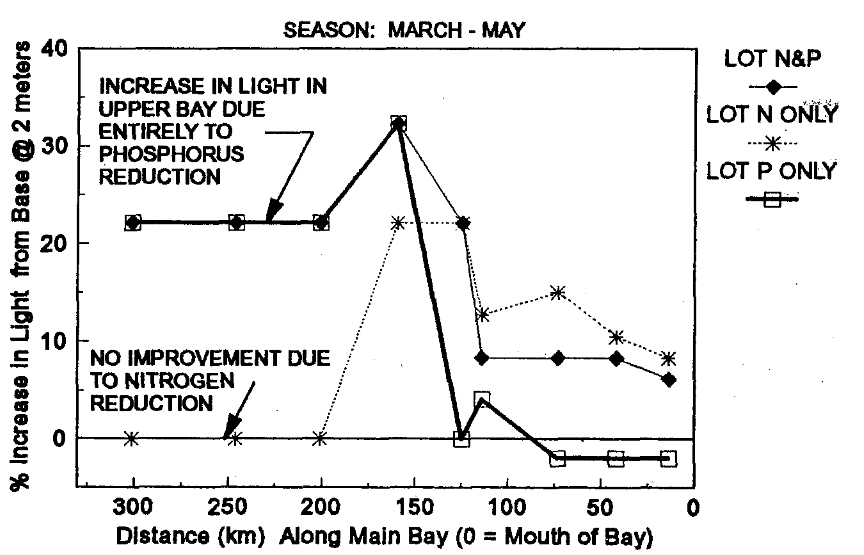
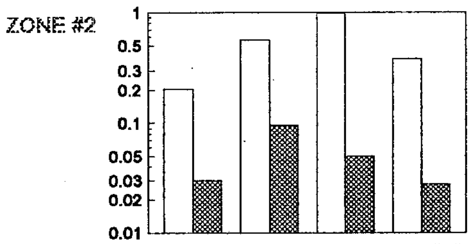
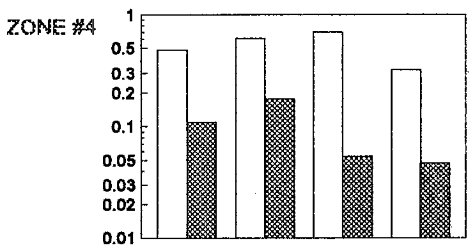


Figure VI - 34. Longitudinal variation of percent increase in light @ 2 meters. Average over zone over season for average year.



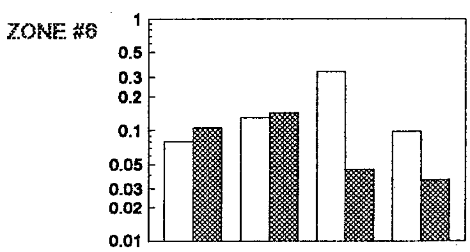
	JAN-FEB	MAR-MAY	JUN-SEPT	OCT-NOV
PRPROD gC/m^2-d ☐	0.21	0.56	0.98	0.36
CHLOR gChlor/m^2 ▨	0.03	0.10	0.05	0.03

Figure VI - 35. Variation of primary production and average phytoplankton biomass, Base Case. Average over zone over season for average year.



	JAN-FEB	MAR-MAY	JUN-SEPT	OCT-NOV
PPROD gC/m^2-d ☐	0.49	0.61	0.69	0.32
gChlor/m^2 ▨	0.11	0.18	0.05	0.05

Figure VI - 36. Variation of primary production and average phytoplankton biomass, Base Case. Average over zone over season for average year.



	JAN-FEB	MAR-MAY	JUN-SEPT	OCT-NOV
PRPROD gC/m^2-d ☐	0.08	0.13	0.34	0.10
CHLOR gChlor/m^2 ▨	0.11	0.14	0.05	0.04

Figure VI - 37. Variation of primary production and average phytoplankton biomass, Base Case. Average over zone over season for average year.

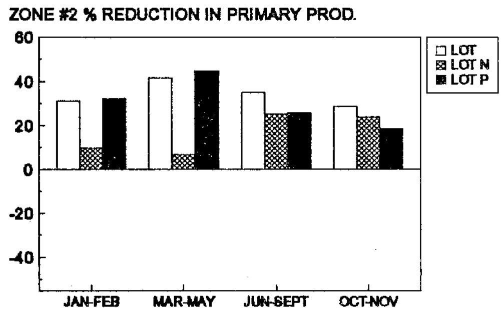


Figure VI - 38. Variation of % reduction from Base of phyto plankton primary production. Zone #2. Average over zone over season for average year.

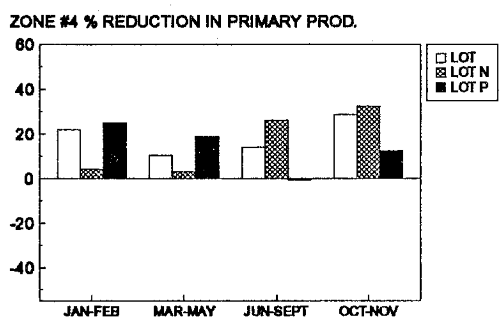


Figure VI - 39. Variation of % reduction from Base of phyto plankton primary production. Zone #4. Average over zone over season for average year.

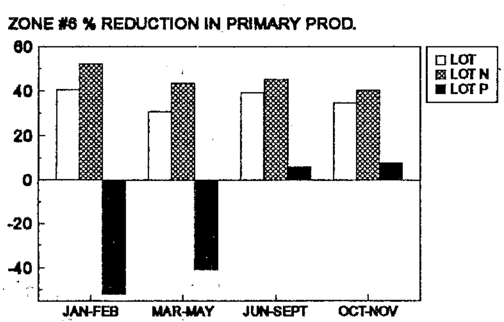


Figure VI - 40. Variation of % reduction from Base of phyto plankton primary production. Zone #6. Average over zone over season for average year.

Only results in virtually no change in production over Base case. Finally, for Zone 6, the impact of downstream transport of nitrogen to the nitrogen poor regions of the Bay is immediately apparent. For the winter and spring seasons, LOT P Only results in an increase in production over Base case due to this down Bay transport of nitrogen. In the summer and fall, this effect is less pronounced because of the relatively lesser impact of phosphorus reductions in the upper Bay regions during these periods.

These results from the LOT scenarios provide further evidence of the calculated down Bay transport of nitrogen by LOT phosphorus load reduction. Such increases in nitrogen increase primary production in the lower nitrogen limited regions of the Bay and as will be seen in the next Section, have a proportional less impact on the DO of the bottom waters of the Bay. On the other hand, phosphorus load reductions have a positive impact in the upper Bay zones where the system is phosphorus limited.

Figure VI - 41 displays the reduction in primary production for a range of selected scenarios. For the 40 % Controllable scenarios (#2 - #4), it is seen that as the load is increasingly reduced for these scenarios, the impact on the primary production approaches the LOT case. The annual averages however tend to mask the actual seasonal dynamics of primary production as discussed in the preceding paragraphs. Thus, the LOT P only annual average reduction is only 10% whereas the spring reduction is over 40%. The impact of reductions in the mid Bay areas (LOT-mid) is also shown to be a significant part of the overall reduction although again seasonal variations may mask the impact of reductions in the upper Bay regions.

D. CARBON RESPONSE

1. TOC and Net Carbon Settling to Sediment

Analysis of the organic carbon concentrations and fluxes aids in the interpretation of the scenarios since this variable has a direct impact on the DO. The Total Organic Carbon (TOC), that is, algal biomass, dissolved plus particulate labile and particulate refractory carbon, for bottom waters and the Base case is shown in Figure VI-42 for the four seasons. Interest is centered on the bottom TOC because of the direct relationship to the DO in those waters. A general down Bay longitudinal gradient is calculated except for winter when carbon is essentially constant with distance.

Figure VI-43 shows the percent reduction in bottom TOC during the spring for the LOT scenarios. It is seen that for the LOT- P only case, the bottom TOC in down Bay waters is increased over LOT of N&P perhaps indicating the effect of increased production in the surface waters during that period. It can also be noted that the bottom TOC for the LOT - P Only case is higher than LOT N&P over a greater distance up the Bay. This may be due to up-Bay advective transport of TOC from the lower Bay. Figures VI- 44 through VI-46 show this behavior more clearly. In these figures, the percent reduction in the TOC net settling to the sediment is shown for the four seasons and three zones. For Zone 2, the reduction in carbon settling is largely a function of the reduction in phosphorus loading with the exception of the fall period. For Zone 6, however, the carbon settling is reduced primarily as a result of nitrogen reductions. Indeed, the LOT P Only scenario is calculated to result in a small increase in carbon net settling during the spring over Base case. For the other seasons, the reduction in phosphorus has a minimal effect on the carbon settling in Zone 6.

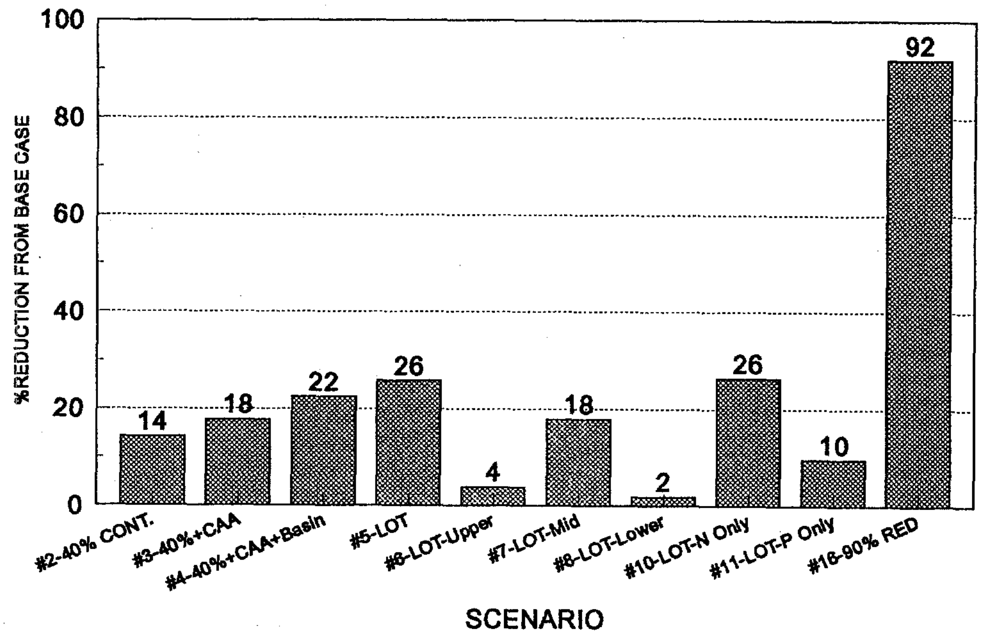


Figure VI- 41. Reductions in Primary Production for Selected Scenarios. Average Year

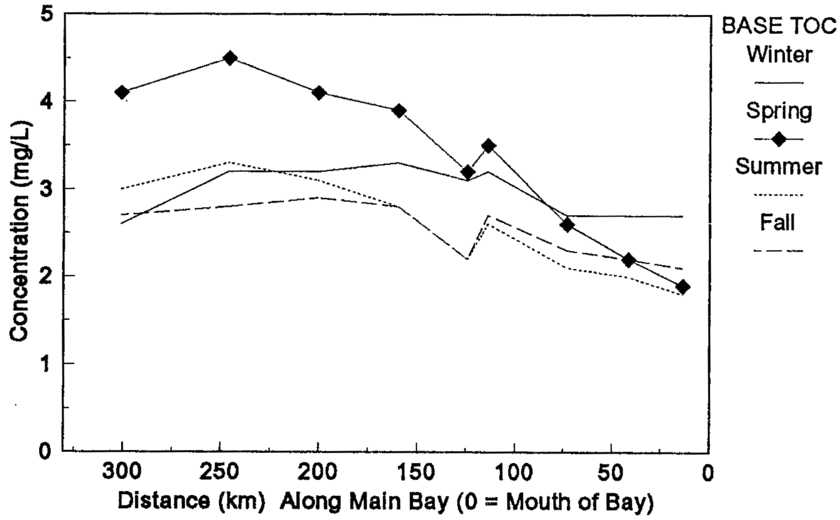


Figure VI - 42 . Longitudinal variation of bottom TOC. Average over zone over season for average year.

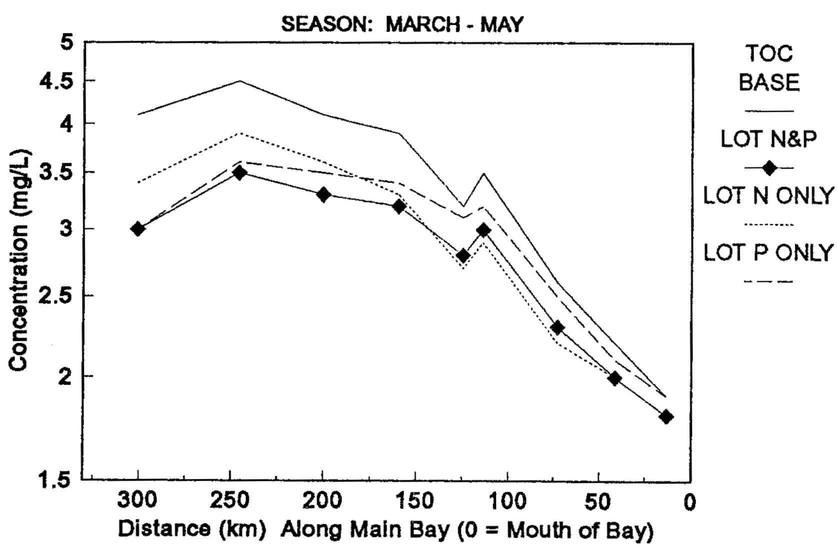


Figure VI - 43 . Longitudinal variation of bottom TOC. Average over zone over season for average year.

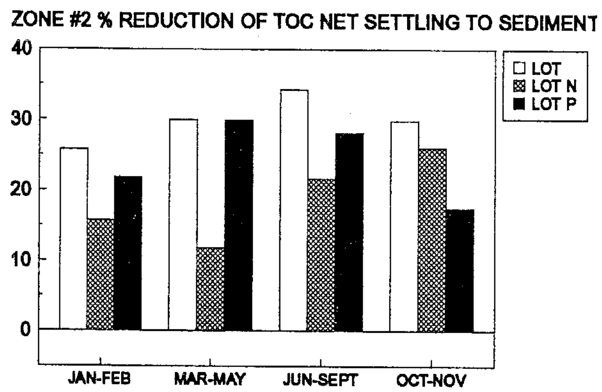


Figure VI - 44 . Variation of % reduction from Base of net TOC to sediment. Zone #2. Average over zone over season for average year.

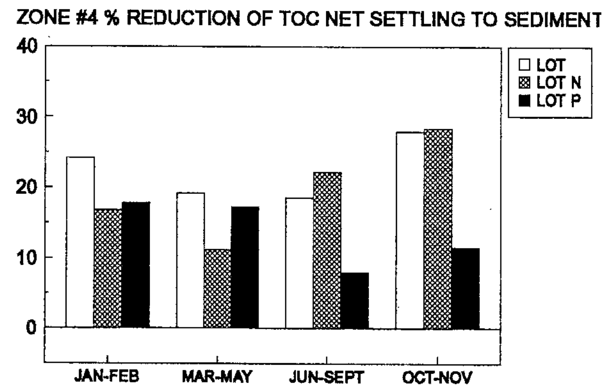


Figure VI - 45. Variation of % reduction from Base of net TOC to sediment. Zone #4. Average over zone over season for average year.

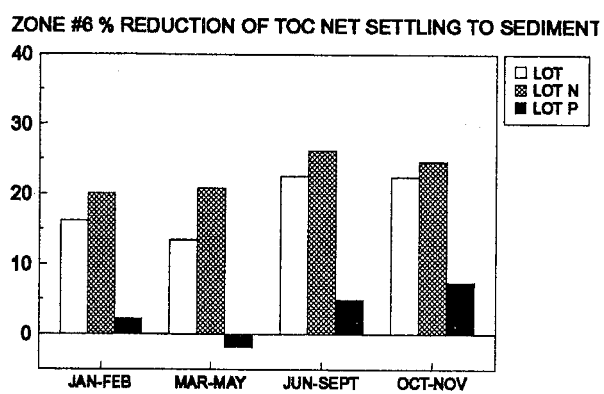


Figure VI - 46. Variation of % reduction from Base of net TOC to sediment. Zone #6. Average over zone over season for average year.

