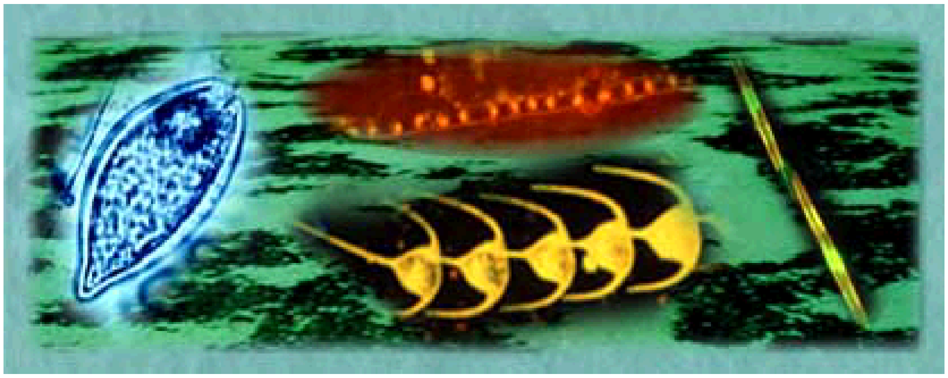
OXYGEN DEPLETION IN COASTAL WATERS



Oxygen depletion occurs primarily during the summer in over half of the major estuaries in the United States. Its duration and extent range from a few weeks and limited areas to several months and expansive areas. Because the physics of some estuarine and coastal systems isolate the bottom waters from interaction with the atmosphere they become susceptible to oxygen depletion; however, human activities increase the likelihood of the phenomenon. Evidence associates oxygen depletion with changes in landscape use and nutrient management that result in nutrient enrichment of receiving waters. Increases in nutrient inputs clearly and directly relate to population density in watersheds draining to coastal areas, and population-driven increases in nutrient loading are causing problems in the form of oxygen depletion, habitat loss, fish kills and the frequency of harmful algal blooms.

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INTRODUCTION

The occurrence of severe oxygen depletion, either hypoxia (<2 milligrams of oxygen per liter, or <3 mg/l in some systems) or anoxia (0 mg/l), is a growing concern for U.S. estuarine and coastal waters. Prolonged oxygen depletion not only can disrupt benthic and demersal communities but also can cause mass mortalities of aquatic life (Diaz and Rosenberg, 1995). Among other problems, the consequences to coastal commercial fisheries can be disastrous (Baden et al., 1990; Zaitsev, 1991, 1993).

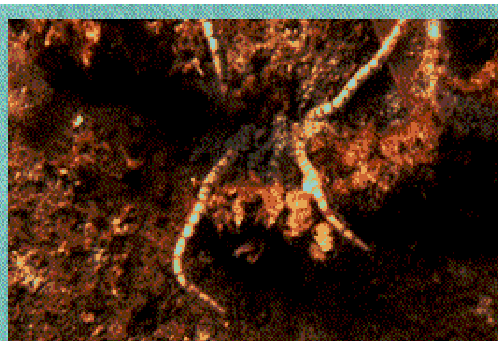


Photo 1. This brittle star has succumbed either because of low levels of dissolved oxygen in bottom waters or possibly because of the presence of toxic hydrogen sulfide.

Oxygen depletion results from the combination of several physical and biological processes. Many estuarine and coastal systems have a natural propensity for oxygen depletion due to their basin morphology, estuarine circulation, residence time of water and high freshwater discharge. Added to this structure is the cumulative load of point source inputs of organics and nutrients, as well as the more diffuse inputs of nutrients from nonpoint sources associated with the freshwater influx. In most coastal plain estuaries, such as the Chesapeake Bay, and the watershed of the Mississippi River, the level of nutrients from diffuse nonpoint sources far exceeds the point sources. Other systems, such as the Hudson River and Long Island Sound, receive a concentration of point source inputs near the mouth of the estuary. Nutrient enrichment over long periods leads to broad-scale degradation of the marine environment.

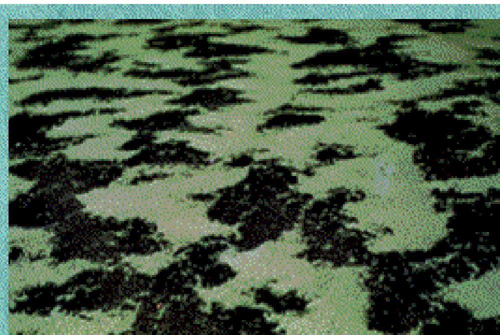


Photo 2. Oxygen depletion often starts with dense surface algae blooms caused by excess nutrient input.

As a general rule, the nutrients delivered to estuarine and coastal systems support biological productivity. Excessive levels of nutrients, however, can cause intense biological productivity that depletes oxygen. The remains of algal blooms and zooplankton fecal pellets sink to the lower water column and the seabed. The rate of depletion of oxygen during processes that decompose the fluxed organic matter exceeds the rate of production and resupply from the surface waters. Following a fairly predictable annual cycle, oxygen depletion becomes most widespread, persistent and severe during the summer months.

