Assessment of Nitrogen and Phosphorus Control Tradeoffs Using A Water Quality Model with A Response Surface Method

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Abstract: Excessive nutrient loads to the Chesapeake Bay cause violations of the new dissolved oxygen water quality standard established to protect the Bay's living resources. Reducing nitrogen and phosphorus loads is necessary to achieve the dissolved oxygen standard. Based on a set of water quality model runs, we used a response surface method to establish a function of dissolved oxygen (DO) versus total nitrogen (TN) and total phosphorus (TP) loads, which plots as a 3-D surface. For a specific criterion for DO, i.e., achievement of the DO standard, a curve of DO versus TN and TP loads that meet the DO criterion can be isolated. Each of the paired TN and TP loads on this tradeoff curve results in an equivalent level of DO, but usually at different nutrient reduction costs. This paper explores cost-effective alternatives in nutrient reduction to achieve the DO water quality standard in the Deep Water designated use of Segment CB4, which is the last and most difficult region for achievement of DO standards in the Chesapeake. This paper analyzes DO response surface plots and nitrogen-phosphorus tradeoff curves. The effects of nutrient limitation on algal growth, water clarity, and DO concentrations in two different nitrogen and phosphorus load scenarios are examined to understand the responses of water quality to nitrogen and phosphorus trades.

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Introduction

The Chesapeake Bay is one of the largest and most biologically productive estuaries in the world. In the later part of the 20th century, degradation of water quality due to excessive nutrient inputs from the 166,000 km^2 watershed resulted in increasing volumes of hypoxic and anoxic waters (Adelson et al, 2001; Kemp et al., 2005). The Chesapeake 2000 Agreement (CEC, 2000) set a goal of achieving dissolved oxygen (DO) and other water quality standards to remove the Bay from the list of impaired waters by 2010. Throughout the history of the Chesapeake Bay Program partnership (www.chesapeakebay.net), there have been numerous analyses of the influence of nitrogen (N) and phosphorus (P) loads on Bay hypoxia and anoxia (Gillelan et al., 1983; Thomann et al., 1994; Boynton et al. 1995; Kemp et al., 2005). Early on, the important role that both nitrogen and phosphorus play in controlling algal production and subsequent low DO conditions in tidally influenced waters was firmly established (Gillelan et al., 1983; D'Elia et al., 1992). During the development of nutrient allocations in 1992, the importance of controlling both nitrogen and phosphorus loads was reaffirmed (Boynton et al., 1995), as it was again in the 2003 development of nitrogen, phosphorus, and sediment allocation caps (CBPO, 2003). Controlling both nitrogen and phosphorus loads is necessary due to spatial and temporal variations in nitrogen versus phosphorus limitation in the Chesapeake.

The relative importance of nitrogen versus phosphorus loads on water quality and the tradeoffs between relative amounts of nitrogen-phosphorus control have been suggested (Thomann et al., 1994), and the Chesapeake Bay Estuarine Model (Cerco and Meyers, 2003;

Cerco and Noel, 2004) has been used to specifically address the problem of anoxia. However, a model scenario provides insight to only a specific loading condition. In order to find nutrient loads that correlate to a specific response requirement many trial scenarios are required. In a complex system, like the Chesapeake Bay, there is no simple equation to relate DO with nutrient loads. After all, more than 80 governing partial differential equations are involved in the water quality model. However, a response surface (Thomann et al., 1994; Khuri and Cornell, 1996), based on a set of a few model scenarios, can provide an analytic expression of water quality response as a function of independent variables, such as nutrient loads. Wang et al. (2002; 2006) used the response surface method to analyze the response of Chesapeake Bay's ecosystem to nutrient and sediment loads, indicating that the same level of water quality can be achieved by different combinations of nitrogen, phosphorus, and sediment reductions. In this paper, the authors further apply the response surface method to analyze nitrogen-phosphorus tradeoffs for development of cost-effective load reductions to achieve the DO water quality goal. This provides flexibility in water quality management in planning and implementing cost-effective point source and nonpoint source controls.

Method

Based on a set of water quality model results, we used a response surface method to establish a function of *DO* as the dependent variable and total nitrogen (*TN*) and total phosphorus (*TP*) loads as independent variables, e.g., *DO* = f (*TN*, *TP*). For a specific *DO* criterion, a set of *TN* and *TP* tradeoff loads can be determined (Wang et al., 2006). The *DO* problem in the Chesapeake Bay is due to excessive algal growth and subsequent decay of algal biomass in bottom waters below the pycnocline. While algal growth requires dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP), the Chesapeake Bay Program has long determined that controls of *TN* and *TP* loads from the watershed are needed due to the long residence time of nitrogen and phosphorus loads in the estuary and multiple opportunities for conversion among organic and inorganic nutrients (Thomann et al.,1994; Koroncai et al., 2003). Therefore, *TN* and *TP* loads are selected as the explanatory variables in the response surface in this paper.

The year 2002 version (i.e., with 12,920 model cells) of the Chesapeake Bay Estuarine Model (Cerco and Noel, 2004) was used. The model was fully calibrated. The average mean errors (i.e., the mean of the differences between model prediction and field observation) of the simulated chlorophyll concentration, bottom *DO*, and light attenuation in the mainstem Bay are -0.53 µg/l, +0.32 mg/l, and +0.02/m, respectively. While the absolute mean errors for them are 5.01 µg/l, 1.47 mg/l, and 0.36/m, respectively.