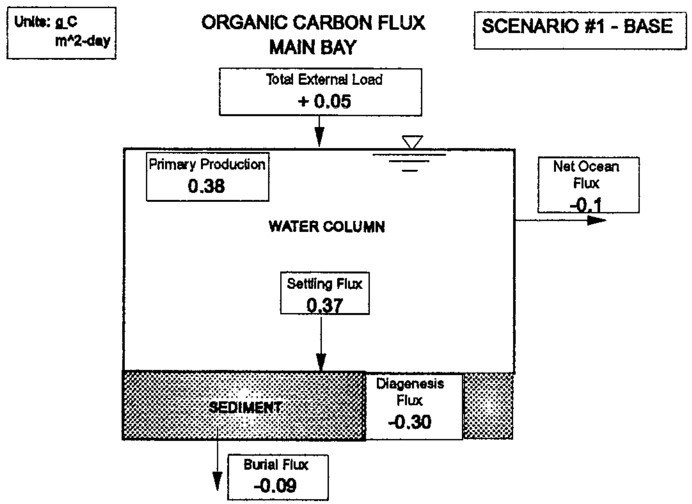


Figure VI - 47. Organic Carbon Flux for Main Bay - Average Year

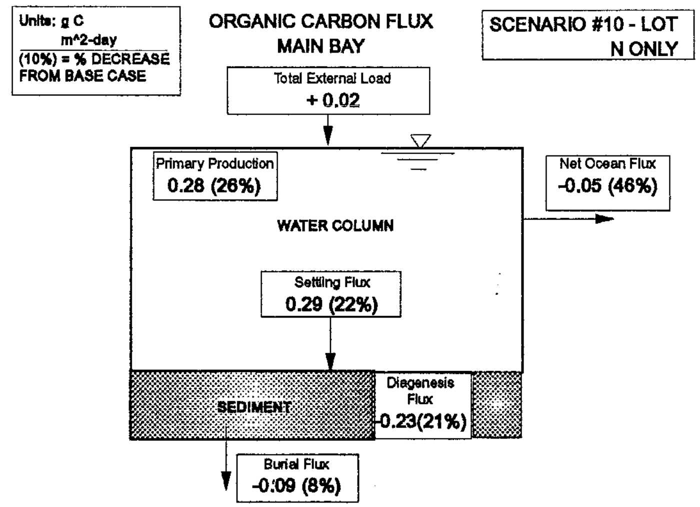


Figure VI - 48. Organic Carbon Flux for Main Bay - Average Year

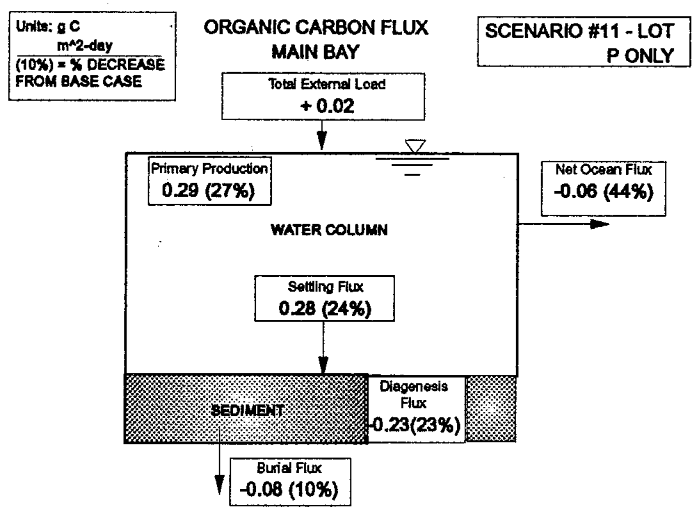


Figure VI - 49. Organic Carbon Flux for Main Bay - Average Year

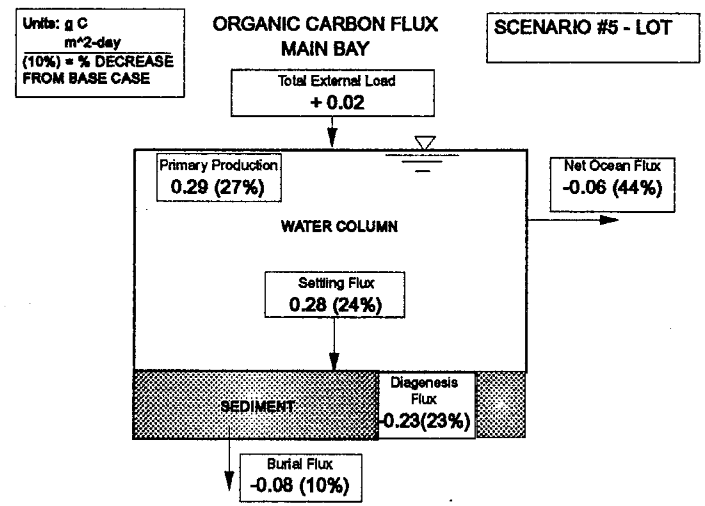


Figure VI - 50. Organic Carbon Flux for Main Bay - Average Year

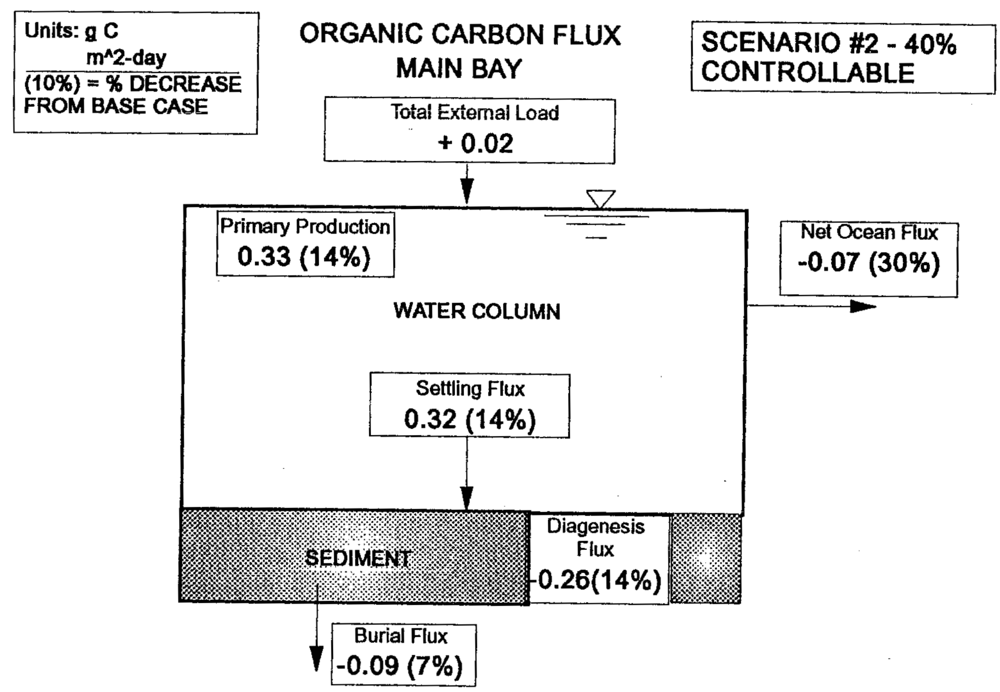


Figure VI - 51. Organic Carbon Flux for Main Bay - Average Year

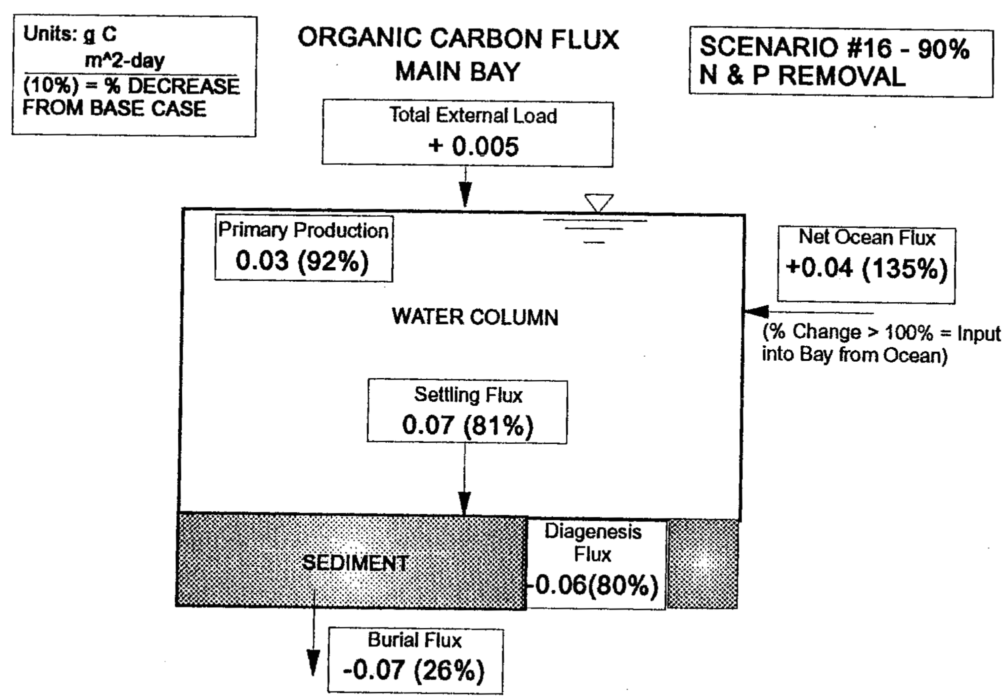


Figure VI - 52. Organic Carbon Flux for Main Bay - Average Year

2. Bay-Wide Carbon Fluxes

Figures VI-47 through VI-52 show the Bay-wide carbon fluxes for selected scenarios and include the Base case fluxes as well as the percent reductions from the Base Case. It is immediately clear that the internal primary carbon production dominates the loading of carbon and that virtually all of the carbon so produced is retained in the Bay and is input to the sediment. Also of the carbon flux to the sediment, about 80% is calculated to be diagenetically degraded. Overall for the Bay, the percent reductions in fluxes are not sensitive to the LOT scenarios. For the 40% controllable scenario, carbon fluxes are generally reduced by about 14% across the key flux elements including the diagenesis flux. Burial fluxes of carbon are approximately constant across the scenarios. Scenario #16, the 90% N&P removal case is the only scenario calculated to result in an input of carbon from the ocean.

E. SEDIMENT OXYGEN DEMAND RESPONSE

The demand of the sediment for oxygen is calculated by the sediment sub-model of the CBWQM and is described in detail in Di Toro et al., (1992). The water column is coupled to the sediment model through the settling of particulate nutrients. The sediment oxygen demand (SOD) is calculated using the net carbon flux to the sediment as the primary input loading.

Figure VI-53 shows the monthly variation in the net carbon flux to the sediment for the three zones discussed earlier in the carbon flux analysis. Maximum loading to the sediment is during the summer months and is the highest in the upper Bay zones. Peak values in this region is about 0.8 gC/m^2-d. The percent reductions for the three zones shown as a function of the time of year are shown in the succeeding three figures (VI-54 through VI-56). (Reference should also be made to Figures VI -44 through VI-46 which show similar plots but by individual zone.) The most notable feature of Figures VI-54 through VI-56 is the dramatic effect of LOT P Only versus LOT N Only. For the former case (VI-56), phosphorus removal has a maximum impact in Zone 2 throughout the year whereas the impact on Zone 6 is to increase (over Base) the carbon settling to the sediment in the spring and during the summer decrease the settling over Base by only about 5%. On the other hand, LOT N only has its maximum effect in Zone 6 up through July and then equally affects the three zones after that. These results are yet another reflection of the preceding discussion indicating the effect of down Bay transport of nitrogen which now is seen to significantly affect the net carbon flux to the sediment. Given this carbon sediment flux behavior, it is now important to examine the resultant behavior of the SOD.

Figure VI-57 shows the variation in the SOD for the Base case across the zones and for the four seasons. Maximum SOD is calculated to occur in the summer and in Zones 3 to 6. This is in contrast to the carbon flux to the sediment which is maximum in the upper Bay Zone 2 region. The lower SOD in Zone 2 may be a result of the periods of zero DO in Zone 2 during which there is zero SOD thereby lowering the overall average. On the other hand, the difference may be related to the labile and refractory components of the carbon used in the model. The fall line particulate loadings are considered to be all refractory while the point sources are assumed to be 70% labile and particulate carbon produced from phytoplankton is assumed to be 55% labile (Cerco and Cole, 1992). Thus, while the sediment of the upper zones receive more carbon, the nature of the carbon is largely refractory in contrast to the middle and lower zones where the

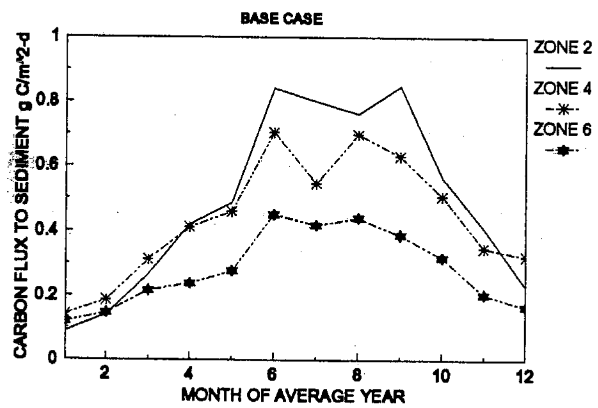


Figure VI - 53 . Monthly variation of carbon flux to sediment for average year. Average over zone.

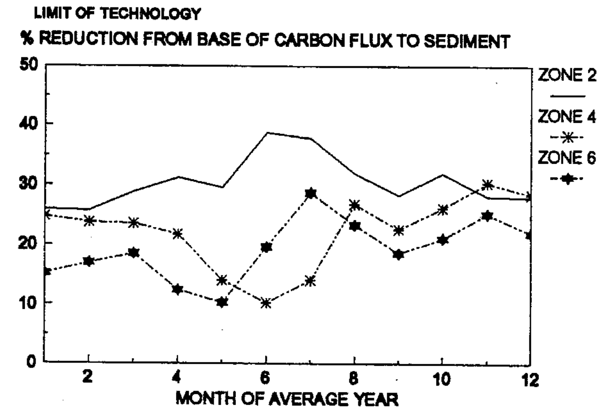


Figure VI - 54 . Monthly percent reduction of carbon flux to sediment from Base case to LOT for average year. Average over zone.

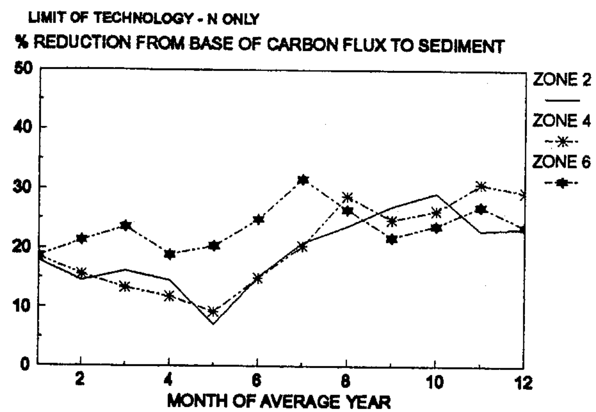


Figure VI - 55 . Monthly percent reduction of LOT - N ONLY from Base case for average year. Average over zone.

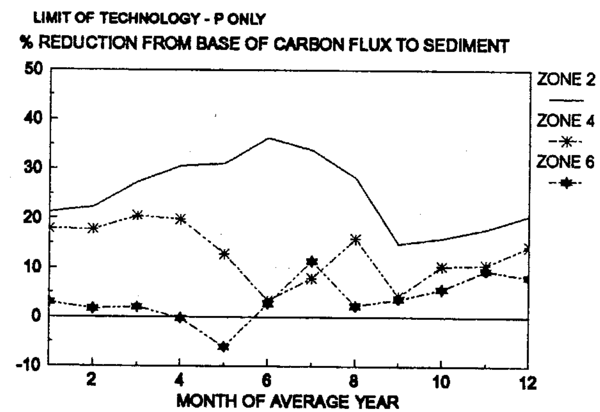


Figure VI - 56 . Monthly percent reduction of LOT - P ONLY from Base case for average year. Average over zone.

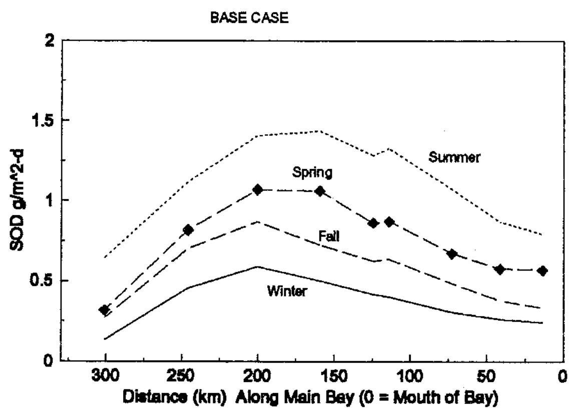


Figure VI - 57. Longitudinal variation of sediment oxygen demand for BASE case. Average over zone over season for average year.

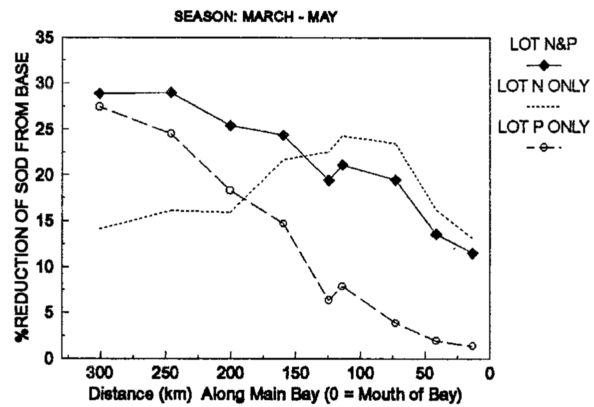


Figure VI - 58 . Longitudinal variation of percent reduction of SOD from Base case. Average over zone over season for average year.

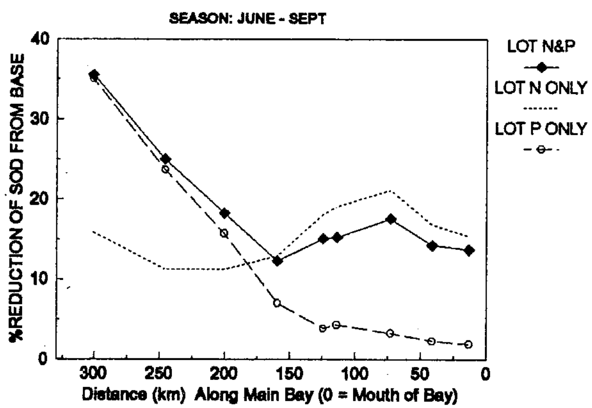


Figure VI - 59. Longitudinal variation of percent reduction of SOD from Base case. Average over zone over season for average year.

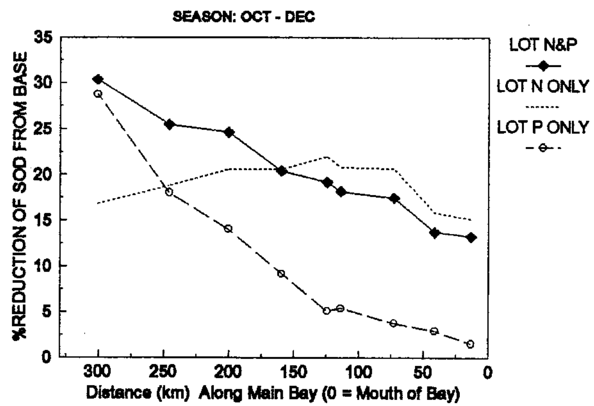


Figure VI - 60. Longitudinal variation of percent reduction of SOD from Base case. Average over zone over season for average year.

carbon results from primary production and is considerably more labile. Since the calculated diagenesis rate in Zones 3 and 4 is higher than in Zone 2, one concludes that the variable carbon fractions has an effect on the SOD in Zone 2 and together with the periods of zero DO is contributing to the lower calculated SOD in that Zone.

Therefore, it appears that maximum SOD levels are calculated for the middle Bay region as a result of the variable labile and refractory nature of the external and internal carbon loadings to the Bay. The effect of load reductions therefore would be expected to have varying influences on the SOD (and hence DO) as a result of the variable carbon fluxes and degree of carbon lability. Figures VI-58 through 60 show the percent reduction in SOD from the Base case for the LOT scenarios for three seasons. Directing attention to the summer season, it is seen the LOT P Only has a significant effect on the SOD in the first three zones, but has relatively little effect on the SOD in the middle and lower zones of the Bay. In contrast, the maximum reduction in SOD in those regions is due to nitrogen reduction. Indeed, one can see again that for LOT N Only, the reduction in SOD is higher than for LOT N&P, due presumably to the impact of nitrogen transport increases for the latter scenario. Although, the percent reduction in SOD in the upper three zones is controlled by phosphorus, the SOD is relatively small in the first two zones, so that the maximum impact of the reduction is considerably more in Zones 3 through 6.

Figure VI-61 shows the percent reductions in SOD for the 40% Controllable scenarios (#2 - #4) in comparison to the LOT N&P scenario. The upper Bay reductions in SOD are higher under this latter scenario due presumably to the higher degree of phosphorus removal in the LOT than in the 40% controllable. The differences in nitrogen loading are not as great (see Section II). For the middle and lower regions of the Bay, the 40% controllable scenarios approach the LOT N&P loading in reducing SOD. In fact, the 40% + CAA + Basin control is at the LOT level of reduction for zones 4 through the rest of the Bay.

F. TIDAL TRIBUTARY LOADING TO BAY

The net input of the tidal tributaries to the main Bay is of particular interest since such loadings represent actual contributions to the Bay proper. As part of the Bay model calculations, mass balances were conducted around the principal tributaries and the exchange of load across the interfaces of the tributaries was calculated for each of the scenarios. For each tributary interface, the cells that had flows entering the estuary were separated from the cells that had flows leaving the estuary. All cells with inflows to the tributary were not necessarily at the bottom of the interface. This review first focuses on the Potomac and the James estuaries as illustrations of the dynamic and interactive behavior between tributaries and the Bay. The section closes with a review of the net nutrient input from all of the tributaries.

1. Potomac and James Estuaries

Figure VI - 62 shows the dynamic behavior of the loads (for the average hydrologic year) at the interface between the Potomac estuary and the main Bay. "To Bay" includes gross output to the Bay while "From Bay" is gross input from the Bay to the Potomac. "Net" is the difference between inflow mass and outflow mass. As seen, peak loadings to/from the Bay occur in the spring. Net loads to the Bay from the Potomac represent the difference between two large loadings entering the tributary and leaving the tributary. It can also be noted that the net transport of nitrogen and phosphorus is small outside of the spring period.

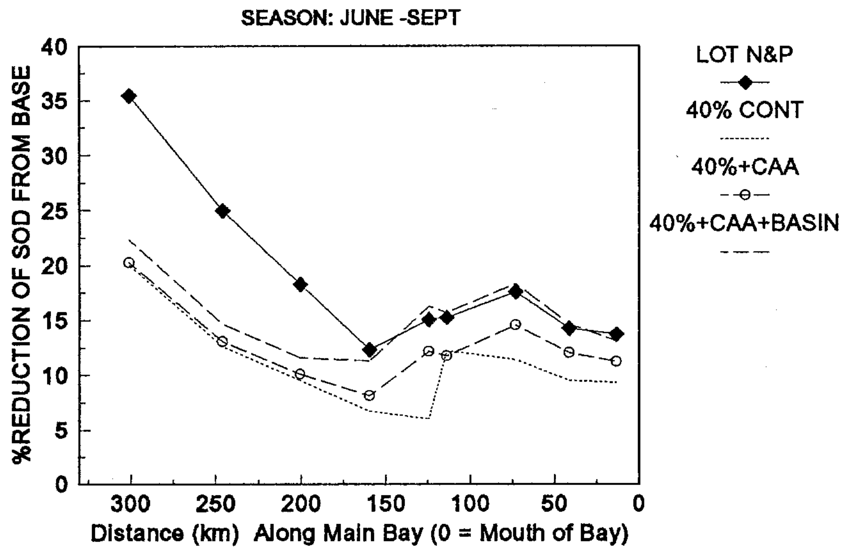
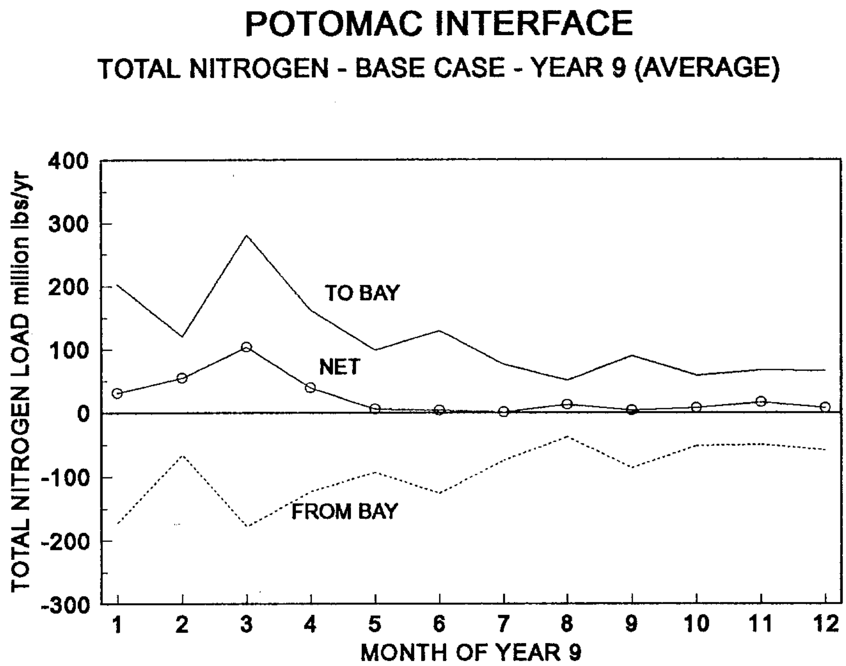


Figure VI - 61. Longitudinal variation of percent reduction of SOD from Base case. Average over zone over season for average year.



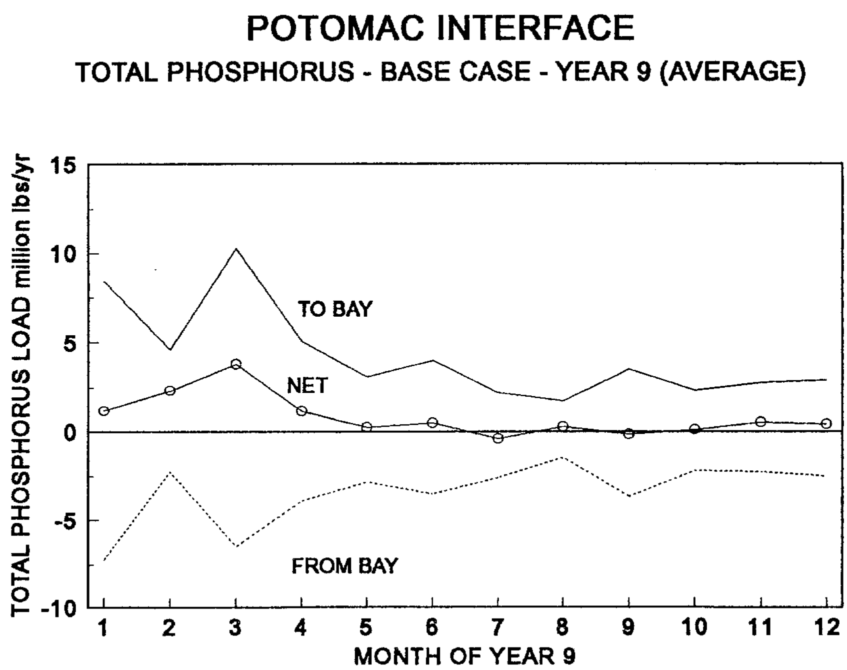


Figure VI -62. (Top) Monthly variation of TN at Potomac interface with Bay. (Bottom) Monthly variation of TP at Potomac interface with Bay.