Many estuarine systems remain stratified to varying degrees on seasonal time scales, depending on the annual cycle of freshwater discharge. The turbulence from high winds that mix the water column reduces the strength of the stratification during the winter. Phytoplankton production is also less in the winter. In the spring, turbulent mixing decreases as winds subside and storm frequency diminishes. Calmer seas and warmer surface waters result in a stable water column, extending the strength of the stratification into upper and lower layers. In addition, freshwater discharges reach an annual maximum in the spring, and they bring with them high levels of nutrients (nitrogen, phosphorus and silicate) that stimulate a peak in primary productivity. The increased freshwater inputs can further contribute to a strengthening of the stratification. In systems without a dominant freshwater input, seasonal stratification results from solar warming of the surface waters. In the autumn, the water column again undergoes mixing from a variety of physical processes, including strong winds from tropical storms or frontal passages, or thermal turnover of the water column as cooled surface waters sink. The autumn mixing of the water column reduces and often diminishes the oxygen depletion until the following spring and summer when the cycle repeats.

Hypoxia affects living resources, biological diversity and the capacity of aquatic systems to support biological populations. When oxygen levels fall below critical values (e.g., 2 to 3 mg/l, depending on the system), those organisms capable of swimming (e.g., demersal fish, portunid crabs, and shrimp) evacuate the area. The stress on less motile fauna caused by declining oxygen levels varies according to the oxygen requirements of the organism. Animals resident in the seabed are usually more resistant to low oxygen concentrations, but they also experience stress or die as oxygen concentrations decline from 1 mg/l to anoxia. Important fishery resources are variably affected by direct mortality, forced migration, reduction in suitable habitat, increased susceptibility to predation, changes in food resources and disruption of life cycles.

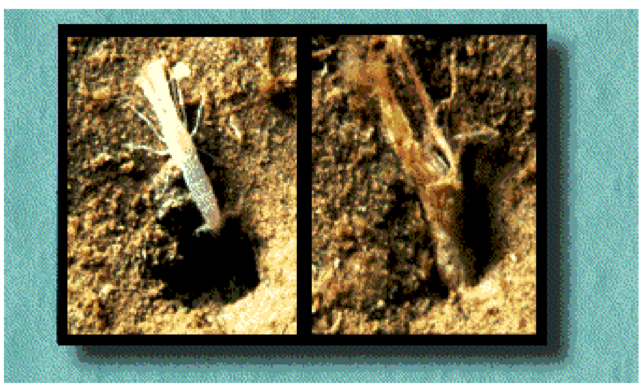


Photo 3. The benthic shrimp on the left is experiencing stress, reaching beyond its burrow in an attempt to capture more oxygen; on the right is a dead shrimp covered with bacteria and organic debris.

The timing and location of low dissolved oxygen conditions in U.S. coastal waters is now fairly well documented, and there are studies that link the frequency and volume of summer oxygen depletion to increased nutrient inputs (Officer et al., 1984; Larsson et al., 1985; Tolmazin, 1985; Andersson and Rydberg, 1987; Justic et al., 1987; Cooper and Brush, 1991; Diaz and Rosenberg, 1995; Rabalais et al., 1996). Other coastal systems are receiving organic inputs. Many coastal ecosystems have been subject to changes in nutrient inputs that reflect patterns of land use in their respective watersheds and airsheds. Growth in population, changes in land cover, and increases of fertilizer use and animal husbandry have resulted in two- to tenfold increases in the level of nutrient inputs during this century, with particularly dramatic increases since the 1950s (Turner and Rabalais, 1991; Justic et al., 1995a, 1995b; Howarth et al., 1996; Nixon, 1997) (Figure 1).

Dead zone blamed for fish kil

Photo 4. The numbers and extent of hypoxic episodes are increasing, especially in areas important to commercial fishing. Concern is spreading as the media report the consequences of these events.

(top)

NATIONAL PICTURE

Oxygen depletion occurs during the spring, summer and fall in over half of the major estuaries in the United States (Table 1). Differences in freshwater inputs, point or diffuse nutrient loadings, the location of the nutrient inputs, geomorphology and circulation affect the severity of oxygen depletion in the various estuaries. Some are clearly overenriched with nitrogen and phosphorus and then suffer notable oxygen depletion problems that have been identified for a number of years. Others are beginning to experience the telltale signs of degraded water quality, including hypoxia. Still others are less enriched, but are physically susceptible to oxygen-depleted bottom waters under certain circumstances.

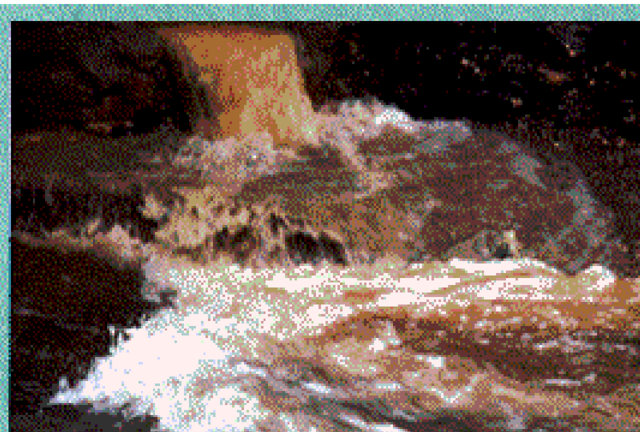


Photo 5. Oxygen depletion is linked to freshwater discharge and the levels of nutrients that it contains.

