

Chesapeake Bay Anoxia: Origin, Development, and Significance

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As far back as the 1930's, Newcombe and colleagues (1) observed that the deep waters of the midportion of Chesapeake Bay were anoxic for short periods in the summer. The anoxia has become more widespread and of longer duration in the ensuing years. In this article we explore the origin, historical development, and possible ecological significance of the Chesapeake Bay anoxia.

Origin

Taft *et al.* (2) have described the sequence of events related to the seasonal depletion of oxygen in Chesapeake Bay. The concentration of dissolved oxygen in deep water begins to decrease with the onset of increased stratification of the water column in February and March. The salinity stratification or halocline is controlled by the spring freshet from the Susquehanna River. Oxygen levels decrease to near zero over the ensuing 2- to 3-month period at a rate of around 0.10 mg per liter per day and remain at this level until the return to a more mixed water column in September and October. Development of the anoxia is not directly associated with the seasonal phytoplankton bloom, which occurs later during the midsummer period. Taft *et al.* (2) suggested that respiration of organic matter from the previous summer and fall creates the oxygen demand leading to the anoxia; Kemp and Boynton (3) specified the involvement of benthic rather than deepwater column respira-

tion. We agree with these speculations, as explained below.

The anoxic water mass of Chesapeake Bay is bounded laterally by the bay channel itself. The anoxia has a considerably longitudinal extent and is also

Abstract. *Anoxia occurs annually in deeper waters of the central portion of the Chesapeake Bay and presently extends from Baltimore to the mouth of the Potomac estuary. This condition, which encompasses some 5 billion cubic meters of water and lasts from May to September, is the result of increased stratification of the water column in early spring, with consequent curtailment of reoxygenation of the bottom waters across the halocline, and benthic decay of organic detritus accumulated from plankton blooms of the previous summer and fall. The Chesapeake Bay anoxia appears to have had significant ecological effects on many marine species, including several of economic importance.*

bounded longitudinally by the deep portion of the channel. Biggs and Flemer (4) showed that the source of carbon to the mid-bay region is internal primary production and that there is a net loss of only 16 percent from circulation effects. Thus, for a location in the midportion of the bay, we may consider the concentration of dissolved oxygen to be determined by the vertical exchange rate relation

$$\frac{dC}{dt} = -\frac{1}{d} \frac{dR}{dt} + K_1 (C_1 - C) - K_2 C \quad (1)$$

where C is mean concentration of dissolved oxygen in the lower water mass (milligrams per liter), C_1 is mean oxygen concentration in the upper water mass; dR/dt is benthic respiration rate (grams of oxygen per square meter per day), d is average thickness of the lower water mass (meters), K_1 is the nonadvective vertical exchange coefficient (reciprocal days), and K_2 is the advective vertical exchange coefficient. Equation 1 simply states that the rate of change of oxygen concentration in the lower water mass is determined by the relative magnitudes of the benthic respiration rate and the reoxygenation rate across the halocline. In

this equation the third term is usually unimportant with respect to the first two; the critical condition relates to the magnitude of the $(1/d)(dR/dt)$ term with respect to the $K_1(C_1 - C)$ term.

The benthic respiration rate may be expressed in terms of the benthic oxygen demand c by the first-order decay relation

$$-\frac{dR}{dt} = \frac{dc}{dt} = -kc \quad (2)$$

where k is the decay constant (reciprocal days). Nixon (5) showed, from a synthesis of measurements taken for a variety of coastal marine ecosystems, that there is a linear relation between the yearly, integrated value of primary production and the corresponding value of benthic respiration, with a proportionality constant α of around 0.25. Thus we may express the mean respiration rate for the

mid-bay region at any given time t in terms of the mean primary production rate $p(t_0)$ at some earlier time t_0 by

$$\left(\frac{dR}{dt}\right)_t = k(t) \int_{-\infty}^t \alpha p(t_0) \exp \left[-\int_{t_0}^t k(\tau) d\tau \right] dt_0 \quad (3)$$

where we have ignored the sinking time of the detritus from the photosynthetic zone to the bottom in favor of the seasonal time variations of interest. The organic detritus that reaches the bottom may be some combination of dead or dying phytoplankton, fecal pellets, zooplankton remains, animal parts, and, perhaps most importantly, organic aggregates including dissolved organic substances that have been adsorbed (6). In the mid-bay region Van Valkenburg *et al.* (7) observed that the detritus particles composed 66 percent of the yearly volume of suspended organic matter, compared to 34 percent for living cells, and that the size of the detritus particles peaked at 20 to 35 μm , considerably larger than living cells. In the York estuary Patten *et al.* (8) observed a settling time for the organic detritus of 0.34 day from 0.6 to 6.7 m. Yanada and Maita (9)