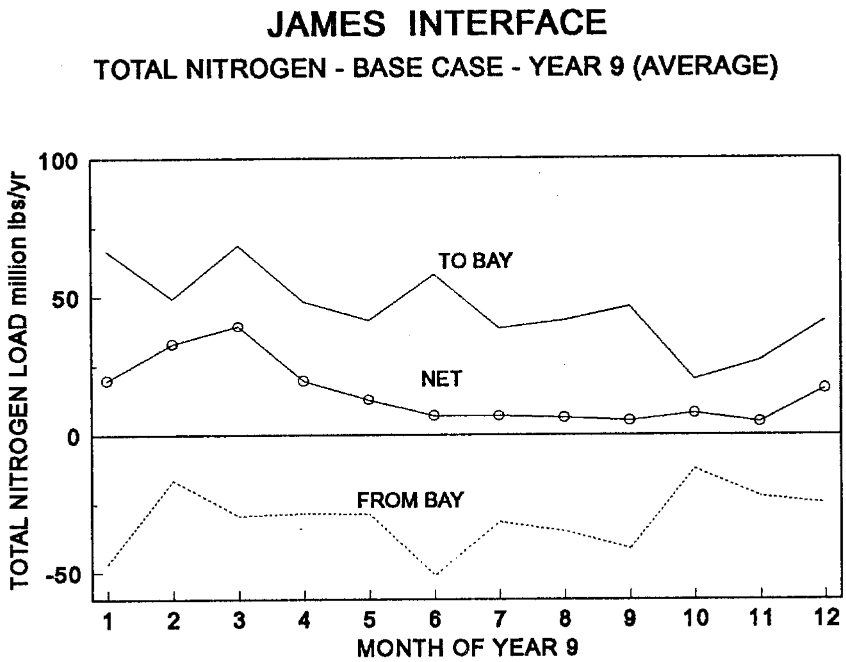
The Potomac results can be contrasted to those from the James estuary shown in Figure VI - 63. Here there is a less pronounced spring peak of loading in either nutrient and the net loading from the James to the Bay extends throughout the year. Net flows show similar patterns. Note also the change in scale. In addition, while the net nitrogen loadings from the Potomac are substantially larger (by a factor of two) than that from the James, net phosphorus loadings are very similar. Finally, it can be recalled from the tracer studies that inputs from the James tend to remain highly localized to the lower Bay.

Further results for the range from the Base case to the LOT case are shown in Figures VI - 64 to VI-69 for the Potomac and James estuaries. Figure VI - 64 shows that for the average hydrology year, the net output load of total nitrogen for the base and LOT cases is calculated at 40% and 33%, respectively of input load. These results are similar to those for the James total nitrogen flux (Figure VI - 65). The net phosphorus loading is about half of total nitrogen for the Potomac (Figure VI - 66). The James is significantly different as seen in Figure VI - 67 where for the base case, the net phosphorus from the James to the Bay is calculated at 38% of the input load whereas for LOT, the net load is only about 2% of the input total phosphorus load. This is due primarily to the large influx of phosphorus from the ocean boundary to the James via inflows into the bottom of that estuary. (Note that the influx of phosphorus remains approximately the same over the range of loading from the base case to the LOT.)

Figures VI - 68 and VI - 69 display the relative percent change of the interfacial loads from the base case loads over the range from the 40% controllable case (S02) to the LOT case including the geographical runs (S06-S08) where LOT was selectively applied to the three geographical regions of the Bay, discussed in Section II. Scenario Loads. For the Potomac, the maximum reduction in TN and TP loads is about 50%. The effect of LOT in the Upper Bay only or LOT in the lower Bay only on the Potomac loading to the Bay is negligible, indicating little influence from up-Bay or down-Bay loading on the net Potomac load to the Bay. Figure VI - 69 shows that for the James up-Bay and mid-Bay load LOT reductions have no influence on the James. The rather substantial reductions from the base case for the James TN and TP are to be noted.

Figure VI - 70 shows a rather remarkable linearity in the net load from these two tributaries over the range of loadings from the base to the LOT (not including the geographical runs). As seen for TN, if the total input load of TN to the Potomac or James is reduced by, say, 30% from the base case load, then the net load of TN exiting from the Potomac or James is reduced about 35% from the base case net load. For TP an approximate linearity is also observed. Therefore, in spite of the rather complex nonlinear interactions that exist in the overall model framework, and the apparent interactions between the Bay and the tributaries, the relationship of net load from these two tributaries to the Bay is directly proportional to the reduction in external load to the tributary.

In summary, the net loading of TN from the Potomac and James estuaries is about 40% of the input TN load for the base case and average hydrology and for TP is about 33% of input TP loads to those two tributaries. The relationship between percent reduction from base case of input load to the tributaries and the resulting percent reduction from base case of the net load exiting from the tributaries is approximately linear. Thus, a 20% reduction from base case in TN and TP input load to the Potomac and James estuaries results in about a 20% reduction in net loading of TN and TP from the two tributaries to the Bay.



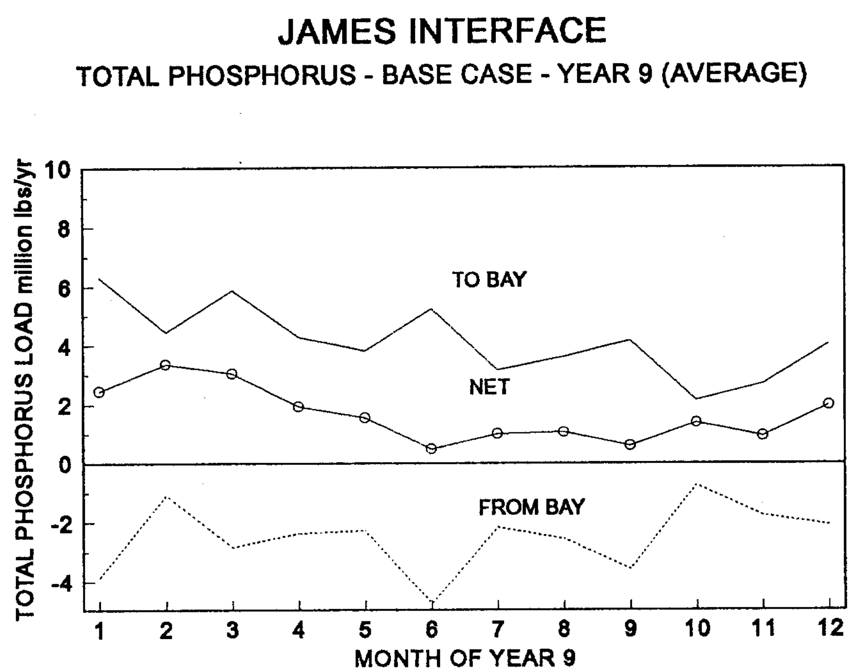
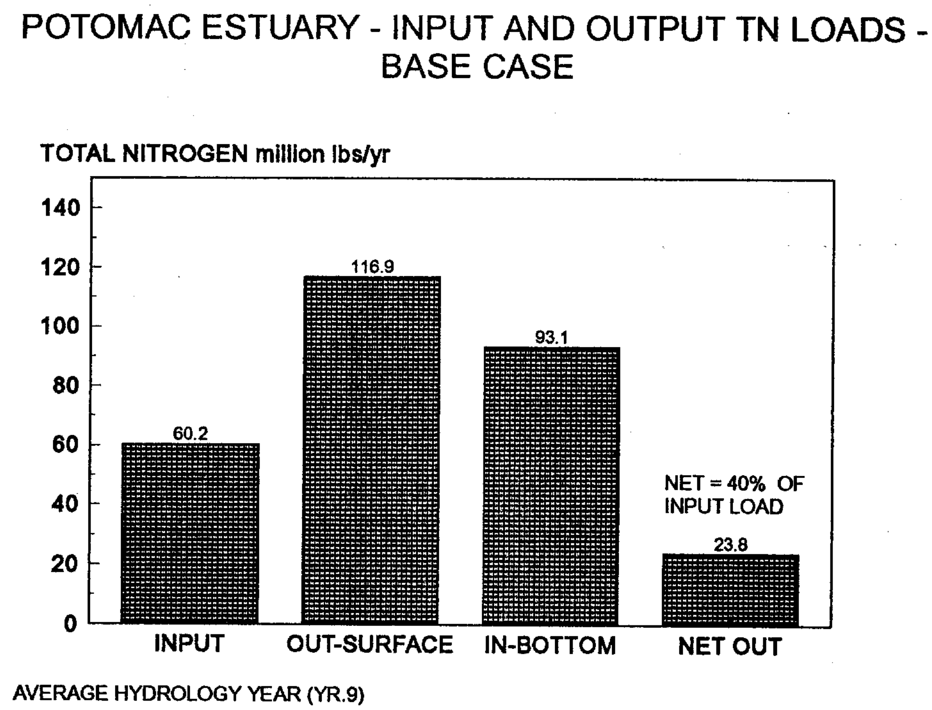


Figure VI -63. (Top) Monthly variation of TN at James interface with Bay. (Bottom) Monthly variation of TP at James interface with Bay.



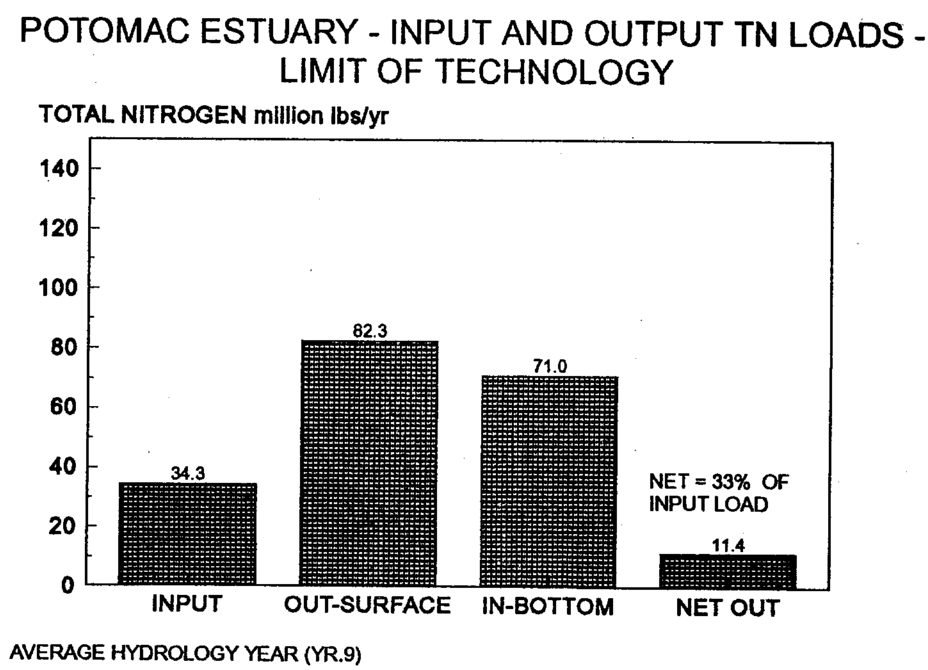
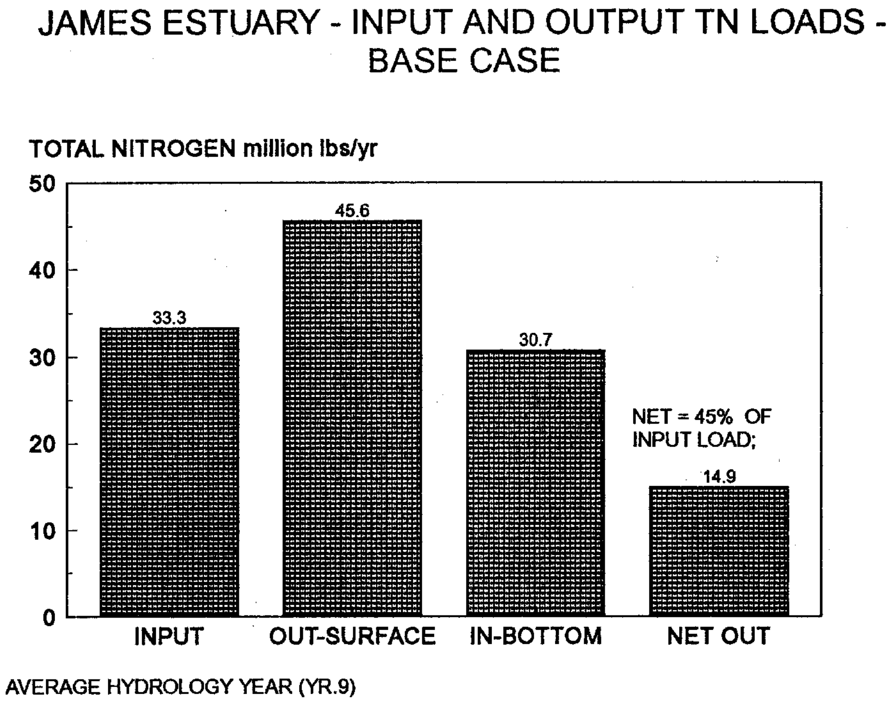


Figure VI -64. (Top) Input and output TN loads at Potomac interface with Bay, Base case.(Bottom) Input and output TN loads at Potomac interface, LOT.



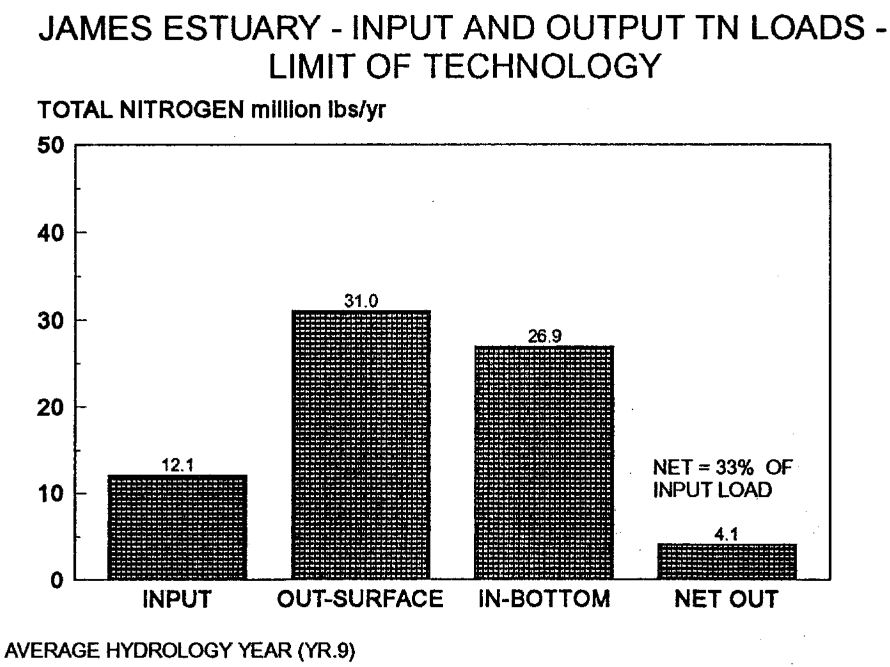
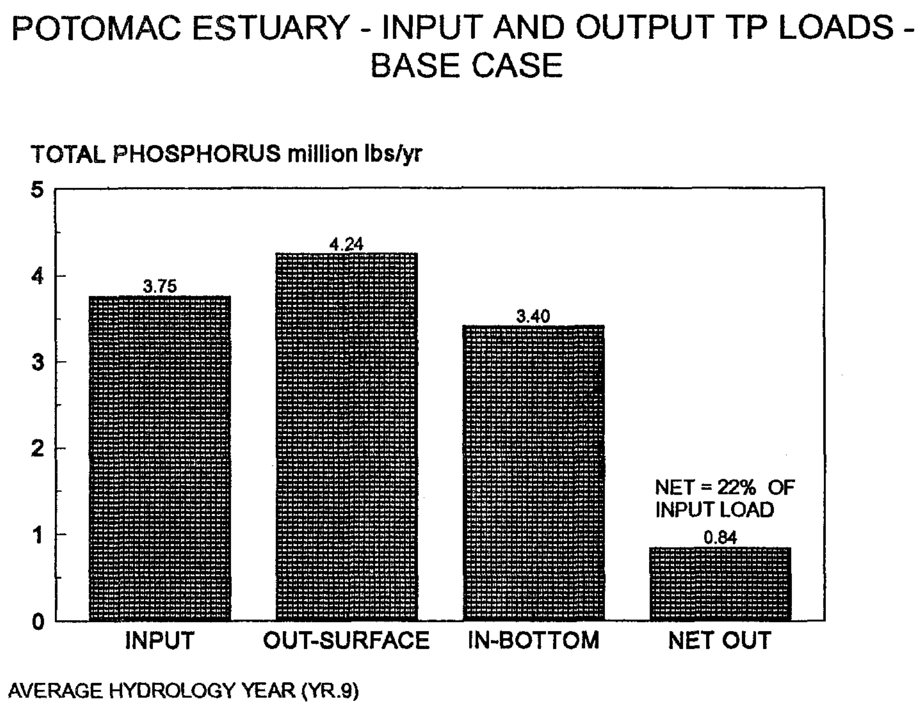


Figure VI -65. (Top) Input and output TN loads at James interface with Bay, Base case.(Bottom) Input and output TN loads at James interface, LOT.



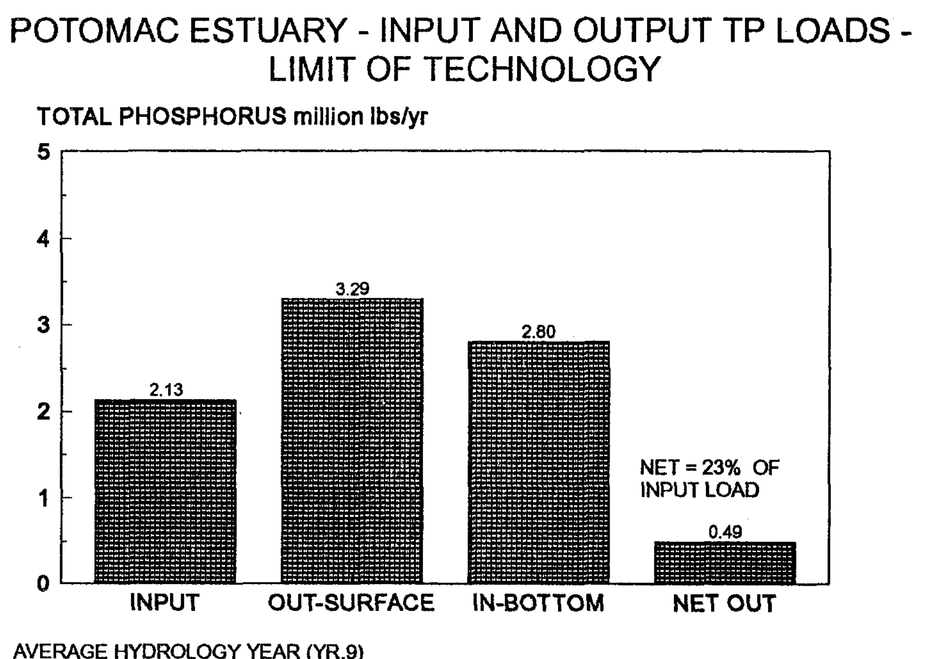
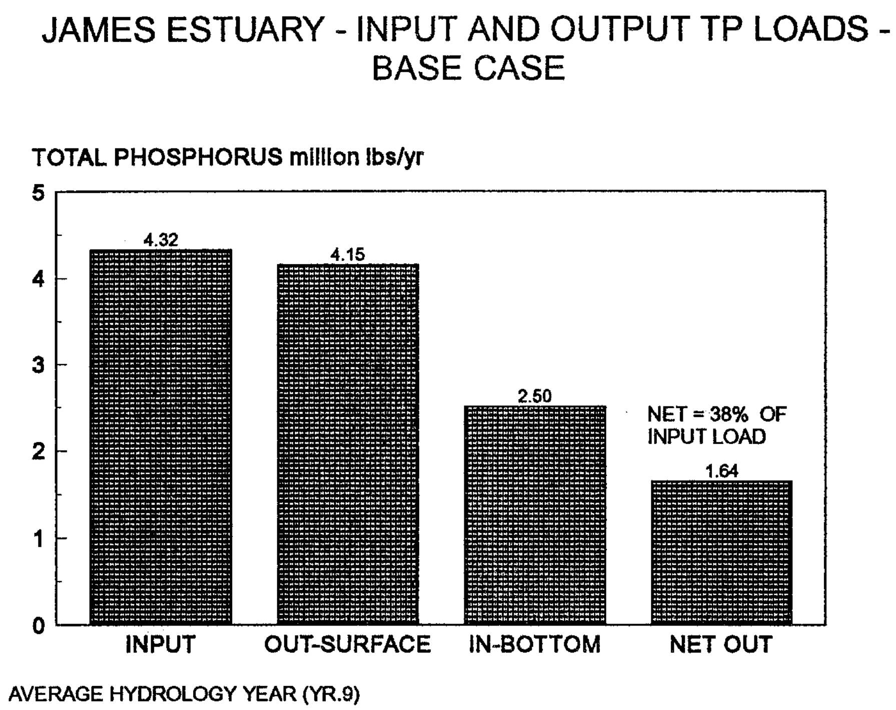


Figure VI -66. (Top) Input and output TP loads at Potomac interface with Bay, Base case.(Bottom) Input and output TP loads at Potomac interface, LOT.