(top)

Oxygen Depletion and Nutrient Enrichment

One priority for coastal researchers and managers is to address the potential causes and the timing of oxygen depletion so that they can implement appropriate management strategies. Studies in the Chesapeake Bay and the northern Gulf of Mexico, among other systems, provide evidence that the timing, spatial extent and severity of oxygen depletion, as well as changes over time, are linked to freshwater discharge and nutrient flux (Justic et al., 1993, 1996, 1997; Rabalais et al., 1996; Malone, 1992). In both the Chesapeake Bay and the northern Gulf of Mexico, seasonal nutrient fluxes stimulate biological production in the spring, resulting in organic matter flux to bottom waters that is usually more than sufficient to cause bottom water oxygen depletion during the summer (Malone, 1992; Qureshi, 1995). The timing of Mississippi River discharge and nutrient flux, surface water phytoplankton production, and oxygen depletion are strongly correlated on the southeastern Louisiana shelf. The highest surface water productivity occurs one month after the maximum river discharge, and oxygen depletion in bottom waters occurs two months after the highest river discharge (Justic et al., 1993). A similar one month lag in surface water phytoplankton biomass following peak freshwater discharge occurs in the Chesapeake Bay (Malone, 1992).

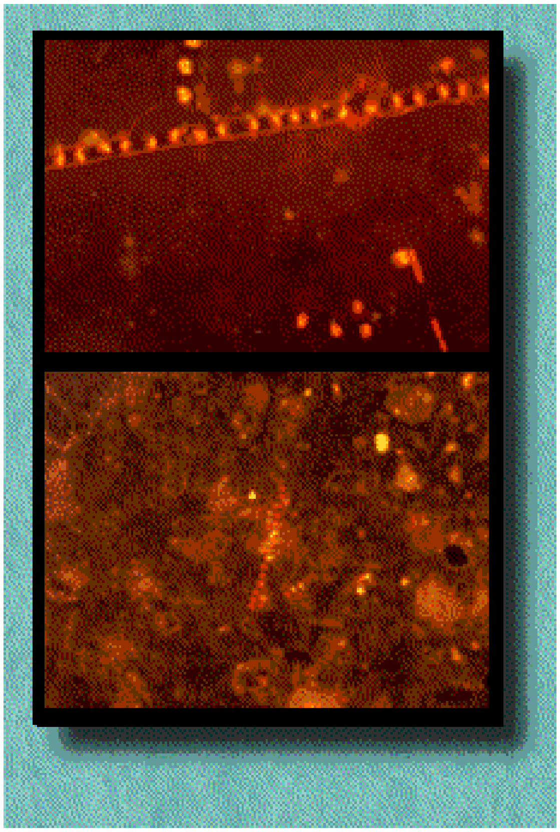


Photo 6. Finding the same type of phytoplankton (e.g., the *Skeletonema costatum* shown here) in both the water column (top) and the sediment (bottom) helps scientists to trace the history of productivity in the overlying coastal waters.

Changes in the productivity of surface waters and oxygen deficiency over time can be reconstructed by chemical and biological analysis of bottom sediments. In several U.S. estuaries and coastal waters, there is evidence of decade- and century-long increases in nutrient enrichment, hypoxia and eutrophication. In the northern Gulf of Mexico, for example, sediment analysis shows clearly that the productivity of surface waters adjacent to the Mississippi River has risen as the nitrogen level in the river has risen (Eadie et al., 1994; Turner and Rabalais, 1994). Higher surface water production results in larger carbon fluxes to the bottom, thus increasing the severity and spatial extent of hypoxia (Qureshi, 1995; Rabalais et al., 1998, in press). Taken together, these findings suggest that given the appropriate physical structure of the water column, oxygen dynamics depend ultimately on nutrients coming from rivers.

Recent studies in the Gulf of Mexico have focused on predicting the occurrence of hypoxia in an effort to develop management strategies to minimize its effects. Coupled with the amount of nitrogen loading, the freshwater turnover time for an estuary provides a basis for predicting the likelihood of oxygen depletion (Turner and Rabalais, 1998, in press). For example, there are no hypoxic events in Gulf of Mexico estuaries where the annual nitrogen loading is below a threshold value of 200 mM N/km^2. Among estuaries with the same flushing rate, those with the higher loading of nitrogen tend to be those with hypoxia. These relationships support the hypothesis that nutrient loading increases the likelihood of eutrophication and subsequent hypoxic water formation in estuaries where nutrient loading is relatively high and flushing is relatively slow. The implication is that hypoxia is at least a partially manageable phenomenon in estuaries with slower flushing rates (Figure 2).

Photo 7. These scientists are collecting samples from a CTD/sample bottle array, an instrument that measures the physical properties of the water column in order to better understand the processes controlling or influencing the development of hypoxia.

(top)

Documentation of Oxygen Depletion

Two surveys, one completed in 1984 (Whitledge, 1985) and the other in 1996 (Bricker, 1997), documented the existence of oxygen depletion in a large number of estuarine and coastal waters of the United States (Table 1). In the more recent survey, NOAA's National Estuarine Eutrophication Survey, investigators found oxygen depletion to varying degrees in 71 (52%) of the 136 major estuaries along the Atlantic, Gulf of Mexico and Pacific Coasts (Bricker, 1997; NOAA, 1996, 1997, 1997a, 1997b, 1997c; Appendix A, Table 1).