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cited an average sinking velocity of 1 m/day for particulate organic material in Funka Bay, Japan.

Equation 3 states that the respiration rate at a time t is given by the product of the decay constant at the same time and the total amount of organic detritus available for oxidation. The most sensitive parameter in this relation is the decay constant k . In particular, if the decay constant is large, essentially all the organic detritus related to a given period of plankton bloom will be oxidized during or shortly after the bloom, and little will be left for oxidation during the following spring, when stratification of the water column occurs.

The decay constant is a function of ambient water temperature T and dissolved oxygen concentration C . It is often expressed by an empirical relation of the form

$$k = k_0 \left(\frac{T}{10} \right)^a \left(\frac{C}{6} \right)^b \quad (4)$$

where T is in degrees Celsius and C here is in milliliters of oxygen per liter (1.429 mg of oxygen per liter = 1 ml of oxygen per liter). There have been a number of observations related to the parameters a and b (Table 1); there have been fewer determinations of the multiplying factor k_0 . The most extensive is that given by Nixon *et al.* (10) for respiration rate observations taken over a 120-day period at 15°C for bottom samples from Narragansett Bay. Biggs (11) made a single laboratory determination for carbon depletion of Chesapeake Bay organic detritus over 90 days at 20°C. The average for these two measurements is $k_0 = 0.0053$ per day, or $1/k_0 = 190$ days. An indirect assessment of the reasonableness of this value can be obtained from the observed decrease in particulate carbon (12) and respiration rate (13) as a function of depth below the photosynthetic zone in oceanic regions. The values in Table 1 are for an assumed sinking rate of 1 m/day; for a sinking rate of 0.5 m/day, they would be halved.

From Eqs. 3 and 4 with $a = 0.45$, $b = 0.57$, $k_0 = 0.0053$, and $\alpha = 0.25$, the seasonal variation in the benthic respiration rate may be determined. The characteristic values for primary productivity and near-bottom temperature and dissolved oxygen that were used in the calculations are shown graphically in Fig. 1. The productivity values are from Taft *et al.* (2) for calendar year 1970, as corrected for day-night effects. It is to be noted that the yearly primary production of 1178 g of carbon per square meter is high and that it is related principally to the midsummer blooms with productivi-

ty increases of six to eight times. From $\alpha = 0.25$ and a respiratory quotient of unity (10), the calculated yearly benthic respiration rate is 785 g of oxygen per square meter, also a high value. No possible effects of anaerobic decomposi-

tion have been included in the calculations. As illustrated in Fig. 2, the principal result is that the small value of k_0 , in conjunction with the low levels of dissolved oxygen in summer and the low temperatures during winter, has the ef-

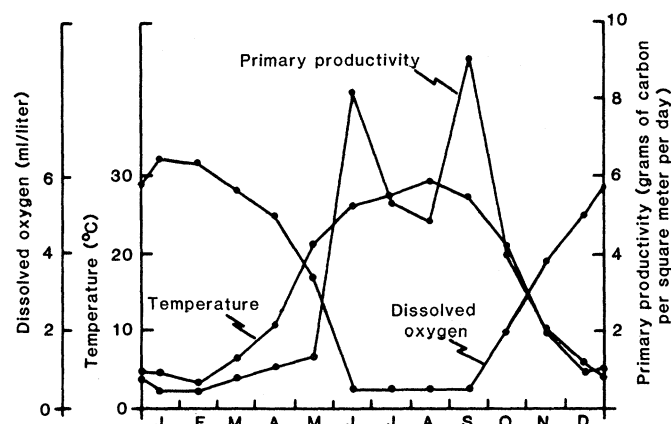


Fig. 1. Characteristic temperatures, dissolved oxygen, and primary productivity versus seasonal time for the midportion of Chesapeake Bay.

