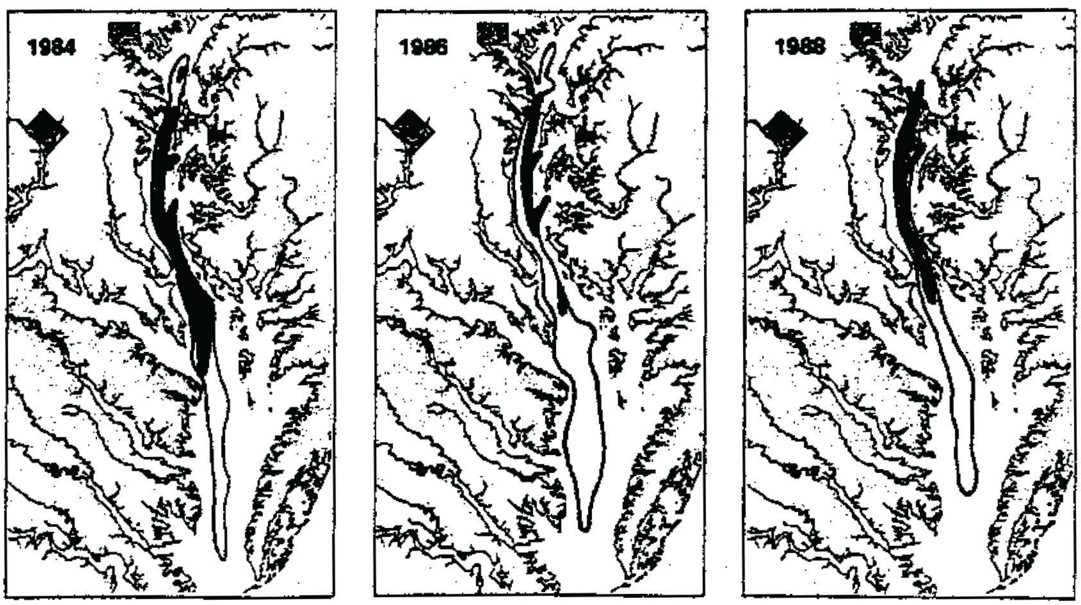
A WORKSHOP REPORT

DISSOLVED OXYGEN IN THE CHESAPEAKE BAY:
A Scientific Consensus



Prepared by the Sea Grant College Programs of Maryland and Virginia

A Maryland Sea Grant Publication
College Park, Maryland

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Dissolved Oxygen in the Chesapeake Bay: *A Scientific Consensus*

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Contents

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Dissolved Oxygen in the Chesapeake Bay:
A Scientific Consensus

Introduction

The Chesapeake Bay is the largest estuary in the United States, covering an area of 4,400 square miles and draining a watershed of over 64,000 square miles spanning five states. Its historical productivity has depended on a balance of nutrient inputs, a balance which is now greatly altered. Nutrients, particularly various compounds containing nitrogen, phosphorus and silicon, are natural and necessary constituents of a healthy, productive Chesapeake Bay. These essential elements support the growth of primary producers, the phytoplankton, that form the base of the Bay's productive food chains.

A functioning and efficient *nutrient to primary producer to consumer* linkage has historically been responsible for the high production of harvestable species in the estuary. Since the early to mid-19th century, however, continued increases in nutrient loads to the Bay by human activities have stimulated the growth of phytoplankton beyond the assimilative capacities of higher consumers (i.e., zooplankton, clams, oysters). This process of overenrichment with nutrients, often referred to as "eutrophication," can lead to degraded water quality and, at an extreme, widespread oxygen depletion when the cycle of production and consumption becomes unbalanced. In Chesapeake Bay, this outcome has been expressed as phytoplankton biomass that is no longer efficiently assimilated in food chains leading to harvestable species, but that sinks from the water column and supports the production of microorganisms, especially bacteria, that consume oxygen.

Over the several centuries of development of the Chesapeake Bay watershed, eutrophication has exacted a steep price in terms of the health of the Bay ecosystem. One particularly serious problem that is believed to have worsened in recent years is oxygen depletion in bottom waters during spring and summer. *Hypoxia* refers to low concentrations of dissolved oxygen, in the range of 0.5 to 3 mg $liter^{-1}$, while *anoxia* is the complete absence of oxygen with concentrations of 0 mg $liter^{-1}$. Oxygen depletion is most severe beneath the seasonal *pycnocline*, the density gradient in the water column that separates the layer of less dense, fresh water flowing seaward over more dense, saltier water flowing into the estuary from the ocean. This *stratification* restricts exchange between waters above and below the pycnocline and can suppress reaeration of oxygen-depleted bottom waters from the well-oxygenated overlying waters.

Because of its impact on living organisms and their habitats, the seasonal decline of dissolved oxygen concentrations in bottom waters of the Chesapeake Bay is an important barometer of the Bay's water quality and restoration of the estuary's "health" has as its centerpiece the remediation of summer oxygen depletion. Accordingly, dissolved oxygen in the Bay has been the focus of much recent study and debate. The overriding question is, "Will reductions of nutrient inputs, specifically those of nitrogen and phosphorus, stem the growth of phytoplankton sufficiently to permit increased concentrations of dissolved oxygen in waters beneath the pycnocline?"

This report summarizes the results of studies on oxygen depletion in the Chesapeake Bay that have been undertaken during the last several years, and presents a consensus of opinion based on these findings and the deliberations of participants in a Workshop sponsored by the Maryland and Virginia Sea Grant Programs.

Workshop Background

It is generally accepted that dissolved oxygen has decreased in the Bay, and that the decrease is at least partly a consequence of increases in nutrient loading. This consensus belief has lead to efforts to improve water quality that are focused on reducing inputs of nitrogen and phosphorus. Signatories to the revised Chesapeake Bay Agreement in 1987 committed state and federal governments to a 40% reduction in nutrient loads from agriculture, sewage and other sources by the turn of the century. The agreement called for a reevaluation in 1992 of the effectiveness of the mandated nutrient reductions toward improving dissolved oxygen concentrations in the Chesapeake.

