Use of Surface Analysis on Water Quality Model Outputs to Assess Tradeoff of Nitrogen and Phosphorus Controls

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Abstract: Low summer dissolved oxygen (DO) in the Chesapeake Bay is primarily due to excessive nitrogen (N) and phosphorus (P) inputs. These nutrients cause algal blooms in the spring and summer with subsequent algal decay leading to summer oxygen depletion. In the Chesapeake Bay, N and P are generally higher than their half saturation constants for algal growth. Controlling both N and P loads are necessary due to spatial and temporal shift in nutrient limitation. Based on a set of water quality model runs, we used a surface analysis technique to establish a function of DO versus N and P loads, which plots as a 3-D surface. For a specific criterion for DO, a continuous curve of DO versus N and P loads that meet the DO criterion can be isolated. Each of the paired N and P loads on this tradeoff curve results in an equivalent level of DO, but usually at different costs. This paper explores cost-effective alternatives in nutrient reduction to achieve DO water quality standards 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, by analyzing DO surface plots and N-P tradeoff curves. The effects of nutrient limitation on algae growth, water clarity, and DO concentrations in two different N and P load scenarios are examined to understand the responses of water quality to N and P trades.

Keywords: N-P tradeoff; Surface analysis; Estuarine model; Nutrient limitation; Dissolved oxygen

1. INTRODUCTION

The Chesapeake Bay is one of the most productive estuaries in the world. Degradation of water quality, such as low dissolved oxygen (DO), was primarily due to excess nutrient inputs from the 166,000 km^2 watershed. The Chesapeake 2000 Agreement (CEC, 2000) set a goal of correcting all nutrient and sediment related problems to remove the Bay from the list of impaired waters by the year 2010. Throughout the history of the Chesapeake Bay Program partnership, there have been numerous analyses on the influence of nitrogen (N) and phosphorus (P) on tidal water quality conditions (Gillelan et al., 1983; Thomann et al., 1994). Early on, the important role that both N and P play in controlling algal production in tidally influenced waters was firmly established (Gillelan et al., 1983; D'Elia at al., 1992). During the development of nutrient allocations in 1992 the importance of controlling both N and P loads was reaffirmed (Boynton et al., 1995), as it was again in the 2003 development of N, P, and sediment Allocation Caps (CBPO, 2003). On the other hand, the relative importance of N versus P loads on water quality, and the tradeoffs between relative amounts of N-P control has been suggested (Thomann et al., 1994). However, so far there is no detailed analysis of how differential control of N-P affects the Chesapeake Bay's water quality. Wang et al. (2002) used the surface method (Thomann et al., 1994) to analyze the response of Chesapeake Bay's ecosystem to nutrient and sediment loads, indicating that there are many different N and/or P reductions to achieve a same level of water quality. This paper is a further application of the surface analysis method to analyze N-P tradeoffs for development of cost-effective load reductions to achieve water quality goals.

2. METHOD

Based on a set of water quality model results, we used a surface analysis technique (Thomann et al., 1994; Wang et al., 2006) to establish a function of DO as an dependent variable and N and P loads as independent variables, e.g., DO = f (N, P). According to a specific DO criterion, the required N-P loads can be acquired (Wang et al., 2006).

The year 2000 version (i.e., with 12920 model cells) of the Chesapeake Bay Estuarine Model (Cerco and Meyers, 2002) was used. Nine scenarios were designed. The 2000 Progress Scenario (PR2000) is our reference condition that is estimated the highest level of loads to the Chesapeake as in the future management plans to reduce nutrient loads and remove water quality impairments. The other eight scenarios involved have varying combinations of 0, 30, and 60 percent reductions from the PR2000 reference in N and P loads delivered to the tidal Bay waters. Each model scenario was run for 10 years using 1985-1994 hydrology, with a 5-minute time-step and daily or monthly outputs.

This paper focuses on the attainability of DO criteria in key designated-use-areas of the Bay (USEPA, 2003a) versus N-P 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. We examined how reductions of N-P loads cause reductions of algae and improvements in water clarity and DO. Algal limitation factors of N, P, or light, which reflect the effectiveness of nutrient reduction, also are examined. Note that this paper mainly analyzes total nitrogen (TN) and total phosphorus (TP) in the nutrient assessment.