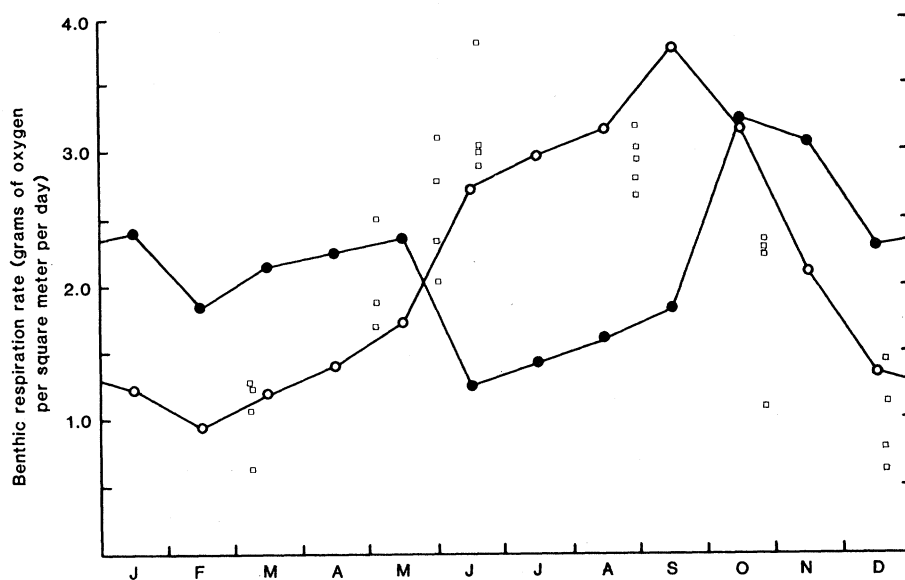


Fig. 2. Predicted benthic respiration rates including (●) and excluding (○) the effect of dissolved oxygen level. (□) Measurements of Boynton *et al.* (14).

Table 1. Summary of determinations of benthic respiration parameters a , b , and k_0 in Eq. 4.

Region	Reference	a	b	k_0
Puget Sound	(36)	0.37		
Georgia coast	(15)	0.36		
Loch Ewe	(37)	0.61		
Mean		0.45		
Ivel River	(38)		0.45	
Spring Creek	(39)		0.30	
Marion Lake	(40)		0.76	
Puget Sound	(41)		0.62	
Ramsen Lake	(42)		0.48	
Narragansett Bay	(10)		0.79	
Mean			0.57	
Narragansett Bay	(10)			0.0049
Chesapeake Bay	(11)			0.0056
Pacific Ocean	(12)			0.0077
Pacific Ocean	(13)			0.0066
Mean				0.0053*

*Mean of the first two listed determinations only.

fect of lengthening the decay time for the organic detritus such that high respiration rates exist during the following spring, when increased water column stratification occurs.

Boynton *et al.* (14) made seasonal benthic respiration measurements at four shoal stations of 3-m depth in the Patuxent River estuary during 1978 and 1979. At these locations the bottom waters were found to be well oxygenated year-round. The observed respiration rates range from 2 to 4 g and 1 to 2 g of oxygen per square meter per day during the summer and following spring, respec-

tively. Boynton *et al.* (14) noted that the yearly respiration rate of 730 g of oxygen per square meter was comparable to the highest values observed by others (15, 16). For comparison we made the additional calculations excluding the dissolved oxygen effect of Eq. 4 (Fig. 2). The results are in reasonable agreement with the observations, both as to the magnitude of the benthic respiration rate and as to the seasonal trend.