Despite widespread agreement among scientists, managers, and legislators on the link between nutrient inputs and oxygen depletion, there remained significant uncertainties in the mid-1980s about how nutrient reductions would translate into improved oxygen conditions. To address the need for additional information on processes influencing dissolved oxygen in the Bay, the National Oceanic and Atmospheric Administration (NOAA) sponsored an interdisciplinary research program from 1984-90. This program consisted of a set of coordinated research projects under the auspices of the Sea Grant Programs of Maryland and Virginia. This work recently culminated in a book entitled, *Oxygen Dynamics in Chesapeake Bay: A Synthesis of Recent Research*, published by Maryland Sea Grant College.

An important message from this research program is that natural characteristics of the estuary greatly increase its susceptibility to oxygen depletion. These include: (1) a large watershed area relative to the area and volume of the Bay; (2) a deep central channel flanked by broad shoals; (3) large and seasonally variable riverine nutrient inputs; (4) high freshwater inflow combined with relatively weak tidal mixing; (5) two-layered estuarine flow. The net effect of these characteristics is to increase the residence time and recycling of nutrients, to enhance the production of organic matter by phytoplankton, to increase the demand for oxygen in bottom waters, and to restrict the resupply of oxygen to bottom waters. The conclusion that the Bay has a propensity for the formation of oxygen-depleted bottom waters recognizes the fact that nutrient loading driving high phytoplankton production is intimately associated with oxygen depletion, but it leaves the contemporary question, **"To what extent have anthropogenic increases in nutrient loading exacerbated the natural tendency toward oxygen depletion in the estuary?"**

On the occasion of the publication of *Oxygen Dynamics in Chesapeake Bay: A Synthesis of Recent Research*, the Maryland and Virginia Sea Grant College Programs sponsored a workshop in December, 1991, at the Belmont Center of the American Chemical Society in Elkridge, Maryland. The goal of the workshop was to synthesize our current understanding of the processes regulating dissolved oxygen concentrations in the Chesapeake and their impact on living resources. The workshop brought together scientists from research institutions around the Bay to develop a consensus on what is known about this important aspect of water quality. Four questions served as the focus of the discussions.

- What are the principal causes of seasonal oxygen depletion in the Chesapeake Bay?
- Have the extent and duration of seasonal oxygen depletion increased?
- How does oxygen depletion influence the capacity of the Bay to support natural resources?
- Will a 40% reduction of nutrient inputs eventually lead to increases in dissolved oxygen concentrations in the bottom waters of the Bay?

This report highlights the major findings of the workshop and provides a summary of the discussions on each of these questions. It is intended that this synthesis summarize our current understanding of these issues and provide a context for future research and monitoring.

Major Findings: A Consensus

• **The historical record, preserved in the Bay's sediments, indicates that oxygen depletion has increased in severity since colonial settlement as the watershed has been modified through deforestation, farming and increases in population density.** There is also evidence that episodes of anoxia have increased since the turn of the century and that there has been a concurrent shift from a benthic to a planktonic dominated microalgal flora; the latter shift began in the 19th century but has accelerated in the 20th. Some change preceded the large increases in sewage production and fertilizer use of the last 50 years and is indicative of the sensitivity of the Bay to nutrient enrichment.

• **The volume of water depleted of oxygen each summer is determined largely by the spring flow of the Susquehanna River and the intensity of vertical density stratification during summer.** The effect of river flow is complex, influencing both nutrient input and vertical stratification on scales from days to months. Year-to-year climatic variations in spring runoff are sufficiently large to hamper the detection of underlying trends in the 40-year oxygen record which, prior to the current monitoring program (initiated in 1984), is sparse. Detection of the effects of decreased nutrient loading on oxygen depletion (and an evaluation of the 40% nutrient reduction agreement) will require careful statistical consideration and treatment of this natural variability to resolve trends. Other measures of oxygen depletion, i.e., time of onset, may be important as well (Figure 1).

• **The annual cycle of phytoplankton production is characterized by a spring biomass maximum supported by riverine nutrient input and a summer productivity maximum that is supported by the release of regenerated nutrients from the sediments (Figure 2).** The spring bloom supplies the organic matter that fuels the seasonal oxygen depletion in spring-summer associated with high rates of bacterial metabolism. Nutrient mass balances and bioassay experiments indicate that inputs of both nitrogen and phosphorus must be reduced by at least 40% to achieve improvements in water quality and in the Bay's capacity to support natural resources.

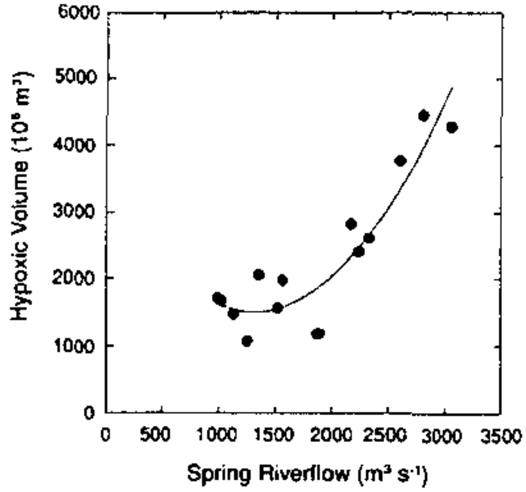

Figure 1. Relationship between volume of summertime hypoxic (< 1 mg O_2 liter^{-1}) water and spring flow of the Susquehanna River during the years 1949-1985 (from Boicourt and Alcock, in preparation).

