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THE CONSEQUENCES OF NUTRIENT ENRICHMENT IN ESTUARIES

A Report to the Eutrophication Program,
U. S. Environmental Protection Agency Chesapeake Bay Program
Grant No. R-806-189-010
Thomas Pheiffer, Project Officer

From

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ABSTRACT

A "paper study" was conducted to determine the consequences of nutrient enrichment in an estuary. First, a classification scheme was developed to assign a "Level of Nutrient Enrichment" to a water body based on concentrations of Total Phosphorus and Total Nitrogen. The impacts of nutrient enrichment on the various uses of estuaries there were described and assessed. Finally, "safe" nutrient levels for Chesapeake Bay and its tributaries were recommended.

EXECUTIVE SUMMARY

In response to a Eutrophication Work Plan (EPA, 1977) research was undertaken to determine the consequences of nutrient enrichment in estuaries. This research was directed by the Work Plan to proceed with the assumption that nutrient enrichment in moderation results in increasing productivity but that at some point, this may decline dramatically. This hypothesis is represented graphically by Figure ES-1.

The initial task was to make the assessment of nutrient enrichment more quantitative. Research in lakes has shown that the average level of biomass (as measured by chlorophyll a concentrations), the clarity of the water (as measured by Secchi depth), and the oxygen balance (as measured by the hypolimnetic oxygen depletion rate) are correlated with total phosphorus concentrations in the lake (and also total phosphorus loading rates). Therefore, it appeared reasonable to assume that total nutrient concentrations might play a similar role in estuaries.

A review of nutrient levels observed in estuaries indicated that the variation was great. Nutrient levels in the Chesapeake Bay system varied over several orders of magnitude, as shown in Figure ES-2. A classification system was proposed (Table ES-1) which has nutrient concentrations vary logarithmically as nutrient enrichment levels vary arithmetically. Although many marine systems are nitrogen-limited, it is not clear that this will be true for all cases. Therefore, total phosphorus concentrations have been

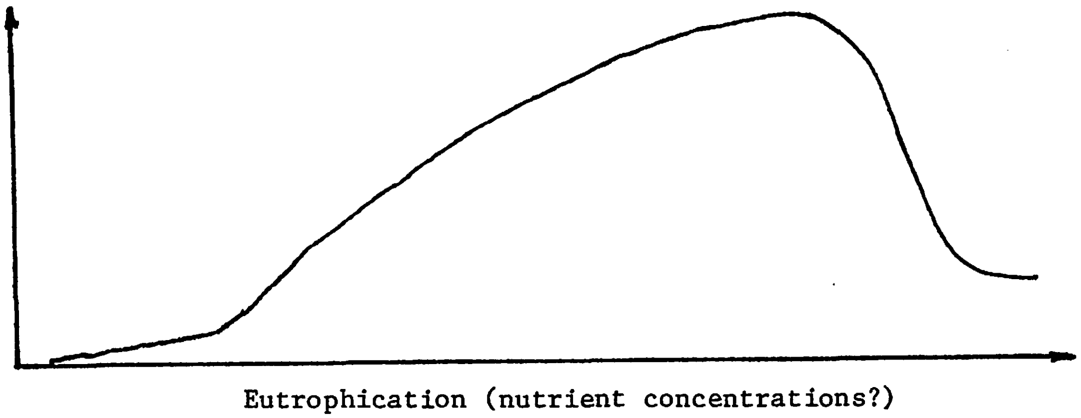

Figure ES-1. Hypothetical response of estuarine ecosystem to increasing levels of nutrient enrichment (from Eutrophication Work Plan, EPA, 1977).

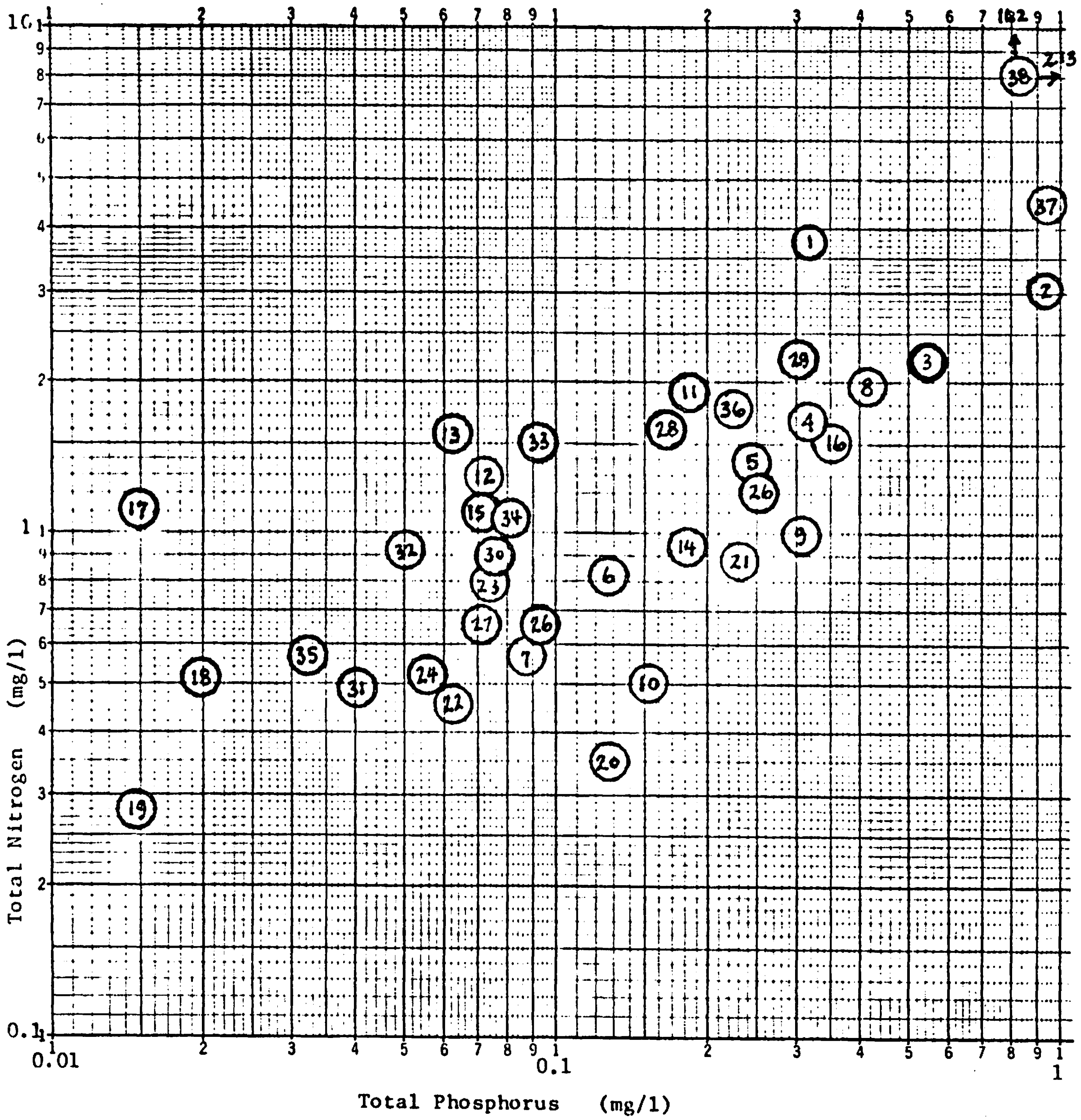

Figure ES-2. **Total Phosphorus and Total Nitrogen concentrations observed in the estuaries of the Chesapeake Bay system.**

Key to Figure ES-2.

1	Algal Bloom		Loftus et al, 1972
2	Fall Line	Patuxent River	Flemer et al, 1970
3	Sta. 1	Patuxent River	
4	Sta. 4	Patuxent River	
5	Sta. 6	Patuxent River	
6	Sta. 10	Patuxent River	
7	Sta. 14	Patuxent River	
8	Eastern Branch, Elizabeth River		Neilson & Sturm, 1977
9	Southern Branch, Elizabeth River		
10	Mouth, Elizabeth River		
11	Potomac River Fall Line		Guide & Villa, 1971
12	James River Fall Line		
13	Susquehanna River Fall Line		
34	Rappahannock River Fall Line		
14	Mouth, Pagan River		Rosenbaum & Neilson, 1977
15	Head, Pagan River		
16	Middle reaches, Pagan River		
17	York River near West Point		Sturm & Neilson, 1978
18	York River near Gloucester Point		
19	York River mouth		
20	James River mouth		Neilson & Ferry, 1978
21	James River in turbidity maximum		
22	Poquoson River mouth		Neilson, 1976
23	Poquoson River		
24	Back River, Virginia		
25	Little Creek Harbor		
26	Lynnhaven Bay		
27	Lynnhaven Bay mouth		
28	Wicomico River, MD		Hydroscience
29	Wicomic River - headwaters		
30	Wicomico River mouth		
31	Chesapeake Bay near mouth of Potomac River		
32	Chesapeake Bay near Baltimore Harbor		
33	Chesapeake Bay below Susquehanna River		
35	Potomac River mouth		
36	Back River,Md	Rocky Point	Ferguson & Simmons, 1974
37	Back River, Md	Stansbury Point	
33	Back River, Md	Cox Point	

TABLE ES-1. Classification Scheme for Nutrient Enrichment in Estuaries.

Level of Nutrient Enrichment	Total Nitrogen mg/l	Total Phosphorus mg/l
0	0.003	0.0004
1	0.010	0.001
2	0.032	0.004
3	0.10	0.014
4	0.32	0.044
5	1.0	0.14
6	3.2	0.44
7	10	0.4
8	32	4.4
9	100	13.8
10	320	44

calculated for each total nitrogen concentration according to the Redfield ratios.

The second task was to relate ecosystem consequences to levels of nutrient enrichment. The terms "ecosystem health" and "ecosystem productivity" are nebulous and difficult to define in any quantitative fashion. Therefore, efforts were devoted to determining the impacts of nutrient enrichment on water uses. Increased levels of inorganic nutrients (primary impacts) primarily damage only uses of freshwater. Additionally, the levels necessary to impair uses generally are much higher than levels observed in estuaries. Increased plant biomass (secondary impacts) reduces water clarity and its aesthetic value. Additionally, this alters the oxygen balance and the structure of the algal community. Increased levels of detritus in the system (tertiary impacts) alter sediment characteristics (and therefore, also the benthic communities) and generally reduce oxygen levels. The overall impacts of nutrient enrichment are shown in Table ES-2.