The rate of reoxygenation across the halocline may be estimated from the distribution of salinity in the water column by using a two-dimensional, box

model approach for the midportion of Chesapeake Bay (17). The vertical nonadvective (E_v) and advective (Q_v) exchange rates are given by

$$E_v = \frac{\bar{s}(s_2' - \bar{s}')}{(\bar{s}' - \bar{s})(s_2' - \bar{s})} R \quad (5)$$

and

$$Q_v = \frac{\bar{s} \bar{s}' - s_1 s_2'}{(s_2' - \bar{s})(\bar{s}' - s_1)} R \quad (6)$$

where R is Susquehanna River flow in cubic meters per day and the various salinities are as defined in Fig. 3. The coefficients of Eq. 1 are given, in turn, by $K_1 = E_v/V$ and $K_2 = Q_v/V$, where V is total volume (cubic meters) of the water mass beneath the halocline in the mid-bay portion. Taft *et al.* (18) followed the box model procedure in making an analysis of Chesapeake Bay ammonium and nitrate fluxes for the calendar year 1975. Using their salinity, river flow, and volume parameters for the mid-bay region, we obtain a value of K_1 of 0.012 per day, or $1/K_1 = 80$ days for May (representing the stratified conditions of summer) and 0.120 per day, or $1/K_1 = 8$ days, for February (representing the less stratified winter conditions). The corresponding values for K_2 are 0.015 and 0.062 per day. The important result is that E_v changes by a factor of 10 from winter to summer. On a different temporal scale similar results, with a corresponding change in E_v , are obtained for the neap-to-spring tidal cycle, stratification-destratification events that occur in the York and Rappahannock estuaries (19).

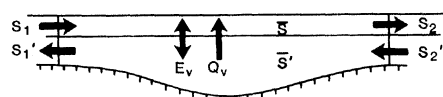


Fig. 3. Box model representation of the longitudinal extent of the midportion of Chesapeake Bay.

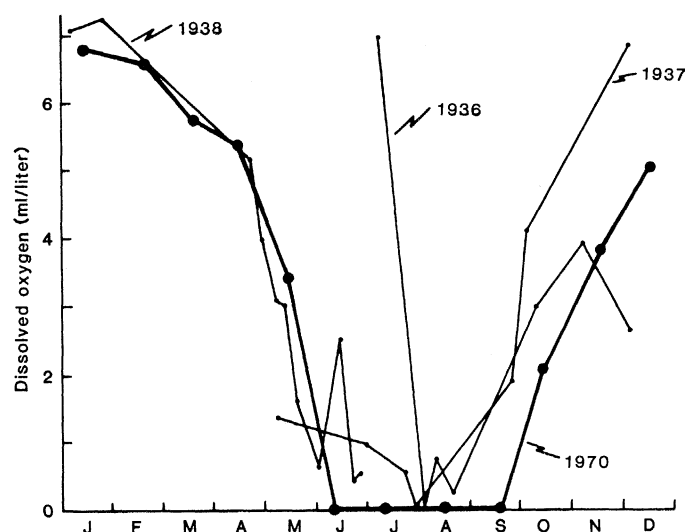


Fig. 4. Comparison of seasonal dissolved oxygen levels at 20 m depth at a station in the Chesapeake Bay channel off the mouth of the Patuxent estuary for 1936 to 1938 (1) and 1970 (20).