• **Oxygen depletion in bottom waters inhibits the coupled microbial processes of nitrification and denitrification**[1], resulting in an increase in phytoplankton production by shifting the flow of nitrogen to pathways that enhance nitrogen recycling within the Bay, rather than those leading to gaseous nitrogen export from the Bay. To the extent that higher phytoplankton production causes greater oxygen depletion, this exacerbates the tendency toward anoxia during summer (Figure 3a). Furthermore, anoxia leads to the production of hydrogen sulfide, a toxic compound that further consumes oxygen during its chemical breakdown.

• **The effects of oxygen depletion on living resources are highly organism- and habitat-specific, making the prospects for future impacts complex and difficult to predict (Figure 4).** For example, we know that: (1) oxygen concentrations that currently occur in deep, bottom waters of the Bay cause extensive mortality of benthic organisms and restrict the habitat utilized by pelagic organisms; (2) the survival and distribution of organisms in the flanks of the Bay may be influenced by low oxygen because severely hypoxic waters sometimes intrude into shallow waters; (3) distributional impacts on some organisms, such as fish larvae and zooplankton, result from avoidance of severely hypoxic water, and restriction of organisms to the well-oxygenated surface layer; (4) even the modest increases in dissolved oxygen that are expected to occur following nutrient reductions will yield conditions that have significant ecological impacts, such as the alteration of predator-prey interactions by low oxygen concentrations.

• **Models and observations strongly suggest that the response of dissolved oxygen to reductions in nutrient loading will be nonlinear, once the effects of climatic variability have been considered.** Thus, a 40% reduction in nitrogen and phosphorus inputs to the Bay cannot be expected to result in an equivalent increase in oxygen concentrations. Nutrient reductions of 40-50% will be required to achieve small increases in the mean summer levels of bottom water oxygen (e.g., from < 0.5 to 1-2 mg liter^{-1}). **These increases in bottom water oxygen reflect a return to conditions of 40-50 years ago, and are likely to elicit a significant increase in benthic faunal production because many benthic animals are able to survive and grow at oxygen concentrations as low as 1-2 mg liter^{-1}.**

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[1] Nitrification (the oxidation of ammonium to nitrate, NH_4^+ to NO_3^-) and denitrification (the reduction of nitrate to nitrogen gas, NO_3^- to N_2) in Bay sediments remove 25-30% of the total nitrogen in a gaseous form (N_2) from the system. Anoxic conditions prevent the conversion of ammonium (NH_4^+) to nitrate (NO_3^-) by aerobic bacteria; such conditions enhance regeneration of ammonium that supports further growth of phytoplankton in summer, thus exacerbating the problem of eutrophication.

Workshop Discussions

The workshop discussions were framed by the four questions presented above on the causes of oxygen depletion in the Chesapeake Bay; historical and recent trends in the severity of oxygen depletion; the observed and expected consequences for the biota; the prognosis for improved water quality when 40% nutrient reductions are realized. The following sections summarize the discussions.

• *What are the principal causes of seasonal oxygen depletion in the Chesapeake Bay?*

The research findings on causes of low summer oxygen concentrations that have emerged from the workshop discussions and the book, *Oxygen Dynamics in Chesapeake Bay: A Synthesis of Recent Research*, are:

1. Nutrient loading in the winter-spring during maximum freshwater flow drives the production of phytoplankton biomass in spring (Figure 2). The intensity of this "spring bloom" is regulated by the relative supplies of nitrogen, phosphorus and silicon.

2. Particulate organic material derived from the phytoplankton bloom sinks from the surface mixed layer and serves as the metabolic substrate for an abundant microbial flora with its attendant consumption of oxygen.

3. The depletion of oxygen in bottom waters of the Bay occurs when rate of oxygen consumption exceeds the resupply of oxygen from vertical and horizontal transport of aerated water. Resupply of oxygen is inhibited primarily by vertical density stratification that is, in turn, controlled by vertical salinity and temperature gradients.

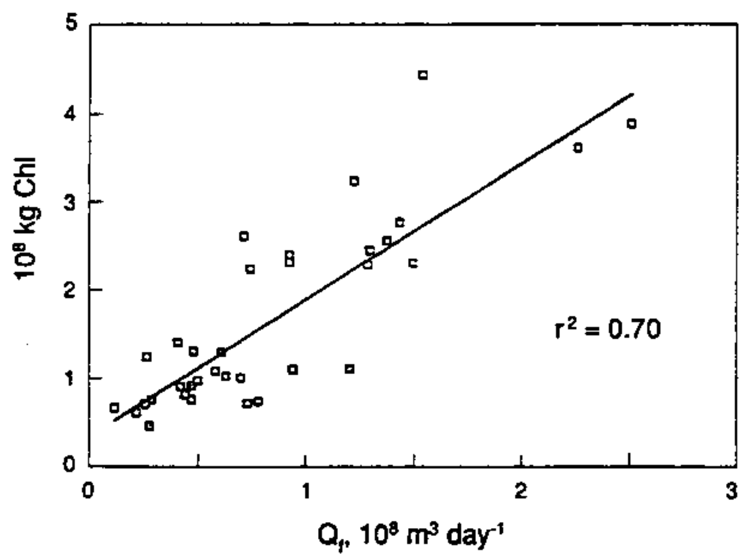

Figure 2. Relationship between phytoplankton biomass as chlorophyll a production in the mesohaline reach of Chesapeake Bay and average flow of the Susquehanna River.

4. Low oxygen conditions commence in late spring following the peak in freshwater flow from the Susquehanna River and once vertical stratification is established.

5. The volume of water that becomes oxygen depleted during summer appears to be related to the magnitude of river flow from the Susquehanna River in April-May and the strength of vertical stratification (Figure 1).