It has been recommended that:

1) Analyses of nutrient enrichment should be made more quantitative.
2) The estuarine analog to total phosphorus in lake ecosystems should be determined.
3) System responses should be determined as a function of the estuarine analog determined in (2).
4) An overall index of nutrient enrichment should be developed to facilitate comparisons and allow temporal trends to be charted.
5) More scientific studies are needed to determine the rates and routes of nutrient transfer. Field studies are especially important.
6) To be safe, nutrient concentrations in the Chesapeake Bay system should be kept below Enrichment Level 4, or Total N = 0.32 mg/l and Total P = 0.044 mg/l.
7) Environmental managers should consider nutrient concentrations above Level 5 (Total N = 1.0 and Total P = 0.14) to be a warning or danger signal.

Level of Nutrient Enrichment	Public Drinking Water Supply	Livestock Drinking Water	Irrigation	Freshwater Aquatic Life
0	Acceptable	ACCEPTABLE	Acceptable Increased Nutrient Levels Could Enhance Usefulness	Acceptable (oligotrophic)
1	Minor Purification Required			
2				(mesotrophic) Problems Arise Periodically
3	More Extensive Treatment Needed			
4				(eutrophic) Marginally Acceptable
5	Marginally Acceptable and Sometimes not Acceptable	Algae May Clog Intake Pipes	Generally Acceptable But Algae Could Clog Pipes and Pumps and There Could be Nitrate Build-up in Ground Water	Generally Not Acceptable
6				
7	Not Acceptable	Marginally Acceptable		
8				
9		Not Acceptable		
10				

TABLE ES-2. Impacts of Nutrient Enrichment on Water Uses
a) uses limited to freshwater portions of estuaries.

Level of Nutrient Enrichment	Marine Aquatic Life	Recreation and Aesthetics	Industry	Commercial Shipping
0	Acceptable (oligotrophic)	Acceptable	A C C E P T A B L E	A C C E P T A B L E
1				
2	Problems arise Infrequently or due to Local Conditions	Infrequent Episodes when not Acceptable		
3				
4	(mesotrophic) Marginally Acceptable	Frequent Episodes when not Acceptable		
5	(eutrophic) Marginally Acceptable		Algae May Clog Intake Pipes	
6	Generally Not Acceptable	Not Acceptable		
7				Problems May Arise with Hydrogen Sulfide
8			Not Acceptable for some Purposes	
9				
10				

TABLE ES-2. Impact of Nutrient Enrichment on Water Uses
b) uses which apply to brackish portions of estuaries.

INTRODUCTION

Eutrophication was identified as one of three high priority problem areas to be addressed by the U.S. Environmental Protection Agency's Chesapeake Bay Program (EPA, 1980a). In response to this ranking, a Eutrophication Work Group was formed and a Eutrophication Work Program was formulated (EPA, 1977). This program identified five principle tasks:

A. Operational Definition of the Study Problem
B. Ecosystem Simulation
C. Data Acquisition and Synthesis
D. Identification of Control Alternatives
E. Decision Analysis

In October 1978 the Chesapeake Research Consortium, Inc. was awarded a grant entitled "Definition of Chesapeake Bay Problems of Excessive Enrichment or Eutrophication" which addresses many of the components of Task A. The work presented in this report concerns Task A.4 - Relation Between Eutrophication Level and Ecosystem Consequences. This and the other subprojects of the CRC grant were "paper studies"; that is, the literature and the available data sources were utilized. No field or laboratory studies to generate new data were planned, authorized or undertaken.

One item not identified in the Work Program which was carried out was the organization of a symposium on the effects of nutrient enrichment in estuaries which was held in Williamsburg, Virginia, in May, 1979. The papers presented at that symposium especially the invited review papers, have been used extensively in the preparation of this report; they are identified in later sections by the author's names and an asterisk and are listed separately in the references.

Approach to the Problem

The Work Program "established a series of tasks and described in some detail their content and interrelationships" (EPA, 1977). Since this document provided the framework for the research conducted, it is appropriate to review the conceptual model of eutrophication upon which the Work Group based these tasks. This conceptual model is perhaps best represented by Figure 1 and the following quote:

> "In the absence of nutrients, there is no aquatic ecosystem. As the nutrient concentrations increase, the ecosystem productivity increases. The hypothesis is that at some point a further increase in nutrient concentrations will cause the ecosystem health to decline (perhaps drastically)."
>
> EPA, 1977

The hypothesis described provides, in general terms, a coherent and logical, philosophical approach to the problem. However, Figure 1 implies extensive knowledge of how ecosystems work in a very quantitative and precise fashion. Difficulties arise when one attempts to construct such a diagram. For example, the abscissa in Figure 1 is labelled "Eutrophication", yet this term is poorly defined, at least in any quantitative sense, and is believed to be totally inappropriate for estuaries by the author and others (Cronin, 1980a). Similarly, ecosystem health and productivity (the ordinate values) are general, non-quantifiable terms and they refer to quite dissimilar attributes of systems.

The approach taken by the author has been to opt for the second label on the X-axis in Figure 1, namely, nutrient concentrations. In the next chapter, a classification scheme to define levels of nutrient enrichment is proposed. The task of defining ecosystem health and productivity was judged to be futile and hopelessly difficult. Instead, the impacts of nutrient enrichment on beneficial uses of estuaries have been assessed, and these are presented in the following chapter. The final chapter of the report includes some conclusions and recommendations.

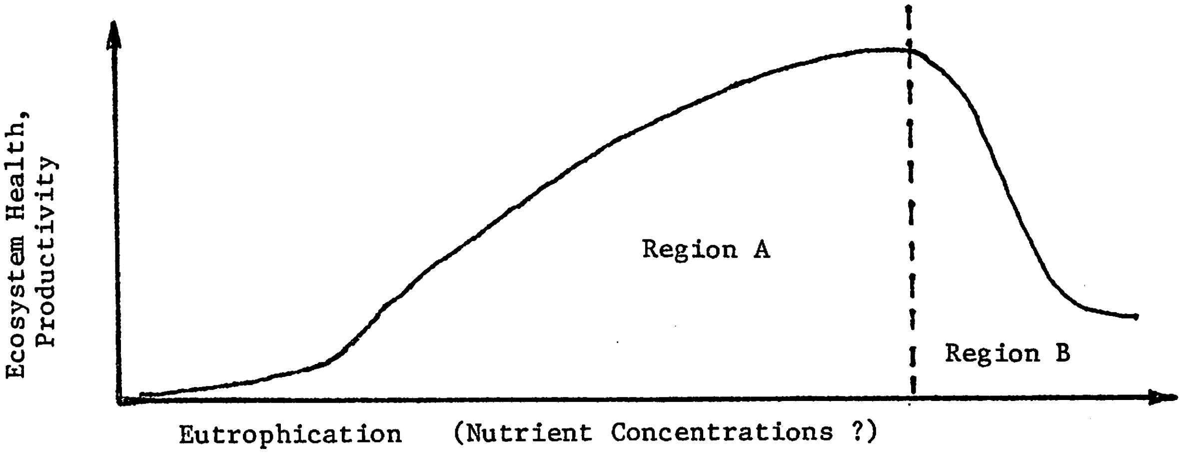

Figure 1. Hypothetical estuarine ecosystem response to increasing levels of nutrient enrichment. (From EPA, 1977)

MEASURING NUTRIENT ENRICHMENT

Implicit in the approach outlined in the Work Plan (EPA, 1977), is the existence of a measure or index of nutrient enrichment. The value of indexes is clear (Train, 1972). For this case, an index would define the status of an estuary with respect to nutrient enrichment and thereby allow temporal trends to be charted and different geographical areas to be compared (See Task A.2 and Figure 4 of the Work Program for specific intended uses of the index.). Use of the term index, rather than variable, implies that the Work Group believed that a combination of environmental factors was important and that some formulation incorporating all of these factors would provide a better measure of the level of enrichment than any single factor.

Water quality indices have been used in the United States (Ott, 1978), but not to the same extent as air quality and economic indexes. McErlean and Reed (1979) reviewed and evaluated many water quality indexes with respect to their applicability to nutrient enrichment in estuaries. They also utilized a DELPHI approach to formulate an estuarine index of enrichment. However, they were not able to test this proposed index. Additionally, neither it nor any other water quality index has been used widely in assessing nutrient enrichment or other water quality problems in estuaries (Ott, 1978). Thus, although the concept of an index of nutrient enrichment for estuaries is an appealing one, no true index exists at present. Therefore, an alternate method to quantify nutrient enrichment was needed.

Intuitively, one would expect nutrient concentrations in an estuary to increase with increasing nutrient enrichment. This might not occur in all instances, nor is there likely to be an exact formula relating nutrient concentrations to nutrient enrichment levels. Nevertheless, for the moment nutrient concentrations appear to be the best available measure of nutrient enrichment. Since phosphorus concentrations have been used in the assessment of eutrophication problems in lakes, some of the findings of lake researchers will be reviewed in the next section. In the following section, nutrient levels observed in estuaries will be presented and in the final section of this chapter, a classification system based on nutrient concentrations will be proposed.

Eutrophication in Lakes

In a recent article, Harris (1980) addressed the response of phytoplankton to variability in the environment. While much of the discussion concerns phytoplankton ecology, the paper also covered models and water quality management. Harris divided the models currently being used into two general types: empirically based models and kinetic, mass-balance models. It is his opinion that the mass-balance models do not adequately represent the temporal and spatial scales of variability in the environment. Therefore he concludes that:

> "Clearly the complex mass-balance models lack biological realism at a number of scales and ... they may achieve generality, but they lack both realism and precision. The predictions are therefore not to be trusted." (Harris, 1980)

The empirical models of the Vollenweider-type relate average chlorophyll levels to the amount of total phosphorus in the system. This approach "has generality and realism; the precision may be low but the model is valid and the predictions do work" (Harris, 1980). Although Vollenweider's work has been seminal, most of his publications are not readily available to American readers. Fortunately his work, and that of many other lake researchers, has been summarized in a report on the North American portion of the OECD Eutrophication Project (Rast and Lee, 1978). Very briefly, phosphorus levels appear to control phytoplankton levels in most lakes. Average chlorophyll concentrations, Secchi depth readings and hypolimnetic oxygen depletion rates have been shown to be correlated with a phosphorus loading function, as indicated in the following three figures from Rast and Lee (1978). Note that L(P) = the areal total phosphorus loading rate (in mg P/square metre/year); q_s = hydraulic loading (in metres/year); $\bar{z}$ = the mean depth (in metres); and t_w = hydraulic residence time (in years) = $\bar{z}/q_s$. P_∞, the steady state total phosphorus concentration in the lake, has been shown to be equal to the total phosphorus loading function, $(L(P)/q_s) \;/\; (1 + \sqrt{\bar{z}/q_s})$ (Rast and Lee, 1978). Thus, either the external loading or the total phosphorus concentration in the water column can be utilized in assessing conditions in a lake.