Nine model scenarios were selected to elucidate the response surface decision space. The 2000 Progress Scenario (PR2000) is our reference condition and has relatively high levels of nutrient loads compared to the future nutrient reductions that are planned to remove water quality impairments. The 2000 Progress Scenario uses input loads associated with year 2000 landuse, populations, nutrient applications, point source loads, and management conditions, and runs for a 10 year simulation period covering the 1985 to 1994 hydrology. This scenario represents the Bay's responses, under average hydrological conditions, to the year 2000 management conditions (Koroncai et al., 2003). In this scenario the *TN* and *TP* loads from the watershed were 129.3 and 8.664 kt/year, respectively. The other eight scenarios have varying 0%, 30% and 60% reductions from the PR2000 reference in nitrogen and phosphorus loads. Each scenario was run for 10 years using the 1985-1994 hydrology, using a 5-minute time-step and daily outputs. We used the averaged annual, seasonal, or monthly values as required in this study.

Based on the previous study (Wang et al., 2006) we selected the aforementioned nine model scenarios and used a linear regression method to establish a quadratic polynomial equation of *DO* as a function of *TN* and *TP* loads. The least squares method was applied to derive regression coefficients.

This paper focuses on the attainability of *DO* criteria in key designated use areas of the Bay (USEPA, 2003a) versus total nitrogen and total phosphorus loads to the Bay. The *DO* criteria in Deep Water of segment CB4 (CB4-DW) is most difficult to achieve. Segment CB4 is in the center of a large anoxic\hypoxic region of the Bay, and is the region of focus for nutrient reduction for basins of the upper and middle Bay. The authors examine how reductions of nitrogen and phosphorus loads cause reductions of algae and improvements in *DO* and water clarity. Algal limitation from nitrogen, phosphorus, or light, which reflect the effectiveness of nutrient reduction, are also examined.

The model simulates three types of algae, diatoms, green algae, and blue-green algae, and converts these state variables to chlorophyll concentrations for comparison with observed concentrations during model calibration. The following discussion is based on surface chlorophyll concentrations.

Nitrogen and Phosphorus Load Control for *DO* Attainment in CB4-DW

Dissolved Oxygen Response Surface and its Attainment Curve for N-P Equivalence

The authors used the response surface method to establish a quadratic function of average summer *DO* in CB4-DW versus *TN* and *TP* loads to the Bay:

$$DO = a\,TN^2 + b\,TP^2 + c\,TN\,TP + d\,TN + e\,TP + f \qquad (1)$$

Where, a through f are coefficients derived from regression; a = 3.127; b = 0.7923; c = -1.743; d = - 4.583; e = - 0.9773; f = 7.553. *DO* is in mg/l; the *TN* and *TP* loads are expressed as a fraction of PR2000 conditions. The R^2 is 0.99 and the root mean square error is 0.001 mg/l. Eq. 1 can be plotted graphically as a 3-D surface of *DO* versus *TN* and *TP* loads (Fig. 1).

The CB4-DW consists of more than 100 model cells. A strict application of the *DO* criterion (USEPA, 2003b) for a deep-water designated use area would apply limits of *DO* equal to or greater than 3 mg/l at all times in the criteria months of June, July, August, and September and for all the individual cells. Dissolved oxygen less than 3 mg/l would be a violation of this strict criteria. The criteria violation of a designated use area is calculated by the ratio of the cumulative volume for the cells in the months with violations divided by the total cumulative volume for all cells in the designated use area in all criteria months over the 10 years of the simulation period. To ensure all cells in CB4-DW have *DO* no less than 3 mg/l (i.e., zero violation of any time or space), the summer average *DO* in CB4-DW is higher than 3 mg/l. Still using the set of nine model outputs, we applied a linear regression method to get a relationship between violation (*V*) and summer average *DO* in CB4-DW:

$$DO = y(V) = -131.5\, V^3 + 39.75\, V^2 - 11.80\, V + 5.403\ .$$

Denoting DO_o as the summer average *DO* when *V* approaches to zero, we have:

$$DO_o = \lim_{V \to +0} y(V) = 5.4 \text{ mg/l}\ .$$

It yields DO_o=5.4 mg/l, which is the minimum summer average *DO* in CB4-DW which would ensure that all 100 cells of CB4-DW have *DO*≥3 mg/l at all times.

Using a plane of *DO*=5.4 mg/l to cut the surface of Fig. 1 yields a curve, called the *DO*=5.4 mg/l tradeoff curve. The equation of this tradeoff curve can be derived by substituting 5.4 for *DO* in Eq. 1: $a\,TN^2 + b\,TP^2 + c\,TN\,TP + d\,TN + e\,TP + g = 0$, where g=f-5.4.

The equation of the curve can be rearranged as *TN* in terms of *TP*:

$$TN = \{ -(d + c\,TP) - [(d + c\,TP)^2 - 4a (b\,TP^2 + e\,TP + g)]^{1/2} \} / 2a . \quad (2)$$

On this curve, the summer average *DO* of the designated use area equals 5.4 mg/l. The dashed curve in Fig. 2 is a plane view of the *DO*=5.4 mg/l tradeoff curve for *TN* and *TP* loads. The *TN* and *TP* loads at any point of this curve would just meet the strict *DO* criteria. For example, a reduction of 56.7% *TN* and 40% *TP* (at Point A), i.e., total nitrogen and phosphorus loads at 43.3% and 60% of the 2000 Progress Scenario loads, would achieve the strict *DO* criteria as would Point B with less reduction of *TN* (46.6% of the 2000 Progress Scenario loads) and more reduction of *TP* (50% of the 2000 Progress Scenario loads). Any pairs of *TN*-*TP* loads on this tradeoff curve will yield approximately equal *DO* responses.