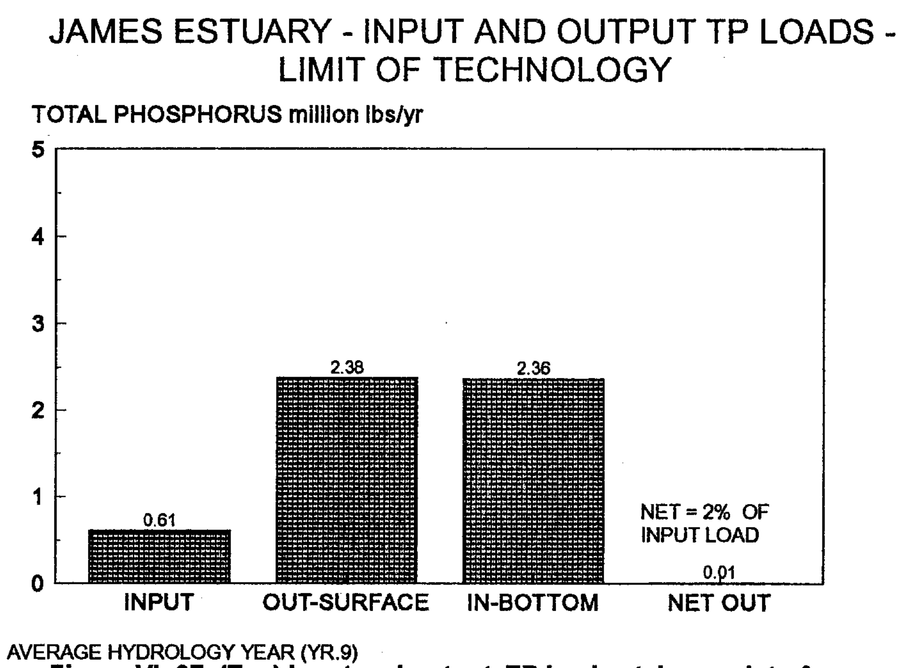
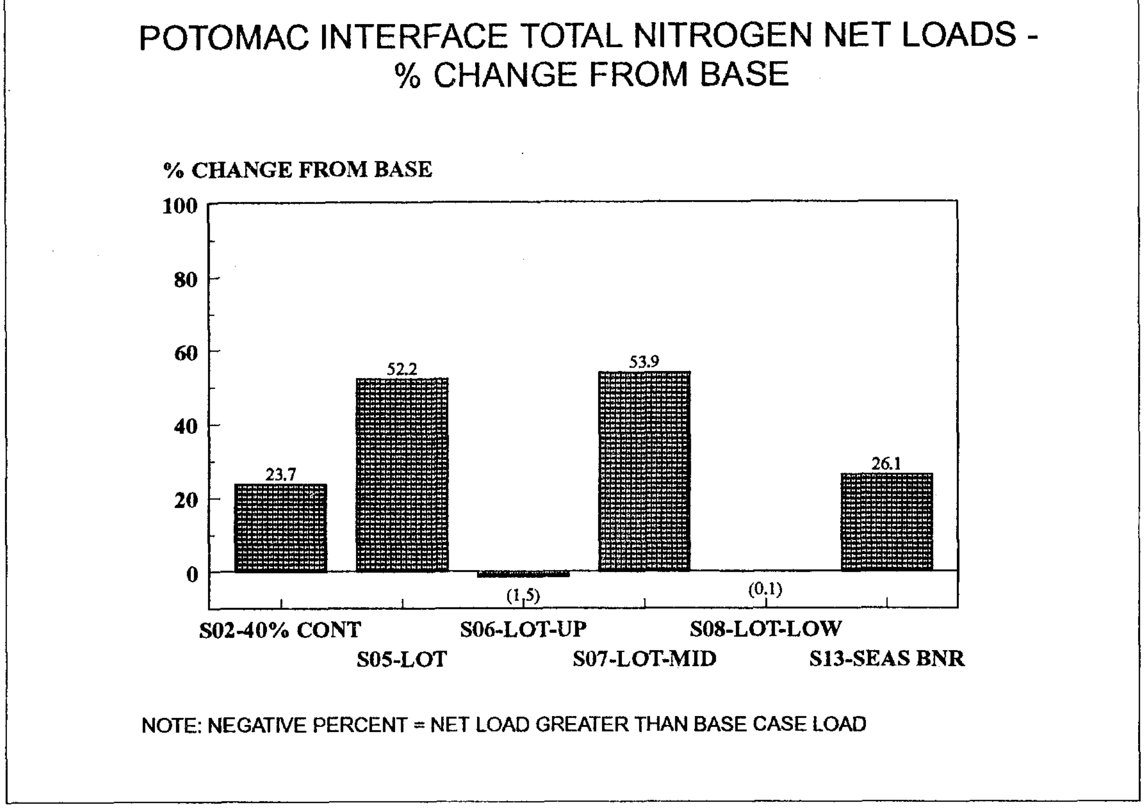


Figure VI -67. (Top) Input and output TP loads at James interface with Bay, Base case.(Bottom) Input and output TP loads at James interface, LOT.



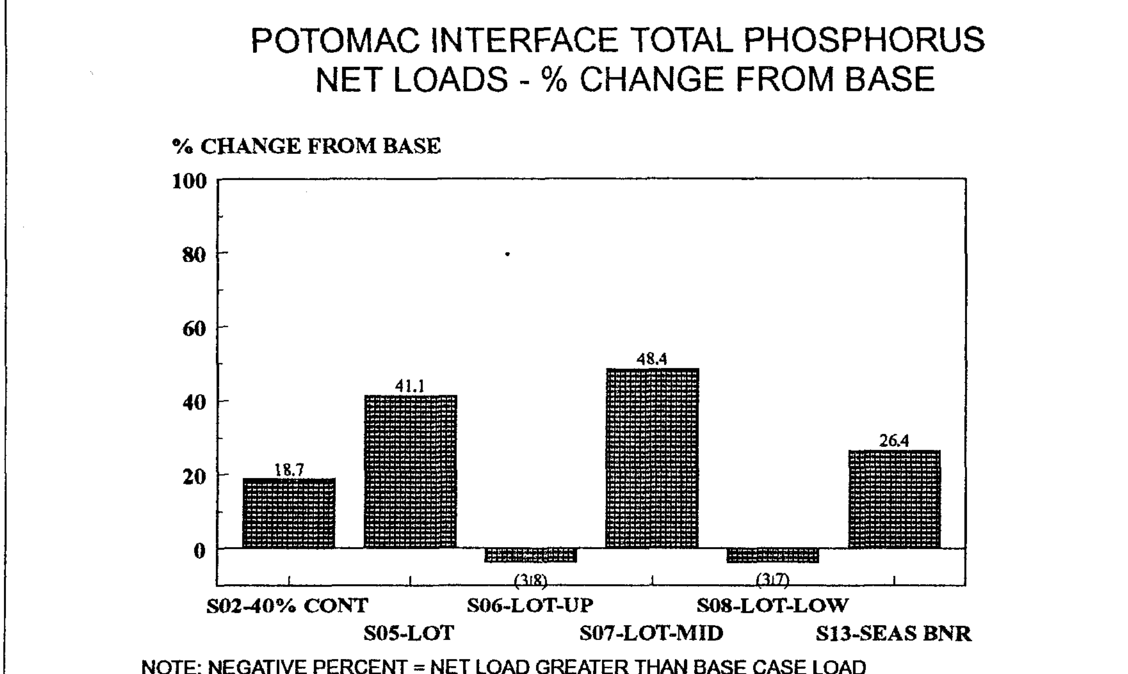
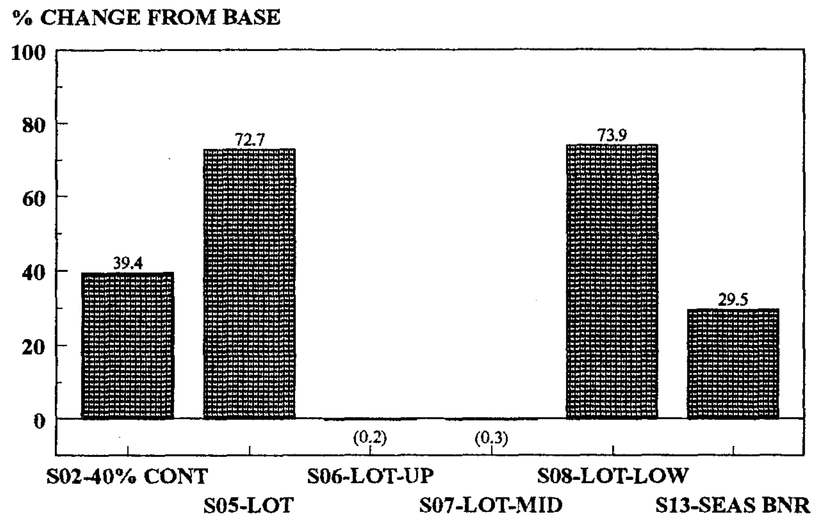


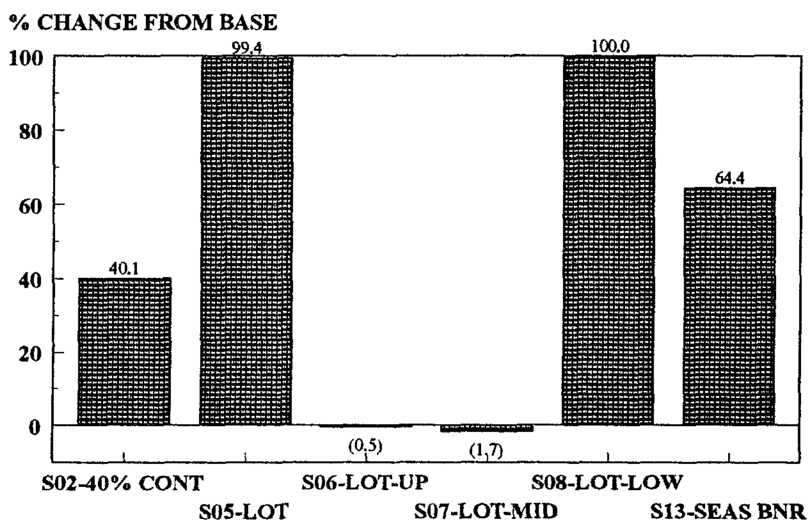
Figure VI -68. (Top) Percent change from Base case of net TN loads at Potomac interface with Bay. (Bottom) Percent change from Base of net TP loads at Potomac interface with Bay.

JAMES INTERFACE TOTAL NITROGEN NET LOADS - % CHANGE FROM BASE



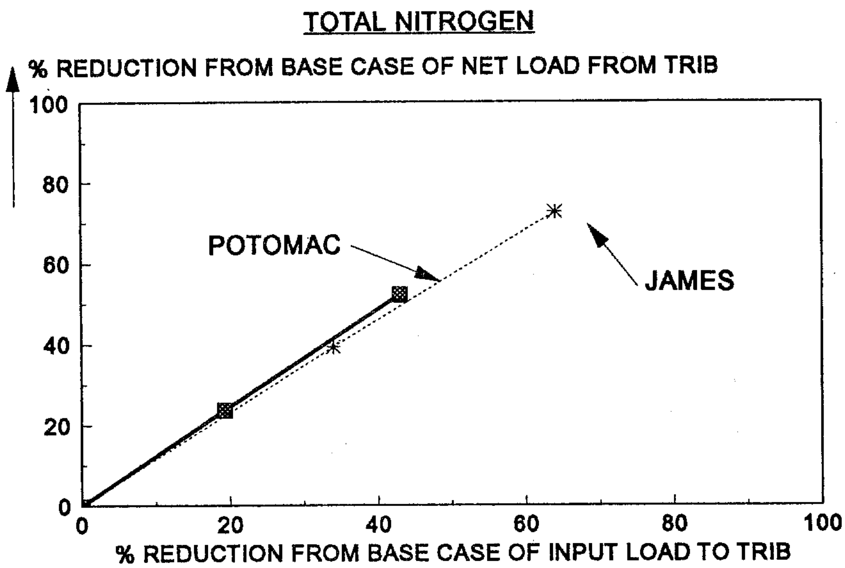
NOTE: NEGATIVE PERCENT = NET LOAD GREATER THAN BASE CASE LOAD

JAMES INTERFACE TOTAL PHOSPHORUS NET LOADS - % CHANGE FROM BASE



NOTE: NEGATIVE PERCENT = NET LOAD GREATER THAN BASE CASE LOAD

Figure VI -69. (Top) Percent change from Base case of net TN loads at James interface with Bay. (Bottom) Percent change from Base of net TP loads at James interface with Bay.



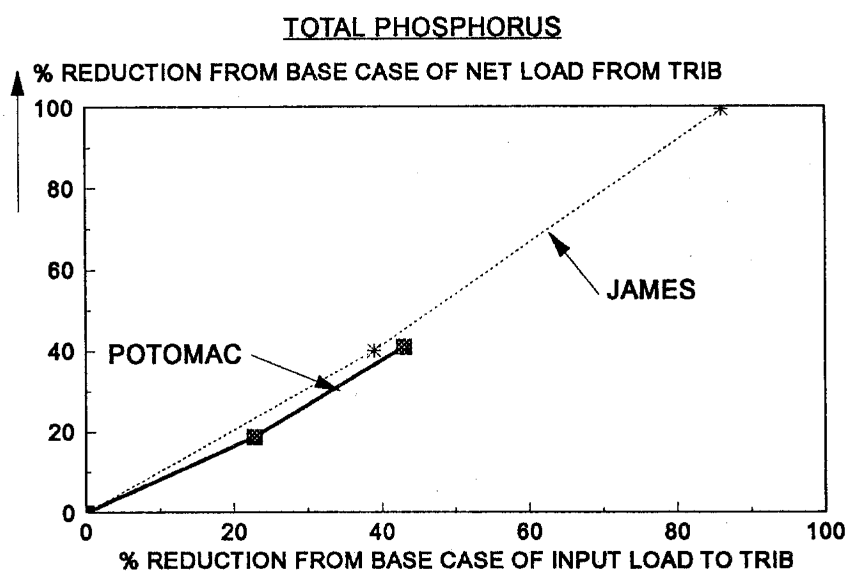


Figure VI -70. (Top) Relationship between % reduction of input load to tributary and net load exiting tributary to Bay for TN. (Bottom) Relationship between % reduction of input load to tributary and net load exiting tributary to Bay for TP.

2. All Major Tidal Tributaries

Figures VI-71 through VI-73 show the net flux of nitrogen for all of the major tidal tributaries. The most interesting point of these runs is that the Rappahannock and York rivers are calculated to receive input nitrogen load from the Bay as opposed to these tributaries providing a net input to the Bay. Indeed, under several removal programs (e.g., 40% Cont. and LOT N&P) the input net nitrogen load increases from the Bay to the tributary (see Figure VI-73). This is undoubtedly a result of a complex interaction of transport and nutrient concentration where the gradient from the Bay to these tributaries is increased under various removal programs. The relative magnitude of the net nitrogen loads by tributary can also be seen in Figure VI-71. For the Base case, the three largest inputs are the Patapsco/Back, Potomac and James estuaries. The Patuxent contributes a small input and as noted previously, the remaining two lower Bay tributaries receive a net input from the Bay.

Figures VI-74 and VI-75 show a similar behavior for the net phosphorus loadings from the tributaries. Again, the Rappahannock and York rivers are calculated to receive a net input of phosphorus from the Bay. The change in loading under different control scenarios is approximately similar to that of nitrogen.

G. DISCUSSION AND CONCLUSIONS

This section has reviewed the results of the scenarios from the point of view of the behavior of nitrogen, phosphorus, phytoplankton (and associated effect on light penetration), carbon and sediment oxygen demand. Particular attention was paid to the behavior of the phytoplankton production and resulting carbon fluxes as a result of reductions in nitrogen and phosphorus, either together or separately. The ability to examine the behavior of the Bay with the calibrated CBWQM under different removal levels of nutrients in combination is a particularly important use of the model. Such behavior is not directly observable in the Bay and can only be predicted by a credible model. The degree to which phosphorus and nitrogen load reductions have an impact on the water quality of the Bay is of course an important consideration in the decision making process.

In general, the Bay can be divided into three broad regions: the upper approximately 100 km of the Bay where control of phytoplankton growth and production is by phosphorus, the approximately 100 km of the lower Bay where the phytoplankton production is controlled by nitrogen and a middle Bay region of about 100 km where a transition takes place. The extent of nitrogen control proceeds up the estuary during the summer and fall and is a function of fresh water hydrology and resulting circulation. This general conclusion drawn for the Base case is consistent with interpretations of observations made on the Bay by a variety of investigators (see, e.g., Fisher et al., 1992).

What is not obvious from the existing data is that as phosphorus loadings to the Bay are reduced (with nitrogen loadings remaining at approximately Base levels), excess nitrogen is transported down the Bay in the surface waters. This transport of nitrogen then is calculated to stimulate phytoplankton production in this nitrogen limited region of the Bay. This "additional" relatively labile biomass then settles in the downstream region and contributes to higher SOD in that area.

Phosphorus removal however has a distinctly positive effect in the surface waters of the upper Bay where spring and summer phytoplankton biomass are reduced considerably more than if only nitrogen were removed. Such reductions of biomass of 20-30% have an impact on light penetration with a 20% increase in light calculated for the 2 m depth at LOT levels.

Reductions in nitrogen have of course a direct effect on phytoplankton production in the nitrogen limited areas and subsequently on the carbon fluxes and the SOD. In addition, the nitrogen load reductions result in improvement in meeting the DIN habitat requirements for the SAV.

It is concluded from the analyses in this Section, that load reductions of both phosphorus and nitrogen are necessary to result in reductions in the nutrients, phytoplankton biomass, (with increases in light penetration) and sediment oxygen demand. Phosphorus load reductions are most effective in achieving improvement in these measures of water quality in the upper Bay. Nitrogen removal is required throughout the Bay: in the upper Bay to reduce nitrogen loads that would be transported down Bay under the phosphorus reduction and in the middle and lower Bay to directly reduce biomass and hence SOD.

The impact of these reductions in phytoplankton carbon and SOD on the DO, especially of the deep bottom waters of the Bay trench is explored in the next Section.

The net input of nutrients from the principal tidal tributaries to the Bay is exclusively from the Patapsco/Back, Potomac and James estuaries. The Rappahannock and York estuaries are calculated to receive a net input of nitrogen and phosphorus from the Bay. For the Potomac and James estuaries, the net nutrient load exiting the tributary to the Bay is approximately linear to the external load of nutrient to the tributary.

VII. DISSOLVED OXYGEN RESPONSE

A. INTRODUCTION

The calculated response of the dissolved oxygen of the Bay assumes particular importance in analyzing the effects of scenario nutrient load reductions. The dissolved oxygen focus in this Section is twofold: (1) evaluation of the seasonal (specifically summer) average DO response, and (2) analysis of the response of the DO concentrations below 1 mg/L, the assigned level of anoxia. The latter quantity is determined by calculating the volumetric extent and temporal extent of DO below 1 mg/L. These "anoxic volume-days" have units of m^3 - days.

B. SEASONAL AVERAGE BASE CASE DISSOLVED OXYGEN

Figures VII -1 and VII - 2 show the model calculated spring and summer average longitudinal DO profile for the Base case loading condition and for the average hydrology flow year. The summer profile is the basis for comparison of assessing the effect of nutrient reduction scenarios. The rapid drop of the minimum bottom DO between the spring level of greater than 5 mg/L to the minimum summer average level of 0.1 mg/l can be noted. The steep increase in the bottom DO beyond the upper limit of the deep trench at approximately 260 km is due to a rapid decrease in depth. The marked vertical gradient in DO during the summer can also be seen where average surface DO is generally supersaturated due to algal productivity and the bottom DO is responding to deep water sinks of oxygen. The marked difference in the longitudinal profiles between the surface and pycnocline levels and the bottom level can also be noted. Some interpretation of the bottom DO is given in the next sub-section.

1. Analysis of Base Case Bottom DO

Examination of the bottom DO longitudinal summer profile indicates an approximate linear decrease in DO as one progresses up the Bay. A simple analysis of the behavior of the DO in the bottom waters can be made to help understand this behavior.

The principal sinks of oxygen in the bottom water are the sediment oxygen demand (SOD), the oxidation of the dissolved organic carbon (DOC) and the immediate uptake of oxygen to satisfy the chemical oxygen demand (COD) of reduced substances released from the sediment. Phytoplankton respiration is neglected since during the summer the bottom layer phytoplankton biomass is small. In the CBWQM, the sediment and water column are interactive and not separated. However, since the output from the sediment model is computed as equivalent SOD and COD, an analysis can be made considering these processes as external sinks of DO. The rates of utilization of oxygen in the model are oxygen dependent, but this complication is not considered here in this simple analysis. Also, vertical mixing of oxygen is not included which simplifies the analysis considerably. (See Kuo et al, 1991, for a more detailed analysis of bottom DO in the Rapphannock River which includes vertical exchange processes.)

For these assumptions, consider then the following equation for DO in bottom waters:

$$u\frac{dc}{dx} = \frac{dc}{dt^*} = -\frac{S}{H} - K_{DOC}a_{DOC}c_{DOC} - \frac{COD}{H}$$

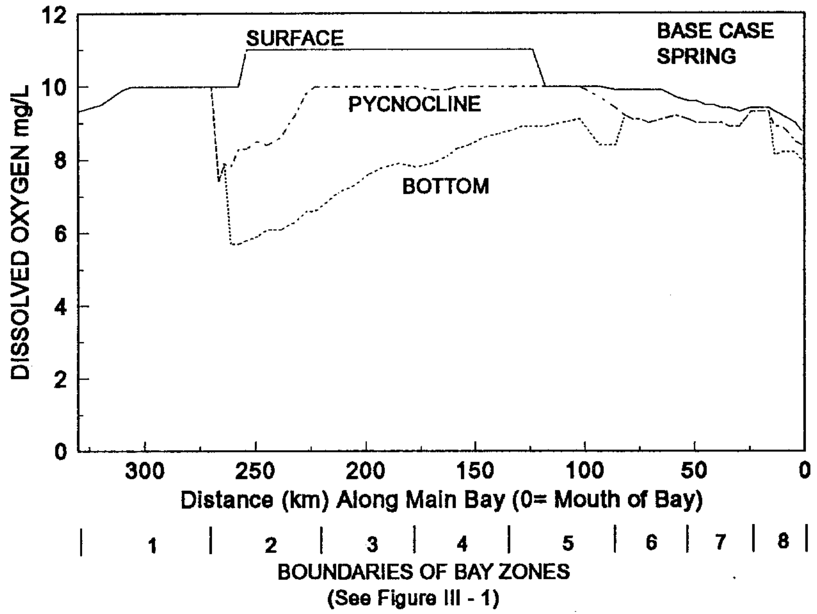


Figure VII - 1. Calculated longitudinal variation of DO for Base case averaged over SPRING for average year.

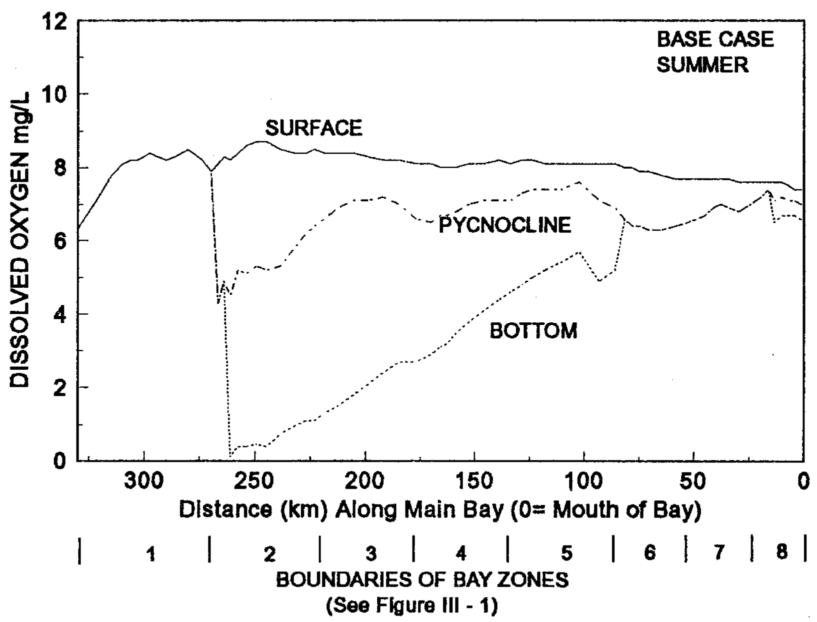


Figure VII - 2. Calculated longitudinal variation of DO for Base case averaged over SUMMER for average year.

where c is the DO (g/m^3), u is the average velocity of bottom waters (m/d), t* is the average time of travel (days) for x measured in the up Bay direction beginning from the Bay mouth, S is the SOD (g/m^2-d), H is the depth of the bottom mixed layer (m), K_{DOC} is the respiration rate of the dissolved organic carbon (1/d), a_{DOC} is the stoichiometric oxygen equivalent of the DOC (2.67 mg DO/mg carbon), c_{DOC} is the dissolved organic carbon concentration (g/m^3) and COD is the areal uptake of oxygen due to immediate chemical oxygen demand of reduced substances (g/m^2-d).