Although these empirical relationships are general and imprecise, they provide guidance to engineers and managers who seek to reverse the eutrophication process and ameliorate its negative effects. They have been used to design remedial measures in a number of lakes, for example Medical Lake (EPA, 1980b), Lake Temescal (EPA, 1980c), and Lake Cobbossee (EPA, 1980d).

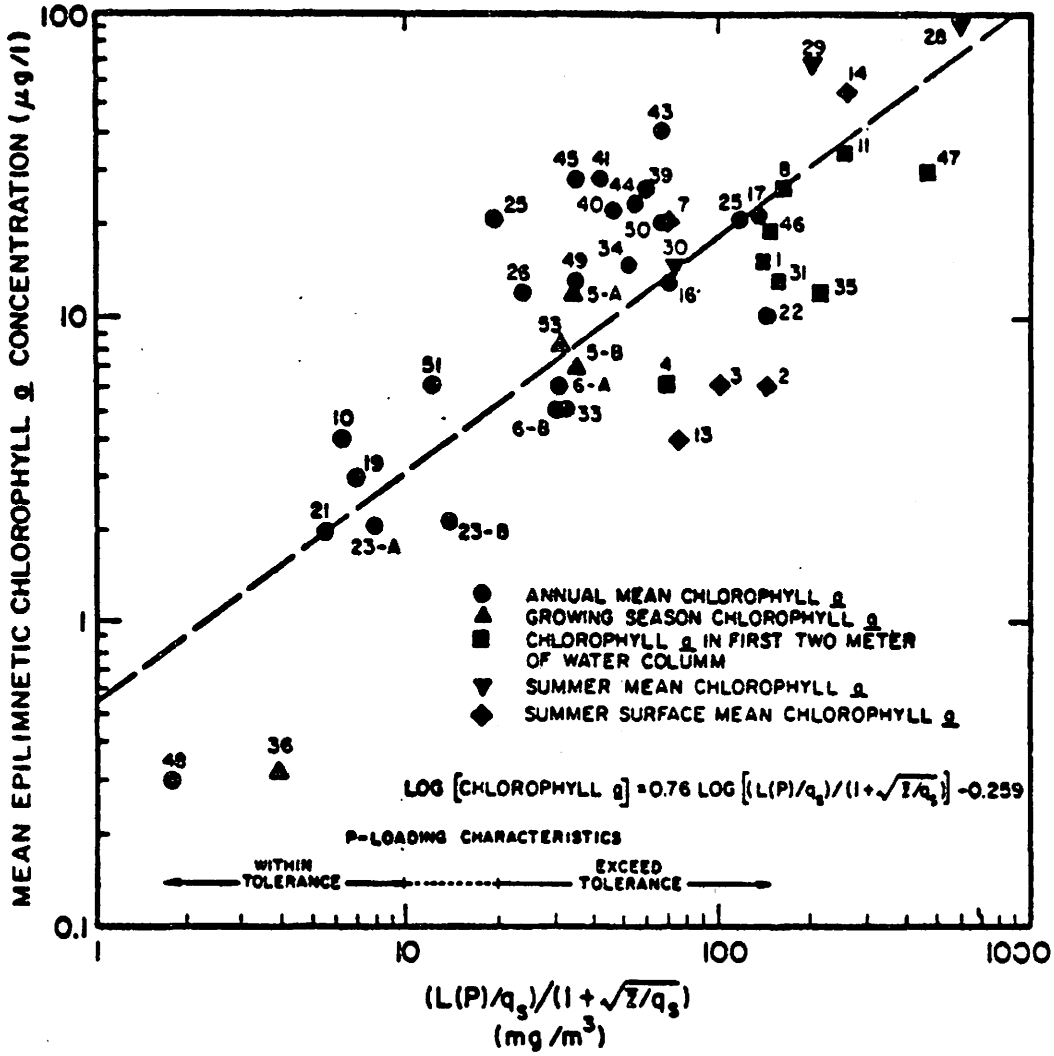

Figure 22. US OECD Data Applied to Vollenweider Phosphorus Loading Characteristics and Mean Chlorophyll a Relationship

Figure 2. Lake data showing the relationship between the phosphorus load (abscissa) and the average level of plant biomass (ordinate). (Figure 22 from Rast & Lee, 1978).

Figure 3. Lake data showing the relationship between the phosphorus load (abscissa) and clarity of the water (ordinate). (Figure 23 from Rast & Lee, 1978).

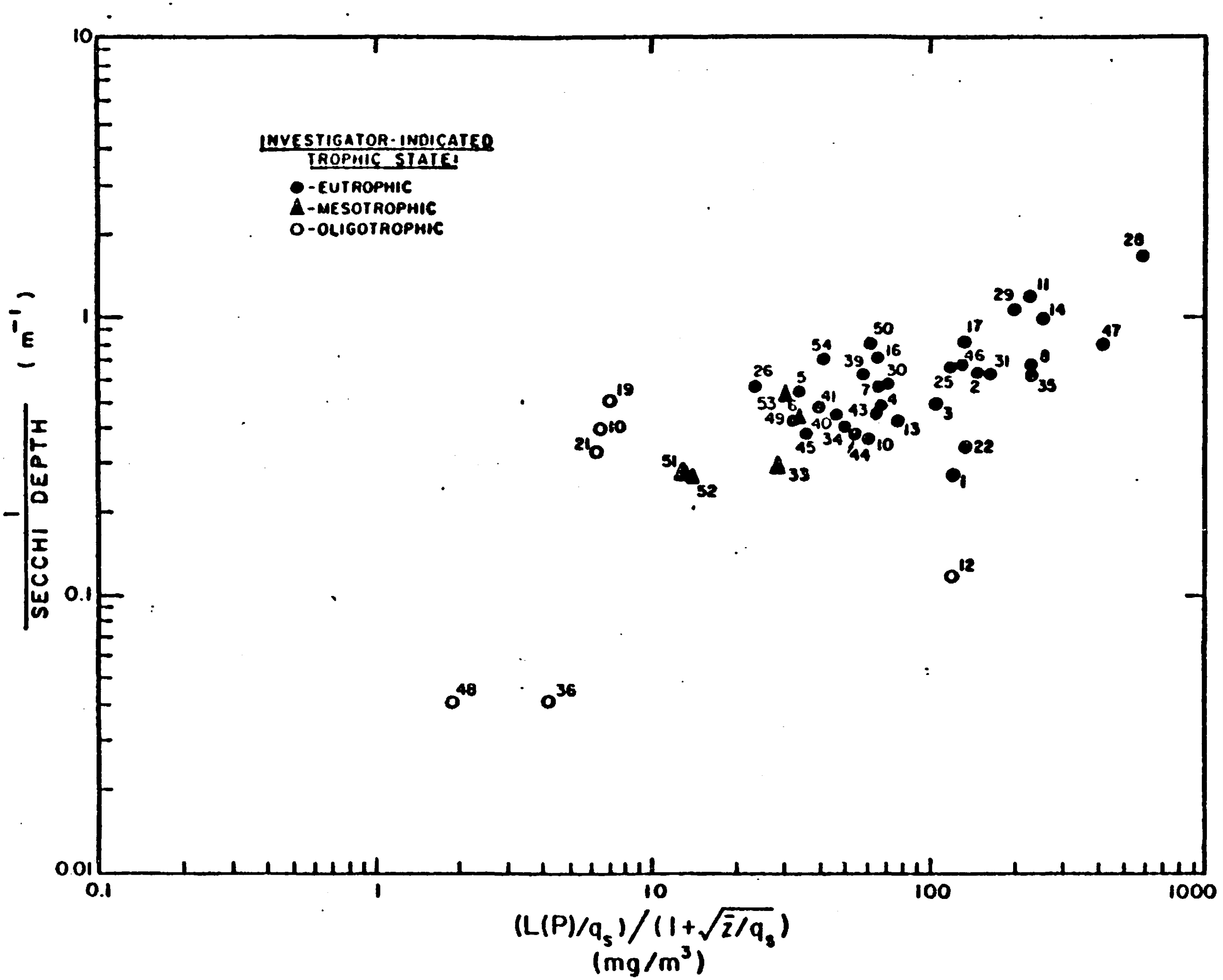

Figure 23. US OECD Data Applied to Phosphorus Loading and Secchi Depth Relationship (Log-Log Scale).