6. As the organic material produced in the "spring bloom" is metabolized during spring and summer, the nutrients that were tied up in phytoplankton biomass are liberated. These recycled nutrients support high rates of algal productivity in summer and provide the substrate for continued oxygen depletion.

7. The nitrogen removal associated with coupled nitrification and denitrification in Bay sediments accounts for only 25-30% of total nitrogen as N_2 gas, as compared to 50-55% in estuaries less affected by anoxic conditions (Figure 3b); this is because the absence of dissolved oxygen depresses the microbially-mediated conversion of NH_4^+ to NO_3^- by obligately-aerobic bacteria. The result is a feedback loop wherein N is retained and cycled throughout the summer, producing additional metabolizable substrate by driving high phytoplankton production.

8. Once anoxic conditions are attained, the biogeochemical cycling of sulphur and the production of hydrogen sulfide (H_2S) in waters beneath the pycnocline operate as an additional oxygen "sink" in the sulfide-rich, anoxic bottom layer. H_2S is also very toxic to plants and animals.

9. Oxygen-depleted conditions persist until autumnal winds cause vertical mixing and the reaeration of bottom waters during the fall overturn in September-October.

• *Have the extent and duration of seasonal oxygen depletion increased?*

There have been several attempts in the past decade to address the question of changes in the severity of hypoxia and anoxia in the Chesapeake Bay (cf. Taft et al. 1980; Officer et al. 1984; Seliger et al. 1985). Based on the data collected since 1950, these efforts have used the volume of water with low oxygen concentrations (< 0.5 mg liter^{-1}) as the principal measure; the focuses have been on year-to-year differences in the anoxic volume and on the relation to primary causes such as river flow and stratification (Figure 1).

While these analyses are important, the limitation of this approach is that it provides no insight to the **historical** development of seasonal oxygen depletion in the estuary. Without some way to scale the problem with respect to past conditions, how can we make informed judgments of solutions? It is thus important to know how long hypoxia and anoxia have been features of the Chesapeake Bay system, and to gauge how recently oxygen depletion has occurred to the extent we now observe it in summer.

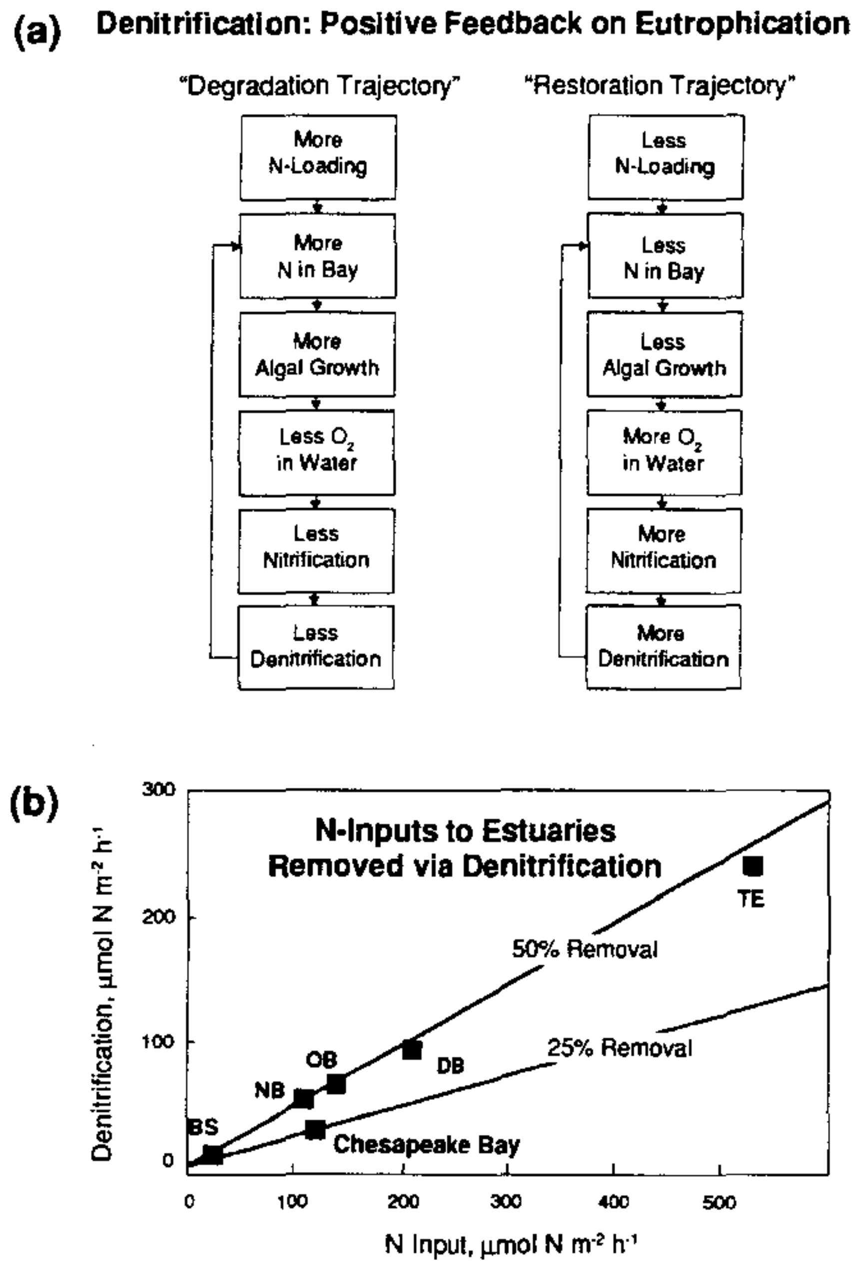

Figure 3. (a) Nitrogen loading to the Chesapeake Bay affects coupled nitrification-denitrification: high nitrogen inputs will ultimately result in less nitrogen removal from the benthos, while significant decreases in those inputs will lead to greater removal. (b) Denitrification in Chesapeake Bay accounts for less nitrogen removal than in other estuaries: BS (Baltic Sea), NB (Narragansett Bay), Ochlockonee Bay (OB), Delaware Bay (DE), Tejo Estuary (TE) (Seitzinger 1988).