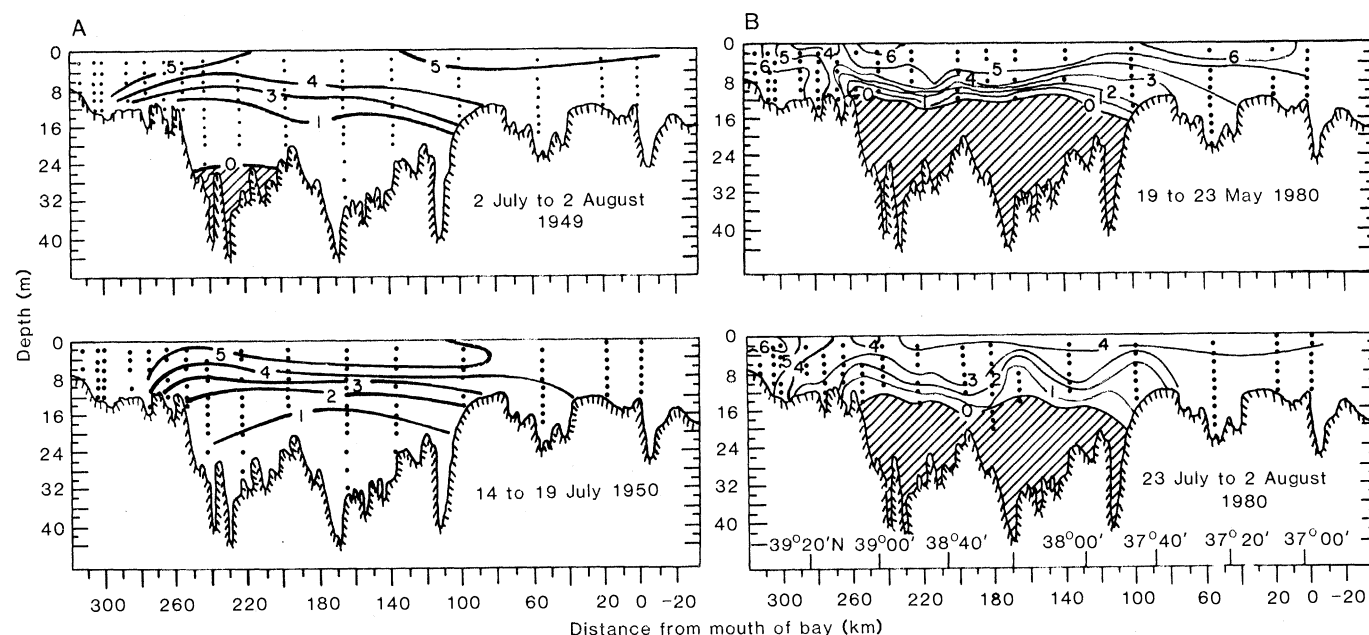


Fig. 5. Dissolved oxygen levels (milliliters per liter) along the main channel of Chesapeake Bay in summer 1949 and 1950 (43) (A) and in summer 1980 (21) (B). Dots indicate measurement locations.

The preceding analyses for benthic respiration and reoxygenation rates provide representative values for the present conditions in the midportion of Chesapeake Bay. Taking nominal values for benthic respiration rate in spring of $dR/dt = 2.0$ g of oxygen per square meter per day and $d = 10$ m, the first term in Eq. 1 will be -0.20 mg of oxygen per liter per day. The second term will have a maximum value when the lower water mass is nearly anoxic and the upper water mass saturated, or $C_1 - C = 10$ mg of oxygen per liter, giving values of 0.12 and 1.20 mg per liter per day during summer and winter, respectively. Thus with the onset of spring stratification the benthic respiration rate will be dominant over the reoxygenation rate, and dissolved oxygen in the lower water mass will decrease to zero and stay there as long as the water column remains stratified. With the return to a more mixed column in fall the reoxygenation rate will be considerably in excess of the benthic respiration rate, and the level of dissolved oxygen in the deep waters will return rapidly to normal.

Starting with an equilibrium condition for the winter months, dissolved oxygen in the lower water mass will be around $C = 10 - (0.20/0.120) = 8.3$ mg/liter. With the onset of increased stratification, the dissolved oxygen will decrease at a rate of $dC/dt = -0.20 + 0.012(10 - 8.3) = -0.18$ mg/liter per day. With the approach of anoxic conditions, the rate will decrease to around $dC/dt = -0.20 + 0.12(10 - 0) = -0.08$ mg/liter per day. These computed rates are of the same order of magnitude as the rate observed by Taft *et al.* (2), -0.10 mg/liter per day.

We have sought to demonstrate quantitatively that the principal causative agents for the Chesapeake Bay anoxia are a combination of benthic respiration and increased water column stratification during summer. To extend the analysis, particularly toward a definition of the widespread hypoxic conditions found at present, a number of additional processes must be considered:

1) Both the longitudinal and lateral circulation and tidal mixing exchanges from the mid-bay to the upper and lower portions of Chesapeake Bay and to the Patuxent and Potomac estuaries have to be included.

2) It is important to know the nutrient inputs to the bay ecosystem as a whole and to the mid-bay portion in particular.

3) The dynamics of internal recycling of nutrients through photosynthesis and respiration and through benthic remineralization are important. For example,

there may be a positive feedback when the bottom areas covered by anoxic waters expand, causing increased remineralization of phosphorus from the sediments, which may further stimulate primary production.

4) The degree of summer water column stratification is critical. It is important to have a quantitative description of its seasonal development and dependence on Susquehanna River flow and other factors.