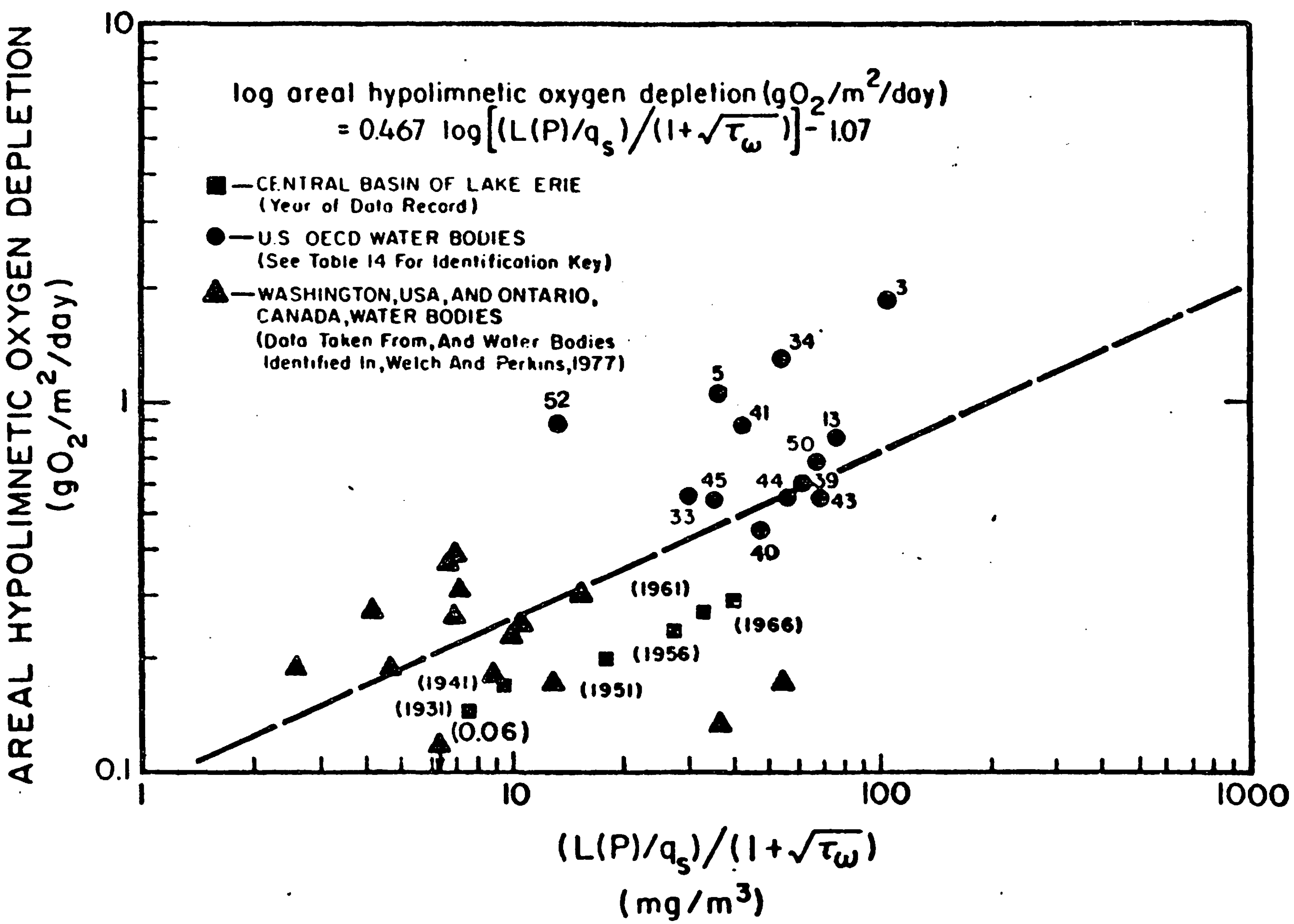

Figure 80. Phosphorus Loading Characteristics and Hypolimnetic Oxygen Depletion Relationship in Natural Waters

Figure 4. Lake data showing the relationship between the phosphorus load (abscissa) and the rate at which oxygen is removed from bottom waters (ordinate). (Figure 80 from Rast and Lee, 1978).

To summarize, researchers have found that the overall biomass in a lake is related to the amount of total phosphorus available. This empirical relationship does not tell when peak chlorophyll levels will occur or give information on productivity, growth rates or small scale variations. However, water quality management involves long-term considerations, so that the average conditions predicted by the empirical model usually are suitable for management purposes.

One might expect that similar empirical relationships can be elucidated for estuaries. Since estuarine and marine systems often are nitrogen-limited, nitrogen might control, but it is more likely that both nitrogen and phosphorus need to be considered, at least during initial efforts to determine the nutrient-biomass relationships. The experience in lakes further suggests that concentrations of Total Nitrogen and Total Phosphorus are more likely to be correlated with system responses than concentrations of the inorganic forms of nitrogen and phosphorus.

Nutrient Levels in Estuaries

Nutrient levels in estuaries vary considerably, as a result of drainage basin characteristics, discharges from municipal and industrial wastewater treatment facilities, and other factors. In order to demonstrate this variability graphically, nitrogen and phosphorus concentrations for estuaries in general and for the estuaries of the Chesapeake Bay system have been plotted in Figures 5 and 6 respectively. Since total nutrient values are not available for many systems, values for total nutrients and for inorganic nutrients have been plotted in Figure 5, part a and part b respectively.

These figures show that there is considerable variation in nutrient concentrations. Although both nutrients vary over several orders of magnitude, the variability in nitrogen levels is somewhat less than that for phosphorus. Clearly, any rating or ranking scheme for nutrient enrichment must account for the very large range in nutrient concentrations.

A Classification System for Nutrient Enrichment in Estuaries

Research on eutrophication in lakes has shown that average algal biomass and other factors vary with the nutrient supply. It is possible that similar correlations exist for estuaries, but first there must be a method to determine the level of nutrient enrichment. The ranking system in Table 1

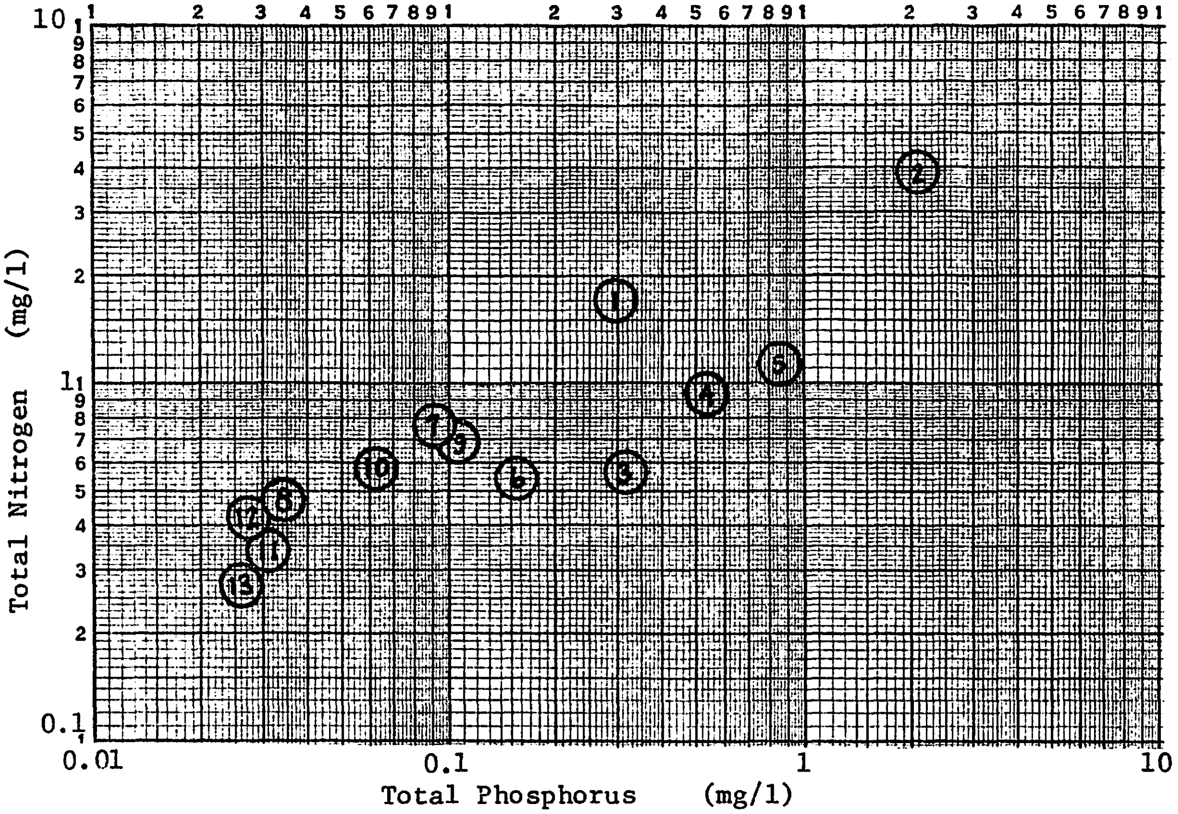

Figure 5-a. Total Phosphorus and Total Nitrogen concentrations observed in estuaries.

Key to Figure 5a.

1	San Antonio Bay	Copeland & Wohlschlag,
	Galveston Bay	Copeland & Frah, 1969
2	Station 36	
3	Station 3	
4	Station 4	
5	Station 5	
6	Sacramento-San Joaquin Delta; Grizzly Bay	O'Connor *
	Peel-Harvey Estuary Western Australia	McComb et al *
7	Harvey	
8	Peel	
9	Chowan River, NC	Witherspoon et al.
	Danish Straits	Gargas, Nielsen and Mortenseu
10	Station D 31	
11	Station D 3	
12	Escambia Bay	Olinger et al
13	Pensacola Bay	Olinger et al

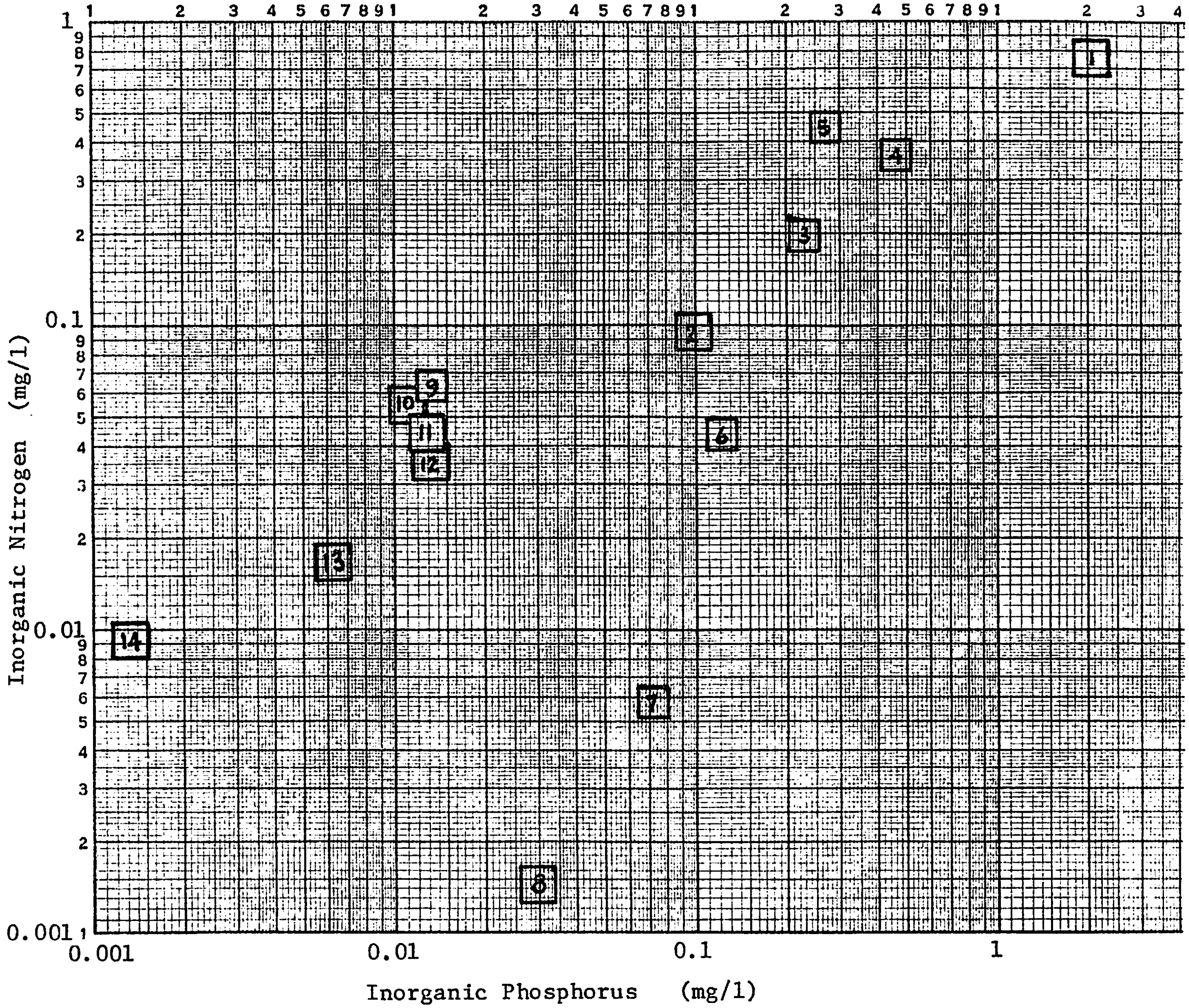

Figure 5-b. Inorganic Phosphorus and Inorganic Nitrogen concentrations observed in estuaries.