3. N-P LOAD CONTROL FOR DO ATTAINMENT IN CB4-DW

3.1. DO response surface and its attainment curve for N-P equivalent

We used the surface analysis technique to establish a quadratic function of average summer DO in CB4-DW versus N-P loads to the Bay:

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

where, coefficients a through f are derived from the regression. The unit of DO is in mg/l, and N and P loads are expressed as a fraction of PR2000 conditions. Equation 1 can be plot as a 3-dimensional surface (Fig. 1).

The CB4-DW consists of more than 100 model cells. The DO criterion (USEPA, 2003b) for a deep water designated-use is equal or greater than 3 mg/L in each of the criteria months (June, July, August and September) for individual cells. A DO less than 3 mg/l is a violation of the criteria. The criteria violation (V) 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.

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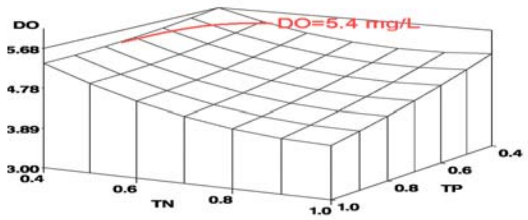

Figure 1. Response of summer average DO in CB4-DW to TN-TP loads to the Bay. The TN and TP axes are loads in fraction of PR2000

To ensure all cells in CB4-DW to have summer DO no less than 3 mg/l (i.e., zero violation), the summer average DO in CB4-DW would be much higher than 3 mg/l. From the nine model scenarios we can establish a relationship between criteria violation (V) and summer DO in CB4-DW:

$$DO = y(V) .$$

Denoting DO_o as the summer DO when violation, V, approaches zero:

$$DO_o = \lim_{V \to +0} y(V) .$$

It yields DO_o=5.4 mg/l, which is the minimum average summer DO in CB4-DW to ensure all cells of CB4-DW to have DO≥3 mg/l. Using a plane of DO=5.4 mg/l to cut the surface of Fig. 1 yields a 2-dimensional curve, called the DO=5.4 mg/l curve. The equation of this curve can be defined by substituting 5.4 for DO in Equation 1, and expressed as, in a general form,

$$g(N, P) = 0 . \qquad (2)$$

In this curve, the summer average DO of this 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 isopleths versus N-P loads. The N-P loads at any point of this curve would just meet the minimum DO criteria. This curve provides alternative N-P controls to meet the DO criteria. For example, from the initial N-P load in the PR2000 condition, a reduction of 56.7% N and 40% P (Point A, i.e., N and P at 43.3% and 60% PR2000), or a less reduction of N (53.4%) and more reduction of P (50%) (Point B) would both comply with the DO standard. We also call this curve the N-P tradeoff curve or N-P equivalent curve for a DO standard.

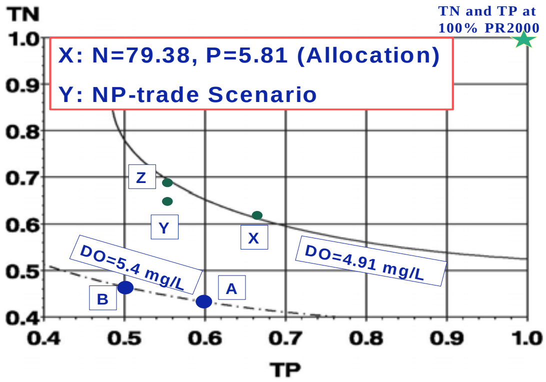

Figure 2. Contours of DO curve versus N-P loads for CB4-DW. The TN and TP axes are loads in fraction of PR2000

3.2. Using DO isopleths for N-P tradeoff

From the curve g(N, P)=0 (i.e., Equation 2), if P is specified, then N can be defined accordingly. The tradeoff rate, dN/dP, at any point can be obtained by the derivative of Equation 2.