5) Effects of the spring diatom bloom in the lower Chesapeake Bay have to be considered in terms of the contribution to the expanded hypoxic conditions and the loading of organic detritus through gravitational circulation to the mid-bay region.

6) It is important to assess water column respiration effects beneath the halocline, particularly during the summer and fall months.

Historical Development

The anoxic conditions in the midportion of Chesapeake Bay have reached their present state gradually in recent historical time. In several of our figures we have attempted to illustrate these historical changes within the limits of existing data.

Figure 4 shows the seasonal change in dissolved oxygen at a 20-m depth for a

station in the bay channel off the mouth of the Patuxent estuary as observed by Newcombe and colleagues (1) in 1936 to 1938 and as observed at the same station and depth in 1970 by Taylor and Cronin (20). In 1936 to 1938 there were generally low levels of dissolved oxygen during summer, with occasional zeros; by 1970 there was consistent anoxia in the summer months. The anoxia now begins in May and extends into September.

Figure 5 illustrates the change in dissolved oxygen along the main channel of Chesapeake Bay between the summers of 1949 and 1950 (Fig. 5A) and the summer of 1980 (Fig. 5B). During 1949 and 1950 the deep portion of the bay channel, extending from about 100 to 260 km, had low dissolved oxygen levels and would be described as hypoxic. By 1980 these same waters were anoxic.

Figure 6 shows the corresponding changes in the areal extent of the hypoxic and anoxic condition for the waters at the bay bottom. In 1950 (Fig. 6A), hypoxic conditions were restricted to the mid-bay channel. By 1980 (Fig. 6B), these waters were anoxic, and the hypoxic conditions covered much of the remainder of the bay bottom.

Figure 7 shows the total volume of bay water affected from 1950 through 1980. By 1980 the waters with dissolved oxygen levels less than 0.5 ml/liter had gradually increased to around 5 billion cubic meters. The region affected extends from

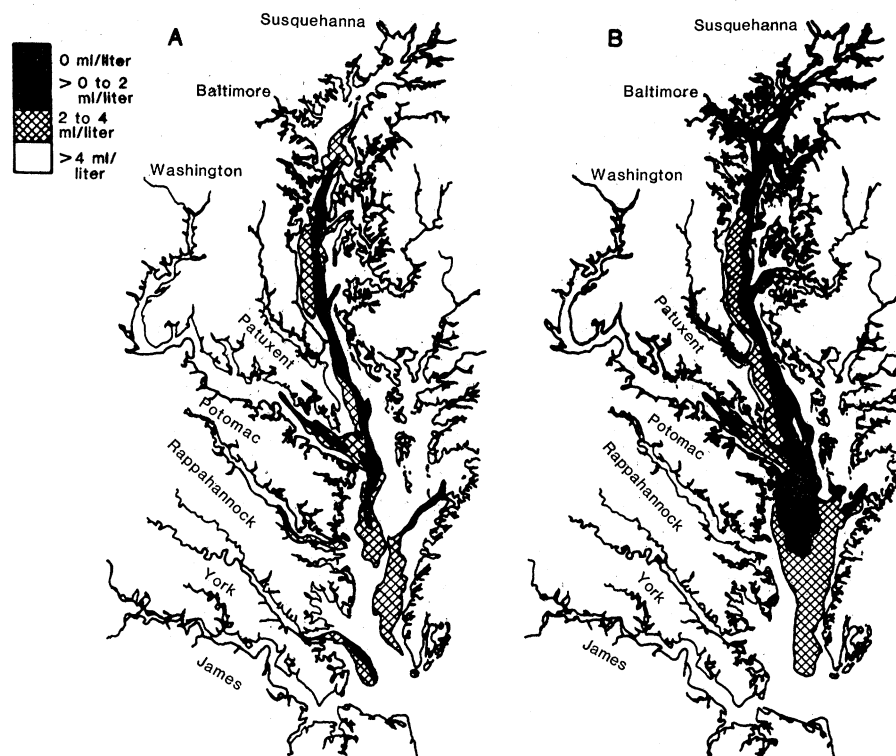


Fig. 6. Area of Chesapeake Bay bottom affected by low dissolved oxygen levels in summer 1950 (21) (A) and in 1980 (21) (B).