Notice that in this simplified form, the DO is a conservative variable (i.e., there are no kinetic terms for the state variable, only sources and sinks). The DO concentration is thus given by a linear equation as

$$c = c_o - \{S/H + K_{DOC}a_{DOC}c_{DOC} + COD/H\}t^*$$

for c_o as the initial bottom DO at t* = 0, i.e., at the approximate mouth of the Bay. Figure VII - 3 illustrates this behavior. Calculated values for the various sink terms can now be assigned to determine the relative magnitude of the impact of each process.

The average summer SOD over the distance from the mouth of the Bay to about 260 km is approximately 1.2 g/m^2-d (see Figure VI - 57). K_{DOC} is given as 0.01/d and c_{DOC} is about 2 mg/L (see Cerco and Cole, 1992). COD is calculated to occur only in the region from about 200-260 km at about 0.5 g/m^2-d. Using Table IV - 2, the travel time is about 13.6 days to 200 km and about 17.2 days to reach 260 km. For an assumed bottom depth of about 4m, the bottom DO is

$$\begin{aligned} c &= c_0 - \{(0.3 + 0.05)\,t^*\} && \text{for } 0 \le t^* \le 13.6 \\ &= c_o - \{(0.3 + 0.05)t^* + 0.12(t^*-13.6)\} && \text{for } 13.6 < t^* \le 17.2 \end{aligned}$$

The first equation includes the SOD and DOC oxidation while the second equation incorporates the COD in the remaining approximate 4 days of travel time. The first term in the braces is the SOD sink and the second term is the DOC sink. The SOD can be seen to be about an order of magnitude higher than the DOC effect. The COD effect is significant but only for a relatively short reach of the bottom waters.

At the head end of the trench after the approximately 17 days of total travel time, the total DO decline is then about 6.5 mg/L or for an initial bottom DO at the mouth of the Bay of about 7 mg/L, a DO of about 0. 5 mg/L is calculated. This is of course only an approximation but the decline in DO is approximately similar to that shown in Figure VII -2. But the analysis represents a general process of bottom water moving up the Bay, losing oxygen during the time of travel of the parcel (due principally to a constant withdrawal of oxygen to satisfy the SOS) and arriving at the head end of the trench at anoxic levels.

C. SUMMER AVERAGE DO RESPONSE FOR LOT AND 40% CONTROLLABLE SCENARIOS

Figure VII - 4 shows the calculated summer average DO for the LOT N&P scenario as representative of the upper bound of potentially feasible load reductions. As seen, the bottom DO is improved, but not to the point of raising the DO above anoxia (i.e., DO < 1 mg/L) on a

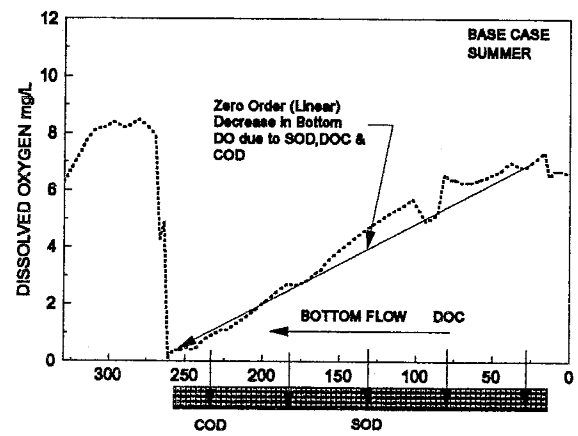


Figure VII - 3. Showing approximate zero order (linear) decrease in bottom DO, Base case, Summer, average year.

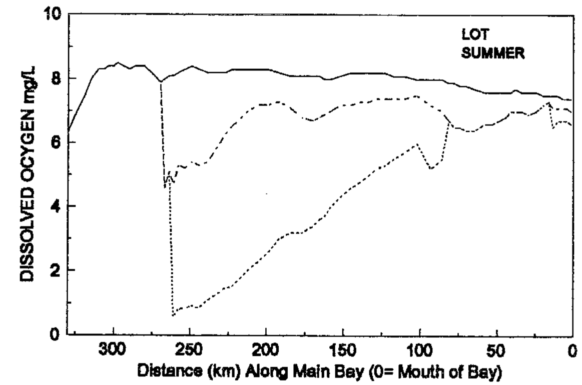


Figure VII - 4. Longitudinal variation of DO for LOT averaged over summer for average year.

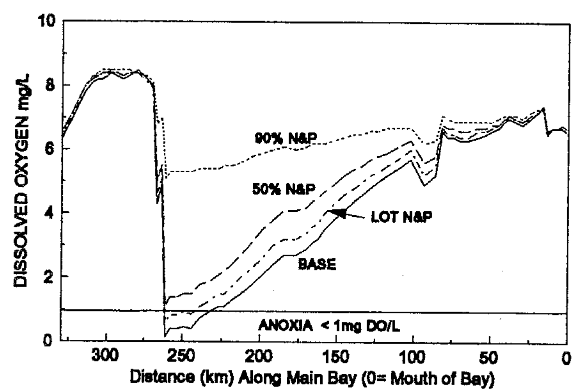


Figure VII - 5. Longitudinal variation of bottom DO for selected scenarios averaged over summer for average year.

summer average basis. Figure VII - 5 shows the summer average bottom DO profile for several scenarios. Only when the incoming loads are reduced by 50% is the summer average bottom DO calculated to be greater than 1.0 mg/L. It should of course be recognized that one of the DO objectives as summarized in Table I -1 is for DO concentrations to be greater than 1.0 mg/L at all times. It is of interest to note that a significant change in the slope of the bottom DO profile does not occur until beyond the 50% removal level and at 90% removal the change in slope is significant, reflecting the substantial reduction in oxygen sinks.

The differences in summer average DO between a given scenario and the Base case are shown in Figures VII -6 through VII - 9. For the LOT - Base case (Figure VII - 6), surface DO is decreased as would be expected from the reduction of phytoplankton biomass in that layer. The difference in bottom DO of about 0.4 mg/L is approximately constant over the distance from 75 km to 270 km indicating that the LOT has a linear slope approximately the same as the Base case. Comparing the LOT N Only and LOT P Only in the vicinity of km 270, there appears to be a beneficial additive effect of removing both nutrients. Removal of N and P alone results in a DO improvement in that vicinity of about 0.3 mg/L, but LOT N&P results in an improvement of another 0.1 mg/L. The 40% controllable scenario (Figure VII - 9) improves the bottom DO by about a constant 0.2 mg/L on a summer average basis which is about half of the LOT N&P scenario.

The LOT P Only case shows significantly less DO improvement than LOT N Only, indicating that phosphorus reductions do not have as significant an effect on the DO in bottom waters as do nitrogen reductions. This is a result of all of the previously discussed processes that are a consequence of phosphorus reductions, namely, the increased transport of nitrogen to down Bay regions resulting in a stimulation of biomass, resulting in an increase in carbon deposition to the sediment and subsequent increase in SOD. As shown by the simple analysis above, it is the SOD in the down Bay region that has more of an effect on trench DO that up Bay SOD. The net result of all these processes is that while phosphorus load reductions have a significant impact on up Bay biomass, the bottom DO is not affected as significantly as with nitrogen removal.

D. ANOXIC VOLUME DAYS RESPONSE

As noted above, a useful measure of the degree of anoxia is the total volume - days where the DO was calculated to be less than 1 mg/L. That is, model output is tracked on a cell by cell basis over time and a product sum is accumulated over zone, season and annually for each scenario. A complete listing of the anoxic volume days for all scenarios across season is given in the Appendix as Table A-3 and for anoxic volume days by zone across the year is given in the Appendix as Table A-4.

Figures VII -10 and VII -11 show the seasonal and zone totals, respectively for the Base case. As expected, maximum anoxia, as defined by the anoxic volume days occurs in the summer with about 16% occurring in the spring and fall. The longitudinal variation of the anoxia shown in Figure VII - 11 indicates peak regions in zones 2 and 3 where about 70% of the annual total occurs. An additional 24% occurs in Zones 4 and 9 (Eastern Shore).

The percent reductions in total annual anoxic volume days from the Base case for selected scenarios is shown in Figure VII - 12. Complete elimination occurs at 90% N&P removal

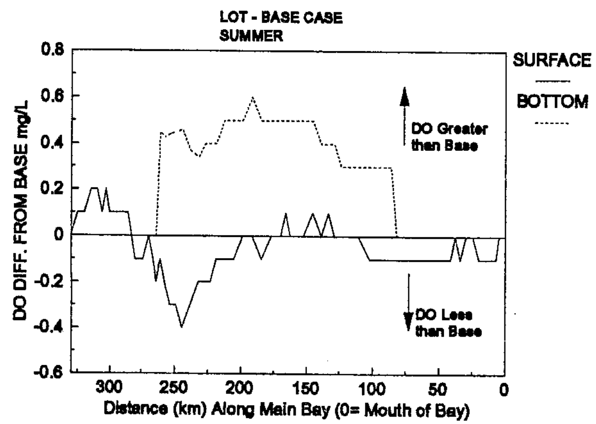


Figure VII - 6. Longitudinal variation of DO difference between LOT and Base case averaged over summer for average year.

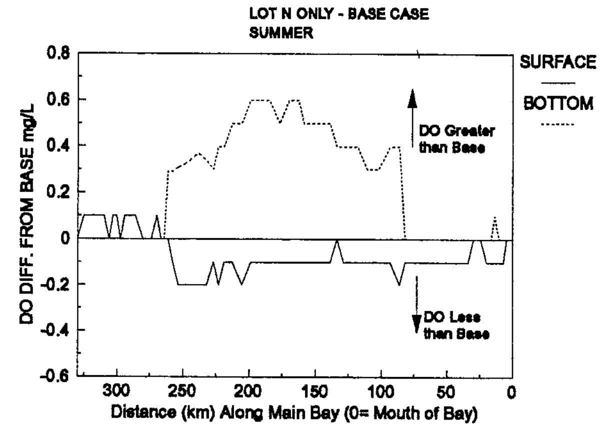


Figure VII - 7. Longitudinal variation of DO difference between LOT-N ONLY and Base case averaged over summer for average year.

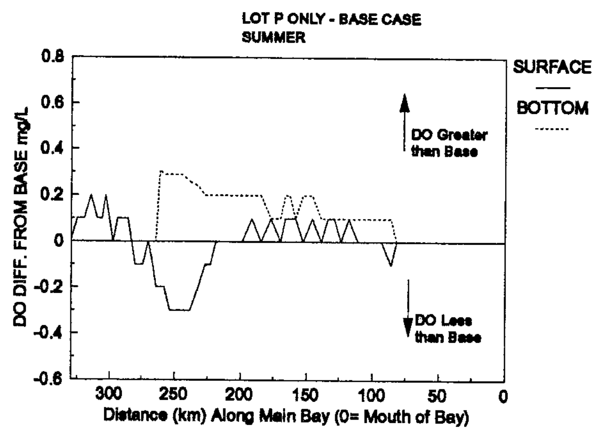


Figure VII - 8. Longitudinal variation of DO difference between LOT-P ONLY and Base case averaged over summer for average year.

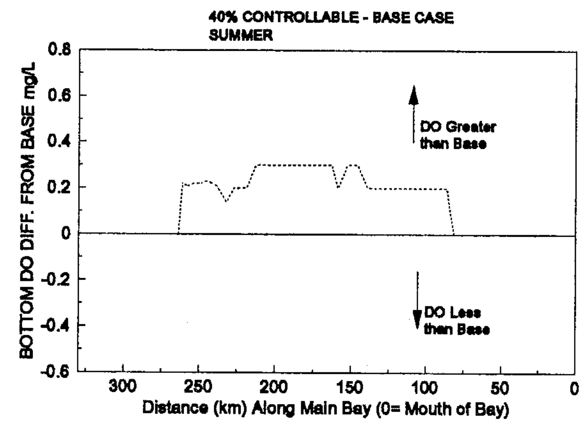


Figure VII - 9. Longitudinal variation of bottom DO difference between 40% Controllable scenario and Base case averaged over summer for average year.

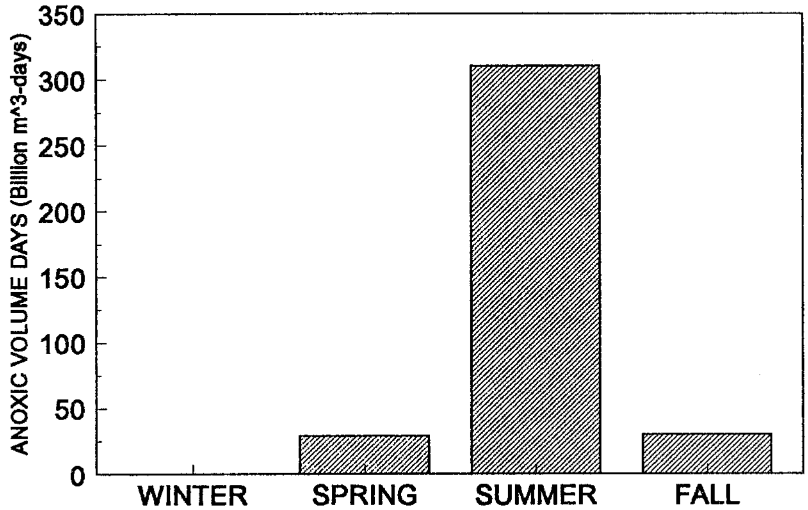


Figure VII - 10. Seasonal toals of anoxic volume days for Base case for average year.

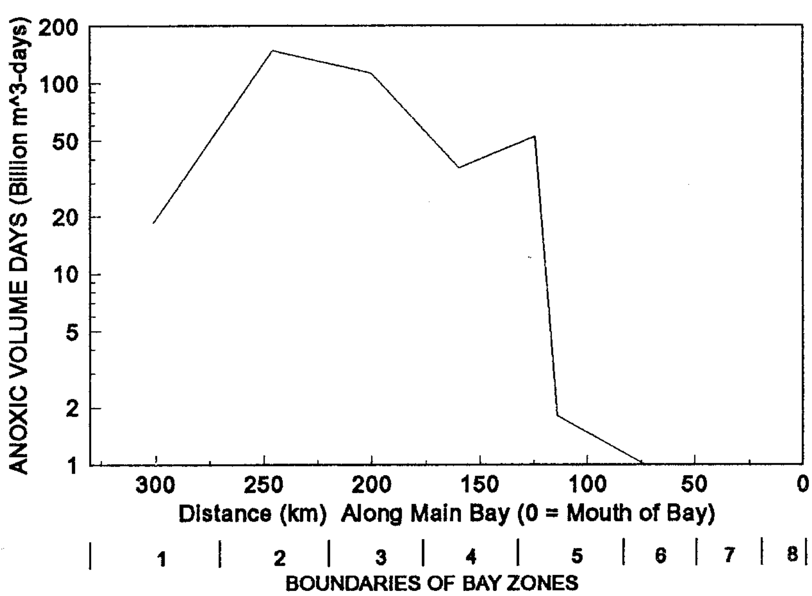


Figure VII - 11. Longitudinal variation of anoxic volume days for Base case total over zone for average year.

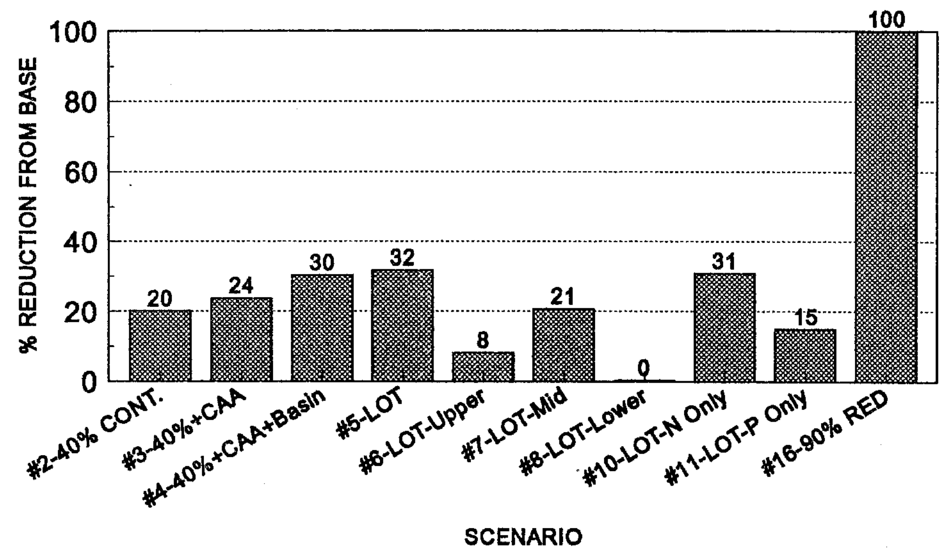


Figure VII- 12. Percent reductions in anoxic - volume - days from Base case for selected scenarios. Average Year

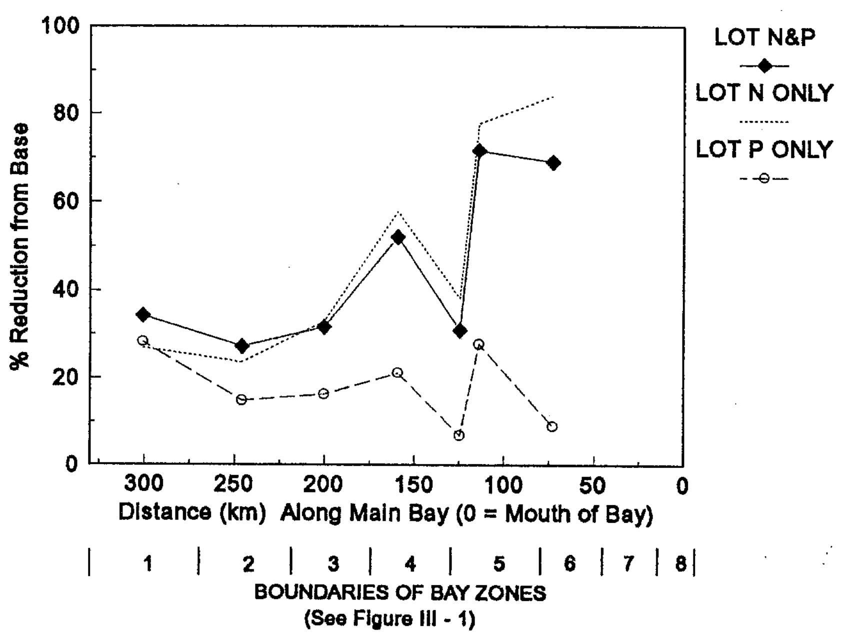


Figure VII - 13. Longitudinal variation of percent reduction from Base case of total anoxic volume days for average year, by zone .

(Scenario #16). The feasible range of anoxia reduction from 40% controllable to LOT is about 20-30%. Note that 40% controllable +CAA+Basin control (Scenario #4) approaches the improvement from LOT N&P (#5).

The relative impact of nitrogen and phosphorus is also seen by comparing #10 and #11 with #5. As noted above, LOT P Only has less of an impact on the bottom DO and as shown in Figure VII - 12, only a 15% improvement in anoxia is calculated which is half that from LOT N Only. The reasons for this difference have been hypothesized previously as being due primarily to increased nitrogen transport to down Bay nitrogen limited regions. The subsequent simulation of phytoplankton results in increased deposition of relatively labile carbon to the sediment in the down Bay areas. The resulting SOD is therefore elevated with a concomitant lessening of improvement in anoxia. However, it should also be noted that LOT N Only does have a greater reduction in primary production during the summer months in the mid to lower Bay regions (see Figures VI - 38 to VI - 40). Since maximum anoxia occurs during the summer, LOT N Only can be expected to also have a relatively larger impact on summer anoxia than LOT P Only.

In addition to this hypothesized effect, two other effects may also contribute to the reduced effect on anoxic volume-day response to the LOT - P Only scenario. As noted in Section VI, reduced phosphorus loading reduces primary production in the surface waters of the upper Bay. Such a reduction has the following two consequences:

(1) the reduced algal growth at the surface decreases surface water DO (see Figures VII - 6 through VII - 8) which in turn decreases the vertical concentration gradient thereby reducing the exchange of DO and replenishment of bottom DO in the upper Bay, and

(2) the reduced algal growth will not assimilate as much ammonium with the result that nitrification will increase in the surface waters, decreasing the DO and again decreasing the vertical transport of oxygen to bottom waters of the upper Bay.

It can also be noted that the location of where LOT load reductions are applied is also significant. Thus, comparing Scenarios #6,#7 and #8 indicates that maximum impact on bottom anoxia is from load reductions in the mid-Bay region. That is, as Figure VII - 12 indicates, there is a negligible percent reduction in anoxic volume days under Scenario #8 (LOT - Lower Bay) as compared to 8% for Scenario #6 (LOT - Upper Bay) and 21% for Scenario #7 (LOT - Middle Bay). The minimum impact on anoxia for LOT in the lower Bay only is apparently a consequence of (a) no net input of nutrients from the Rappahannock and York estuaries (but an input from the Bay into these tributaries, see Section VI, Figures VI - 71 to VI - 75), and (b) possible transport of nutrient input from the James out through the mouth of the Bay more than transport of nutrients up the Bay proper.

Figures VII - 13 and VII - 14 show the percent reduction of anoxia from Base as a function of zone annual totals. Caution should be exercised in interpreting these plots since a high percent reduction as in the lower Bay zones generally means a reduction from an already low value. Figure VII -13 indicates the relatively low percent reduction of the LOT P only case and as a result the improvement given for LOT N&P is almost all due to nitrogen reduction.

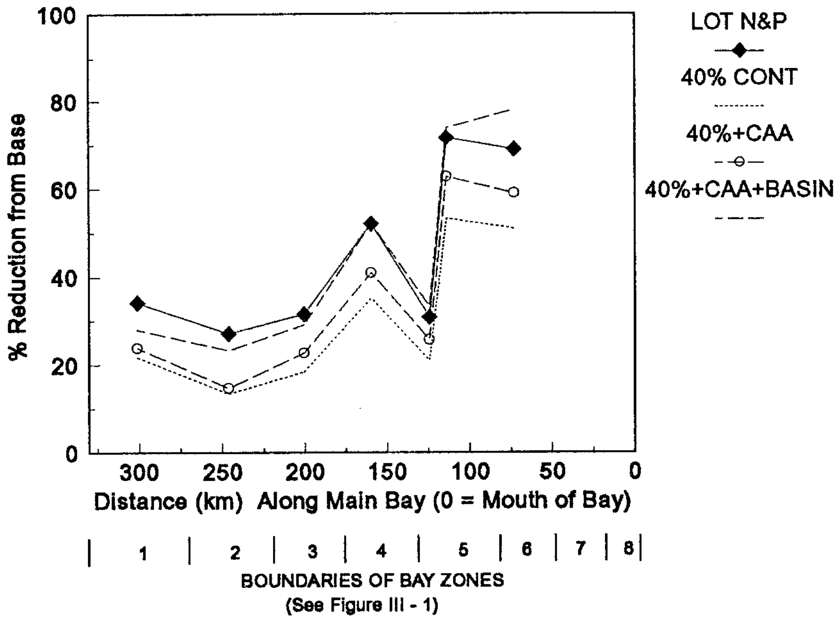


Figure VII - 14. Longitudinal variation of percent reduction from Base case of total anoxic volume days for average year, by zone .