The N-P tradeoff rates vary along the curve (Fig. 2). For example, at Point A, dN/dP = -0.268. The N:P tradeoff rate is -26.8:100 by referring to percent reduction from PR2000. By referring to mass reduction (the unit is kilo-ton/year throughout this paper), since the mass load of N=129.3 and P=8.664 kilo-ton/yr in PR2000, the N:P mass tradeoff rate is 4.00:-1. A decrement of one weight unit of P with an increment of 4.0 weight units of N is estimated to achieve the same DO response in the critical region of CB4-DW.

If the change of one loading constituent (e.g., P) is specified, for example,)P=-0.1, from 0.6 (Point A) to 0.5 (Point B) of PR2000, the tradeoff rate can be estimated from curve DO=5.4 mg/l of Figure 1. We have)N:)P = 0.033:-0.1. Referring to mass reduction, the N:P tradeoff is 4.92:-1.

3.3 Exploration of N-P trade allocations

Allocation Scenario. The preceding section discusses load reductions and N-P tradeoffs for full attainment of DO water quality standards in CB4-DW, which requires high N-P load reductions from PR2000 to reach a summer average DO of 5.4 mg/l. The Bay Program proposed an interim load cap of N and P loads to the Bay in 2007 which are 79.38 and 5.81 kilo-ton/yr respectively, which correspond to N=61.4% and P=67% of PR2000 as Point X in Figure 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% criteria violation in CB4-DW. The following explores an alternative N-P reduction to achieve similar DO conditions in CB4-DW.

NP-Trade Scenario. The Blue Plains municipal wastewater treatment plant in the District of Columbia contributes significant N-P loads to the Potomac River and influences CB4 water quality. The initial proposal of N-P load allocation to the Blue Plains was N at 60% of PR2000, and no further reduction of P, since P loads from the Blue Plains were already low. The Blue Plains' operational costs are less for reducing P than for reducing N. Here we are seeking an alternative N-P reduction allocation: allowing the District of Columbia and the other four basins that have significant influence on CB4-DW to have less N reduction but more P reduction from PR2000 -- in other words, these sources have lower P load but higher N load than the Allocation Scenario. Through such an N-P tradeoff, if the paired loads remain on the tradeoff curve, then CB4-DW should still meet the same water quality as in the Allocation Scenario. The N-P loads at any point of the DO=4.91 tradeoff-curve in Fig. 2 is a candidate. For example, at Point Z, the P load is 55.5% of PR2000 and the N load is 69% of PR2000, having a higher N load than that at Point X (61.4% of PR2000). Since the model and the surface analysis have uncertainty, to ensure the tradeoff causes no adverse effects on water quality attainment in other designated-use-areas, a safety factor is applied and the proposed N load is only at 65% of PR2000 (Point Y). The N and P loads are 84.19 and 4.81 kilo-ton/yr, respectively. This NP-Trade Scenario further decreases the P load by 0.998 kilo-ton/yr, but increases the N load by 4.809 kilo-ton/yr from the Allocation Scenario. The NP-Trade Scenario yields average summer DO in CB4-DW at 4.95 mg/l with a violation of 6.9%, a slight improvement over the initial target of the Allocation Scenario. Such a tradeoff significantly reduces Blue Plain's operation cost.

In summary, the DO criteria attainability is improved greatly from PR2000 to the Allocation Scenario due to significant N and P reductions. The water quality criteria in most designated-use-areas is further improved in the NP-Trade Scenario over the Allocation Scenario. The next section discusses the mechanism of effect of N-P tradeoff on water quality attainment.

4. DISCUSSION

4.1. Scientific background of nutrient equivalence for N-P trading

The nutrient reduction for DO improvement is mainly through the reduction of algal boimass. Growth of algae requires light and nutrients, such as dissolve inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), and silica (for diatoms). Algal production increases as a function of light intensity until an optimal intensity is reached (Cerco, 1995). Algal growth should not be controlled by reducing light, because water clarity is important to sea grasses and other living resources. Based on our study, in 99% 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-Menton saturation kinetics to simulate nutrient-dependent algal growth. Between DIN and DIP nutrients (in mg/l), according to Liebig's "law of the minimum" (Odum, 1971) growth is determined by the nutrient in least supply:

minimum [DIN/(Kn + DIN), DIP/(Kp + DIN)],

where, Kn and Kp are the half-saturation constants of DIN and DIP for algal growth. If the system is originally P-limited, a further decrease in P intensifies P-limitation. Therefore, the system can receive a higher N load with the decrease of P load, and yields a similar level of algal population and DO conditions as the original system. The N-P trade curves in Figure 2 display the equal effect on water quality by different N-P loads.