Baltimore to the mouth of the Potomac estuary and includes portions of the lower reaches of the Potomac and Patuxent estuaries.

Although there are year-to-year variations in the degree of water column stratification, there apparently has not been a long-term trend in the related Susquehanna River flow. For example, the Susquehanna spring flows for 1950 and 1980 (Figs. 5 and 6) were the same. On the other hand, there has been a historical increase in yearly plankton production and related nutrient inputs to the bay system (21, 22). Of the two causative agents it appears that benthic respiration rather than water column stratification has been the controlling factor in the historical increase in anoxia.

Ecological Significance

The ecological and economic significance of summer anoxia and hypoxia in Chesapeake Bay may be substantial. The specific effects and their magnitude are only partly known, but some conclusions can be drawn from limited published observations, anecdotal reports (especially from commercial fishermen), and speculations based on current knowledge of the biological components and processes of the bay.

Sessile benthic biota in the bay includes oysters, clams, many additional molluscs, coelenterates, crustaceans, worms, algae, the spores of resting stages of diatoms, other phytoplankton, and bacteria. These organisms are killed when the combination of temperature, hypoxia, and duration of exposure exceeds their tolerances. Some species, like the oyster, have impressive defense mechanisms, but these are overcome relatively quickly. Very large quantities of benthic organisms may be killed in the central Chesapeake during the summer, and the areal extent and therefore the magnitude of the effect have increased substantially. The results might extirpate species, reduce the food supply of benthic feeders, and interfere with the life cycle of such merobenthic species as the sea nettle (*Dactylometra quinquecirrha*) and some diatoms.

Mountford *et al.* (23) reported regular depletions of oxygen to near zero each summer from 1971 to 1974 at 9 m near Cove Point on the western shore north of the Patuxent estuary mouth. The companion paper by Holland *et al.* (24) described high mortalities each summer in the macrobenthic community, resulting in near-total faunal depletion. Recolonization followed each fall and resulted in

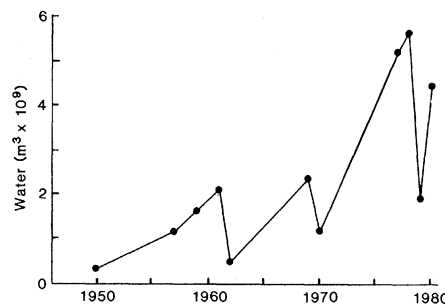


Fig. 7. Volume of water in Chesapeake Bay with dissolved oxygen levels less than 0.5 ml/liter during summer from 1950 to 1980 (21).

communal dominance by fall spawners.

In recent decades there have been many disturbing anecdotal reports on benthic effects of the anoxia. Carpenter and Cargo (25) received reports from commercial crabbers on the death of blue crabs (*Callinectes sapidus*) in pots in the mid-bay region during 1952 and 1953. Their field observations showed 50 percent or more mortality when oxygen was less than 2.0 ml/liter below 7 m.

One of us (R.B.B.) recently received the following opinions from crab fishermen from Tilghman Island, which is adjacent to the bay's midportion. Before 1965 there were abundant crabs in deep water (> 20 m), both early in the season (prior to mid-May) and later in the season (after mid-September). There is no longer any deepwater crabbing. In past years the male blue crabs hibernated in the mud in deep water. They now hibernate in shallow water. During the summer of 1982 no crabs were caught in water deeper than 4 m. The crabs appeared to be in a stressed condition; many died before they could be transported to market.

In the lower Potomac, which also has a hypoxic water mass in continuity with that of the bay, all crabs below 6 m are reported to have died in 1973; and crabs were driven ashore in large numbers in many late summer periods (26). Similarly, in the mid-bay region there have been reports of "crab wars," in which tens of thousands of crabs crowd into shoal waters and may actually leave the water. A seiche could cause such an affect. Carter *et al.* (27) reported that seicheing of the anoxic water mass at mid-bay does occur at frequent intervals during summer. With a cross-channel wind the surface water mass moves toward the windward shore, concurrently raising the anoxic water mass into shoal waters on the lee shore.