The Survey included characterization of the Mississsippi/Atchafalaya River Plume (MARP; also known as the Dead Zone in the popular press), which is not technically an estuary. Its national importance as habitat for several major commercial fisheries and its influence on water quality in coastal waters to the west of the Mississippi River and Atchafalaya River outflows warranted its inclusion. Consideration of this river plume skews estimates of the cumulative national coastal water area affected, however, because of its very large area. For proper context, the data below are provided for (1) estuaries only and for (2) estuarine and coastal waters that include the MARP.
(top)

Existing Conditions

Oxygen depletion occurs in 8% to 19% of the cumulative spatial area of the national estuarine resource, most often found in the mixing (0.5-25 ppt) and seawater (>25 ppt) zones. When the MARP is considered, the cumulative total national estuarine and coastal water area affected by hypoxia increases to 21% to 43%. On a national basis, hypoxia is evident from May through October. Occurrence is periodic, or annual, with some exceptions in which hypoxia is episodic. Hypoxia is generally limited to bottom waters and the lower water column, but may extend up to 20 m from the bottom in the MARP. In 80% of the cases, stratification is a major influencing factor; however, there are reports of hypoxia extending throughout the water column in some estuaries where stratification is not an influencing factor (e.g., Great South Bay, Neuse River, Newport Bay).

Photo 8. Scientists collect sediment samples and benthic organisms from a sediment core in an area of hypoxia.

There are distinct regional differences in the occurrence of hypoxia. Most hypoxia occurs in the Mid-Atlantic, South Atlantic and Gulf of Mexico regions because of the volume of nutrients discharged and the physical factors that control the processing of the nutrients within the estuaries there.

The Mid-Atlantic region is the most densely populated region, having greater than twice the number of people per square mile in any other region. In addition to the sewage-based nutrients that accompany large population density, the significant agricultural activity in the Mid-Atlantic region provides nutrients through runoff. Atmospheric deposition of nitrogen (e.g., from fossil fuel combustion and forest fires) is also a large contributor of nutrients. In South Atlantic estuaries, the warmer climate leads to stratification in some estuaries and subsequent hypoxia. Agriculture and animal husbandry (hog farms) lead to high organic nutrient production that depletes dissolved oxygen. In the Gulf of Mexico estuaries, the occurrence of hypoxia is likely due to the warmer climate and high loads of nonpoint source nutrients. In the North Atlantic region (St. Croix River/Cobscook Bay in Maine to Cape Cod Bay in Massachusetts), a region not severely affected by oxygen depletion, estuaries in general have a very large tidal amplitude and low population density, which result in a low input of nutrients and a significant degree of flushing. High organic loadings from productivity in surface waters and stratification do not occur. The estuaries that experience hypoxia in the North Atlantic region are those with high population density (i.e., Massachusetts Bay and Cape Cod Bay). Similarly, in the Pacific region, hypoxia occurs in estuaries that have a high population density leading to high levels of nutrients (e.g., San Diego Bay, Newport Bay, Alamitos Bay) or restricted circulation (e.g., Hood Canal, Whidbey Basin/Skagit Bay).

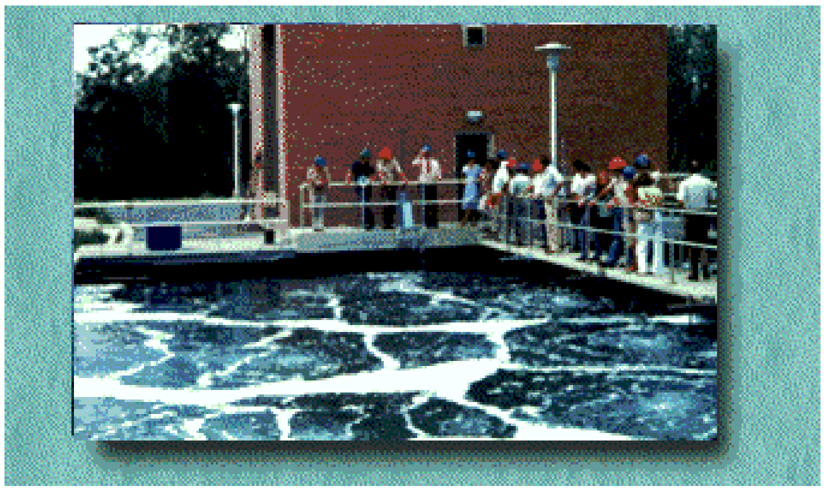


Photo 9. The high population density of the Mid-Atlantic region necessitates many sewage treatment plants that are one source of nutrients to estuaries.

Photo 10. A high-technology combine computes corn yield as the crop is harvested from a field in Illinois. Agricultural activities contribute to the flux of nonpoint source nutrients to coastal waters.

(top)

National Trends

NOAA's National Estuarine Eutrophication Survey collected trend information from 1970 to the present about three characteristics of oxygen depletion: (1) spatial coverage, (2) frequency of occurrence and(3) seasonal duration. In many instances (49%), the data were too sparse to identify trends. Even for those estuaries with sufficient data, no trend in hypoxia was evident for the great majority. Of observed trends, an increase in spatial coverage and duration of hypoxia was reported for only 4% of estuaries and an increase in frequency of occurrence for 3%. Decreases in spatial coverage and duration of events were reported for 7% of estuaries, and a decrease in frequency of occurrence of hypoxia for 5% (Appendix B).

(top)

REGIONAL CONTRASTS

Weather conditions, large-scale physical processes, biological productivity, amount of nutrients and other factors affect oxygen depletion in coastal waters. The combination of these processes results in considerable variation in the severity of oxygen depletion from estuary to estuary, and from year to year. Three regions–the Mid-Atlantic, South Atlantic and Gulf of Mexico–represent the majority of instances of hypoxia–59%, 62% and 84%, respectively (Table 1 and Appendix A).