Key to Figure 5b.

1	Peace River at Arcadia	Charlotte Harbor, Florida
2	Harbor Station 2	Fraser & Wilcox *
3	Harbor Station 9	
4	Calico Creek, NC	Sanders & Kuenzer
5	Werribee Station Max levels	Port Phillip Bay, Australia
6	Werribee Station Min levels	Axelrad et al *
7	St. Leonards Sta. Max levels	
8	St. Leonards Sta. Min levels	
9	Apalachicola Sta. 1A	Apalachicola and Ocklockonee
10	Apalachicola Sta. 7	Estuaries, Florida
11	Ocklockonee Sta. 2	Meyers & Iverson *
12	Ocklockonee Sta. 1	
13	Station ML between Apalachicola & Ocklockonee Estuaries	
14	Econfina Estuary Station 12	

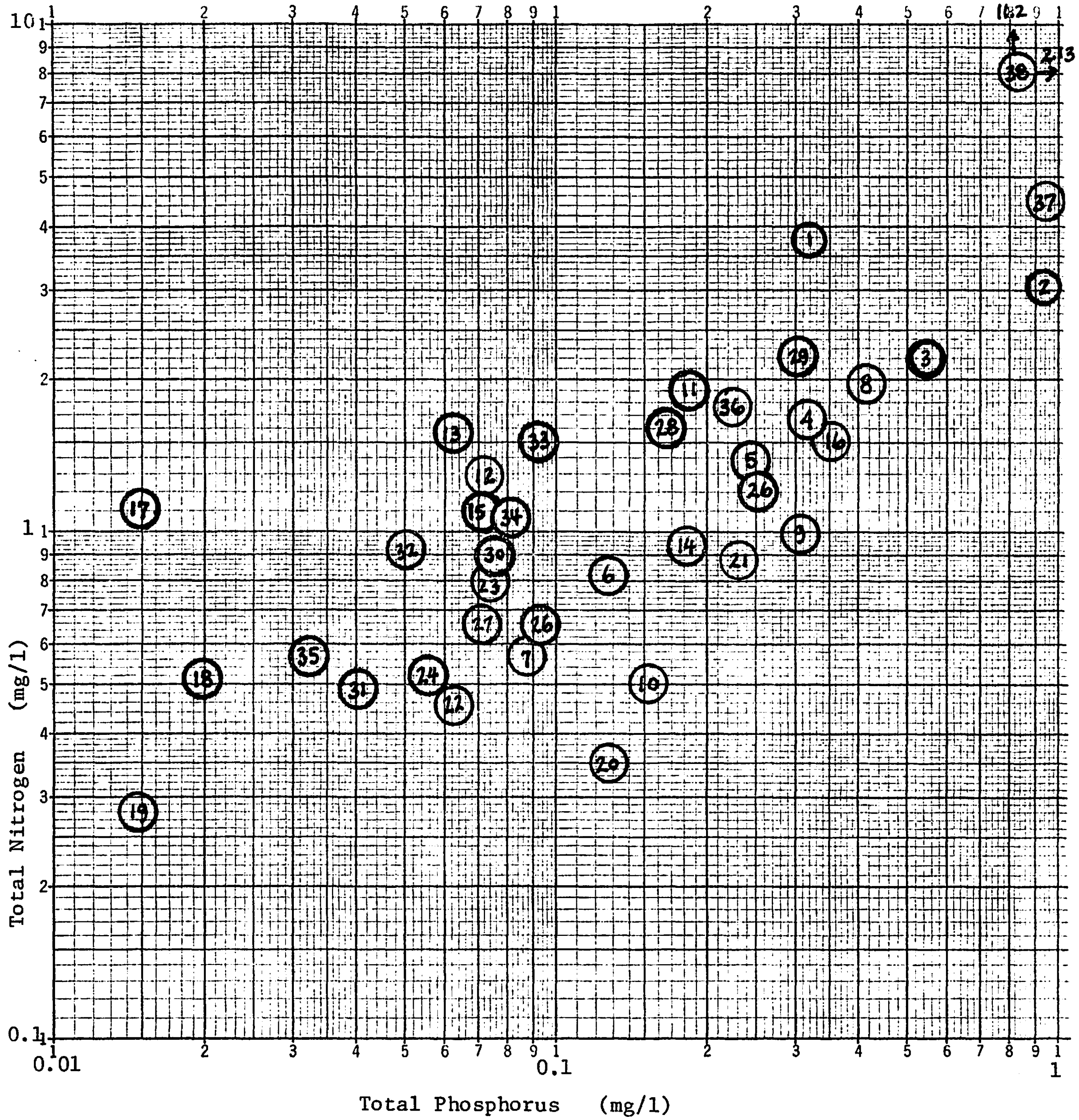

Figure 6. Total Phosphorus and Total Nitrogen concentrations observed in the estuaries of the Chesapeake Bay system.

Key to Figure 6

1	Algal Bloom	Loftus et al, 1972
2	Fall Line Patuxent River	Flemer et al, 1970
3	Sta. 1 Patuxent River	
4	Sta. 4 Patuxent River	
5	Sta. 6 Patuxent River	
6	Sta. 10 Patuxent River	
7	Sta. 14 Patuxent River	
8	Eastern Branch, Elizabeth River	Neilson & Sturm, 1977
9	Southern Branch, Elizabeth River	
10	Mouth, Elizabeth River	
11	Potomac River Fall Line	Guide & Villa, 1971
12	James River Fall Line	
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24	Back River, Virginia	
25	Little Creek Harbor	
26	Lynnhaven Bay	
27	Lynnhaven Bay mouth	
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32	Chesapeake Bay near Baltimore Harbor	
33	Chesapeake Bay below Susquehanna River	
35	Potomac River mouth	
36	Back River,Md Rocky Point	Ferguson & Simmons, 1974
37	Back River, Md Stansbury Point	
38	Back River, Md Cox Point	

assigns nutrient enrichment level according to the Total Nitrogen concentration. Nitrogen values vary logarithmically as enrichment values change arithmetically in order to encompass the broad range of values observed in nature. As proposed, the enrichment level increases as nitrogen concentrations increase. However, this could be inverted if one desired to have the high rankings go with "clean", high quality waters and the low rankings be assigned to low quality, highly enriched waters.

Even though many estuarine systems will be nitrogen limited, this is unlikely to be the case for all estuaries. Therefore, the enrichment levels have been related to equivalent values for total phosphorus and for chlorophyll a and dissolved oxygen in Table 2. The phosphorus and oxygen values have been scaled according to the Redfield ratios; the negative oxygen values indicate that oxygen is released as nutrients are incorporated into plant cells during photosynthesis, and consumed when detritus is decomposed. Chlorophyll values have been related to nutrient levels by a ratio in the range of reported nutrient to chlorophyll ratios (e.g. Clark et al., 1980). The chlorophyll values give an indication of the biomass that would result if all nutrients were taken up and growth were not limited by other factors. Similarly the oxygen values give an indication of the amount of oxygen that would be consumed during the oxidation of the biomass. At high enrichment levels these values are not meaningful, but for moderate and low levels of enrichment they provide some insights into the magnitude of the problems which could occur if nutrients were taken up by phytoplankton and if the algae were to die suddenly.

TABLE 1. Classification System for Nutrient Enrichment in Estuaries

Level of Nutrient Enrichment	Total Nitrogen (mg/1)	Total Nitrogen (μg-atoms/1)
0	0.003	0.2
1	0.01	0.7
2	0.032	2
3	0.1	7
4	0.32	23
5	1.0	71
6	3.2	226
7	10	710
8	32	2,260
9	100	7,140
10	320	22,600

TABLE 2. Nutrient Enrichment Classification Scheme for Estuaries, including Equivalent Values for Other Environmental Variables.

		Phosphorus, Oxygen & Chlorophyll Equivalents		
Level of Nutrient Enrichment	Total Nitrogen (mg/1)	Total Phosphorus (mg/1)	Dissolved Oxygen (mg/1)	Chlorophyll a (μg/1)
0	0.003	0.0004	-0.06	0.6
1	0.010	0.001	-0.2	2
2	0.032	0.004	-0.6	6
3	0.10	0.014	-1.9	20
4	0.32	0.044	-6.0	60
5	1.0	0.14	-19	200
6	3.2	0.44	-60	600
7	10	1.4	-190	2,000
8	32	4.4	-600	6,000
9	100	13.8	-1,900	20,000
10	320	44	-6,000	60,000

IMPACTS ON USES OF ESTUARIES

According to the Work Plan, the research program was designed to "assure that eutrophication does not interfere with a maximization of beneficial uses of the Chesapeake Bay system" (EPA, 1977). Before beneficial uses can be maximized (assuming that this can be done), one must first determine how nutrient enrichment affects the various uses of estuaries. The approach taken in this study has been to formulate a conceptual model which differentiates between classes of effects, to assess the impacts on uses for each class, and finally to summarize the overall impacts of nutrient enrichment on estuaries.