We assessed N and P concentrations and light intensities on a daily basis in spring (March to May) and summer (June to August) to determine which of them is the dominant limiting factor for major segments in the mainstem Bay. In the Allocation Scenario, P-limitation is predominant in the upper and mid Bay, including CB1, CB2, CB3, CB4, and CB5 (Fig. 3). With the N-P trade (Fig. 4), reduced P loads cause increased P limitation compared to the Allocation Scenario; light-limitation is reduced with decreased algal biomass; N limitation is reduced with the increase of N load. Both scenarios were simulated with the same amount of sediment loads. The decrease of light-limitation by the N-P trade reflects a reduction of algal production due to increasing overall nutrient limitation (Fig. 5, in both spring and summer).

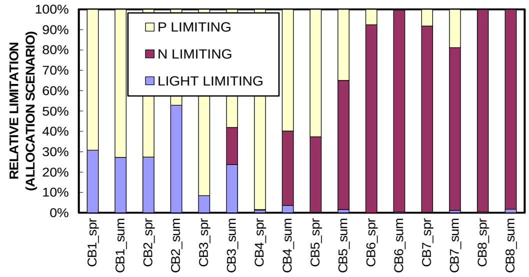

Figure 3. N, P and Light limitations in surface water (Allocation Scenario).

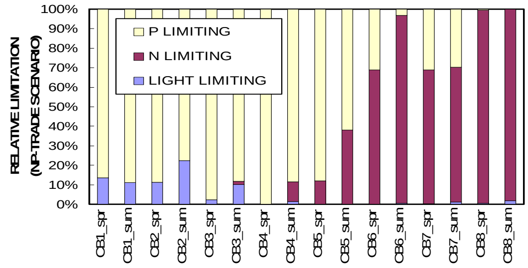

Figure 4. N, P and light limitations in surface water (NP-Trade Scenario)

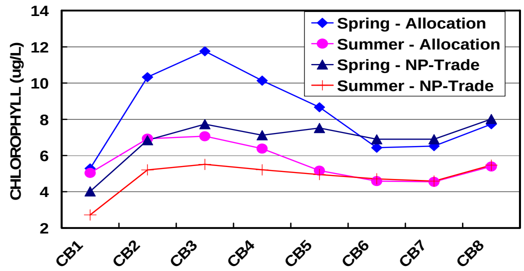

Figure 5. Surface chlorophyll concentration.

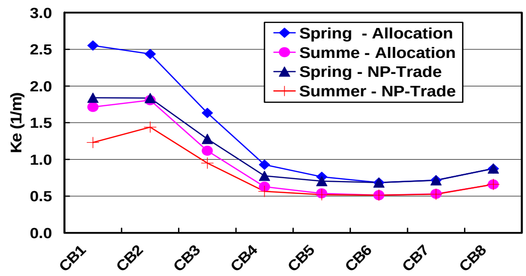

Figure 6. Light extinction (Ke).

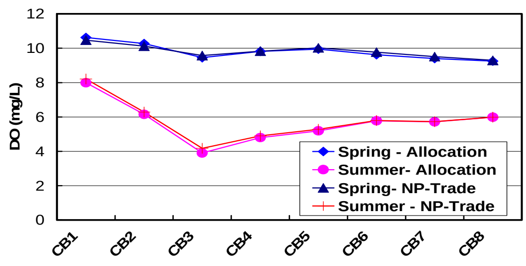

Figure 7. Bottom DO concentration (mg/L).

Consequently, water clarity improves (Fig. 6), and summer bottom DO increases (Fig. 7). These plots indicate that the N-P trade loads (Point Y of Fig. 2) improve water quality in most portions of the Bay, especially the middle and upper Bay, CB1-CB5. The following section further discusses N versus P limitation both geographically and seasonally.

4.2. Geographical variation of N- and P-limitation

The acceptance of an N-P trade is based not only on the improvement in CB4-DW, but also on the condition that no significant degradation of water quality occurs in other designated-use-areas.