TN-TP Tradeoff Rates

From the curve of Eq. 2, if *TP* is specified, then *TN* can be defined accordingly. The tradeoff rate, *dTN*/*dTP*, at any point can be obtained by the derivative of Eq. 2:

$$dTN/dTP = \{-c - 0.5[(d + c\,TP)^2 - 4a(b\,TP^2 + e\,TP + g)]^{-1/2} * 2c(d + c\,TP) - 4a(2b\,TP + e)\}/2a ,$$

or it can be estimated from Fig. 2.

The N-P tradeoff rates vary along the curve (Fig. 2). For example, at Point A, *dTN*/*dTP* = -0.268. The instantaneous *TN*:*TP* tradeoff rate is -26.8:100 using the metric of a percent *TN* or *TP* reduction from the 2000 Progress Scenario. Using the metric of mass with units of kt/year and the mass loads of *TN*=129.3 and *TP*=8.664 kt/year in the 2000 Progress Scenario, the *TN*:*TP* mass tradeoff rate is -129.3x26.8 to 8.664x100, or 4.00 to -1. A decrement of one mass unit of *TP* with an increment of 4.0 mass units of *TN* is estimated to achieve the same *DO* response in the critical region of CB4-DW at point A on the tradeoff curve.

If the change of one loading constituent (e.g., *TP*) is specified over a segment of the tradeoff curve, for example, *dTP*=-0.1 from 0.6 (Point A) to 0.5 (Point B) of PR2000, the average tradeoff rate can be estimated from the curve of *DO*=5.4 mg/l in Figure 2. We have *dTN*:*dTP* = 0.033:-0.1. Referring to units of mass, the *TN*:*TP* tradeoff is 4.92 to -1. In other words, an average estimated increase of 4.92 kt/year of nitrogen is offset by an additional 1.0 kt/year decrease in phosphorus to yield the same *DO* response over the curve from A to B in Fig. 2.

Exploration of TN-TP Trade Allocations

Allocation Scenario. The preceding section discussed load reductions and the nitrogen and phosphorus tradeoffs for an absolute and unequivocal attainment of *DO* not less than 3.0 mg/l at any time or place in CB4-DW. This requires high nitrogen and phosphorus load reductions to reach a summer average *DO* of 5.4 mg/l. This strict imposition of non-violation at any time or in any space of the 3.0 mg/l *DO* minimum in CB4-DW is unnecessary for the protection of living resources and for achieving the water quality standards based on USEPA guidelines allow about a 10% exceedance of the *DO* criteria in time and space (Koroncai et al, 2003).

The 10% allowable exceedance corresponds to an independent assessment by the Bay Program that an approximately equivalent level of occasional time and space incursions of *DO* less than 3.0 mg/l are ecologically unharmful to the key biological communities protected by the *DO* standard.

The Bay Program has caps on nitrogen and phosphorus loads to the Bay that achieve the *DO* water quality standard with loads of 79.38 and 5.81 kt/year for *TN* and *TP* respectively (Koroncai et al., 2003). This corresponds to *TN*=61.4% and *TP*=67% of the Progress 2000 Scenario loads as shown by Point X in Fig. 2. The cap loads are allocated to nine major river basins. The corresponding scenario is called the Allocation Scenario, with an estimated summer average *DO* concentration of 4.91 mg/l and a level of 7% time and space incursions of *DO*<3.0 mg/l in CB4-DW. The following explores alternative nitrogen and phosphorus reductions to achieve similar *DO* conditions as in the Allocation Scenario in CB4-DW.

The NP-Trade Scenario. Municipal wastewater treatment plants contribute significant nitrogen and phosphorus loads to the Chesapeake and influence CB4 water quality. In some cases, operational costs are less for reducing phosphorus than for reducing nitrogen at wastewater treatment plants. Thus, we explore an alternative hypothetical nitrogen and phosphorus reduction allocation which would allow the five basins that have a significant influence on CB4-DW to have less nitrogen reduction but more reductions in phosphorus. The five basins having a significant influence on CB4-DW are the Susquehanna, Western Shore Maryland, Patuxent, Potomac, and Eastern Shore Virginia basins (Koroncai et al., 2003). In these basins the hypothetical allocation would have a lower total phosphorus load but a higher total nitrogen load than the Allocation Scenario. If the paired loads remain on the tradeoff curve, then CB4-DW should still meet the same water quality as in the Allocation Scenario, although this would need to be ultimately confirmed by a verification scenario. Any point of the *DO*=4.91 mg/l tradeoff-curve in Fig. 2 would be a potential candidate for this hypothetical tradeoff.

For example, at Point Z, the *TP* load is 55.5% and the *TN* load is 69% of the PR2000 load. Considering errors in the model and the response surface, and to avoid tradeoffs causing possible adverse effects on water quality attainment in other designated use areas, the proposed *TN* load could be conservatively set to 65% of PR2000 (Point Y). The *TN* and *TP* loads at Point Y are 84.05 and 4.81 kt/year, respectively. This NP-Trade Scenario decreases the *TP* load by 1.00 kt/year, but increases the *TN* load by 4.67 kt/year from the Allocation Scenario.