Mid-Atlantic Region (Buzzards Bay, MA through Tangier/Pocomoke Sounds, VA)

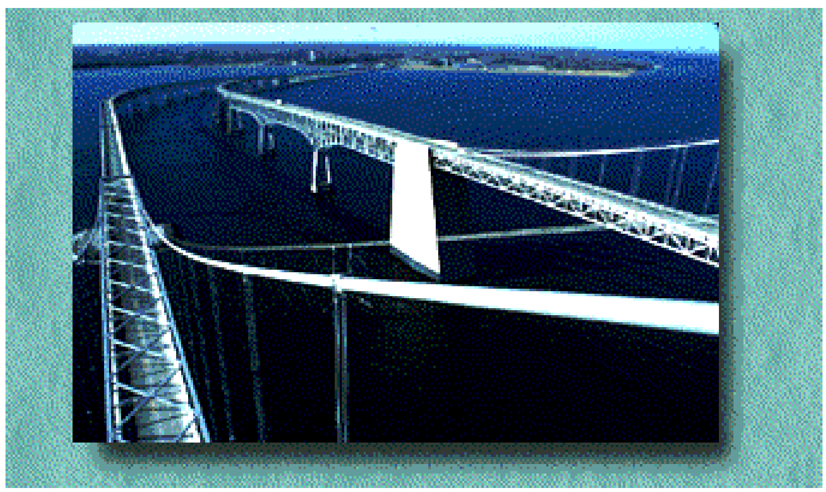
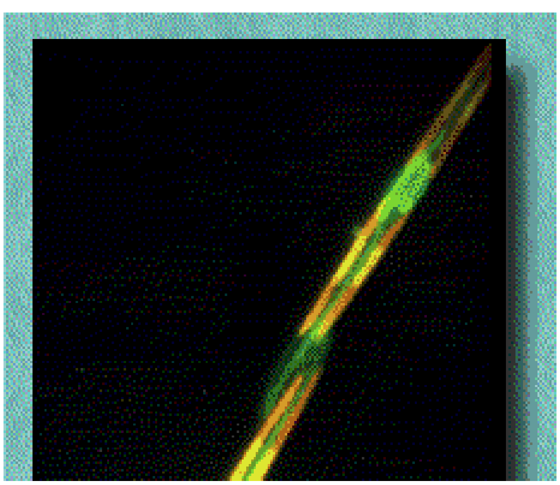


Photo 11. The Chesapeake Bay suffers from hypoxia annually.



Hypoxic and anoxic events occur in 13 of the 22 Mid-Atlantic estuaries (Bricker, 1997; NOAA, 1997a). Since 1970 anoxia has increased (in either duration, frequency or spatial coverage) for Long Island Sound (see Case Studies), Chesapeake Bay (see Case Studies) and the Choptank River. Serious oxygen depletion occurs annually in Long Island Sound and Chesapeake Bay. The apex of the New York Bight experiences frequent, but spatially limited hypoxia, although a severe event (i.e., over 7,000 km^2) occurred in the summer of 1976 (Swanson and Sindermann, 1979). Indicators of nutrient overenrichment, such as elevations in chlorophyll levels and losses of submerged aquatic vegetation, have increased in numerous other estuaries (e.g., Buzzards Bay, Gardiners Bay, Great South Bay, Hudson River/Raritan Bay, New Jersey Inland Bays, Rappahannock River, York River, James River, Tangier/Pocomoke Sounds) (Appendix B). These trends, however, have not paralleled worsening oxygen conditions.

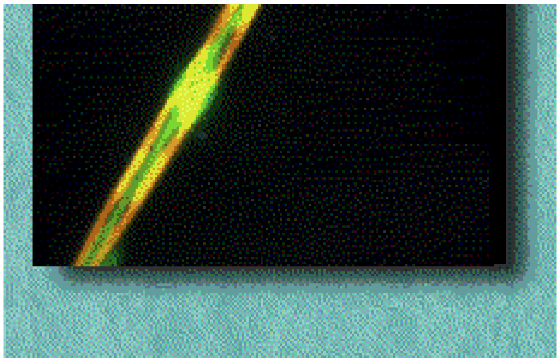


Photo 12. Often the second most dominant diatom in Gulf coastal waters, some species of this genus, *Pseudo-nitzschia* , cause amnesic shellfish poisoning.

(top)

South Atlantic Region (Albemarle/Pamlico Sounds, NC through Biscayne Bay, FL)

Hypoxic and anoxic events occur in 13 of the 21 South Atlantic estuaries (Bricker, 1997; NOAA, 1996). The most notable are associated with blue green algal blooms in the lower Chowan and upper Neuse Rivers in North Carolina (Whitledge, 1985). Dissolved oxygen concentrations are low in the Pamlico River as well, even though algal blooms are not present. Rather, stratification acts to restrict the supply of oxygen to bottom waters. Hypoxia and anoxia in estuaries of the South Atlantic region are mostly short-lived (Whitledge, 1985). More recent water quality problems in the Neuse, New and Pamlico River estuaries have been associated with blooms of noxious and toxic algae. Increasing trends in anoxia since 1970 (in either duration, frequency or spatial coverage) have been documented only for the Neuse River. Less is known about trends for the South Atlantic region than for either the Mid-Atlantic or Gulf of Mexico regions, which indicates a large gap in water quality data for the South Atlantic region. Other indicators of eutrophication (e.g., increase in chlorophyll levels and loss of submerged aquatic vegetation) (Appendix B) suggest worsening estuarine water quality in the Pamlico/Pungo Rivers, St. Johns River and Indian River, but these trends have not paralleled worsening oxygen conditions.