The geographical variation in N and P limitation in the Chesapeake is primarily due to the N-P composition of the loading sources. Research indicates that P is more limiting in the upper Bay, and N is more limiting in the lower Bay (Cerco, 1995). At the fall-line of the Susquehanna River in the upper Bay, mass loading of DIN to DIP is about 139:1. Algae take up N and P at about 7:1 by mass (Redfield et al., 1966), and will deplete P before N in the upper Bay. The DIN/DIP ratio of the water entering from the ocean in the lower Bay is about 1.33:1 N:P. Algae in the lower Bay (e.g., CB7 and CB8), taking up N and P at the ratio of 7:1 will deplete N before P. Figure 8 shows that DIN/DIP ratio is greater than 7 in the upper and middle bay (CB1-CB5) in both the Allocation and NP-Trade scenarios. The latter scenario has higher N/P ratio than the former, and intensifies P limitation in the upper Bay. As addressed in the previous section, the N-P trade improves summer bottom DO in the upper and middle Bay (Fig. 7).

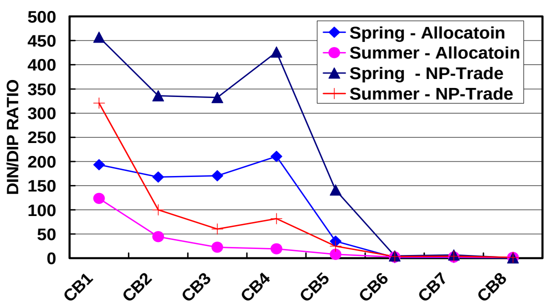

Figure 8. DIN/DIP ratio.

In contrast, the lower mainstem Bay (CB6, CB7 and CB8) has low N/P ratios, and is predominately in N limiting. The N-P trade with increasing N loads can have an adverse effect. In CB8, almost everyday in the spring and summer is with N limiting in both scenarios (Figs. 3 and 4). Compared to the Allocation Scenario, after the N-P trade, the increased N loads by the N-P trade increase algae (Fig. 5). Consequently, DO in CB8 is decreased, 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 CB6 and CB7 are transitional between the two regions of predominate P limiting versus predominate N limiting. The days with P limitation increase after the N-P trade (Figs. 3 and 4). There, the decrease of bottom DO is insignificant, especially in the summer critical season (Fig. 7), and the DO concentration still achieves the criteria attainment with the NP-Trade Scenario

The extent of the N-P trading is also important. We ran a scenario in which only the Blue Plains had the N-P trade, while other sources retained the Allocation Scenario. This resulted in lower DO criteria attainability in CB4 and in some other designated-use-areas, although the effect was not significant. The NP-Trade Scenario in this article involves five major contributing sources. A bay-wide scale of trading could be more beneficial, since it intensifies P-limitation. The above discussion indicates that although reducing both N and P from the PR2000 level is important to attain water quality standards in the Chesapeake Bay, there is flexibility in the relative N versus P reductions to achieve an equivalent water quality response.

4.3. Seasonal variation of N and P limitation

To examine whether an N-P tradeoff is practical, we also need to investigate flow and seasonal effects. The annual peak of phytoplankton biomass occurs in the spring, driven by the high flows and nutrient loads of the spring freshet (Harding et al., 2002). The organic material of spring bloom origin subsequently provides the organic substrate for the development of a robust microbial community whose metabolic activities delete oxygen while regenerating nutrients that support a summer phytoplankton 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 TN in the sediments, 12% in the water column, and <1% in the biota; stocks of TP 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 (as well as ammonia) from the sediment to overlying waters. The runoff from the watershed brings high nutrients with high N/P ratios (usually greater than 50:1) of nonpoint source loads to the Bay, playing an important role on the Bay's eutrophication. Comparing to the spring freshet, the river discharge reduces in the summer. All of the above reasons cause the Bay to have a weaker P-limitation in the summer than in the spring.