Historical changes. A recent paleostratigraphic analysis of sediment cores from the Chesapeake Bay dating back several hundred years strongly suggests that the seasonal occurrence of oxygen depletion has been a feature of the estuary since colonial settlement, not just during the past several decades. Cooper and Brush (1991) report a consistent increase in biological and geochemical indicators of organic enrichment from the time of first European colonization, although these indicators of eutrophication are lacking in the centuries immediately prior to this period.

The first indications of nutrient enrichment appeared soon after colonization: it took relatively little human impact to bring about pronounced ecological changes quite early, an indication that the Chesapeake is prone to eutrophication. Rates of sedimentation and the preservation of total organic carbon, nitrogen and sulfur increased dramatically in the late 18th through the 19th century, when rates and extent of land clearance were greatest.

There is also evidence of significant changes in water quality in the last 50 years, measured as the degree of pyritization of iron in the sediments, considered an indicator of more severe oxygen depletion. This change is accompanied by an accelerated shift in the species composition of the phytoplankton that first began in the 19th century (Figure 5); the fossil record indicates a recent increase in the abundance of centric, pelagic diatoms as compared to benthic, pennate diatoms, considered an indication of eutrophication and decreased water clarity.

Cores taken from the deepest channels of the Bay show little evidence, even in their oldest portions, of the presence of deep-burrowing benthic organisms that would be expected to inhabit well-oxygenated bottom sediments. The absence of these organisms could be the result of persistent hypoxia or anoxia in these regions, even prior to the more recent impacts of human activity, or could reflect sedimentation rates in the deep channels that have always been sufficiently high to preclude the establishment of diverse benthic communities. This is an unresolved issue, but it can be concluded from the lack of bioturbation in long cores from the northern and central main stem channel that benthic community function has been depressed historically, i.e., over hundreds of years, not tens of years.

These changes in the Bay have accompanied the expanded influence of human activities on the landscape as the population has increased dramatically. For example, over 80% of the available land in the Chesapeake Bay region was cleared of forests and used for agricultural purposes between 1830 and 1880. Since that period, various influences have been manifested in changed water quality in the estuary, including greatly increased loads of sediment and nutrients, and inputs of industrial and domestic wastes.

Recent changes. Measurements of dissolved oxygen concentrations made by the Chesapeake Bay Institute from 1950-1980, and by the Chesapeake Bay Monitoring Program from mid-1984 to the present, do not unequivocally demonstrate a recent trend in the extent and duration of hypoxia and anoxia over the past 40 years. This is because: (1) the data on oxygen concentrations in the Bay from the early 1950s to the late 1970s are relatively sparse, and computations of the volume of water that becomes severely hypoxic or completely anoxic produce

Dissolved Oxygen Levels and Living Resources in the Chesapeake Bay

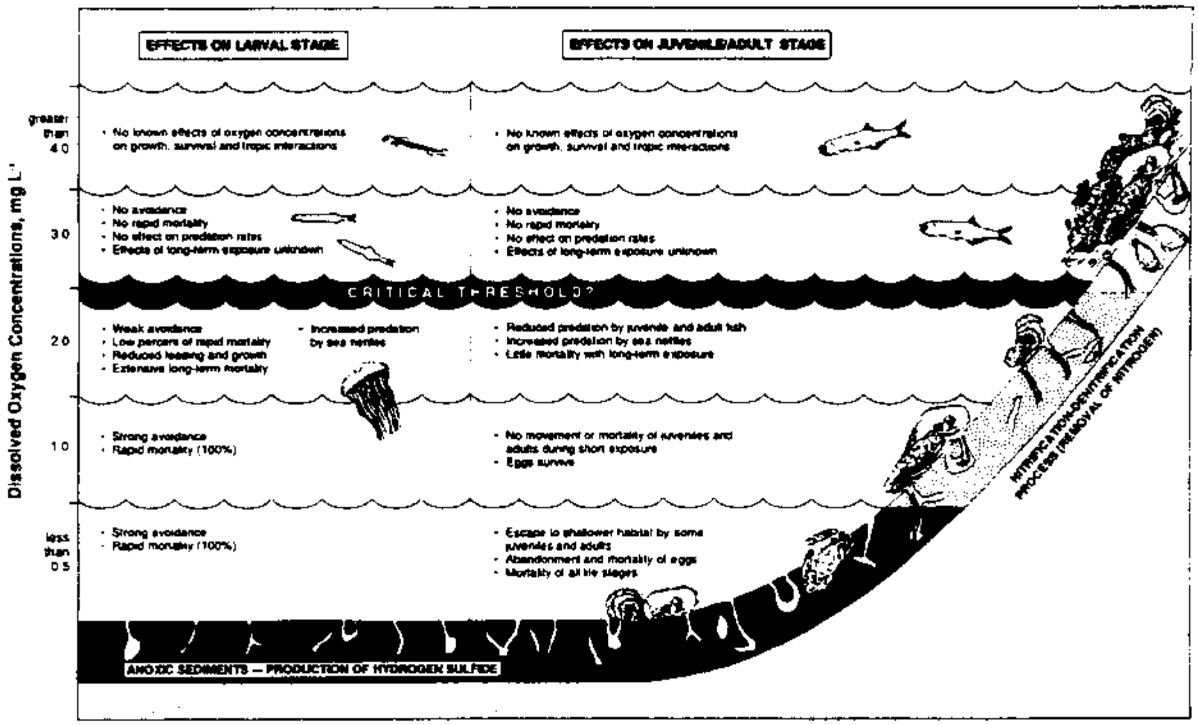

Figure 4. The extent to which oxygen depletion affects living resources is specific for each species, its life history stage and the duration and severity of oxygen depletion.