"Black bottoms" in the lower Rappahannock are reported by Virginia oystermen late in the summer of some years. Sediments are black and foul-smelling,

and oysters and other benthic biota are dead (28).

The presence of large masses of hypoxic water may also be detrimental to finfish. Assuming that most or all can sense such waters and move to escape them, they will be crowded into a smaller volume and be excluded from the food supply and space previously available. There have been serious declines in many species of important fish (21, 22, 29). Anadromous fish such as alewife (*Alosa pseudoharengus*), American shad (*Alosa sapidissima*), striped bass (*Morone saxatilis*), and white perch (*Morone americana*) travel up estuary in spring to spawn in shoal waters. The juveniles progress down estuary later in the season. Commercial landings of striped bass decreased from about 3000 tons per year during 1960 to 1975 to 700 tons in 1980. Some marine spawners tend to enter the bay in late spring and summer as larvae and juveniles. Anoxia of bottom waters during the period from May to September can restrict their habitat and the availability of their food, particularly for spot (*Leiostomus xanthurus*) and croaker (*Micropogonias undulatus*), which feed on the bottom. Commercial landings of croaker decreased from about 20,000 tons annually in the 10-year period before 1950 to around 5000 tons in the succeeding years. In addition, there has been a steady increase in the landings of menhaden (*Brevoortia tyrannus*) over the past 30 years, to the point where menhaden now account for around 90 percent of the total finfish landings in Chesapeake Bay. The menhaden is a planktivorous fish that can withstand substantial environmental stress.

The earliest phytoplankton counts for the middle to upper bay region showed a summer minimum of dinoflagellates and prominent spring and smaller fall-winter maxima dominated by diatoms (30). Today the same region shows a summer maximum dominated by small flagellates and green algae (Fig. 1) (31). It is difficult, if not impossible, to compare the early determinations with present measurements because of advances in collection procedures and recognition of the importance of smaller plankters to the total biomass. Nevertheless, there have been changes in the timing, quality, and size of the plankton blooms. The change in quality can be considered to be in an undesirable direction, altering the populations from those used as a food source by higher trophic levels to those of little value in the food chain (32). The shift from a diatom to a flagellate community may have been caused by changes in the type and quantity of the nutrient supply,

by the introduction of toxins, or by the mid-bay anoxia. The early summer bloom of dinoflagellates is dominated by *Prorocentrum*, which follow an annual cycle based on the estuarine gravitational circulation pattern; the late summer bloom is dominated by *Gyrodinium*, which germinate in situ from overwintering cysts. *Prorocentrum* progress up estuary in the deep waters during early spring from the bay mouth to the upper bay regions, bloom during the late spring and summer in the surface waters of the middle and upper bay, progress down estuary in the surface waters during fall and winter, and eventually collect in the deep waters along frontal surfaces near the bay mouth (33). Dinoflagellates are motile; when they encounter the anoxic water mass during their spring transport, they avoid it and continue moving up estuary along the surface of the anoxic waters near the halocline. Diatoms, on the other hand, are not motile; when they encounter the anoxic waters in a corresponding early spring transport, they sink to the bottom and are prevented from passing into the upper and middle bay (34). In addition, recent experiments demonstrate that exposure to low oxygen concentrations inhibits the germination of diatom spores (35).

Thus it appears that the ecological effects of the anoxic and hypoxic water are large. Many species that play fundamental roles in the food web and biology of Chesapeake Bay are in decline, as are several species of key economic importance to the region.

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AAAS Board Statement on Politics and Science

In response to concerns that decisions regarding the funding of scientific research are being made in a political atmosphere, on 10 December 1983 the AAAS Board of Directors issued the following statement:

"In the long-standing relationship between government and science in the United States, major responsibility for funding basic scientific research has settled upon the government partner. For its part, the scientific community has accepted primary responsibility for defining research needs and opportunities and providing assurance that public funds are allocated on a priority basis, through peer

review. For either partner to breach its responsibility carries serious risk to the solidarity of what has proved an extraordinarily effective partnership.

"The Board of Directors of the American Association for the Advancement of Science is concerned that failures to adhere both in principle and in practice to criteria of scientific choice at all times will serve only to diminish public confidence in the peer review system as the basis for allocating national resources, with serious negative consequences for the integrity and advancement of science."