Approach to the Problem

Eutrophication in lakes is characterized by a variety of system changes; these have been summarized in the 1968 Water Quality Criteria:

> "Conditions indicative of organic enrichment are: (1) A slow overall decrease year after year in the dissolved oxygen in the hypolimnion as indicated by determinations made a short time before fall overturn and an increase in anaerobic areas in the lower portion of the hypolimnion. (2) An increase in dissolved solids - especially nutrient material such as nitrogen, phosphorus, and simple carbohydrates. (3) An increase in suspended solids - especially organic materials. (4) A shift from a diatom-dominated plankton population to one dominated by blue-green and/or green algae, associated with increases in amounts and changes in relative abundance of nutrients. (5) A steady though slow decrease in light penetration. (6) An increase in organic materials and nutrients, especially phosphorus, in bottom deposits.
>
> (FWPCA, 1968)

One would expect similar conditions to develop in over-enriched estuaries. However, it is difficult to discuss impacts in terms of degree of enrichment when the full suite of conditions is considered. In order to simplify and clarify the discussion which follows, the impacts of nutrient enrichment have been classified as follows: Primary impacts are those due to elevated nutrient concentrations; Secondary impacts are those due to high levels of plant biomass; and Tertiary impacts are those resulting from the accumulation of detritus. The conceptual model for this system is shown in Figure 7. and is perhaps best illustrated in nature by the sequence of events surrounding an algal bloom. Prior to an algal bloom, inorganic nutrient concentrations will be high. As the bloom develops, the supply of inorganic

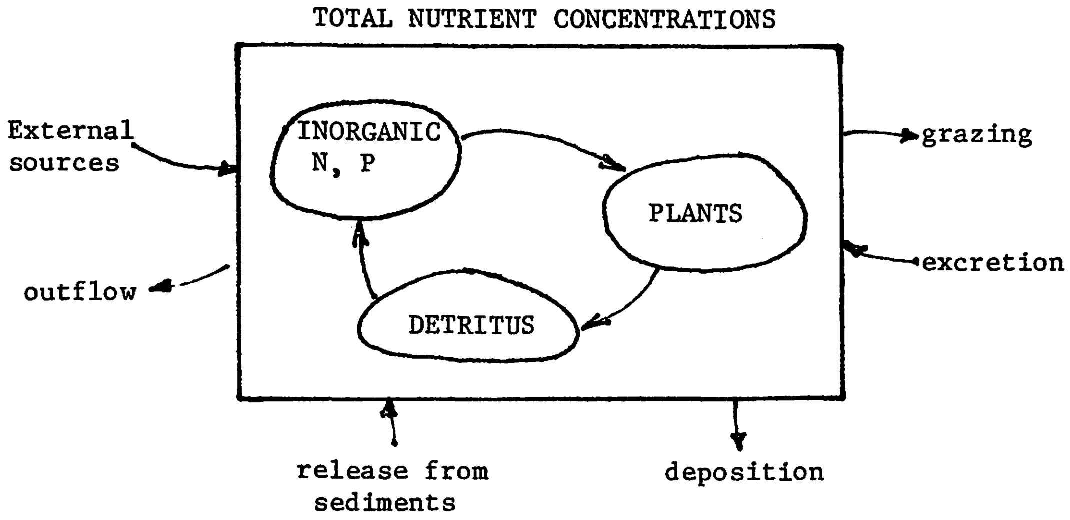

Figure 7. Conceptual model showing the three compartments of the total nutrient concentrations in the water column and some of the factors which control these nutrient levels.

nutrients will be depleted and most of the nutrients will be incorporated into living plants. Depending on physical conditions algal species, etc., it is not unusual for a rapid die-off to follow peak algal levels; this transfers much of the nutrient supply to the detritus compartment. At least the first two stages of this sequence were observed by Loftus et al. (1972) following a heavy rainfall which introduced a pulse of nutrient-rich water into Chesapeake Bay near Annapolis. As stated earlier, the primary reason for classifying impacts is to facilitate the discussion which follows.

Primary Impacts of Nutrient Enrichment

The primary impacts are those which result from elevated levels of inorganic nutrients without biological uptake. This may appear to be an academic exercise, but it is not necessarily so. In turbid estuaries, phytosynthesis is likely to be limited by light. Acidity, strong mixing and other factors also could inhibit biological uptake.

Nutrient concentrations must reach very high levels to impact water uses, as shown in Table 3. It is noteworthy that many of the criteria relate to freshwater only, for example the criteria for public and livestock drinking water supplies. The concentrations listed are an order of magnitude higher than those found in most estuaries and tidal rivers. Even at such high levels,

TABLE 3. Water Quality Criteria Pertaining to Primary Impacts.

	Use	Maximum Permissable Level	Reference
Nitrite + Nitrate	Public Drinking Water Supply	10 mg-N/1	1, 2
	Livestock Water Supply	100 mg-N/1	2
Nitrite	Public Drinking Water	1 mg-N/1	2
	Livestock	10 mg-N/1	2
Nitrate	Industry - cooling water (fresh)	30 mg/1	1, 2
	Petroleum industry	8 mg/1	1, 2
Phosphate	Industry - boiler makeup water	50 mg/1	1, 2
	Industry - cooling water (fresh)	4 mg/1	1, 2
	Industry - cooling water (brackish)	5 mg/1	1, 2

1 Federal Water Pollution Control Administration, 1968. "Water Quality Criteria".

2 National Academy of Sciences - National Academy of Engineering, 1972. "Water Quality Criteria 1972".

there would be virtually no impact on shipping, aesthetics and recreation. The presence of nutrients might even enhance the utility of freshwater for irrigation. In short, the inorganic nutrient levels observed in most estuaries will have little, if any, impact on water uses.

Secondary Impacts of Nutrient Enrichment

Secondary impacts are those related to increased algal levels. Changes in the biomass of rooted aquatic vegetation also are important, but these plants can obtain nutrients from sediments as well as the water column, so there is no easy way to relate changes in abundance to nutrient concentrations in the water. Therefore, the discussion will be limited to changes in the phytoplankton community only.

In general, if more nutrients are available, the size of each of the compartments should increase. When the standing crop of phytoplankton increases, this will affect water clarity, aesthetic values, the dissolved oxygen regime, and the algal community structure.

Clarity: Clear waters are perceived by most people to be of higher quality than turbid waters (Bishop and Aukermann, 1970). Clear waters are safer for bathers and swimmers, and the ability of some fish to locate and catch their prey will be adversely affected by decreased water clarity (FWPCA, 1968). The increased phytoplankton standing crop sometimes comes at the expense of the submerged aquatic vegetation, since the phytoplankton shade the rooted plants and deprive them of the sunlight needed for growth.

The maximum recommended levels of turbidity for warm-water lakes and streams are 25 and 50 Jackson turbidity units respectively, and for cold-water lakes and streams the limit is 10 JTU (FWPCA, 1968). Any turbidity in drinking water supplies should be readily removed by traditional water treatment methods (FWPCA, 1968).

Aesthetics: An increase in the standing crop of algae generally decreases the aesthetic appeal of waters by changing color and reducing clarity. If the algae are of the types which form mats, filamentous colonies or float on the surface, such "pea soup" conditions are considered objectionable by many. In eutrophic lakes and reservoirs, some of these less desirable algal species give the water a taste and an odor that may not be harmful, but certainly makes the water less appetizing to those who drink it.

In an EPA study of the Potomac River, four water quality criteria were evaluated. The criterion which proved to be most restrictive was a chlorophyll a limit of 25 μg/l "to enhance the aesthetic conditions in the upper estuary" and eliminate the "large green mats (which) develop during the months of June through October and create objectionable odors, clog marinas, cover beaches and shorelines, and in general reduce the potential of the estuary for recreational purposes such as fishing, boating, and water skiing" (Jaworski, et al., 1971). In light of the large sums of money needed to reduce nutrient levels sufficiently that this criterion is met, it is unfortunate that there was no documentation of the method by which this criterion was established.

Dissolved Oxygen: The dissolved oxygen regime is affected by the phytoplankton, since oxygen is a by-product of photosynthesis and also because the plants consume oxygen. During the summer when the waters are warm and the days long, daily average dissolved oxygen concentrations are likely to be high and variations about the daily mean large. For example, in June 1976 the dissolved oxygen concentrations at a station in the upper reaches of the Pagan River, a tributary of the James River, ranged from more than 11 mg/l in late afternoon to about 3 mg/l in the early morning (Rosenbaum and Neilson, 1977). Chlorophyll levels for that period were about 100 μg/l but varied with tidal stage. The saturation concentration of oxygen in water with the observed temperature ($29^{o}C$) and salinity (about 5 ppt) is around 7.5 mg/l, which is also about the midpoint of the diurnal range. Clearly surface waters were supersaturated during part of the day, while the early morning values did not meet the state's water quality standard of a minimum of at least 4 mg/l. The daily average, however, did meet the state standard of a mean above 5 mg/l.

Neither the depressed nor the elevated oxygen levels is desirable. Reduced oxygen concentrations makes respiration more difficult for aquatic organisms, especially when the water temperatures also are high (Reid and Wood, 1976). It has been recommended that concentrations of dissolved gases never exceed 110% of the saturation values (NAS-NAE, 1972).

Changes in Community Structure: Changes in the nutrient supplies can produce a variety of responses from the algal community. In general, the larger organisms are believed to be given greater advantage as nutrient levels rise (Webb*). Even if there are no species shifts, the chemical make-up of the algae can change in response to the availability or non-availability of each nutrient, thereby altering its value as food for other aquatic organisms (Webb*). Ryther and Officer* have suggested a classification scheme which would allow different algal communities to be compared and rated with respect to their usefulness for man's purposes. This approach would make analysis of species shifts much more quantitative than is the case at present.

Schindler* indicates that the relative abundance of nitrogen and phosphorus is a key factor in species shifts in lakes. Briefly stated, when nutrient additions are nitrogen rich (N to P ratio greater than 16) the biomass will increase but there may not be a species shift. When the nutrient addition is nitrogen poor, this favors the blue-green algae which are capable of fixing nitrogen from the atmosphere. Perhaps similar mechanisms are at work in estuaries. At any rate, it is recommended that the natural relative abundances of the nutrients remain constant and not vary as new discharges are added to the estuary (FWPCA, 1968; NAS-NAE, 1972).

Tertiary Impacts of Nutrient Enrichment

Tertiary impacts result form the accumulation of detritus in the system. This often alters the bottom sediment characteristics and produces localized conditions of depressed oxygen tension or even anoxia. Detritus is defined as "all types of biogenic material in various stages of microbial decomposition ... which includes all dead organisms as well as the secretions, regurgitation, excretions and egestions of living organisms, together with all subsequent products of decomposition which still represent potential sources of energy" (Darnell, 1967).