estimates with large error bounds because they are based on few or infrequent measurements; (2) while there appears to be a relationship between the magnitude of April-May flow from the Susquehanna River and the volume of anoxic water that occurs in summer, the year-to-year variability is high and it is difficult to distinguish change from variability, i.e., the signal-to-noise ratio is low; (3) bottom waters in stratified estuaries such as the Chesapeake Bay (also in fjords) have a **natural** propensity for hypoxia because of the negligible vertical exchange, for periods of weeks to months, with oxygenated surface waters. Consequently, *changes* in the severity of hypoxia, given its natural occurrence, may be difficult to resolve; (4) several decades of data on dissolved oxygen concentrations may simply be too brief a record to draw conclusions on the centuries-long development of this condition.

• *What are the consequences of oxygen depletion for the estuary's biota?*

Oxygen depletion can: (1) directly affect the growth, behavior, and survival of the estuary's biota, and (2) indirectly affect organisms by reducing the availability of suitable habitat or depressing the food supply. The degree to which hypoxia has altered the functioning and productivity of the Chesapeake Bay is unclear, but some inferences can be drawn from recent research findings. At non-lethal oxygen concentrations, for example, hypoxia is likely to cause significant changes in trophic interactions in the ecosystem: low oxygen concentrations have very strong effects on spatial distributions, vertically and laterally, as well as on the attack rate of predators and the ability of prey to escape. The effects of oxygen depletion are highly organism-specific.

Benthic organisms that live in or on the sediments are of particular importance because their habitat is severely impacted by oxygen depletion in summer. Persistent **anoxia** causes rapid, widespread mortality in benthic communities within hours to days; the effects of **hypoxia** vary as a function of the severity, extent and duration of exposure to low oxygen concentrations, and whether a given species is sessile or mobile. For example, infauna can generally survive at oxygen concentrations ~1 mg liter^{-1}, but concentrations <1 mg liter^{-1} appear to cause significant mortality. Some benthic organisms, such as oysters and tube worms, may survive for several days in anoxic conditions because of behavioral or physiological mechanisms. Benthic fish are somewhat more tolerant than pelagic species, although there is a great deal of variability. Lethal levels for most species vary from 0.5-2.0 mg liter^{-1} for exposures of <24 hours.

Sublethal effects of hypoxia at concentrations <2 mg liter^{-1} can affect burrowing and feeding behavior in benthic organisms, and are known to evoke escape responses that make animals more susceptible to predators. There are also ramifications of behavioral responses for the benthic environment as sediment ventilation and bioturbation may be altered. The oxygen concentrations that elicit *specific* behaviors, e.g., migration, are highly species-specific. For example, mobile species such as low-oxygen tolerant fish migrate inshore at concentrations of 0.5 mg liter^{-1}, while less tolerant fish disappear from their bottom habitats at 1-2 mg liter^{-1}. Other important Bay organisms, including the blue crab (and other invertebrates), show the same types and range of responses as fish.

From a broad ecological perspective, a recent analysis shows that the detrital trophic pathway has been severely compromised in the Chesapeake Bay (Ulanowicz 1992). This is not surprising given the profound influence of oxygen depletion on the benthos. But it is apparent from the body of research on effects of hypoxia and anoxia that **functioning benthic communities can exist at oxygen concentrations between 1-2 mg liter^{-1}**, levels that are well below those initially thought necessary to restore ecosystem functioning.

These findings have major implications for the cycling of organic material in the Bay and for food web dynamics if modest remediation of the oxygen depletion problem can be attained. For example, many benthic species are detritivores and, under unimpacted conditions, consume a significant portion of the particulate organic matter falling to the benthos, shunting it away from microbial decomposers. In turn, they provide an important food source for higher level consumers. Restoration of this portion of the Bay's food web could enhance overall productivity, especially of species such as striped bass and crabs that rely to a major extent on benthic prey.

For larval and adult pelagic fish, the major consequences of hypoxia in stratified waters are likely to be sublethal effects, rather than rapid mortality (Figure 4). Generally speaking, the dissolved oxygen requirements of pelagic species are higher than those of benthic species, but the major effect of low oxygen concentrations is probably habitat restriction as the organisms

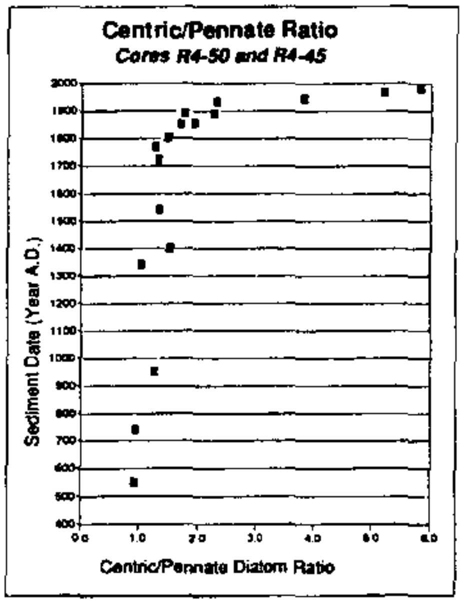

Figure 5. Since the 19th century, the abundance of centric, pelagic diatoms, compared with pennate, benthic diatoms has been increasing; the rate of increase has accelerated in the 20th century.

can migrate from undesirable water masses. In addition, trophic relationships can change, i.e., access to benthic prey may be restricted, encounter rates with pelagic prey may increase because of restricted habitat availability, larval fish may be more vulnerable to predation by less sensitive species, such as sea nettles.