The hypothetical tradeoff allows an additional 1.00 kt/year of *TP* from the Susquehanna, Western Shore Maryland, Patuxent, Potomac, and Eastern Shore Virginia basins to be traded for 4.67 kt/year of nitrogen load increase. The NP-Trade Scenario yields average summer *DO* in CB4-DW at 4.95 mg/l, a slight improvement over the initial target of the Allocation Scenario. Such a hypothetical tradeoff may reduce the overall cost of compliance with the water quality standard. The next section discusses the mechanisms and nutrient dynamics of *TN*-*TP* tradeoff on water quality attainment.

Discussion

The Basis of Nutrient Equivalence for TN-TP Trading

The nutrient reduction for *DO* improvement is mainly through the reduction of algal biomass. Algal growth requires light and nutrients, such as dissolve inorganic nitrogen (*DIN*), dissolved inorganic phosphorus (*DIP*), and silica (for diatoms). Algal production also increases as a function of light intensity until an optimal intensity is reached (Cerco, 1995).

Based on our study, in 99% of the cases, silica is not a limiting factor for algae in the Chesapeake and is, therefore, excluded from our discussion.

The Chesapeake Bay Estuarine Model uses the Michaelis-Menten saturation kinetics to simulate nutrient-dependent algal growth. Appling the principal of Liebig's "law of the minimum" (Odum, 1971) growth is determined by the nutrient in the least supply:

$$\text{minimum}\ [DIN/(K_{DIN} + DIN),\ \text{DIP}/(K_{DIP} + DIP)],$$

where, K_{DIN} and K_{DIP} are the half-saturation constants for *DIN* and *DIP* uptake by algae. The K_{DIN} and K_{DIP} for total phytoplankton have a range in the literature of 0.001 to 0.4 g(N)m^{-3}, and 0.0005 to 0.03 g(P)m^{-3} (USEPA, 1985) . The half-saturation constants are set at 0.02 g(N)m^{-3} and 0.0025 g(P)m^{-3}, respectively, in the model (Cerco and Noel, 2004).

If the system is originally phosphorus limited, a further decrease in *DIP* intensifies the phosphorus limitation. Therefore, the system can receive a higher nitrogen load with the decrease of phosphorus load, and still yield a similar level of algal biomass and *DO* as the original system.

Based on modeled daily *DIN*, *DIP*, and light intensity in Bay segments (Fig. 3), we determined which to be the dominant factor limiting algal growth on any day. We then calculated relative frequencies of daily limitations among *DIN*, *DIP*, and light in the spring (March-May) and summer (June-August) seasons (Figs 4 and 5). In the Allocation Scenario, phosphorus-limitation is frequent in the upper and mid-Bay, including CB1, CB2, CB3, and CB4, particularly in the spring (Fig. 4). With the hypothetical *TN-TP* trade (Fig. 5), reduced *TP* loads cause increased phosphorus limitation compared to the Allocation Scenario and nitrogen limitation is reduced with the increase of *TN* load. Both scenarios were simulated with the same amount of sediment loads. The decrease of light-limitation by the *TN-TP* trade is in part due to the increased frequency of phosphorus limitation but also reflects in part a reduction of algal production particularly in the tidal fresh and oligohaline upper Bay due to increasing overall nutrient limitation (Fig. 6). Consequently, water clarity improves, the light extinction coefficient (Ke) decreases (Fig. 7), and summer bottom *DO* increases very slightly in the upper Bay (Fig. 8). These plots indicate that the *TN*-*TP* load trade (Point Y of Fig. 2) slightly improves water quality in the upper Bay. The following section further discusses nitrogen versus phosphorus limitation both geographically and seasonally.

Geographical Variation of Nitrogen- and Phosphorus-Limitations

An acceptance of a *TN*-*TP* trade should be based not only on non-degradation or improvement in key regions such as CB4-DW, but also on the condition that no significant degradation of water quality occurs in other designated use areas.

The geographical variation in nitrogen and phosphorus limitation in the Chesapeake is primarily due to the nitrogen and phosphorus composition of the loading sources. Monitoring and research indicates that phosphorus is more limiting in the upper Bay, and nitrogen is more limiting in the lower Bay (D’Elia et al., 1986; D’Elia et al., 1992; Cerco, 1995). At the head of tide (i.e., the fall-line) of the Susquehanna River in the upper Bay, mass loading of *DIN* to *DIP* is about 139:1 N:P. Algae take up nitrogen and phosphorus at a ratio of about 7:1 by mass (Redfield et al., 1966), and will deplete phosphorus before nitrogen in the upper Bay. The *DIN*/*DIP* ratio of the water entering from the ocean in the lower Bay is about 1.3:1. Algae in the lower Bay (e.g., CB7 and CB8), taking up nitrogen and phosphorus at the ratio of 7:1, will deplete nitrogen before phosphorus. Figure 9 shows that *DIN*/*DIP* ratio is greater than 7 in the upper Bay (CB1-CB4) in both the Allocation and NP-Trade scenarios. The latter scenario has a higher *DIN*/*DIP* ratio than the former, and intensifies P-limitation in the upper

Bay.