E. ANOXIC VOLUME DAYS RESPONSE SURFACE ANALYSES

1. Whole Bay Response

The relationship between nitrogen and phosphorus loadings and the response in terms of anoxic volume days can be explored using the response surface analysis discussed in Section III. It has become apparent that the response of the DO to reductions in phosphorus, for example, is less than that from reductions in nitrogen. Response surface analysis of the anoxic volume days provides a quantitative means for relating load reduction to this overall measure of anoxia.

The response surface analysis for the anoxia goal indicates that there is a strong relationship between nitrogen reduction and improvement in anoxia and a lesser overall relationship between improvement in anoxia and phosphorus reduction. Figure VII - 15 shows the relationship between nutrient removal and the improvement in anoxia from the base case scenario for the whole Bay in an average year. Nutrient reduction is scaled from 0 to 1 with 0 being Base case nutrient removal and 1 indicating 100% removal, with analogous scaling for anoxia. The analysis indicates that 100% removal of phosphorus (with 0% removal of nitrogen) would fall well short of eliminating anoxia. A 90% reduction in nitrogen totally eliminates anoxia.

Broken down by season (Figure VII - 16), and recalling that the major contribution to the annual anoxia is during the summer (see Figure VII -10), it is clear that the whole Bay full year response is dominated by the whole Bay summer response. The two surfaces are quite similar, with a strong linear response to nitrogen removal and a much weaker response to phosphorus removal. Spring reduction approaches 100 % but the amount of anoxia during this season is small. Nitrogen is the controlling nutrient in these graphs, as evidenced by the slight improvement in anoxia achieved by relatively large reductions in phosphorus. However, in the spring, phosphorus reduction plays a greater role in the control of anoxia compared to other seasons.

2. Response by Zone and Season

Similar analyses can be made by regressing the responses in the different Bay zones on bay-wide nutrient reductions. Not all surfaces were represented equally well by the statistical analyses as discussed below. Representative responses are shown in Figures VII - 17 through VII - 18 which indicate surfaces for Zones 2 and 4. For Zone 2, summer, the insignificant role of phosphorus is clear. However, for Zone 4 (Figure VII - 18), phosphorus plays an increasing role in reducing anoxia. This was not apparent in earlier analyses since load reductions that were presented did not extend over the range of reductions shown in these surfaces (i.e., 0 - 50%). It should be remembered that Zone 4 accounts for only about 10% of the total anoxic volume days in the Bay.

The individual zones showed a somewhat greater response to phosphorus reduction than seen in the whole Bay surfaces. These details were obscured in the whole Bay analysis because they were overwhelmed by the profound summer anoxia in Zones 2 and 3.

As noted, some response surfaces are fit better than others. For example for Zone 1, the surface does not predict zero improvement in anoxia for zero reduction of N and P (i.e. there is a large residual for the base case datum). Generally the best fits are calculated for the zones with

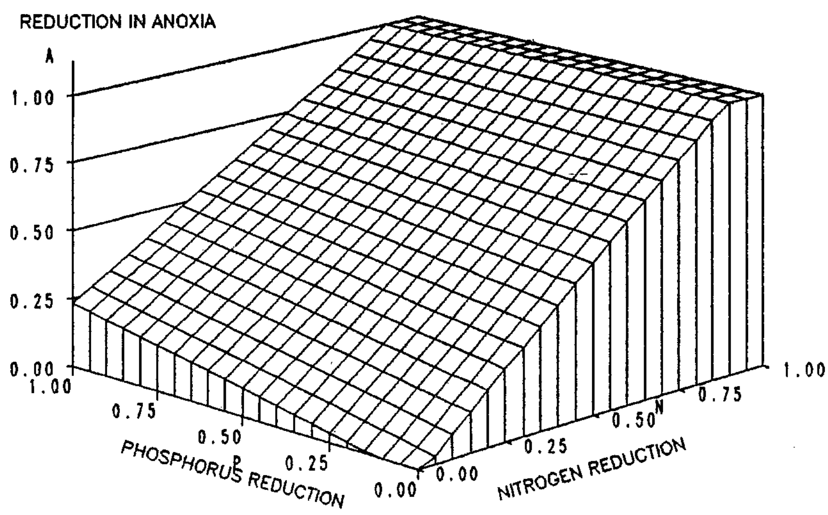


Figure VII - 15. Response surface of total anoxic volume days for average year.

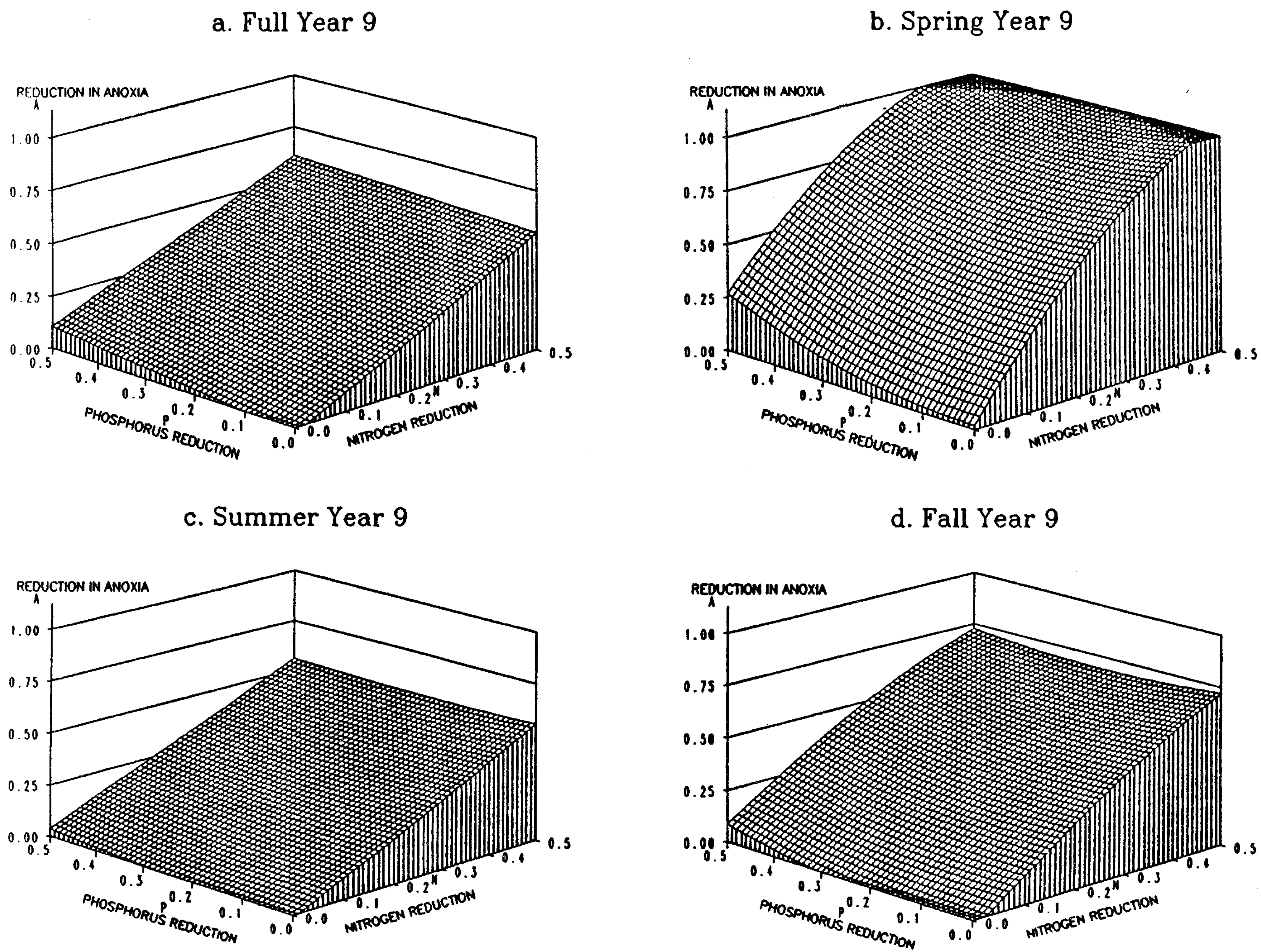


Figure VII - 16. Anoxic volume days response surface for whole Bay for full year and by season.

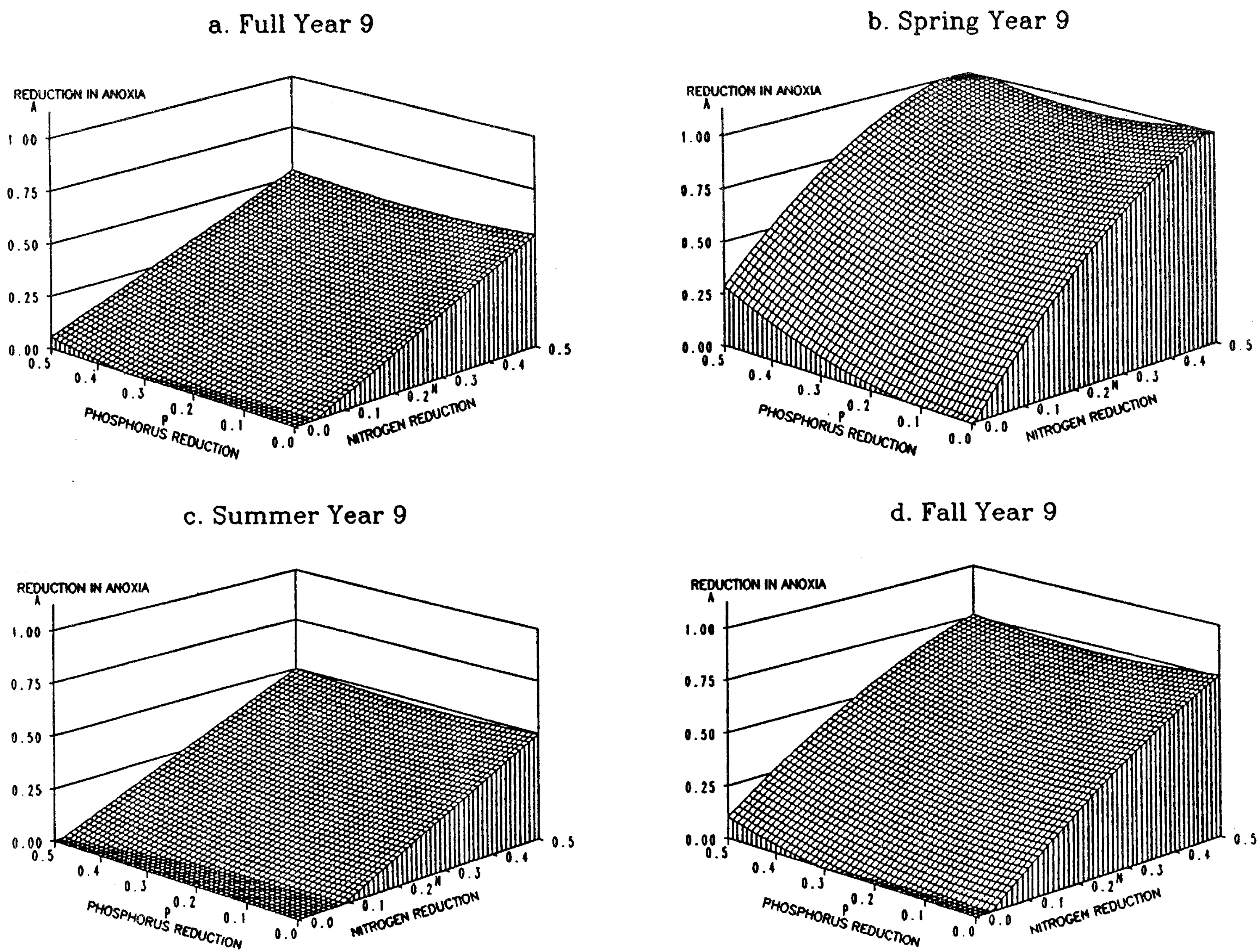


Figure VII - 17. Anoxic volume days response surface for Zone 2 for full year and by season.

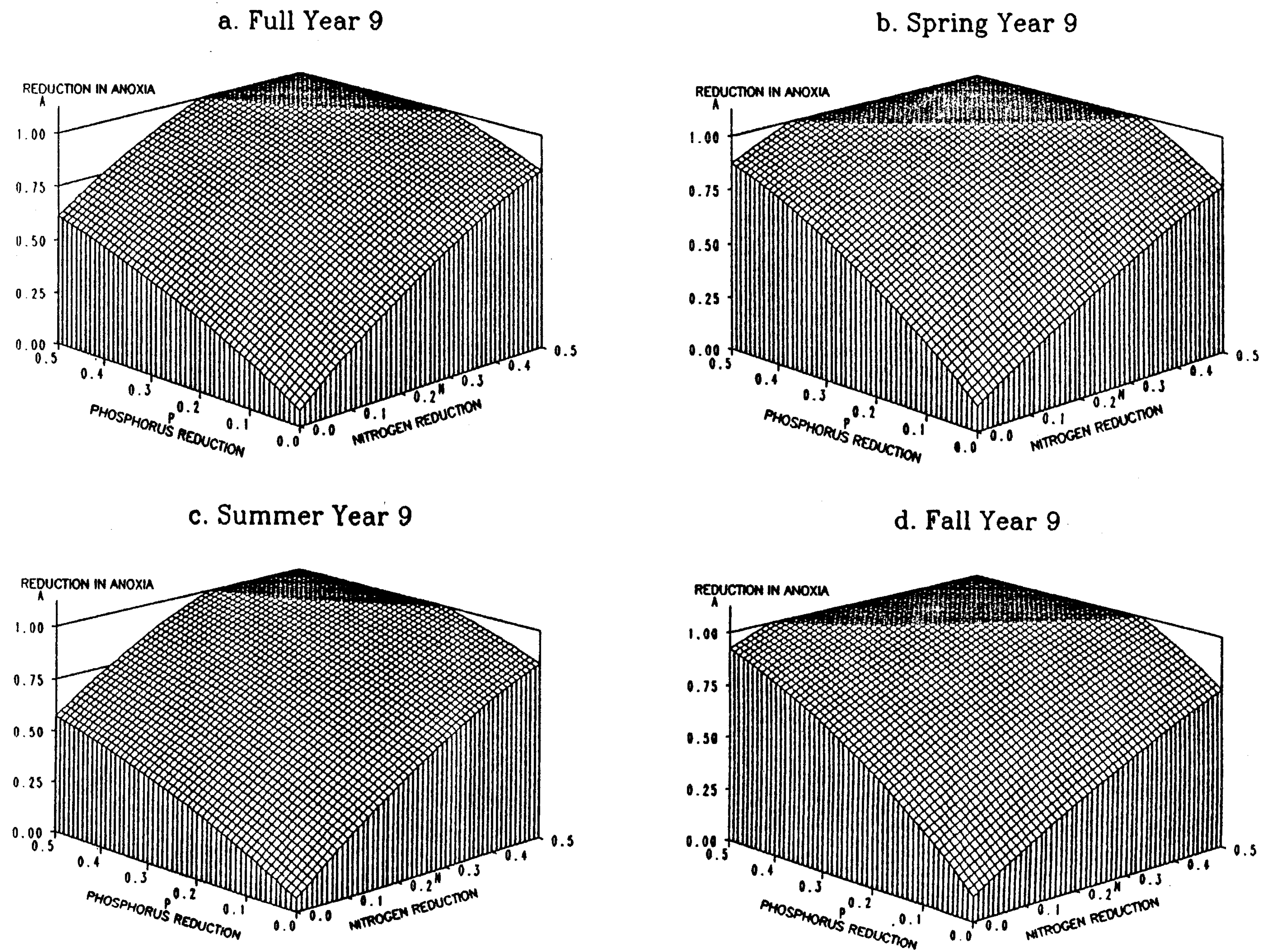


Figure VII - 18. Anoxic volume days response surface for Zone 4 for full year and by season.

strong anoxic events. Despite occasional weakness, the overall success of this procedure can be seen in Table VII - 1, which lists the coefficients of determination (r^2) for the surfaces shown in the preceding Figures. (A listing of the regression equations is given in Appendix B.) In general, most of the fits would be considered excellent, with small residuals and significant parameters resulting in the high r^2 values. Spring was the most difficult season to fit, consistent with the general pattern of strong regressions corresponding to strong anoxia. However, spring anoxic volume days is not a significant fraction of the annual total. Likewise all the regressions for Zone 4 were relatively less strong. However, even the weak regressions contain valid "general trend" information on the influence of N and P reductions on anoxia.

Table VII - 1
Coefficients of Determination (r^2) for Seasonal Response Surface

Region	Full Year	Spring	Summer	Fall
Whole Bay	0.9804	0.9895	0.9839	0.9816
Zone 1	0.9990	0.9486	0.9993	0.9991
Zone 2	0.9846	0.9895	0.9800	0.9676
Zone 3	0.9666	0.9269	0.9730	0.9415
Zone 4	0.9405	0.8776	0.9483	0.8686
Zone 5	0.9905	no anoxia	0.9905	no anoxia
Zone 6	0.9769	no anoxia	0.9769	no anoxia
Zones 7 & 8	no anoxia	no anoxia	no anoxia	no anoxia
Zone 9	0.9852	0.9169	0.9884	0.9983

F. CONCLUSIONS

The results presented in this Section indicate the following:

1. Bottom DO concentrations under Base case conditions reach minimum summer average levels of less than 1 mg/L. The approximate linear decline in oxygen with distance as one proceeds up the Bay in the direction of the bottom flows is a result of the distributed sink of oxygen occasioned principally by the sediment oxygen demand. As such, the minimum bottom DO at the head end of the trench reflects the accumulated DO depletion of a bottom water parcel since it entered the Bay. All SOD along the path of bottom water contributes to the DO depletion.

2. Feasible reductions in nutrient loadings of about 20 -30% N & P (i.e., LOT and "40% controllable" scenarios) result in improvement in bottom DO over Base by about 0.2 - 0.4 mg/L

as a summer average. Load reductions of about 50% or greater result in minimum summer average DO concentrations above 1 mg/L. 90% N & P reductions are calculated after the ten year simulation to result in average summer DO of greater than 5 mg/L.

3. A measure of anoxia as given by the volumetric and temporal extent of DO less than 1 mg/L (the anoxic volume days) is a maximum in the summer and in Zones 2-4 under Base case. The feasible load reduction scenarios result in a range of reduction in anoxic volume days of about 20 - 30% from Base. This reduction in anoxia is directly proportional to the load reduction of nitrogen of about 20-30%.

4. Response surface analysis of anoxic volume days on a Bay wide basis indicates a generally linear response in anoxia reduction as a function of nitrogen with little effect due to phosphorus reductions. The maximum effect of phosphorus is in Zone 4, a region that contributes a relatively smaller fraction to the Bay wide total anoxia.

5. Even though the upper Bay is phosphorus limited, reductions of phosphorus do not have as significant an effect on anoxic volume days as do nitrogen reductions. The reasons for this response are complex . Phosphorus controls primary production in the winter and spring while nitrogen controls primary production in the summer, the period of maximum anoxia. Also, when only phosphorus is removed there is a calculated increased nitrogen transport to down Bay nitrogen limited regions which increased downstream SOD. This effect is apparently coupled with reduced primary production in the surface waters of the upper Bay resulting in a reduced vertical DO gradient and less oxygen transferred to the bottom waters of the upper Bay.

6. The location of where LOT load reductions are applied is also significant. Thus, the scenarios where LOT reduction were selectively applied by Bay regions (Upper, Mid and Lower) indicate that maximum impact on bottom anoxia is from load reductions in the mid-Bay region. A negligible percent reduction in anoxic volume days is calculated for LOT in the Lower Bay only as compared to 8% for LOT for the Upper Bay and 21% for LOT in the Middle Bay. The minimum impact on anoxia for LOT in the lower Bay only is apparently a consequence of (a) no annual net input of nutrients from the Rappahannock and York estuaries (but rather an input from the Bay into these tributaries) and (b) possible transport of nutrient input from the James out through the mouth of the Bay more than transport of nutrients up the Bay proper.

VIII. REFERENCES

Batuik, R., R. Orth, K. Moore, W. Dennison, C. Stevenson. L. Straver, V. Carter, N. Rybicki, W. Hickman, S.Kollar, and S. Bieber. 1992. Chesapeake Bay submerged aquatic vegetation habitat requirements and restoration targets: A technical synthesis. CBP/TRS 83/92, Annapolis, MD.

Blumberg, Af., B.H. Johnson, R.H. Heath, B.B. Hsieh, V.R. Pankow, K.W. Kim and H.L. Butler, 1991. Data employed in the development of a three-dimensional, time-varying numerical hydrodynamic model of Chesapeake Bay. Tec. Rept. HL-91-1, Waterways Exp. Sta., Corps of Eng., Visksburg, Miss., prepared for US army Eng. District, Baltimore, MD, 180 pp.

Cerco, C.F. and T. Cole, 1992. Application of the three-dimensional eutrophication model CE-QUAL-ICM to Chesapeake Bay. Draft Report, XIV Sections.

Chesapeake Bay Program, 1993. Chesapeake Bay living resources habitat-based water quality restoration priorities. Draft report prepared for CBP, 29 pp + Figs.

Dennison, W. C., Orth, R. J., Moore, K. A., Stevenson, J. C., Carter, V., Kollar, S., Bergstrom, P. W., & Batuik, R. A. (1993). Assessing water quality with submersed aquatic vegetation. BioScience, 43(2), 86-94.

Di Toro, D.M. and J.F. Fitzpatrick, 1993. Chesapeake Bay sediment flux model. Prepared by HydroQual, Inc. for U.S. Env. Pro. Agency, Ches. Bay Prog. Office and U.S. Army Engineer District, Baltimore, MD. Monitored by Environ. Lab. U.S. Army Eng. Waterways Exper. Sta., Vicksburg, MS. Contract Report EL-93-2, 200 pp.