Lastly, the timing and duration of low oxygen events are also of considerable importance. With respect to timing, many species have strongly seasonal life cycles, with the early life stages generally being most sensitive to oxygen depletion. Thus, effects on individual species may be strongly mediated by the seasonality of their distributions, life history characteristics and reproductive timing. The duration of low oxygen exposure is also important. While estuarine organisms are well adapted to a changing environment (including low oxygen concentrations), and may possess the ability to withstand hypoxia for a limited period of time, episodes of longer duration can cause serious impact.

We know that these exposures can vary in duration in the Bay, and that habitat impacts are not restricted to the deep channel of the Bay where anoxia is most apparent (Breitburg 1992; Sanford et al. 1990). For example, continuously moored oxygen meters at both deep and shallow stations in the mesohaline portion of the estuary have recorded rapid fluctuations in ambient oxygen concentrations of 1-5 mg liter^{-1} over periods of minutes to days. Wind-driven intrusions of saline, low oxygen water can expose up to 75% of the productive shallow flanks of the mesohaline Bay to hypoxic conditions. Such rapid, episodic events are often accompanied by considerable mortality in species unable to escape to well-oxygenated areas. These observations emphasize the importance of long-term, continuous records in assessing the severity or impact of oxygen depletion on living resources.

• Will the 40% reduction of nutrient inputs lead to increases in dissolved oxygen concentrations in the bottom waters of the Bay?

To answer the question of what impact 40% nutrient reductions will have on dissolved oxygen in the Chesapeake, we must quantify the relations between nutrient loading and the magnitude of oxygen depletion, and develop a predictive capability for remediation. Unfortunately, the relative contributions of anthropogenic and natural processes to the depletion of oxygen in the Bay are difficult to gauge. That is to say, while we have learned much about summer oxygen depletion in the Bay, the processes involved are complex and the desired predictive capability is not as yet fully realized. We understand the links of nutrient inputs to phytoplankton production and consumption generally, but we do not know specifically how overenriched the Bay is with nutrients. Nor do we know with assurance by how much the aerobic capacity of the Bay to assimilate phytoplankton production has been exceeded, i.e., how much greater primary organic production is than is necessary to elicit low oxygen conditions each year. Thus, several areas require further information before the effect of 40% nutrient reductions on dissolved oxygen can be quantified.

First, the factors that influence the timing and rate of the decline in oxygen during spring, and the spatial and temporal extent of oxygen-depleted waters during summer are not well specified. We believe that freshwater flow in spring (April-May) and its subsequent effect on the intensity of density stratification in summer are critical; there is some evidence for this from simple correlations. But this influence is not as simple as the positive correlation would suggest: flow is also linked with the input of nutrients from the watershed. Thus, an unequivocal separation of stratification and nutrient loading effects on summer oxygen depletion is difficult to achieve, but must be addressed.

Second, the balance between stratification and mixing also determines the strength of the two-layered estuarine circulation, which influences residence time and the rate of horizontal oxygen supply from the southern reaches of the Bay. In turn, pycnocline depth affects both the volume of oxygen-depleted waters and the area of the benthos that is in contact with the oxygenated surface mixed layer. The Bay's geomorphology, with its narrow channel and broad lateral shoals, results in a "threshold effect" on the volume of bottom water when the pycnocline rises from the confines of the deep channel to the shallow, broad flanks. That is, relatively small vertical movements upward of the pycnocline can translate into very large horizontal excursions onto the shelf. This has the potential to produce even more deleterious impacts on living resources as the area of benthic habitat in contact with oxygen- and food-deficient bottom water, relative to that in contact with oxygen- and food-rich surface water, could continue to increase in the absence of nutrient controls.

Third, the sensitivity of the annual oxygen cycle to climatic forcings and the role of anaerobic processes in the cycling of N, S, and P during the summer months suggest that current levels of phytoplankton production provide much more organic matter than is needed to cause summer hypoxia. This bears on the aerobic capacity of the Bay ecosystem to assimilate phytoplankton production: the question is how much of an excess in phytoplankton production currently occurs? As little progress has been made in achieving detectable decreases in nutrients, empirical data are not yet useful in predicting the outcome of significant nitrogen and phosphorus removals that are still to come.

Lastly, scaling the variations of the rates of denitrification and sulfide production, and of the sediment oxidation-reduction potential, may provide critical information on the extent to which nutrient inputs must be reduced for oxygen levels to increase. Changes in the patterns of anaerobic metabolism may provide the first indications that the Bay is responding to reductions in nutrient loading. In fact, small improvements in summer levels of bottom water oxygen may accelerate the response to reduced nutrient loading by stimulating coupled nitrification-denitrification, yielding increased rates of nitrogen loss to the atmosphere by reversing the positive feedback between oxygen depletion, nitrogen recycling, and phytoplankton production (Figure 3).

Summary

While our understanding of hypoxia and anoxia in the Chesapeake Bay is still incomplete, significant progress has been made from the studies conducted through the 1980s. In several areas, e.g., the physical processes that promote hypoxia, the nutrient to phytoplankton to microbial degradation linkage, historical changes in the occurrence of hypoxia, and ecological effects on the biota, the data now available are far richer than they were only a few years ago. Based on the recently-published findings and our deliberations at the workshop, the following conclusions emerge as consensus:

1. Oxygen depletion may be a natural feature of bottom waters in the deep channel of the estuary. The occurrence of low oxygen concentrations in bottom waters of the Bay is probably not a recent occurrence associated only with man's influence. But excessive nutrient enrichment has exacerbated the problem by stimulating too much organic production that cannot be assimilated by higher consumers and that leads to more severe oxygen depletion and its deleterious consequences. Changes in the Bay's ecosystem have, in fact, compromised the processes that tend to remove nutrients and organic material from the system.