In contrast, the lower mainstem Bay (CB5-CB8) has low *DIN*/*DIP* ratios, and is predominately nitrogen limited. The *TN*-*TP* trade with increasing total nitrogen loads can have an adverse effect. In both scenarios, in CB8, almost everyday in the spring and summer is nitrogen limited (Figs. 4 and 5). Compared to the Allocation Scenario, after the *TN*-*TP* trade, the increased nitrogen loads by the N-P trade increase algae levels very slightly (Fig. 6). Consequently, *DO* in CB8 is slightly decreased in the Spring, but the *DO* criteria is still fully achieved, since the *DO* criterion is already attained in CB8 even in the PR2000 Scenario (partly due to the influence of the ocean, which has much lower nutrient level than the upper Bay). Consequently, there is no adverse effect on the lower Bay's tidal tributaries.

Segments CB4 through CB6 are transitional between the two regions of the predominately phosphorus limited upper Bay versus the predominately nitrogen limited lower Bay. The number of days with phosphorus limitation increases slightly in this region after the *TN*-*TP* trade (Figs. 4 and 5). In this region, changes in bottom *DO* are insignificant, especially in the summer critical season (Fig. 8), and the *DO* concentration still achieves the criteria attainment with the NP-Trade Scenario

The above discussion indicates that although reducing both nitrogen and phosphorus from the PR2000 level is important to attain water quality standards in the Chesapeake Bay, there is flexibility in the relative nitrogen versus phosphorus reductions to achieve an equivalent water quality response.

Seasonal Variation of Nitrogen and Phosphorus Limitations

To examine whether a *TN*-*TP* tradeoff is practical, we also need to investigate flow and seasonal effects.

The annual peak of algal biomass occurs in the spring, driven by the high flows and nutrient loads of the spring freshet, the annual incremental spring thaw of snow and ice melt in the watershed resulting in higher spring flows (Harding et al., 2002). The runoff from the watershed brings high nutrient levels with high *TN*:*TP* ratios (usually greater than 50:1 of N:P) of nonpoint source loads to the Bay, playing an important role on the Bay's eutrophication. Organic material of the spring bloom subsequently provides organic substrate for the development of a robust microbial community whose metabolic activities delete oxygen while regenerating nutrients that support a summer algal community.

Bottom nutrient releases come from organic nitrogen and phosphorus that have been deposited over a period time. Boynton et al. (1995) estimated the annual mean pool sizes for nitrogen and phosphorus: 87% of the total nitrogen in the sediments, 12% in the water column, and <1% in the biota; stocks of total phosphorus are similarly distributed, but the sediment stocks are even more dominant. In the summer, low Eh values associated with decay of the spring algae bloom in bottom sediments, promotes flux of phosphate and ammonia from the sediment to overlying waters. Compared to the spring freshet, the river discharge is reduced in the summer with lower *DIN*/*DIP* ratios which cause the Bay to have less phosphorus-limitation in the summer than in the spring.

In the Allocation Scenario, in the upper and middle Bay's designated use areas, CB2-CB5, the spring has more phosphorus limitation than the summer (Fig. 4). The hypothetical N-P trade intensifies phosphorus limitation in both spring and summer (Fig. 5). The increase of phosphorus-limitation from the Allocation Scenario to the NP-Trade Scenario is usually greater in the spring than in the summer. Consistently, the corresponding *TN*:*TP* ratios increase from the Allocation Scenario to the NP-Trade Scenario, with a greater increase in the spring than in the summer (Fig. 9). Consequently, the reduction of chlorophyll and improvement of water clarity are somewhat greater in the spring than in the summer, especially for CB4 (Figs. 6 and 7). Generally, water quality improves in both spring and summer after the *TN*-*TP* trade over the Allocation Scenario in the upper Bay.

Issue Related to TSS Loads

The total suspended solid (TSS) loads to the Bay, and other physical conditions, used in the nine scenarios of this study are the same as the 2000 Progress Scenarios, and only the *TN* and *TP* loads vary. In water quality implementation practice, nitrogen and phosphorus reductions are usually accompanied with TSS reduction, especially in nonpoint source controls. In a separate study, we ran 27 scenarios with variable *TN*, *TP*, and TSS loads, and found that the shapes (or curvatures) of *DO* attainment curves versus *TN* and *TP* loads (e.g., the *DO*=5.4 mg/l curve in Fig. 2) are virtually the same for the TSS load given by the PR2000 Scenario and for 80% of that amount. With more TSS reduction, the curve of *DO*=5.4 mg/l moves toward the point of *TN* and *TP* loads at 100% PR2000. This indicates that a greater TSS reduction would allow less nitrogen and phosphorus reductions to meet an equivalent *DO* water quality standard.

Conclusion

The continuous function of *DO* versus nitrogen and phosphorus loads from the response surface analysis provides tradeoffs in total nitrogen and phosphorus load controls to achieve a specific *DO* requirement in the Chesapeake. The tradeoff curves of total nitrogen and total phosphorus load provide information to explore flexible and/or cost-effective alternatives in nutrient reduction management. An effective tradeoff is one that would generally intensify an existing predominant nitrogen or phosphorus limitation. Whether the water quality is improved or degraded is dependent on the extent of the trade and the nitrogen-phosphorus conditions in local areas, which may vary temporally or geographically. We should avoid the tradeoff that degrades water quality. The acceptable *TN-TP* load tradeoff is that alternative load control yielding a similar or better water quality condition, and this should be verified by model and monitoring data.