Donigian, A.S., Jr., B.R. Bicknell, A.S. Patwardhan, L.C. Linker, D.Y. Alegre, C-H. Chang, R. Reynolds, 1991. Watershed model application to calculate Bay nutrient loadings. Final findings and recommendations. Aqua Terra Conslutants, Comp. Sci. Corp.Chesapeake Bay Program Office, USEPA, Annapolis Md. 283 pp.

Dortch, M.S., 1990. Three-dimensional \, Lagrangian residual transport computed from an intratidal hydrodynamic model. Tech. Report EL-90-11,Waterways Exp.Sta., Corps of Eng., Vicksburg, Miss., prepared for US Army Eng. Dist. Baltimore, MD, 264 pp.

Fisher, T.R., E.R. Peele, J.W. Ammerman, and L.W. Harding, Jr., 1992. Nutrient limiation of phytoplankton in Chesapeake Bay. Mar. ECol. Prog. Ser. 82:51-63.

Funderbuck, S.L., S.J. Jordan, J.A. Mihursky and D. Riley. 1991. Habitat requirements for Chesapeake Bay living resources. Prepared for Living Resources Subcommittee, Chespaeake Bay Program, Annapolis MD. 2nd Edition, 23 Chapters + App.

Illinois Env. Pro. Agency, 1983. Soil erosion and sediment transport. Dynamics on the Blue Creek watershed. IEPA/WPC/83-004, Springfiled, IL.

Johnson, B.H., R.E. Heath, B.B. Hsieh, K.W. Kim and H.L. Butler, 1991. User's guide for a three-dimensional numerical hydrodynamic, salinity, and temperature model of Chesapeake Bay. Tech. Rept. HL-91-20. Waterways Exp. Sta. Corps of Eng., Vicksburg, Miss., prepared for US Army Eng. District, Baltimore, MD, 41 pp + Append.

Johnson, B.H., K.W. Kim, R.E. Heath and H.L. Butler, 1991. Verification of a three-dimensional numerical hydrodynamic model of Chesapeake Bay. Tech. Rept. HL-91-7.Waterways Exp. Sta. Corps of Eng., Vicksburg, Miss., prepared for US Army Eng. District, Baltimore, MD.

Jordan, S., M. Olson, C. Stenger, K. Mountford, and R. Batuik. 1992. Chesapeake Bay dissovled oxygen goral for restpration of living resources habitats. CBP/TRS/88/92. Annapolis, MD.

Kuo, A.Y., Park, K. and Moustafa, M.Z., 1991. Spatial and temporal variabilities of hypoxia in the Rappahannock River, Virginia. Estuaries, 14, 113-121.

Nutrient Reevaluation Workgroup, 1992. Progress report of the Baywide nutrient reduction reevaluation. Printed by USEPA for the Chesapeake Bay Program, Annapolis, MD, 68 pp.

Walling, D.E., 1983. The sediment delivery problem. J. of Hydrology, 65:209-237.

APPENDIX A

SCENARIO DESCRIPTIONS

TABLE A - 1 SUMMARY OF SCENARIO NITROGEN AND PHOSPHORUS LOADINGS

TABLE A - 2 STEADY STATE RESPONSE MATRICES FOR TRACER RUNS

TABLE A - 3 ANOXIC VOLUME DAYS - SEASONAL AND ANNUAL TOTALS

TABLE A - 4 ANOXIC VOLUME DAYS - ZONE ANNUAL TOTALS

APPENDIX A.
SCENARIO DESCRIPTIONS

SCENARIO 1
Base Case scenarios where 1985 loads from Bay Agreement States with nitrogen and phosphorus ocean boundary conditions computed based on mass balance outside the Bay mouth. The scenario is run with Water Quality Model (WQM) calibration optimized to the Phase II Watershed Model (WSM) loads. Atmospheric loads are to the water surfaces only throughout the Bay, its tributaries and the river reaches in the Bay Agreement States.

SCENARIO 2
"40%" Reduction of controllable carbon, nitrogen and phosphorus loads to Bay from Bay Agreement States only (i.e., does not include NY, WV, & DE). The controllable portion of the Base Case was determined by subtracting the load generated by a 3 State all forested watershed with no point sources from the Base case. Ocean boundary conditions were computed by mass balance.

SCENARIO 3
40% + CAA for Bay Agreement States Only simulates a forty-percent reduction of controllable carbon, nitrogen, and phosphorus loads to the Bay from the Bay Agreement states, combined with implementation of the 1990 Clean Air Act (CAA). Nitrate (CAA) load reductions were performed individually for each watershed and for each year according to guidelines provided by the Chesapeake Bay Program Office on May 8, 1992. Atmospheric nitrate loads to the water surface were reduced fourteen percent. The net result was roughly an additional three percent (3%) nitrogen load reduction.

SCENARIO 4
40% + CAA for Bay Basin run simulates a forty-percent reduction of controllable carbon, nitrogen, and phosphorus loads to the Bay from the entire Bay watershed including Delaware, New York, and West Virginia, combined with implementation of the 1990 Clean Air Act (CAA). This differs from Scenario 3 in which controllable loads were reduced in the Bay Agreement states only. Nitrate (CAA) load reductions were performed individually for each watershed and for each year according to guidelines provided by the Chesapeake Bay Program Office on May 8, 1992. Atmospheric nitrate loads to the water surface were reduced fourteen percent. The net result was roughly an additional three percent (3%) nitrogen load reduction.

SCENARIO 5
Limit of Technology (LOT) run for Bay Agreement States only and atmospheric loads consistent with Base Case Scenario. Ocean boundary conditions were computed by mass balance.

SCENARIO 6
LOT Upper Bay run is where Limit of Technology nutrient controls were implemented in the oligohaline region of the Bay. LOT point source nitrogen and phosphorus controls were implemented, along with the most comprehensive best management practices for NPS controls in the entire Susquehanna River basin and in the below fall line basins denoted "Coastal 11" to just above Back River. Atmospheric loads were consistent with Base Case Scenario and ocean boundary conditions were computed by mass balance.

SCENARIO 7
LOT Middle Bay run is where Limit of Technology nutrient controls were implemented in the mesohaline region of the Bay. LOT point source nitrogen and phosphorus controls were implemented, along with the most comprehensive best management practices for NPS controls in the middle Bay region (Patapsco and Back, Patuxent, and Potomac River basins). Atmospheric loads were consistent with Base Case Scenario and ocean boundary conditions were computed by mass balance.

SCENARIO 8

LOT Lower Bay run is where Limit of Technology nutrient controls were implemented in the polyhaline region of the Bay. LOT point source nitrogen and phosphorus controls were implemented, along with the most comprehensive best management practices for NPS controls in the lower Bay region (Rappahannock, York, and James River basins). Atmospheric loads were consistent with Base Case Scenario and ocean boundary conditions were computed by mass balance.

SCENARIO 9

LOT - MID (A) This run investigates the Bays response to Limit of Technology N and P controls from Back River to just above Potomac River; however, unlike Scenario 7, fall line and below fall line PS and NPS loads within the Potomac River and basin were left at Base Case levels.

SCENARIO 10

LOT Nitrogen Only run is where LOT nitrogen controls were implemented throughout Watershed Model and LOT nitrogen limits were specified at all point sources (3.0 mg/l). Point source phosphorus was left at Base Case. Although scenario 10 has the same N & P overall removal rate, this run differs from Scenario #19 where there was a 31% N and 18% P removal uniformly applied to all tributaries. Atmospheric loads were consistent with Base Case Scenario and ocean boundary conditions were computed by mass balance.

SCENARIO 11

LOT Phosphorus Only run is where LOT phosphorus controls were implemented throughout the Watershed Model and LOT phosphorus limits were specified at all point sources (0.075 mg/l). Point source nitrogen was left at Base Case. Although Scenario 11 has the same N & P overall removal rate, this run differs from Scenario #20 where there was a 10% N and 49% P removal uniformly applied to all tributaries. Atmospheric loads were consistent with Base Case Scenario and ocean boundary conditions were computed by mass balance.

SCENARIO 12

65% Limit of Technology 65% Limit of Technology with Clean Air Act run was made using a load reduction from the Base Case equivalent to 65% of the difference between limit of technology loads and Base Case loads. Additionally, segment dependent reductions in atmospheric loads of nitrate over the land surface and non-tidal portion of the water surface in the watershed were applied.

SCENARIO 13

Allocation 2 - Seasonal BNR This scenario consists of NPS loads at limit of technology and point sources loads at three-stage biological nutrient removal (BNR) for the months of May through November. The average effluent value for TN is 8.0 mg/l from May to November, and at base case effluent loads for the remaining five months. The average effluent value for TP is 1.5 mg/l for the entire year.

SCENARIO 14

Allocation 3 This run investigates regional control strategies similar to previously run Scenarios 6 to 8. Loads to Geo-region 1, from Conowingo to Back River, were reduced 73% of the of the difference between Base Case and LOT loads. Loads to Geo-region 3, Potomac to mouth, were set at the 40% reduction level with clean air act. Atmospheric nitrogen loads were reduced 10%.

SCENARIO 15

50% Nitrogen and Phosphorus Reduction reduces above and below fall line loads of carbon, nitrogen and phosphorus to the Bay by 50% each.

SCENARIO 16

90% Load Reductions of 1985 carbon, nitrogen and phosphorus loads to the Bay. Atmospheric loads to all water surface are eliminated. Ocean boundary conditions were computed by mass balance.

SCENARIO 17

90% Nitrogen Reduction reduces existing nitrogen loads to the Bay including atmospheric deposition to the water surface. Phosphorus and carbon loads are left at Base Case as were the nitrogen boundary conditions at the ocean mouth.

SCENARIO 18

90% Phosphorus Reduction reduces existing phosphorus loads to the Bay including atmospheric deposition to the water surface. Nitrogen and carbon loads are left at Base Case as were the phosphorus boundary conditions at the ocean mouth.

SCENARIO 19

31% N - 18% P Load Reduction Run where Base Case nitrogen loads to the Bay are reduced 31% while phosphorus loads are reduced 18% for Bay Agreement States only. Atmospheric loads were consistent with Base Case Scenario and ocean boundary conditions were computed by mass balance.

SCENARIO 20

10% N _ 49% P Load Reduction Run where Base Case nitrogen loads to the Bay are reduced 10% while phosphorus loads are reduced 49% for Bay Agreement States only. Atmospheric loads were consistent with Base Case Scenario and ocean boundary conditions were computed by mass balance.

Tracer Runs These runs trace the transport of dissolved and particulate substances in the Bay. It includes transport in the nine Bay zones and four of the Bay's major tributaries (Susquehanna, Patapsco-Back, Potomac, and James) in addition to the ocean.

TABLE A - 1
SUMMARY OF SCENARIO NITROGEN AND PHOSPHORUS LOADINGS
(ALL LOADINGS IN KG/DAY)

Note: Scenarios are listed in the order in which each was calculated. See Table II - 2 for description of scenarios.

NITROGEN | **PHOSPHORUS**

#1 - BASE					BASE				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line	360,463	166,182	220,823	226,895	Fall Line	25,792.	11,584.	13,050.	15,012.
Below Fall Line	109,824	53,971.	53,208.	64,836.	Below Fall Line	6,386.	5,142.	3,779.	4,846.
Point Source	86,357.	86,357.	86,357.	86,357.	Point Source	7,359.	7,359.	7,359.	7,359.
Atmosphere	43,025.	43,025.	43,025.	43,025.	Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	599,669	349,535	403,413	421,113	Total	41,360.	25,908.	26,011.	29,040.
#16									
90% RED					90% RED				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line	36,046.	16,618.	22,082.	22,689.	Fall Line	2,579.	1,158.	1,305.	1,501.
Below Fall Line	10,982.	5,397.	5,321.	6,484.	Below Fall Line	639	514	378	485
Point Source	8,636.	8,636.	8,636.	8,636.	Point Source	736	736	736	736
Atmosphere	0	0	0	0	Atmosphere	0	0	0	0
Total	55,664.	30,651.	36,039.	37,809.	Total	3,954.	2,408.	2,419.	2,722.
#2									
40% Controllable					40% Controllable				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line	303,387	143,701	194,429	195,929	Fall Line	18,483.	8,288.	9,215.	10,698.
Below Fall Line	81,477.	41,704.	40,983.	49,370.	Below Fall Line	4,131.	3,190.	2,452.	3,083.
Point Source	51,814.	51,814.	51,814.	51,814.	Point Source	4,416.	4,416.	4,416.	4,416.
Atmosphere	43,025.	43,025.	43,025.	43,025.	Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	479,703	280,244	330,251	340,139	Total	28,853.	17,717.	17,906.	20,020.
#5									
LOT					LOT				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line	301,733	140,227	186,722	191,126	Fall Line	16,165.	5,971.	6,712.	8,306.
Below Fall Line	87,772.	43,629.	42,371.	51,954.	Below Fall Line	4,359.	3,245.	2,524.	3,179.
Point Source	13,153.	13,153.	13,153.	13,153.	Point Source	274	274	274	274

NITROGEN						PHOSPHORUS				
#5 (Cont.)										
Atmosphere	43,025.	43,025.	43,025.	43,025.		Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	445,683	240,034	285,271	299,259		Total	22,621.	11,313.	11,333.	13,583.
#19										
31%N-18% P						31%N-18% P				
	Wet	Dry	Average	Mean			Wet	Dry	Average	Mean
Fall Line	248,719	114,666	152,368	156,557		Fall Line	21,149.	9,499.	10,701.	12,310.
Below Fall Line	75,779.	37,240.	36,714.	44,737.		Below Fall Line	5,237.	4,216.	3,099.	3,973.
Point Source	59,586.	59,586.	59,586.	59,586.		Point Source	6,034.	6,034.	6,034.	6,034.
Atmosphere	43,025.	43,025.	43,025.	43,025.		Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	427,109	254,517	291,693	303,906		Total	34,243.	21,573.	21,657.	24,141.
#20						#20				
10%N-49%P						10%N-49%P				
	Wet	Dry	Average	Mean			Wet	Dry	Average	Mean
Fall Line	324,417	149,564	198,741	204,205		Fall Line	13,154.	5,908.	6,656.	7,656.
Below Fall Line	98,842.	48,574.	47,887.	58,353.		Below Fall Line	3,257.	2,622.	1,927.	2,471.
Point Source	77,721.	77,721.	77,721.	77,721.		Point Source	3,753.	3,753.	3,753.	3,753.
Atmosphere	43,025.	43,025.	43,025.	43,025.		Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	544,005	318,884	367,374	383,304		Total	21,987.	14,106.	14,159.	15,703.
#6						#6				
LOT - Upper						LOT - Upper				
	Wet	Dry	Average	Mean			Wet	Dry	Average	Mean
Fall Line, Upper	205,359	95,385	148,782	138,739		Fall Line, Upper	6,748.	2,540.	4,106.	4,008.
Fall Line, Middle	90,019.	43,475.	38,527.	50,805.		Fall Line, Middle	10,108.	4,366.	3,669.	5,236.
Fall Line, Lower	30,006.	12,525.	9,910.	14,975.		Fall Line, Lower	3,932.	1,699.	1,152.	1,927.
BFL, Upper	3,901.	2,349.	2,938.	2,895.		BFL, Upper	249	162	231	207
BFL, Middle	71,106.	32,624.	34,398.	41,030.		BFL, Middle	3,818.	2,960.	2,555.	2,970.
BFL, Lower	33,092.	17,755.	14,590.	19,556.		BFL, Lower	2,055.	1,605.	780	1,365.
Pt Src, Upper	63	63	63	63		Pt Src, Upper	2	2	2	2
Pt Src, Middle	56,263.	56,263.	56,263.	56,263.		Pt Src, Middle	2,431.	2,431.	2,431.	2,431.
Pt src, Lower	29,738.	29,738.	29,738.	29,738.		Pt src, Lower	4,858.	4,858.	4,858.	4,858.
Atmosphere	43,025.	43,025.	43,025.	43,025.		Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	562,572	333,202	378,234	397,089		Total	36,024.	22,446.	21,607.	24,826.
#7						#7				
LOT - Mid						LOT - Mid				
	Wet	Dry	Average	Mean			Wet	Dry	Average	Mean

NITROGEN					**PHOSPHORUS**				
#7 (Cont.)									
Fall Line, Upper	240,516	110,180	172,380	161,127	Fall Line, Upper	11,760.	5,516.	8,229.	7,850.
Fall Line, Middle	71,831.	34,293.	30,181.		Fall Line, Middle	6,656.	2,338.	2,017.	3,073.
Fall Line, Lower	30,006.	12,525.	9,910.	14,975.	Fall Line,Lower	3,932.	1,699.	1,152.	1,927.
BFL, Upper	5,627.	3,592.	4,219.	4,250.	BFL, Upper	483	353	436	412
BFL, Middle	56,431.	26,487.	27,738.	32,976.	BFL, Middle	2,751.	2,062.	1,821.	2,103.
BFL, Lower	33,092.	17,755.	14,590.	19,556.	BFL, Lower	2,055.	1,605.	780	1,365.
Pt Src, Upper	356	356	356	356	Pt Src, Upper	71	71	71	71
Pt Src, Middle	9,348.	9,348.	9,348.	9,348.	Pt Src, Middle	181	181	181	181
Pt src, Lower	29,738.	29,738.	29,738.	29,738.	Pt src, Lower	4,858.	4,858.	4,858.	4,858.
Atmosphere	43,025.	43,025.	43,025.	43,025.	Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	519,970	287,299	341,485	355,508	Total	34,570.	20,506.	(2.)	23,664.
#8					#8				
LOT-Lower					LOT- Lower				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line, Upper	240,516	110,180	172,380	161,127	Fall Line, Upper	11,760.	5,516.	8,229.	7,850.
Fall Line, Middle	90,019.	43,475.	38,527.	50,805.	Fall Line, Middle	10,108.	4,366.	3,669.	5,236.
Fall Line, Lower	24,543.	10,550.	7,759.	12,232.	Fall Line, Lower	2,761.	1,093.	588	1,225.
BFL, Upper	5,627.	3,592.	4,219.	4,250.	BFL, Upper	483	353	436	412
BFL, Middle	71,106.	32,624.	34,398.	41,030.	BFL, Middle	3,818.	2,960.	2,555.	2,970.
BFL, Lower	27,444.	14,794.	11,718.	16,094.	BFL, Lower	1,361.	1,021.	472	869
Pt Src, Upper	356	356	356	356	Pt Src, Upper	71	71	71	71
Pt Src, Middle	56,263.	56,263.	56,263.	56,263.	Pt Src, Middle	2,431.	2,431.	2,431.	2,431.
Pt src, Lower	3,744.	3,744.	3,744.	3,744.	Pt src, Lower	92	92	92	92
Atmosphere	43,025.	43,025.	43,025.	43,025.	Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	562,643	318,603	372,389	388,925	Total	34,708.	19,726.	20,366.	22,978.
#10					#10				
LOT N ONLY					LOT N ONLY				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line	294,285	128,868	179,081	182,037	Fall Line	19,618.	8,775.	9,813.	11,359.
Below Fall Line	87,773.	43,629.	42,371.	51,955.	Below Fall Line	4,359.	3,245.	2,524.	3,179.
Point Source	13,153.	13,153.	13,153.	13,153.	Point Source	7,324.	7,324.	7,324.	7,324.
Atmosphere	43,025.	43,025.	43,025.	43,025.	Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	438,236	228,675	277,630	290,169	Total	33,124.	21,167.	21,484.	23,685.

NITROGEN					PHOSPHORUS				
#11									
LOT P ONLY					LOT P ONLY				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line	318,761	155,346	202,772	206,999	Fall Line	16,164.	5,969.	6,711.	8,305.
Below Fall Line	87,772.	43,629.	42,371.	51,954.	Below Fall Line	4,359.	3,245.	2,524.	3,179.
Point Source	85,418.	85,418.	85,418.	85,418.	Point Source	274	274	274	274
Atmosphere	43,025.	43,025.	43,025.	43,025.	Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	534,976	327,418	373,586	387,397	Total	22,620.	11,311.	11,332.	13,581.
#18					#18				
90% P ONLY					90% P ONLY				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line	360,463	166,182	220,823	226,895	Fall Line	2,579.	1,158.	1,305.	1,501.
Below Fall Line	109,824	53,971.	53,208.	64,836.	Below Fall Line	639	514	378	485
Point Source	86,357.	86,357.	86,357.	86,357.	Point Source	736	736	736	736
Atmosphere	43,025.	43,025.	43,025.	43,025.	Atmosphere	182	182	182	182
Total	599,669	349,535	403,413	421,113	Total	4,136.	2,591.	2,601.	2,904.
#3					#3				
40% + CAA					40% + CAA				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line	293,485	138,238	187,334	188,926	Fall Line	18,483.	8,287.	9,215.	10,697.
Below Fall Line	78,426.	39,946.	39,214.	47,349.	Below Fall Line	4,131.	3,190.	2,452.	3,083.
Point Source	51,814.	51,814.	51,814.	51,814.	Point Source	4,416.	4,416.	4,416.	4,416.
Atmosphere	40,428.	40,428.	40,428.	40,428.	Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	464,153	270,426	318,790	328,517	Total	28,853.	17,716.	17,906.	20,019.
#4					#4				
40% CAA+ BASIN					40% CAA+ BASIN				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line	269,338	127,956	171,883	173,803	Fall Line	16,459.	7,265.	8,088.	9,433.
Below Fall Line	75,508.	39,384.	38,474.	46,245.	Below Fall Line	3,986.	3,103.	2,376.	2,989.
Point Source	51,814.	51,814.	51,814.	51,814.	Point Source	4,416.	4,416.	4,416.	4,416.
Atmosphere	40,428.	40,428.	40,428.	40,428.	Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	437,088	259,582	302,599	312,290	Total	26,684.	16,607.	16,703.	18,661.
#9					#9				
LOG-MID (A)					LOT-MID (A)				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line, Upper	240,516	110,180	172,380	161,127	Fall Line, Upper	11,760.	5,516.	8,229.	7,850.