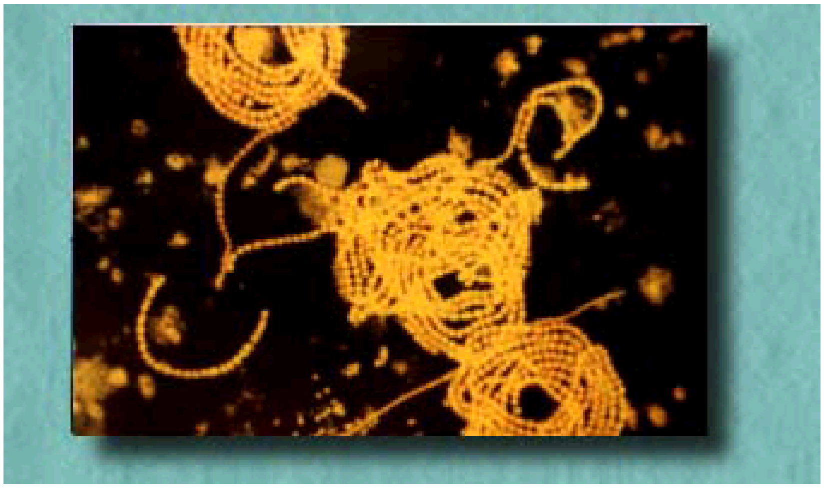


Photo 13. When Mississippi River water was diverted into Lake Pontchartrain, LA in the spring of 1997 for flood control, surface mats of *Anabena* spp. and *Microcystis* sp. turned the water bright green, produced hepatotoxins and caused an advisory against recreational use of the lake.

(top)

Gulf of Mexico Region (Florida Bay, FL through Lower Laguna Madre, TX)

Photo 14. The Mississippi River plume, seen here in the foreground, is light in color because of high concentrations of suspended particulates. It is the dominant source of nutrients to the region. (Gulf of Mexico waters are the darker colored water mass.)

Oxygen depletion (anoxia or hypoxia) events occur in 32 of 38 Gulf of Mexico estuaries (includes the Mississippi/Atchafalaya River Plume (MARP); Bricker, 1997). This percentage is probably high because of warm water temperatures, a condition conducive to reduced oxygen concentrations. Hypoxia is more frequent in the western Gulf with a depositional sedimentary regime and a higher organic content than the eastern Gulf. Loading of nutrients (nitrogen and phosphorus) to Gulf estuaries varies over three orders of magnitude, with the dominant source being the Mississippi River system (Turner and Rabalais, 1998, in press). At the terminus of the Mississippi and Atchafalaya Rivers on the adjacent Louisiana continental shelf is a very expansive area of seasonally severe hypoxia and sometimes anoxia (MARP; see Case Studies). Studies of dated sediment cores show that oxygen stress (either in extent, duration or intensity) has increased on the Louisiana shelf since the turn of the century and has accelerated since the 1950s. This coincides with the increase in nitrogen loading from the Mississippi River system (Turner and Rabalais, 1994; Sen Gupta et al., 1996; Rabalais et al., 1996). Other notable hypoxia problems have developed in Mobile Bay (AL), Lake Pontchartrain (LA), Pensacola and Escambia Bays (FL) and Perdido Bay (AL/FL) (Whitledge, 1985; Rabalais, 1992). The Gulf of Mexico, however, has success stories in Tampa and Sarasota Bays. In both of these systems, the indicators of overenrichment such as hypoxia have decreased, and seagrass coverage has increased, as a result of nutrient management intervention (Johansson and Lewis, 1992; Tomasko and Ries, 1997) (Appendix B).

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CASE STUDIES

The northern Gulf of Mexico, Chesapeake Bay and Long Island Sound are some of the best documented hypoxic areas, including their spatial extent, causative and influencing factors, and historical development. They also represent some of the largest known areas among U.S. estuaries and coastal waters. For comparison of physical characteristics and processes critical to development of low oxygen conditions among the three areas, see Appendix C.

Northern Gulf of Mexico

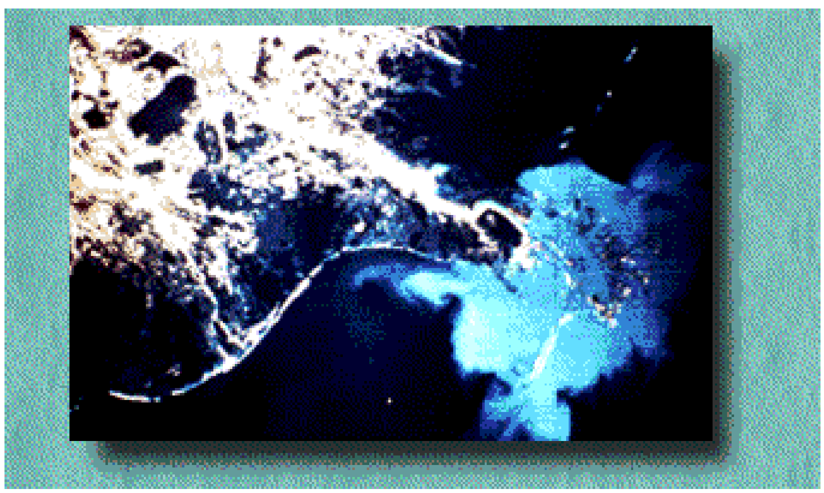

Photo 15. This satellite photo illustrates the magnitude and influence of the Mississippi River sediment plume on the northern Gulf of Mexico.