<u>Sediment Characteristics</u>: Increased nutrient loads can result, either temporarily or for the long term, in increased amounts of organic detritus in the system. Slack tides provide the opportunity for this material to settle out and accumulate on the estuary bottom. Changes in the organic content of the sediments obviously will impact the benthic organisms. Since some organisms, such as oysters, require a firm substrate, they will be at increasing disadvantage as the organic content of the bottom sediments increases. Pearson and Rosenberg (1978) state that the data indicate a consistent pattern of faunal changes along a "gradient of increasing organic input to marine sediments".

Dissolved Oxygen Levels: Alterations in the benthos are affected by the physical environment as well. When the physical conditions provide an ample supply of oxygen along with the organic load, the resulting benthic community will be different from that in a substrate with low organic content, but nonetheless it will be an active, viable assemblage. If water renewal is decreased, then the amount of oxygen provided will decrease as well and eventually oxygen consumption will be greater than the supply. If both the sediments and the overlying water are anaerobic, few organisms will survive. These effects are represented graphically in Figure 8, from Pearson and Rosenberg (1978).

Problems of water renewal and depressed oxygen levels are often in vertically stratified systems. Oxygen from both natural reaeration and photosynthesis is added to the surface waters; stratification inhibits mixing and therefore also the transfer of soluble water constituents throughout the water column. As dead cells settle they pass through the pycnocline and into the bottom waters. There decomposition consumes oxygen and releases nutrients. For this reason bottom waters frequently are rich in nutrients and oxygen poor. Periods of anoxic bottom waters, whether of short duration or over long periods, will result in the decimation of most of the organisms residing in those bottom waters and in the bottom sediments. Also, when anoxia exists, the

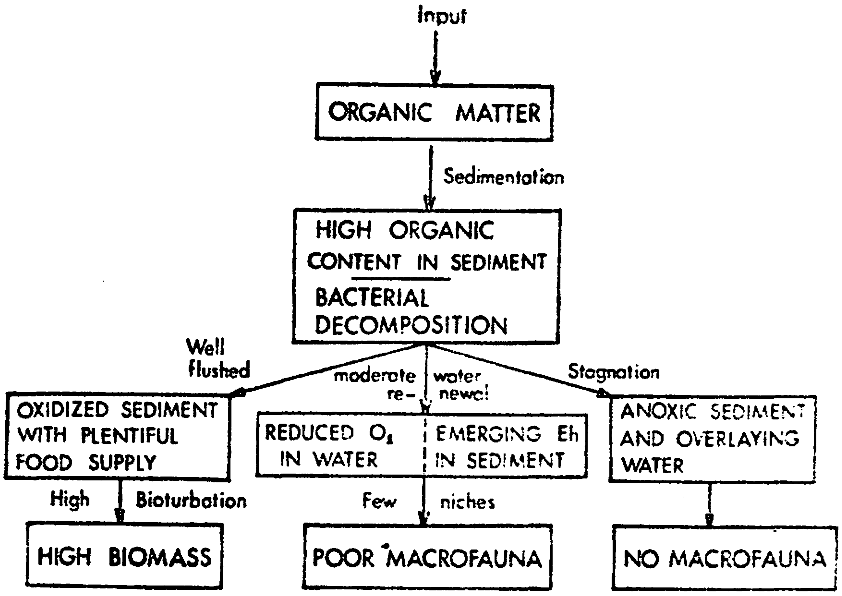

Figure 8. Diagram showing changes in benthic macrofauna as a result of varying physical conditions and oxygen supply (From Pearson and Rosenberg, 1978).

biochemical processes of decomposition are different from those in aerated waters. The production and release of hydrogen sulfide, for example, often occurs when the water is anaerobic.

When nutrient enrichment results in sediments having a high organic content, the aquatic life will be modified; some shellfish species will not thrive under these conditions. Additionally, the soft, mucky bottom resulting will make these areas less desirable for swimming. But if the dissolved oxygen levels are not depressed, the impacts will be relatively minor.

Nutrient enrichment which results in both highly organic bottom sediments and depressed DO levels will produce major impacts. Most forms of aquatic life will be severely stressed or die as a result of these conditions. Finfish may be able to avoid impacted areas, but shellfish, being sessile, probably will die. Anaerobic water containing hydrogen sulfide is toxic, unsuitable for drinking and aesthetically displeasing. Use for cooling and other industrial purposes, as well as shipping, could be affected since such water is corrosive.

Summary

The responses to nutrient enrichment are many, varied and difficult to characterize. Consequently there is no simple picture of the effects of nutrient enrichment. Table 4 provides an overview of the effects by specific use and incorporates the primary, secondary and tertiary effects discussed previously. The levels of nutrient enrichment are those presented in the previous chapter. The ratings and assignment of impacts on uses is subjective, based on professional experience with estuarine systems. The table can and should be revised as more and better information becomes available.

In general, when the level of enrichment is low (say through level 2), the quality of the water is good and suitable for most or all purposes. In the range between level 2 and level 5, there may be periodic episodes when the quality is poor and uses are damaged, or there could be moderate impacts almost continuously. Between levels 5 and 8, the episodes of undesirable conditions will be frequent and localized conditions may render the water unfit for some uses. For higher levels of enrichment, the water is sufficiently poor in quality to preclude or limit its usefulness for virtually all purposes.

This table can be used to compare sets of environmental conditions. First, ambient water characteristics, in particular nutrient concentrations,

TABLE 4. Impacts of Nutrient Enrichment on Water Uses a) uses limited to freshwater portions of estuaries.

Level of Nutrient Enrichment	Public Drinking Water Supply	Livestock Drinking Water	Irrigation	Freshwater Aquatic Life
0	Acceptable	ACCEPTABLE	Acceptable	Acceptable (oligotrophic)
1	Minor Purification Required			
2			Increased Nutrient Levels Could Enhance Usefulness	(mesotrophic) Problems Arise Periodically
3	More Extensive Treatment Needed			
4				(eutrophic) Marginally Acceptable
5	Marginally Acceptable and Sometimes not Acceptable	Algae May Clog Intake Pipes	Generally Acceptable But Algae Could Clog Pipes and Pumps and There Could be Nitrate Build-up in Ground Water	Generally Not Acceptable
6				
7	Not Acceptable	Marginally Acceptable		
8				
9		Not Acceptable		
10				

TABLE 4. Impact of Nutrient Enrichment on Water Uses b) uses which apply to brackish portions of estuaries.

Level of Nutrient Enrichment	Marine Aquatic Life	Recreation and Aesthetics	Industry	Commercial Shipping
0	Acceptable (oligotrophic)	Acceptable	ACCEPTABLE	ACCEPTABLE
1				
2	Problems arise Infrequently or due to Local Conditions	Infrequent Episodes when not Acceptable		
3				
4	(mesotrophic) Marginally Acceptable	Frequent Episodes when not Acceptable		
5	(eutrophic) Marginally Acceptable		Algae May Clog Intake Pipes	
6	Generally Not Acceptable	Not Acceptable		
7				Problems May Arise with Hydrogen Sulfide
8			Not Acceptable for some Purposes	
9				
10				

must be used to determine the level of nutrient enrichment. Then, for that level, the suitability of the water for the various uses can be ascertained in a general sense. At present, only major modifications in water uses are indicated. If the table included greater detail, it might be possible to show how limited changes in nutrient enrichment alter the use of estuaries. However, that remains for future studies.

CONCLUSIONS AND RECOMMENDATIONS

It is clear that there is great variability in the nutrient levels observed in estuaries and that when enrichment is excessive, beneficial uses are impaired. Our colleagues working with lake ecosystems have been able to correlate system responses (average chlorophyll concentrations, water clarity, and the rate that oxygen is depleted in bottom waters) with environmental conditions (total phosphorus loading rates or total phosphorus concentrations in the lake). This knowledge has permitted engineers to design programs which reverse the eutrophication process and ameliorate its negative effects. We can be hopeful that in the future our efforts in estuaries will be fruitful and we can provide similar guidance to managers.

Perhaps the greatest need is to make our analyses more quantitative. The first step is to determine the estuarine analog to Total Phosphorus in lakes ecosystems. Then system responses (such as plant biomass, species shifts and the presence, absence, density and relative abundance of organisms) should be correlated with this measure of nutrient enrichment.

Another tool which could prove to be useful to managers is an index of estuarine enrichment which incorporates all of the major aspects of enrichment and its effects. Such an index would summarize environmental conditions in a simple fashion and provide a means to chart the decline or improvement in water quality conditions.

Additional scientific studies are needed to determine and quantify the rates and routes of nutrient transfer in estuaries. Field work is needed especially, since the observations made during field studies often provide insights which cannot be obtained from paper exercises or laboratory studies. When field measurements are made, it is recommended that sufficient analyses be performed so that the total amounts of nutrients in the water column can be calculated. Since many estuary segments have long residence times and the rates of biochemical transformation are often rapid, it is important to know the entire nutrient supply rather than only those portions which are readily available to the phytoplankton.

A number of scientists or scientific organizations have recommended criteria relative to nutrient enrichment; some of these are listed in Table 5. The limits recommended by Ketchum and by the National Academy of Sciences-National Academy of Engineering are similar, since they are based on the same

TABLE 5. Enrichment Criteria.

Ketchum (1969)	Total Phosphorus 1.7 μg-at/l (0.054 mg/l) - summer 2.55 μg-at/l (0.082 mg/l) - winter	To maintain oxygen demand for decomposition at or below available oxygen supply.
Pritchard (1969)	Total Phosphate 0.1 mg-PO_4/l (0.033 mg-P/l)	Undesirable conditions occur for higher levels.
Jaworski, et al. (1971)	Chlorophyll a 25 μg/l	To maintain recreational and aesthetic values.
NAS-NAE (1972)	Total Phosphorus less than 0.05 mg/l Total Nitrogen less than 0.36 mg/l	To limit organic matter so that oxygen supplies are not depleted at warmest time of the year with poor water circulation.
Heinle, et al. (1980)	Chlorophyll a	
	low salinity areas (less than 8-12 ppt)	high salinity areas (more than 8-12 ppt)
	Moderate enrichment 30-60 μg/l	20-40 μg/l
	Excessive enrichment >60 μg/l	>40 μg/l

analysis, namely relating nutrient concentrations to the amount of oxygen available in the water column. For relatively well-mixed water bodies these levels probably are conservative since they assume no oxygen renewal from the atmosphere. On the other hand, the criteria may not be low enough for systems with vertical stratification that persists for periods of a week or more.