Given the historical occurrence of low oxygen concentrations in the Bay's bottom waters:

2. The goal of restoring dissolved oxygen concentrations needs to be based on what is realistic historically in Chesapeake Bay bottom waters. Even under the most pristine conditions, before European settlement, oxygen levels in the deep channel may never have been as high as 2 mg liter^{-1}. This conclusion stresses that water quality criteria based only on the living resources needs of a few sensitive species, and ignoring the physical propensity of this estuary toward hypoxia, are ill-informed and probably unattainable. Rather, efforts to replenish bottom water oxygen should focus on realistic improvements, and accept that:

3. Modest increases in dissolved oxygen concentrations in Chesapeake Bay from 0 to 1-2 mg liter^{-1} are likely the best we can achieve with reasonable remediation efforts, and will have profound effects on the system. Even small, but attainable increases in the level of oxygenation of Bay bottom waters carry with them: (1) improved survival of many bottom-dwelling organisms that tolerate low oxygen concentrations; (2) elimination of hydrogen sulfide from the water column; and (3) a stimulation of nitrogen loss as N_2 gas as coupled nitrification-denitrification is enabled in the presence of some oxygen. This removal of nitrogen from the system will reduce the recycling of nitrogen in summer when it is the element limiting phytoplankton growth and production, thus reducing the substrate available for maintaining anoxic conditions.

From this observation it follows that:

4. Efforts to reduce nutrient loading by 40-50% must be continued and met; without these reductions in nitrogen and phosphorus, dissolved oxygen concentrations in bottom waters are likely to worsen. The substrate necessary to drive the concentration of oxygen to 0 mg $liter^{-1}$ in bottom waters is produced each year, i.e., there is an excess of organic matter produced in the spring phytoplankton bloom. To effect significant changes in anoxia, nutrient inputs must be controlled. Without decreases in nitrogen and phosphorus, additional organic material will be produced and the severity of anoxia is likely to increase; this could be manifested as an increase in the spatial and temporal extent of anoxic water.

If there are no reductions in nitrogen and phosphorus, or only very modest ones as have been observed since the 1985 agreement, we can expect further deleterious impacts on living resources. To this point, it is clear that:

5. Expressions of the severity of hypoxia and anoxia should reflect the effects on living resources, rather than focusing on the volume of hypoxic water as the only gauge of the problem. The volume of hypoxic water as a gauge of Bay health is only one such measure. It has perhaps been overused to follow interannual and interdecadal changes in the severity of anoxia. There are other inducators that deserve additional attention, e.g., the time of onset of anoxia in the deep, central channel, the spatial/temporal distribution of hypoxic conditions throughout the Bay, the propensity for interruption of anoxia during summer by physical intrusions of oxygenated water. These other expressions of the Bay's water quality need to be integrated with the needs of living resources in the system and a more thorough view of the impact of low oxygen concentrations on the biota derived.

Lastly, the findings generated by studies in the 1980s have focused our attention on the fact that:

6. Feedback loops among physical, biological and geochemical processes play integral roles in controlling oxygen dynamics. Because of these feedbacks, a relatively small initial improvement in dissolved oxygen can cause a cascading chain of events which, in turn, will further improve the system. There is a critical need to improve our understanding of the relationships of processes with feedbacks and the onset, duration, and magnitude of hypoxia and anoxia. In this context, there is a clear need for simple, conceptual models of the projected effects of nutrient reductions on the magnitude of the spring bloom, coupled with predictive models of the influence of flow on summer stratification. From these starting points, it should be possible to estimate to what extent the Bay is saturated with organic material each spring, how much of a reduction in nutrient loading will be required to significantly reduce this excess, how long it will take to observe a change in oxygen concentrations, and what magnitude of change is reasonable to expect.

Recommendations

Management

Given the complexity of the watershed and the Bay ecosystem, and the magnitude of year-to-year climatic variability, a concerted effort should be made to detect significant trends and establish indicators of change that can be used to formulate, evaluate, and guide an environmental management strategy. In this context, it is clear that the current goal of a 40-50% reduction in nutrient loading to the Bay is realistic and well founded, and must be achieved if we are to realize even modest improvements in water quality. Management strategies should emphasize sustainable actions, such as maintaining and restoring forests in the watershed, that reflect our current understanding of the impacts of nutrient loading.

Monitoring

Many of the most important ecosystem processes that affect water quality and natural resources are highly variable on time scales of hours to days. Such variability must be documented with long-term observations to develop a quantitative understanding of the underlying mechanisms. This is critical for formulating and evaluating management strategies, including the current effort to reduce nutrient loading to the Bay. The Chesapeake Bay Monitoring Program is therefore of vital importance and should be continued far into the future. The current ship-based monitoring program should be augmented, however, to include: (1) a system of moored platforms that will provide continuous, high frequency sampling of key ecosystem variables at strategic locations throughout the Bay and (2) remote sensing of key variables to provide a synoptic view in near real-time.

Research

Given the goal of quantifying the relationships between nutrient loading and the magnitude of oxygen depletion, it is important to determine the aerobic capacity of the Bay ecosystem to assimilate phytoplankton production. We need to know to what extent this capacity has been exceeded, and what will be the first indicators that nutrient reductions are having an effect.

The effects of low oxygen on the biota are complex because they include both behavioral and physiological responses. Our current predictions are based on in-depth studies of a very limited numbers of species and yet we know that there are large and important differences among species. It is critical that we improve our understanding of how oxygen depletion affects the resources that are the direct targets of management actions.

Research should also specifically target the effects of low dissolved oxygen concentrations on representative living resources. Studies that combine experimental work with carefully coordinated field sampling are likely to be the most successful at providing needed information on sublethal effects, including habitat shifts, altered trophic interactions and changes in growth and reproduction. Current modeling efforts should be continued and expanded to address higher trophic levels/ecosystem interactions when possible. Use of experimental tools such as mesocosms should also be brought to bear on these questions.

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