The largest zone of oxygen-depleted waters in the United States, indeed in the entire western Atlantic Ocean, is in the northern Gulf of Mexico on the Louisiana continental shelf adjacent to the outflows of the Mississippi and Atchafalaya Rivers (Rabalais et al., 1991, 1996, 1998). In recent years (1993-1997), the extent of bottom water hypoxia (16,000 to 18,000 km^2) has been greater than twice the surface area of the Chesapeake Bay, rivaling extensive hypoxic/anoxic regions of the Baltic and Black Seas. Prior to 1993, the hypoxic zone averaged 8,000 to 9,000 km^2 (1985-1992), but the hypoxic zones have since been consistently greater than 15,000 km^2. Hypoxia occurs from late February through early October, but is most widespread, persistent and severe in June, July and August (Figure 3a-c).

Photo 16. Mississippi and Atchafalaya River outflows, shown here as a light-colored water mass (in front of photo), flow over the Gulf of Mexico waters, bringing with them sediment and nutrients.

Evidence suggests that the severity and duration of oxygen depletion in the northern Gulf of Mexico depend, at least partially, on the amplitude and phasing of discharge from the Mississippi and Atchafalaya Rivers (Justic et al., 1993; Rabalais et al., 1996, 1998, in press). Long-term patterns in oxygen deficiency are temporally consistent with peak river discharges and nutrient flux. Mississippi River nutrient concentrations and loadings to the adjacent continental shelf changed dramatically during this century, with an acceleration of these changes since the 1950s (Turner and Rabalais, 1991; Justic et al., 1995a, 1995b). Analyses of sedimentary records support the inference of increased eutrophication and hypoxia in the Mississippi River delta bight, primarily because of changes in nitrogen loading (Turner and Rabalais, 1994; Eadie et al., 1994; Nelsen et al., 1994; Sen Gupta et al., 1996; Rabalais et al., 1996).
(top)

Chesapeake Bay

Photo 17. Hypoxia is typically at its worst in August in the Chesapeake Bay.

Perhaps the most well-known case of estuarine oxygen depletion is that of the Chesapeake Bay. Like the northern Gulf of Mexico, the Chesapeake Bay is dominated by freshwater discharges with significant nutrient inputs that have increased over time. The annual cycle of oxygen depletion in the Chesapeake Bay begins as surface waters start to warm and accelerates during and following the spring freshet (Malone, 1991, 1992). Waters are hypoxic and anoxic in May through September, with the most severe conditions in August. The Chesapeake Bay is a typical temperate coastal plain estuary–long (320 km), narrow (20 km) and shallow (mean depth = 6.5 m). The largest single source of freshwater, the Susquehanna River, accounts for 50% of freshwater inflow to the entire bay (80% to 90% to the region above the Potomac River mouth), 70% of the nitrogen load and 60% of the phosphorus load. Thus, there are strong north-south gradients in salinity, nutrient concentrations and phytoplankton biomass. The spring accumulation of phytoplankton biomass is more than sufficient to fuel oxygen depletion and summer anoxia (Malone, 1992). Phytoplankton biomass is significantly correlated with monthly mean river flow (lagged one month), suggesting that seasonal variability of phytoplankton is governed by riverine nutrient inputs (similar to the interactions of the Gulf of Mexico/Mississippi River).

Seasonal hypoxia has been a feature of the Chesapeake Bay since deforestation during the colonial period (Cooper and Brush, 1991), but evidence suggests an aggravation of the problem in more recent decades (Taft et al., 1980; Officer et al., 1984; Malone, 1991); (Figure 4a-b). Concentrations of chlorophyll a in the surface mixed layer have increased five- to tenfold in the seaward regions of the bay and one-and-one-half- to twofold elsewhere, paralleling estimates of increased loading of nitrogen and phosphorus to the bay since 1945 (Harding and Perry, 1997).
(top)

Long Island Sound

At its head, Long Island Sound has a tidal strait, the East River, that connects it to the Hudson-Raritan system. Therefore, Long Island Sound is a true sound, or arm of the sea (de Jonge et al., 1994; Welsh et al., 1994). Five topographic regions span its main axis; they are separated from each other by sills and are variably affected by hypoxia. Freshwater runoff is seasonally high in the spring and low in the summer, though not as

Photo 18. Scientists use this instrument to sample surface sediments.

pronounced as in the Chesapeake Bay. Temperature differences in the summer, rather than differences in salinity, control the strength of stratification.

Although the East River discharges only about 3% to 9% of the total freshwater inflow, it is responsible for the majority of the nitrogen and phosphorus loadings. Nitrogen loadings from waste-water treatment plants along the East River tripled between the 1950s and 1980s (Carpenter, 1987, as reported in de Jonge et al., 1994); similar increases occurred along the Narrows and Western Basin. The increasing eutrophication from east to west causes the deep waters in the western Sound to become depleted in oxygen during the summer (Welsh et al., 1994). Oxygen depletion in western waters begins in mid-June, with concentrations frequently less than 1 mg/l in early to mid-August (Figure 5 a-d). The deep water reservoir in the Sound has, in the past, provided a buffer against oxygen depletion, but it appears that this buffering capacity is now being exceeded (Welsh and Eller, 1991).