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Figure captions.

Figure 1. Response of summer average DO in CB4-DW to TN-TP loads to the Bay. The TN and TP axes are loads as fraction of the PR2000 Scenario loads.

Figure 2. Contours of DO curve versus N-P loads for CB4-DW. The TN and TP axes are loads as fraction of the PR2000 Scenario loads.

Figure 3. Chesapeake Bay mainstem and the tidal portion of its major tributaries.

Figure 4. N-, P- and Light-limitations in surface water (Allocation Scenario) of eight mainsten segments in spring (“spr”) and summer (“sum”).

Figure 5. N, P and light limitations in surface water (NP-Trade Scenario) of eight mainsten segments in spring (“spr”) and summer (“sum”).

Figure 6. Surface chlorophyll concentration in spring and summer for the Allocation Scenario and the NP-Trade Scenario.

Figure 7. Light extinction coefficient (Ke) in spring and summer for the Allocation Scenario and the NP-Trade Scenario.

Figure 8. Bottom DO concentration in spring and summer for the Allocation Scenario and the NP-Trade Scenario.

Figure 9. DIN/DIP ratio in spring and summer for the Allocation Scenario and the NP-Trade Scenario.

Fig. 1

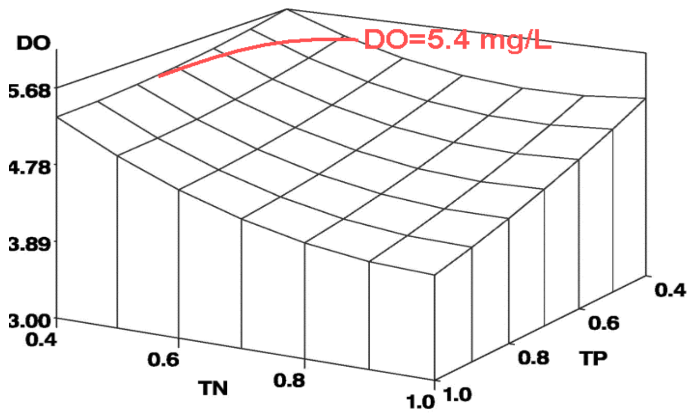


Fig. 2

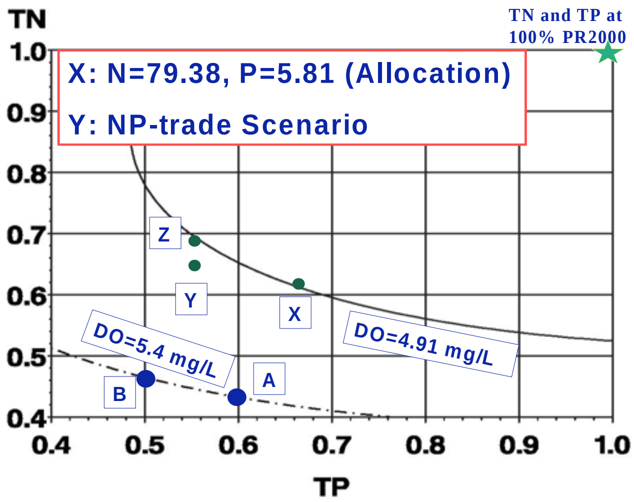
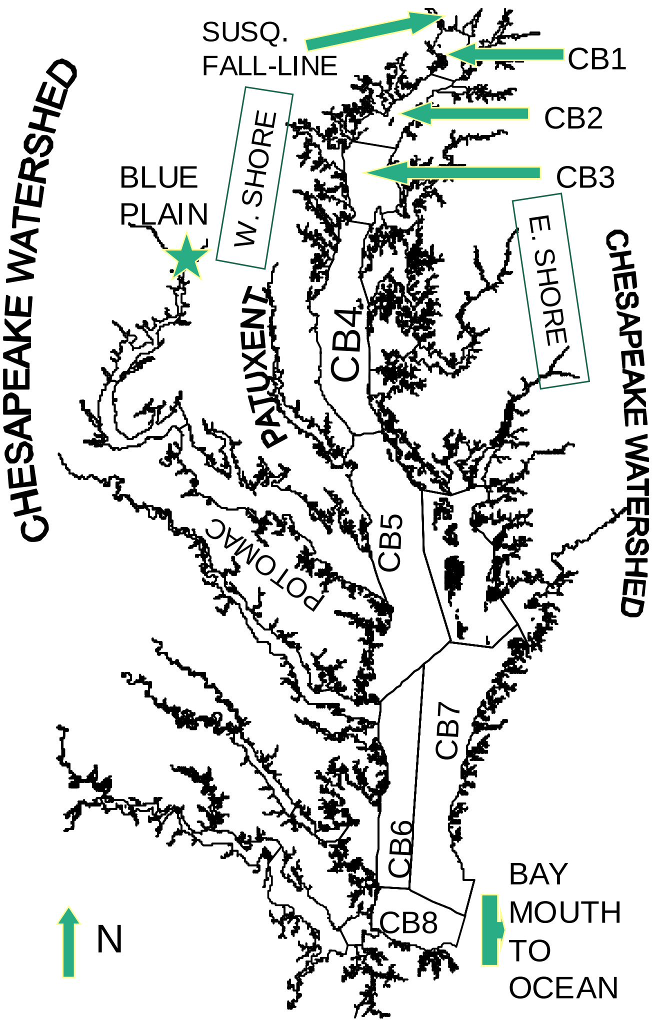
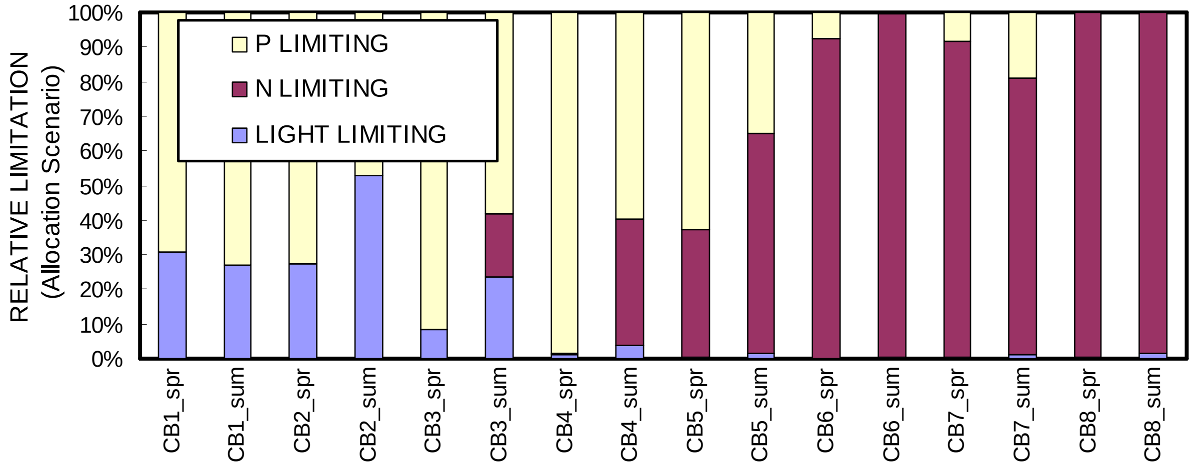