NITROGEN					PHOSPHORUS				
#9 (Cont.)									
Fall Line, Mid.	88,520.	42,208.	37,263.	49,492.	Fall Line, Mid.	9,864.	4,142.	3,540.	5,046.
Fall Line, Lower	30,006.	12,525.	9,910.	14,975.	Fall Line,Lower	3,932.	1,699.	1,152.	1,927.
BFL, Upper	5,627.	3,592.	4,219.	4,250.	BFL, Upper	483	353	436	412
BFL, Middle	59,803.	28,111.	29,595.	35,043.	BFL, Middle	3,020.	2,324.	2,007.	2;336.
BFL, Lower	33,092.	17,755.	14,590.	19,556.	BFL, Lower	2,055.	1,605.	780	1,365.
Pt Src, Upper	356	356	356	356	Pt Src, Upper	71	71	71	71
Pt Src, Middle	33,330.	33,330.	33,330.	33,330.	Pt Src, Middle	486	486	486	486
Pt src, Lower	29,738.	29,738.	29,738.	29,738.	Pt src, Lower	4,858.	4,858.	4,858.	4,858.
Atmosphere	43,025.	43,025.	43,025.	43,025.	Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	564,013	320,820	374,406	390,893	Total	38,352.	22,877.	23,382.	26,174.
#13					#13				
BNR					BNR				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line	309,179	144,258	193,508	196,942	Fall Line	18,212.	7,652.	8,645.	10,161.
Below Fall Line	87,772.	43,629.	42,392.	0	Below Fall Line	4,359.	3,245.	2,525.	3,180.
Point Source	62,692.	62,692.	62,692.	62,692.	Point Source	3,695.	3,695.	3,695.	3,695.
Atmosphere	40,428.	40,428.	40,428.	40,428.	Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	500,071	291,007	339,020	352,025	Total	28,089.	16,415.	16,688.	18,859.
#14					#14				
ALLOC. 2					ALLOC. 2				
	Wet	Dry	Average	Mean		Wet	Dry	Average	Mean
Fall Line, Upper	209,291	96,494.	150,352	140,597	Fall Line, Upper	8,120.	3,354.	5,234.	5,059.
Fall Line,Mid.	73,657.	34,832.	30,705.	40,946.	Fall Line,Mid.	7,630.	2,910.	2,483.	3,683.
Fall Line, Lower	20,813.	8,968.	7,130.	10,602.	Fall Line,Lower	2,589.	1,128.	772	1,278.
BFL, Upper	4,361.	2,740.	3,312.	3,293.	BFL, Upper	331	231	306	281
BFL, Middle	81,276.	49,810.	51,027.	56,590.	BFL, Middle	3,811.	3,087.	2,791.	3,113.
BFL, Lower	40,501.	30,930.	28,198.	31,751.	BFL, Lower	4,200.	3,910.	3,383.	3,757.
Pt Src, Upper					Pt Src, Upper				
Pt Src, Middle					Pt Src, Middle				
Pt src, Lower					Pt src, Lower				
Atmosphere	38,723.	38,723.	38,723.	38,723.	Atmosphere	1,823.	1,823.	1,823.	1,823.
Total	468,622	262,497	309,447	322,502	Total	28,504.	16,443.	16,792.	18,995.

TABLE A-2 STEADY STATE RESPONSE MATRICES FOR TRACER RUNS

			Dissolved Loads From These Sources							
			Susquehanna	Baltimore H	Patuxent	Potomac	Rappahannoc	York	James	Ocean
	Concentration	Normalized by	Load							
	mg-day/m**3-ton									
Result	bay	1	8.92513751	1.5067631	0.54246811	0.44838388	0.14252631	0.02693308	0.011171	0.12613553
in	bay	2	5.60207816	5.29100529	1.67429746	1.36504297	0.42497332	0.07960751	0.03345541	0.38563223
Concentrations	bay	3	4.53860617	4.54429083	2.15601767	1.64352168	0.50496523	0.09438495	0.04007739	0.45843306
in	bay	4	3.66278356	3.62956563	3.44238115	2.11890094	0.58495714	0.10820901	0.04618113	0.52649438
These	bay	9	2.74439993	2.70417307	2.55887218	2.01522129	0.63524522	0.12393984	0.05268795	0.60824754
Segments	bay	5	2.84070476	2.78951186	2.89778153	2.82599059	0.70820201	0.11917292	0.05015432	0.58065334
	bay	6	2.02991947	1.98146015	1.96844519	1.8408169	1.18007613	0.13967066	0.05504883	0.6707877
	bay	7	1.0937541	1.05873443	1.06148967	1.04315062	0.95729735	0.3639541	0.08119127	0.76706586
	bay	8	0.64273346	0.61870626	0.62666257	0.62042026	0.62247778	0.69787662	0.67400267	0.80452281
	jam	1	0.37053778	0.3573562	0.36342166	0.35543924	0.35540381	0.50100296	23.8572185	0.45343152
	yrk	1	1.39847951	1.34141918	1.36309767	1.36425363	1.52688145	31.9340526	0.08769808	0.61641912
	rap	1	1.79699641	1.74144479	1.77767547	1.85987943	77.4342555	0.10844736	0.03737102	0.43092235
	pot	1	1.82372437	1.76811316	1.87465896	16.4423208	0.41429036	0.07484059	0.03155519	0.3583187
	pat	1	3.17993074	3.12553337	222.952263	1.56332486	0.44164916	0.08246766	0.03547079	0.40007106
	balt_h	10	5.3979314	16.9637523	1.68175772	1.39503784	0.4348746	0.08127593	0.0341464	0.39851225

				Particle Loads From These Sources				
				Susquehanna	Baltimore H	Potomac	James	Ocean
	Accumulation	(kg-day/kg-day)						
Produce	bay 1	1		0.85498306	0.02272921	8.616E-07	1.086E-09	0.00001184
Accumulations	bay 2	2		0.11179623	0.29413365	0.00003886	7.105E-08	0.00046145
in	bay 3	3		0.01996046	0.04611994	0.00014167	3.411E-07	0.00164298
These	bay 4	4		0.00438633	0.0095708	0.00047553	9.612E-07	0.00435045
Zones	bay 9	9		0.00104524	0.00208722	0.00023149	5.505E-06	0.02420156
	bay 5	5		0.00111215	0.00234342	0.00156492	4.053E-06	0.01977849
	bay 6	6		0.0001658	0.0003207	0.00032459	0.0000264	0.11604252
	bay 7	7		0.00003448	0.00006282	0.00007628	0.00008365	0.20507373
	bay 8	8		0.00001035	0.00001794	0.00002298	0.00072773	0.21392213
	balt_h	10		0.01059217	0.61571457	1.180E-06	3.105E-09	0.00001854
	jam	1		1.801E-06	3.089E-06	3.777E-06	0.98626712	0.02973328
	yrk	1		0.0000142	0.00002489	0.0000325	0.00001145	0.01581669
	rap	1		0.00002329	0.00004277	0.00006091	6.794E-08	0.00051407
	pot	1		0.00039142	0.00084373	0.99140292	1.799E-07	0.00091116
	pat	1		0.00021422	0.00044433	4.151E-06	6.397E-09	0.00003092

				Particle Loads to the Surface of These Zones								
				Zone_1	Zone_2	Zone_3	Zone_4	Zone_9	Zone_5	Zone_6	Zone_7	Zone_8
	Accumulation	(kg-day/kg-day)										
Produce	bay	1		0.77994334	0.04680254	0.00173556	0.00039286	0.00005187	0.00006845	0.00001296	3.146E-06	2.011E-06
Accumulations	bay	2		0.1644414	0.71892351	0.11189774	0.02318557	0.00220263	0.00454063	0.00092291	0.00022456	0.00008096
in	bay	3		0.01335794	0.15170566	0.68147309	0.11386255	0.0076817	0.02385334	0.00492919	0.0011803	0.00029983
These	bay	4		0.00219687	0.02245628	0.13766988	0.51450425	0.03391252	0.13341736	0.01985488	0.00449297	0.00081293
Zones	bay	9		0.00030923	0.00292525	0.01697778	0.11965372	0.73433428	0.14636914	0.05966105	0.0203966	0.004459
	bay	5		0.00036434	0.00353481	0.02154469	0.13943402	0.09169562	0.46475921	0.11531846	0.02567996	0.00365147
	bay	6		0.0000363	0.00034118	0.0020754	0.01247507	0.08777856	0.09572222	0.44764873	0.15689221	0.02090618
	bay	7		6.414E-06	0.00005793	0.00035002	0.00201443	0.00955991	0.0166754	0.12594884	0.25937677	0.04418114
	bay	8		1.864E-06	0.0000167	0.00010131	0.00057635	0.00237108	0.00481808	0.03271446	0.10449043	0.12878187
	balt_h	10		0.01866077	0.04116202	0.00241336	0.0005109	0.00008465	0.00009022	0.00001755	4.220E-06	3.181E-06
	jam	1		3.528E-07	3.228E-06	0.0000198	0.00011281	0.00046363	0.00097017	0.00645092	0.01805619	0.03244236
	yrk	1		2.565E-06	0.00002354	0.00014305	0.0008146	0.00308957	0.00713105	0.04463407	0.06984789	0.00376309
	rap	1		4.955E-06	0.00004633	0.00028611	0.00163634	0.00332314	0.0154602	0.03041148	0.00180119	0.00008901
	pot	1		0.00011666	0.00115306	0.00717983	0.04042153	0.00553793	0.06056276	0.00540282	0.00112377	0.00016736
	pat	1		0.00009606	0.00097135	0.00604674	0.01867762	0.00025325	0.0014873	0.0002344	0.0000517	5.833E-06

TABLE A - 3 ANOXIC VOLUME DAYS - SEASONAL AND ANNUAL TOTALS

SCENARIO NUMBER	SEASON	ANOXIC VOL-DAYS SEASONAL Billion m^3-d	SEASON % DIFF. FR. BASE	ANOXIC VOL-DAYS ANNUAL SUM Billion m^3-d	ANNUAL % DIFF. FR. BASE
1	1	0	0		
1	2	29	0.00		
1	3	310	0.00		
1	4	30	0.00	369	0.00
2	1	0	0		
2	2	13	55.17		
2	3	260	16.13		
2	4	22	26.67	295	20.05
3	1	0	0		
3	2	11	62.07		
3	3	250	19.35		
3	4	21	30.00	282	23.58
4	1	0	0		
4	2	8	72.41		
4	3	230	25.81		
4	4	19	36.67	257	30.35
5	1	0	0		
5	2	5.1	82.41		
5	3	230	25.81		
5	4	17	43.33	252.1	31.68
6	1	0	0		
6	2	22	24.14		
6	3	290	6.45		
6	4	27	10.00	339	8.13
7	1	0	0		
7	2	12	58.62		
7	3	260	16.13		
7	4	21	30.00	293	20.60
8	1	0	0		
8	2	28	3.45		
8	3	310	0.00		
8	4	30	0.00	368	0.27
9	1	0	0		
9	2	18	37.93		
9	3	280	9.68		
9	4	25	16.67	323	12.47
10	1	0	0		
10	2	7.3	74.83		
10	3	230	25.81		
10	4	18	40.00	255.3	30.81

SCENARIO NUMBER	SEASON	ANOXIC VOL-DAYS SEASONAL Billion m^3-d	SEASON % DIFF. FR. BASE	ANOXIC VOL-DAYS ANNUAL SUM Billion m^3-d	ANNUAL % DIFF. FR. BASE
11	1	0	0		
11	2	12	58.62		
11	3	280	9.68		
11	4	22	26.67	314	14.91
12	1	0	0		
12	2	10	65.52		
12	3	250	19.35		
12	4	20	33.33	280	24.12
13	1	0	0		
13	2	15	48.28		
13	3	270	12.90		
13	4	23	23.33	308	16.53
14	1	0	0		
14	2	9	68.97		
14	3	250	19.35		
14	4	19	36.67	278	24.66
15	1	0	0		
15	2	0.05	99.83		
15	3	120	61.29		
15	4	7	76.67	127.05	65.57
16	1	0	0		
16	2	0	100.00		
16	3	0.23	99.93		
16	4	0	100.00	0.23	99.94
17	1	0	0		
17	2	0	100.00		
17	3	0.29	99.91		
17	4	0	100.00	0.29	99.92
18	1	0	0		
18	2	5.2	82.07		
18	3	260	16.13		
18	4	18	40.00	283.2	23.25
19	1	0	0		
19	2	6	79.31		
19	3	210	32.26		
19	4	17	43.33	233	36.86
20	1	0	0		
20	2	14	51.72		
20	3	280	9.68		
20	4	24	20.00	318	13.82

TABLE A -4 ANOXIC VOLUME DAYS - ZONE ANNUAL TOTALS

SCENARIO NUMBER	ZONE	ANOXIC VOL-DAYS ANNUAL SUM	ANNUAL % DIFF. FR. BASE	SCENARIO NUMBER	ZONE	ANOXIC VOL-DAYS ANNUAL SUM	ANNUAL % DIFF. FR. BASE	SCENARIO NUMBER	ZONE	ANOXIC VOL-DAYS ANNUAL SUM	ANNUAL % DIFF. FR. BASE	SCENARIO NUMBER	ZONE	ANOXIC VOL-DAYS ANNUAL SUM	ANNUAL % DIFF. FR. BASE
1	1	1.860E+10	0.00	6	1	1.680E+10	9.68	11	1	1.334E+10	28.28	16	1	0	100.00
1	2	1.480E+11	0.00	6	2	1.327E+11	10.34	11	2	1.259E+11	14.93	16	2	0	100.00
1	3	1.133E+11	0.00	6	3	1.056E+11	6.80	11	3	9.480E+10	16.33	16	3	0	100.00
1	4	3.592E+10	0.00	6	4	3.054E+10	14.98	11	4	2.828E+10	21.27	16	4	0	100.00
1	9	5.240E+10	0.00	6	5	1300000000	27.78	11	9	4.880E+10	6.87	16	5	0	100.00
1	5	1800000000	0.00	6	6	920000000	8.00	11	5	1300000000	27.78	16	6	0	100.00
1	6	1000000000	0.00	6	7	0	0.00	11	6	910000000	9.00	16	7	0	0.00
1	7	0	0.00	6	8	0	0.00	11	7	0	0.00	16	8	0	0.00
1	8	0	0.00	6	9	5.000E+10	4.58	11	8	0	0.00	16	9	230000000	99.56
2	1	1.456E+10	21.72	7	1	1.456E+10	21.72	12	1	1.377E+10	25.97	17	1	0	100.00
2	2	1.281E+11	13.45	7	2	1.264E+11	14.59	12	2	1.255E+11	15.20	17	2	5600000	100.00
2	3	9.230E+10	18.53	7	3	9.070E+10	19.95	12	3	8.710E+10	23.12	17	3	0	100.00
2	4	2.325E+10	35.27	7	4	2.324E+10	35.30	12	4	2.023E+10	43.68	17	4	0	100.00
2	9	4.140E+10	20.99	7	5	820000000	54.44	12	5	670000000	62.78	17	5	0	100.00
2	5	840000000	53.33	7	6	480000000	52.00	12	6	400000000	60.00	17	6	0	100.00
2	6	490000000	51.00	7	7	0	0.00	12	7	0	0.00	17	7	0	0.00
2	7	0	0.00	7	8	0	0.00	12	8	0	0.00	17	8	0	0.00
2	8	0	0.00	7	9	4.120E+10	21.37	12	9	3.890E+10	25.76	17	9	290000000	99.45
3	1	1.415E+10	23.92	8	1	1.850E+10	0.54	13	1	1.510E+10	18.82	18	1	1.170E+10	37.08
3	2	1.262E+11	14.73	8	2	1.470E+11	0.68	13	2	1.289E+11	12.91	18	2	1.057E+11	28.57
3	3	8.750E+10	22.77	8	3	1.128E+11	0.44	13	3	9.510E+10	16.06	18	3	8.248E+10	27.20
3	4	2.123E+10	40.90	8	4	3.385E+10	5.76	13	4	2.526E+10	29.68	18	4	2.823E+10	21.41
3	9	3.890E+10	25.76	8	5	1700000000	5.56	13	5	920000000	48.89	18	5	1300000000	27.78
3	5	670000000	62.78	8	6	970000000	3.00	13	6	550000000	45.00	18	6	1000000000	0.00
3	6	410000000	59.00	8	7	0	0.00	13	7	0	0.00	18	7	0	0.00
3	7	0	0.00	8	8	0	0.00	13	8	0	0.00	18	8	0	0.00
3	8	0	0.00	8	9	5.130E+10	2.10	13	9	4.370E+10	16.60	18	9	5.190E+10	0.95
4	1	1.337E+10	28.12	9	1	1.610E+10	13.44	14	1	1.340E+10	27.96	19	1	1.356E+10	27.10
4	2	1.135E+11	23.31	9	2	1.305E+11	11.82	14	2	1.141E+11	22.91	19	2	1.089E+11	26.42
4	3	8.028E+10	29.14	9	3	1.006E+11	11.21	14	3	8.469E+10	25.25	19	3	7.158E+10	36.82
4	4	1.720E+10	52.12	9	4	2.837E+10	21.02	14	4	1.921E+10	46.52	19	4	1.309E+10	63.57
4	9	3.490E+10	33.40	9	5	1100000000	38.89	14	5	630000000	65.00	19	5	360000000	80.00
4	5	470000000	73.89	9	6	810000000	19.00	14	6	360000000	64.00	19	6	91000000	90.90
4	6	220000000	78.00	9	7	0	0.00	14	7	0	0.00	19	7	0	0.00
4	7	0	0.00	9	8	0	0.00	14	8	0	0.00	19	8	0	0.00
4	8	0	0.00	9	9	4.630E+10	11.64	14	9	3.770E+10	28.05	19	9	2.880E+10	45.04
5	1	1.223E+10	34.25	10	1	1.359E+10	26.94	15	1	9900000000	46.77	20	1	1.490E+10	19.89
5	2	1.077E+11	27.23	10	2	1.130E+11	23.65	15	2	6.360E+10	57.03	20	2	1.284E+11	13.24
5	3	7.747E+10	31.62	10	3	7.603E+10	32.89	15	3	3.515E+10	68.98	20	3	9.790E+10	13.59
5	4	1.719E+10	52.14	10	4	1.513E+10	57.88	15	4	2200000000	93.88	20	4	2.728E+10	24.05
5	9	3.620E+10	30.92	10	9	3.240E+10	38.17	15	5	80000000	95.56	20	5	1100000000	38.89
5	5	510000000	71.67	10	5	400000000	77.78	15	6	0	100.00	20	6	800000000	20.00
5	6	310000000	69.00	10	6	160000000	84.00	15	7	0	0.00	20	7	0	0.00
5	7	0	0.00	10	7	0	0.00	15	8	0	0.00	20	8	0	0.00
5	8	0	0.00	10	8	0	0.00	15	9	1.545E+10	70.52	20	9	4.640E+10	11.45

APPENDIX B

REGRESSION EQUATIONS FROM RESPONSE SURFACE ANALYSES

ANALYSIS CONDITION AND EQUATION	R-SQUARE
WHOLE BAY FULL YEAR 9	
a=-.027648 +1.159833*n + .267241*p - .308414*n*p;	0.9804
WHOLE BAY SPRING YEAR 9	
a = .020025 + 3.331184 * n - 2.488719 * N*n + .996558 * p*p - .986442 * n*p ;	0.9895
WHOLE BAY SUMMER YEAR 9	
a = -.014463 + 1.146319 * n + .205676 * p*p - .216003 * n*p ;	0.9839
WHOLE BAY FALL YEAR 9	
a = -.053316 + 2.028102 * n - .948373 * n*n + .54995 * p*p - .541366 * n*p ;	0.9816
ZONE 1 FULL YEAR 9	
a = .013408 + .964316 * n + .144493 * n*n + .448454 * p*p -.460693 * n*p ;	0.9990
ZONE 1 SPRING YEAR 9	
a = .093315 + 3.571793 * n - 2.854708 * n*n + 1.147789 * p*p - 1.138452 * n*p ;	0.9486
ZONE 1 SUMMER YEAR 9	
a = .001148 + .184689 * n + 1.026181 * n*n + .285626 * p*p - .30611 * n*p ;	0.9993
ZONE 1 FALL YEAR 9	
a = -.004358 + .853158 * n + .29092 * n*n + .360827 * p*p - .371816 * n*p ;	0.9991
ZONE 2 FULL YEAR 9	
a = -.048278 + 1.16711 * n + .408651 * p*p - .409146 * n*p ;	0.9846
ZONE 2 SPRING YEAR 9	
a = -.018261 + 3.267295 * n - 2.36681 * n*n + 1.209613 * p*p - 1.198076 * n*p ;	0.9895
ZONE 2 SUMMER YEAR 9	
a = -.104308 + 1.205255 * n + .36289 * p*p - .355202 * n*p ;	0.9800
ZONE 2 FALL YEAR 9	
a = -.065619 + 2.2201 * n - 1.148448 * n*n + .668454 * p*p - .649709 * n*p ;	0.9676
ZONE 3 FULL YEAR 9	
a = .017157 + 1.130903 * n + .301765 * p*p - .315226 * n*p ;	0.9666
ZONE 3 SPRING YEAR 9	
a = .11723 + 3.601399 * n - 2.917184 * n*n + 1.112482 * p*p - 1.107638 * n*p ;	0.9269

ZONE 3 SUMMER YEAR 9
a = -.075862 + 1.462213 * n - .289957* N*N + .325289 * p*p - .322662 * n*p ; 0.9730

ZONE 3 FALL YEAR 9
a = -.078155 + 2.891246 * n - 1.872233 * n*n + .709474 * p*p - .692031 * n*p; 0.9415

ZONE 4 FULL YEAR 9
a = .072407 + 2.13494 * n + 1.477261 * p - 1.221717 * n*n - .798939 * p*p -.860225 * n*p ; 0.9405

ZONE 4 SPRING YEAR 9
a = .112264 + 1.720432 * n + 2.226041 * p - .808812 * n*n - 1.406036 * p*p - 1.100668 * n*p 0.8776

ZONE 4 SUMMER YEAR 9
a = .066993 + 2.195415 * n + 1.369103 * p - 1.28241 * n*n - .710283 * p*p - .826618 * n*p ; 0.9483

ZONE 4 FALL YEAR 9
a = .11823 + 1.608643 * n + 2.38506 * p - .691964 * n*n - 1.557117 * p*p - 1.128823 * n*p ; 0.8686

ZONE 5 FULL YEAR 9 AND SUMMER (SAME EQUATIONS)
a = .028591 + 3.308827 * n - 2.475876 * n*n + .313846 * p*p - .310162 * n*p ; 0.9905

ZONE 6 FULL YEAR 9 AND SUMMER (SAME EQUATIONS)
a = -.023671 + 3.705698 * n - 2.84665 * n*n ; 0.9769

ZONE 9 FULL YEAR 9
a = -.026057 + 1.767562 * n - .69466 * n*n ; 0.9852

ZONE 9 SPRING YEAR 9
a = -.040017 + 2.561638 * n - 1.538052 * N*n ; 0.9169

ZONE 9 SUMMER YEAR 9
a = -.02601 + 1.640766 * n - .555784 * n*n ; 0.9884

ZONE 9 FALL YEAR 9
a = -.006908 + 2.521603 * n - 1.55424 * n*n ; 0.9983

DO HABITAT IMPROVEMENT
a = -.005567 + 0.648366 * n - 0.226809* n*n + 0.162846*p*p-0.156327*n*p 0.9977

DIN HABITAT IMPROVEMENT
a = -.018216 + 3.36393 * n - 1.520132* n*n-0.849344*p 0.9983