In the Allocation Scenario, in upper and middle Bay's designated-use-areas, CB2-CB5, the spring has more P limitation than the summer (Fig. 3). Nevertheless, the designed N-P trade intensifies P limitation in both spring and summer (Fig. 4). The increase of P-limitation from the Allocation Scenario to the NP-Trade Scenario is usually greater in the spring than in the summer. Consistently, the corresponding N/P ratios increase from the Allocation Scenario to the NP-Trade Scenario, with a greater increase in the spring than in the summer (Fig. 8). Consequently, the reduction of chlorophyll and improvement of water clarity are greater in the spring than in the summer, especially for CB4 (Figs. 5 and 6). The improvement of DO in the upper Bay's designated-use-areas seems slightly greater in the summer (the critical season for DO in the deep water of the Bay) than in the spring (Fig. 7), which may be due to reduced spring biomass causing improved bottom oxygen conditions and a subsequent reduction of bottom fluxes of N and P in the summer. Generally, water quality improves in both spring and summer after the N-P trade over the Allocation Scenario in the upper Bay.

Detailed analysis of hydrology in dry versus wet years, or spring freshet versus summer low flows on different patterns of N-P loads, and the change in the extent of N versus P limitation is beneficial for refining an N-P tradeoff strategy, however, is beyond the scope of this paper.

5. CONCLUSION

The continuous function of DO versus N-P loads from the surface analysis provides alternative N-P load controls to achieve a specific DO requirement in an ecosystem. Using tradeoff curves of N-P loads can provide cost-effective in nutrient reduction management.

6. REFERENCES

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

CBPO, *Chesapeake 2000 agreement nutrient and sediment allocation reports*, Chesapeake Bay Program Office, Annapolis, MD, USA, 2003.

CEC, C*hesapeake Bay Agreement, 2000 Amendments*, Chesapeake Executive Council, Annapolis, MD, USA, 2000

Cerco C.F., Response of Chesapeake Bay to nutrient load reductions, *J. Envir. Engrg.*, ASCE, 121(8), 549-557, 1995.

Cerco C.F., and M. Meyers, Tributary refinements to the Chesapeake Bay model, *J. Envir. Engrg.*, 126(2), 164-174., 2000.

D'Elia C.F., L.W. Harding, M. Leffler, and G.B. Mackiernan, The role and control of nutrients in Chesapeake Bay, *Water Sci. Tech.*, 26, 2635-2644, 1992.

Gillelan M.E., H. Haberman, G. Mackieman, B.J. Macknis, and H.W. Wells, *Chesapeake Bay: A framework for action*, USEPA Chesapeake Bay Program, Program Report, Annapolis, MD, USA, 1983.

Harding L.W., M.E. Mallonee, and E.S. Perry, Toward a predictive understanding of primary productivity in a temperate partially stratified estuary, *Estuar. Coastal Shelf Sci*. 55, 437-463, 2002.

Odum, E., *Fundamentals of Ecology*, 3rd ed., W.B. Saunders, Philadelphia, PA, pp. 106-7, 1971.

Redfield A., B. Ketchum, and F. Richards, The influence of organism on the composition of sea-water, *The Sea, Volume II*, Interscience Poblushers, New York, NY, 26-48, 1966.

Thomann R.V., J.R. Collier, A. Butt, E. Casman, and L.C. Linker, *Response of the Chesapeake Bay Water Quality Model to Loading Scenarios*, CBP/TRS101/94, USEPA CBPO, Annapolis, MD, USA, 1994.

USEPA, *Technical support document for identify-cation of Chesapeake Bay designated uses and attainability*, EPA903-R-03-004, USEPA CBPO, Annapolis, MD, USA. 2003a.

USEPA, *Ambient Water Quality Criteria for Dissolved Oxygen, Water Clarity and Chlorophyll a for the Chesapeake Bay and Its Tidal Tributaries*, EPA903-R-03-002, pp170, USEPA CBPO. Annapolis, MD, USA, 2003b.

Wang, P., L.C. Linker, and R. Batiuk, Surface analysis of water quality response to load, *Estuarine and Coastal Modeling*, Proc 7th international conference, November, 2001, St. Petersburg, FL, USA, p566-58, 2002.

Wang, P., L.C. Linker, R.A. Batiuk, and C.F. Cerco, Surface analysis of Chesapeake Bay water quality response to different nutrient and sediment loads, *J. Envir. Engrg.*, 132, 377-383, 2006.