TN
TN and TP at
100% PR2000
X: N=79.38, P=5.81 (Allocation)
Y: NP-trade Scenario
Z
Y
X
DO=5.4 mg/L
DO=4.91 mg/L
A
B
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.4
0.5
0.6
0.7
0.8
0.9
1.0
TP

Fig. 3



SUSQ.
FALL-LINE
CB1
CB2
CB3
CHESAPEAKE WATERSHED
BLUE
PLAIN
W. SHORE
E. SHORE
CHESAPEAKE WATERSHED
PATUXENT
CB4
CB5
POTOMAC
CB7
CB6
CB8
BAY
MOUTH
TO
OCEAN
N

Fig 4.



RELATIVE LIMITATION
(Allocation Scenario)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
P LIMITING
N LIMITING
LIGHT LIMITING
CB1_spr
CB1_sum
CB2_spr
CB2_sum
CB3_spr
CB3_sum
CB4_spr
CB4_sum
CB5_spr
CB5_sum
CB6_spr
CB6_sum
CB7_spr
CB7_sum
CB8_spr
CB8_sum

Fig. 5

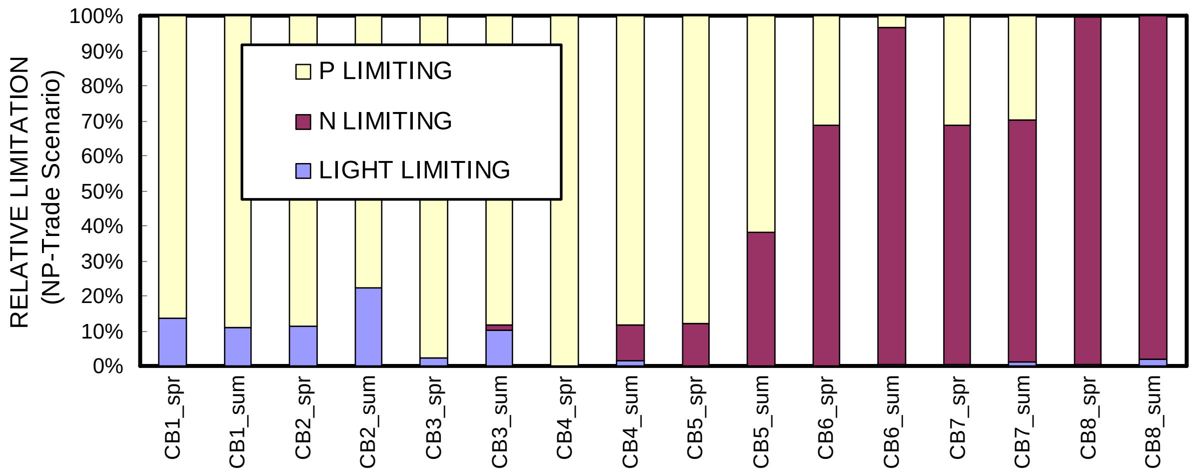
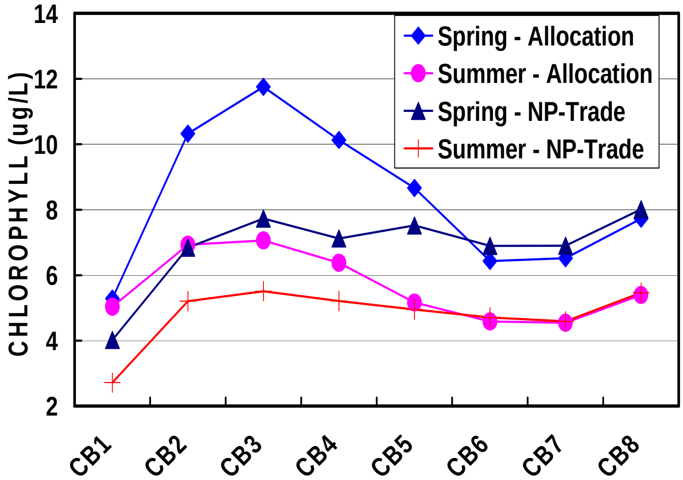
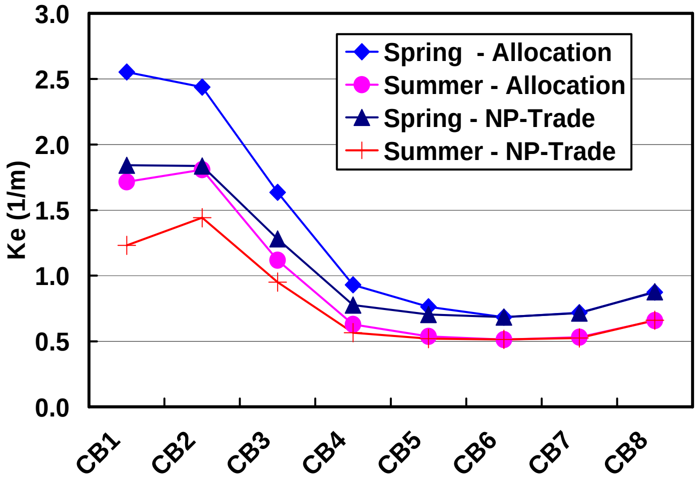