If we assume that total phosphates account for about one-half to two-thirds of the total phosphorus in the water column, then Pritchard's criterion is roughly equal to Ketchum's. Similarly, if we assume that the chlorophyll levels which actually develop in the real world are between one-half to two-thirds of that which is theoretically possible, then the upper limits for chlorophyll set be Heinle et al. are roughly equivalent to the NAS-NAE criteria for nutrients and Ketchum's criterion for phosphorus.

When one considers the range of salinities and the diverse physical environments found in Chesapeake Bay and its subestuaries, it is natural that the effects of nutrient enrichment vary from place to place. The criteria to avoid problems of over-enrichment must vary somewhat too. In this light, the relative agreement between those who have suggested criteria related to enrichment is perhaps more surprising than the fact that they differ slightly.

Even though much remains to be learned about enrichment problems, it is possible to set conservative standards which assure that enrichment will not damage the use of Chesapeake Bay in any serious fashion. As research, field studies, and analysis provide us with better understanding of estuarine ecosystems, we can further define where, when, and under what circumstances additional nutrients can be added without damage or with benefit. It is the author's opinion that the criteria recommended by a number of knowledgeable and competent scientists indicate that these "safe limits" are at about Nutrient Enrichment Level 4, or total nitrogen concentrations at or below 0.32 mg/l and total phosphorus concentrations at or below 0.044 mg/l.

Between levels 4 and 5, it is likely that there will be brief, periodic episodes when conditions are stressful to aquatic organisms and water uses will be impaired. This range might be considered the counterpart to the mesotrophic range for lakes.

It appears that nutrient concentrations above level 5 (TN = 1 mg/l and TP = 0.14 mg/l) represent a danger signal. Episodes of poor quality water and undesirable conditions are likely to occur frequently and persist, at least in a few local areas. Water uses could be impaired significantly during these periods and ecological damage could be great. Given the extraordinary value of Chesapeake Bay and its tributaries, it is imperative that we take these warning signals seriously. Furthermore, the prudent course of action would be to limit nutrient levels to the greatest extent possible until such time as we can be certain that higher levels will not impair uses or result in ecological damage.

REFERENCES

Bishop, Doyle W. and Robert Aukermann, 1970. "Water Quality Criteria for Selected Recreational Uses", University of Illinois, Water Resources Center Research Report No. 33.

Clark, L. J., S. E. Roesch and M. M. Bran, 1980. "Assessment of 1978 Water Quality Conditions in the Upper Potomac Estuary", EPA-903/9-80-002.

Copeland, B. J. and E. Gus Frah, 1970. "Ecological Studies of Galveston Bay 1969", Final Report to Texas Water Quality Board.

Copeland, B. J. and Donald E. Wohlschlag, 1966. "Eutrophication: Saline Water Considerations", circa 1966, complete citation not known.

Cronin, L. Eugene, 1980. Personal communication.

Darnell, R. M., 1967. "The Organic Detritus Problem" in Estuaries, American Association for the Advancement of Science, Washington, D.C. pp. 374-375.

Environmental Protection Agency, 1977. "Eutrophication Work Program for Chesapeake Bay".

Environmental Protection Agency, 1980a. "Research Summary: Chesapeake Bay", EPA-600/8-80-019, May, 1980.

Environmental Protection Agency, 1980b. "Restoration of Medical Lake", EPA-625/2-80-025.

Environmental Protection Agency, 1980c. "Restoration of Lake Temescal", EPA-625/2-80-026.

Environmental Protection Agency, 1980d. "Lake Restoration in Cobbossee Watershed", EPA-625/2-80-027.

Federal Water Pollution Control Administration, 1968. "Water Quality Criteria".

Ferguson, John F. and David Simmons, 1974. "The Fate of Nutrients in Back River", Chesapeake Research Consortium, Publication No. 32, Annapolis, MD.

Flemer, D. A., D. H. Hamilton, C. W. Keife and J. A. Mihursky, 1970. "The Effects of Thermal Loading and Water Quality on Estuarine Primary Production", Chesapeake Biological Laboratory, University of Maryland, Natural Resources Institute Reference No. 71-6.

Gargas, Nielsen and Mortenseu, 1978. "Phytoplankton Production, Chlorophyll-a and Nutrients in the Open Danish Waters 1975-77", National Agency for Environmental Protection, Denmark.

Guide, V. and Orterio Villa, Jr., 1972. "Chesapeake Bay Nutrient Input Study", Annapolis Field Office, EPA Technical Report 47.

References (cont'd)

Harris, Graham P., 1980. "Temporal and Spatial scales in phytoplankton ecology. Mechanisms, methods, models, and management." Can. J. Fish. Aquat. Sci. 37:877-900.

Heinle, D. H., C. F. D'Elia, J. L. Taft, J. S. Wilson, M. Cole-Jones, A. B. Caplins and L. E. Cronin, 1980. "Historical Review of Water Quality and Climatic Data from the Chesapeake Bay with Emphasis on the Effects of Enrichment". Chesapeake Biological Laboratory Solomons, University of Maryland. UMCEES Reference No. 80-15CBL.

Hydroscience, Inc., 1975. "The Chesapeake Bay Waste Load Allocation Study", Hydroscience, Inc., Westwood, NJ.

Jaworski, N. A., D. W. Lear, Jr., and O. Villa, Jr., 1971. "Nutrient Management in the Potomac Estuary". Technical Report No. 45, Chesapeake Technical Support Laboratory, Environmental Protection Agency.

Ketchum, Bostwick H., 1972. "Eutrophication of Estuaries" in "Eutrophication: cause, consequences, correctives". National Academy of Sciences, Washington, D.C.

Loftus, M. E., D. V. Subba Rao and H. H. Seliger, 1972. "Growth and Dissipation of Phytoplankton in Chesapeake Bay. I. Response to a Large Pulse of Rainfall", Chesapeake Science 13:4, pp. 282-299.

McErlean, Andrew J. and Gale J. Reed, 1979. "On the Application of Water Quality Indices to the Detection, Measurement and Assessment of Nutrient Enrichment in Estuaries". Reference Number 79-138 - Horn Point Environmental Laboratory, University of Maryland, Cambridge, Maryland.

National Academy of Sciences and National Academy of Engineering, 1972. "Water Quality Criteria 1972". Washington, D.C. pp. 594.

Neilson, Bruce, 1976. "Water Quality in the Small Coastal Basins". Virginia Institute of Marine Science Special Report #128 in Applied Marine Science and Ocean Engineering.

Neilson, Bruce and Penelope Ferry, 1978. "A Water Quality Study of the Estuarine James River". Virginia Institute of Marine Science Special Report #131 in Applied Marine Science and Ocean Engineering.

Neilson, Bruce and Susan Sturm, 1978. "Elizabeth River Water Quality Report". Virginia Institute of Marine Science Special Report #134 in Applied Marine Science and Ocean Engineering.

Olinger, Rogers, Fore, Todd, Mullins, Bisterfield and Wise, 1975. "Environmental and Recovery Studies of Escambia Bay and the Pensacola Bay System, Florida". EPA 904/9-76-016.

References (cont'd)

Ott, Wayne, R., January, 1978. "Water Quality Indices: A Survey of Indices Used in the United States". U. S. Environmental Protection Agency, EPA-600/4-78-005.

Pearson, T. H. and R. Rosenberg, 1978. "Macrobenthic Succession in Relation to Organic Enrichment and Pollution of the Marine Environment". Oceanog. Mar. Biol. Ann. Rev., 1978, 16:229-311.

Pritchard, D. W., 1969. "Dispersion and flushing of pollutants in Estuaries". ASCE J. Hyd. Div. 95:115-124.

Rast, Walter and G. Fred Lee, 1978. "Summary Analysis of the North American (U. S. Portion) OECD Eutrophication Project: Nutrient Loading - Lake Response Relationships and Trophic State Indices". U. S. Environmental Protection Agency, EPA-600/3-78-008.

Reid, G. K. and R. D. Wood, 1976. Ecology of Inland Waters and Estuaries. Van Nostrand Company. 485 pp.

Rosenbaum, Arlene and Bruce Neilson, 1977. "Water Quality in the Pagan River", Virginia Institute of Marine Science Special Report #132 in Applied Marine Science and Ocean Engineering.

Sanders, James G. and Edward J. Kuenzer, 1979. "Phytoplankton Population Dynamics and Productivity in a Sewage-Enriched Tidal Creek in North Carolina", Estuaries 2:87-96.

Sturm, Susan and Bruce Neilson, 1977. "Water Quality in the York River", Virginia Institute of Marine Science Special Report #130 in Applied Marine Science and Ocean Engineering.

Train, Russell E., 1972. "The Quest for Environmental Indices". SCIENCE Volume 178, Number 4057, 13 October 1972.

Witherspoon, Balducci, Boody and Overton, 1979. "Response of Phytoplankton to Water in the Chowan River System", UNC-WRRI Report No. 129.

WILLIAMSBURG SYMPOSIUM PAPERS

Axelrad, Poore, Arnott, Bauld, Brown, Edwards and Hickman. "The Effects of Treated Sewage Discharge on the Biota of Port Phillip Bay, Victoria, Australia".

Darnell, Rezneat M. and Thomas M. Soniat. "Nutrient Enrichment and Estuarine Health".

Fraser, Thomas and William Wilcos. "Enrichment of a Subtropical Estuary with Nitrogen, Phosphorus and Silica".

Lee, G. Fred and R. Anne Jones. "Application of the OECD Eutrophication Modeling Approach to Estuaries".

McCarthy, James J. "Uptake of Major Nutrients by Estuarine Plants".

McComb, Atkins, Birch, Gordon and Lukatelich. "Eutrophication in the Peel-Harvey Estuarine System, Western Australia".

McErlean, A. J. and Gale Reed. "Indicators and Indices of Estuarine Over-enrichment".

Myers, Vernon and Richard Iverson. "Phosphorus and Nitrogen Limited Phytoplankton Productivity in Northeastern Gulf of Mexico Coastal Estuaries".

Nixon, Scot W. "Remineralization and Nutrient Cycling in Coastal Marine Ecosystems".

O'Connor, Donald J. "Modelling Eutrophication in Estuaries".

Ryther, John H. and Charles B. Officer. "Impact of Nutrient Enrichment on Water Uses".

Schindler, D. W. "Studies of Eutrophication in Lakes and their Relevance to the Estuarine Environment".

Webb, Kenneth L. "Conceptual Models and Process of Nutrient cycling in Estuaries".