RELATIVE LIMITATION
(NP-Trade Scenario)
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
P LIMITING
N LIMITING
LIGHT LIMITING
CB1_spr
CB1_sum
CB2_spr
CB2_sum
CB3_spr
CB3_sum
CB4_spr
CB4_sum
CB5_spr
CB5_sum
CB6_spr
CB6_sum
CB7_spr
CB7_sum
CB8_spr
CB8_sum

Fig. 6



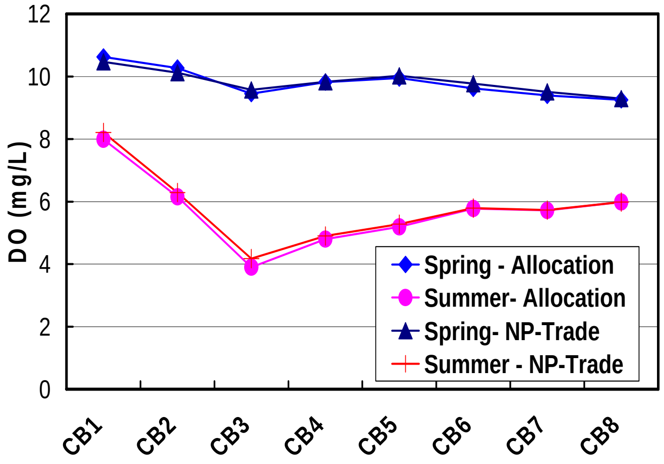
Spring - Allocation
Summer - Allocation
Spring - NP-Trade
Summer - NP-Trade
CHLOROPHYLL (ug/L)
14
12
10
8
6
4
2
CB1
CB2
CB3
CB4
CB5
CB6
CB7
CB8

Fig. 7



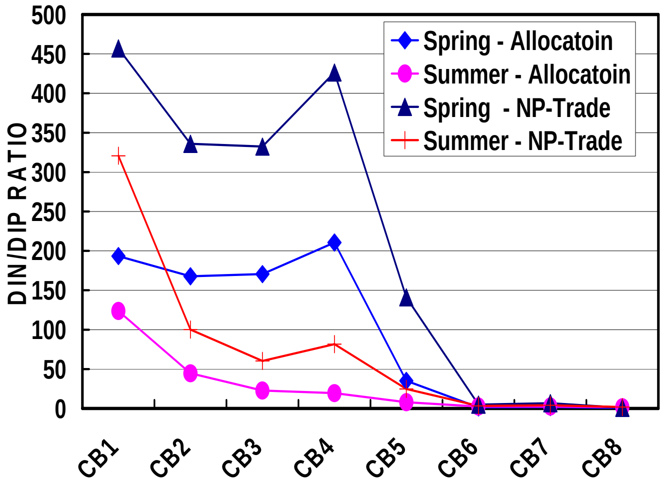
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Ke (1/m)
CB1
CB2
CB3
CB4
CB5
CB6
CB7
CB8
Spring - Allocation
Summer - Allocation
Spring - NP-Trade
Summer - NP-Trade

Fig. 8



12
10
8
6
4
2
0
DO (mg/L)
CB1
CB2
CB3
CB4
CB5
CB6
CB7
CB8
Spring - Allocation
Summer- Allocation
Spring- NP-Trade
Summer - NP-Trade

Fig. 9



500
450
400
350
300
250
200
150
100
50
0
DIN/DIP RATIO
Spring - Allocatoin
Summer - Allocatoin
Spring - NP-Trade
Summer - NP-Trade
CB1
CB2
CB3
CB4
CB5
CB6
CB7
CB8