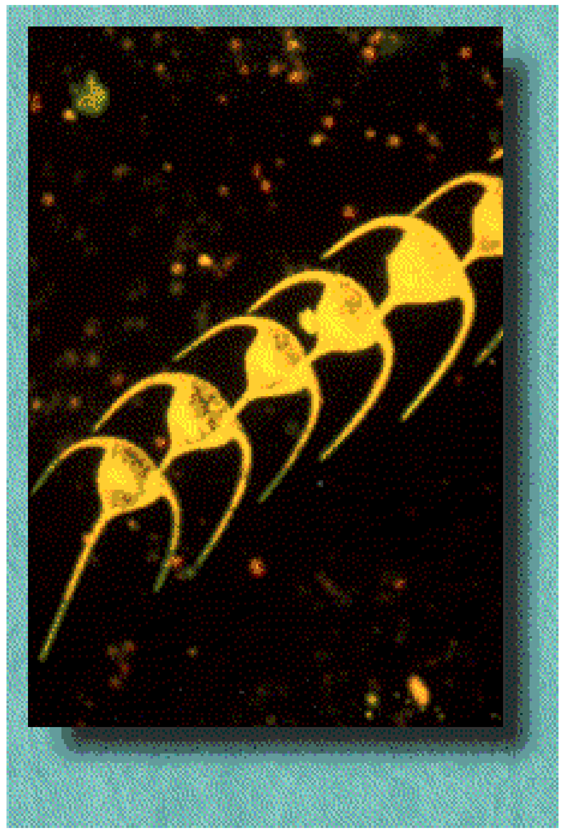

Photo 19. This type of plankton, *Ceratium tripos*, was responsible for a hypoxic event in the New York Bight in 1976.

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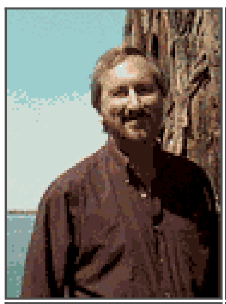
EXPERT INTERPRETATION

The five individuals below are experts in the topic of oxygen depletion in coastal waters. Here they voice their opinions on two questions relevant to that topic.

Question 1. Is hypoxia a natural phenomenon? Is it affected by human activities? Have these human activities led to a worsening of hypoxia?

Question 2. What levels of reduction of nutrient loading, if any at all, will lead to an alleviation of hypoxia problems in U.S. estuaries and coastal regions?

Experts



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Chistopher F. D'Elia

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Thomas Torgersen

Barbara L. Welsh

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President and Professor, University of Maryland Center for Environmental Science

Dr. Boesch was trained as a biological oceanographer. For the past 17 years, he has developed and directed programs in environmental science, first as Executive Director of the Louisiana Universities Marine Consortium and presently with the University of Maryland. His experience in the Mississippi Delta and the Chesapeake Bay led him to focus his research on the scientific understanding of nutrient enrichment and on its application in ecosystem management and restoration.

Question 1. Is hypoxia a natural phenomenon? Is it affected by human activities? Have these human activities led to a worsening of hypoxia?

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The primary conditions leading to hypoxia in coastal waters–large inputs of nutrients or organic matter and density stratification of water masses–have always been characteristic of estuaries and shelf regions receiving river flows. However, abundant scientific evidence from such well-studied places as the Chesapeake Bay, Long Island Sound, the Louisiana shelf, and the Baltic, North Adriatic and Black Seas in Europe documents the worsening of hypoxia (greater depletion of oxygen, extending over a larger area, and lasting longer) during the last half of the 20th century. Chemical and biological tracers in Chesapeake Bay sediments show that the natural conditions of moderate and occasional hypoxia first worsened with expanded land clearing in the late 1700s, but dramatically intensified after 1950, coincident with population growth, increased waste discharges and the widespread use of chemical fertilizers.
(top)

Question 2. What levels of reduction of nutrient loading, if any at all, will lead to an alleviation of hypoxia problems in U.S. estuaries and coastal regions?

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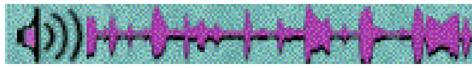
The delivery of nitrogen to the ecosystems of the U.S. East and Gulf Coasts has increased as much as five- to tenfold as a result of human activities. However, reduction of nutrient loadings by 80% or more in order to return to natural conditions is impractical, considering the levels of human population and activities that must be sustained today and in the future. The states surrounding the Chesapeake Bay have committed to reducing controllable loads of nitrogen and phosphorus by 40% (approximately 25% of the total loads) by the year 2000. Other governments, for example, Denmark, have committed to even greater reductions of up to 50% of total loads. I believe that reductions of about 50% of total loadings are achievable and will result in significant alleviation, although not elimination, of hypoxia problems in U.S. estuaries and coastal regions. Moreover, I predict that even more limited reductions will have significant and surprising beneficial effects on these ecosystems.
(top)

Christopher F. D'Elia

Professor, Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, and Director, Maryland Sea Grant College Program

Dr. D'Elia joined the University of Maryland in 1977. His research focuses on nutrient/productivity relationships in coastal aquatic ecosystems, especially nutrient enrichment of the Chesapeake Bay. He has served on numerous advisory panels to the National Science Foundation and other public and private funding institutions, and has held leadership positions with numerous scientific committees and organizations. He has authored more than 50 scientific publications and published reviews.

Question 1. Is hypoxia a natural phenomenon? Is it affected by human activities? Have these human activities led to a worsening of hypoxia?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Hypoxia, a state of oxygen depletion in natural waters, occurs when oxygen concentrations fall below 2 mg/l, which stresses or kills most oxygen-respiring organisms. Anoxia refers to total oxygen depletion, which, if prolonged, is inevitably lethal. Hypoxia can be a natural phenomenon, particularly in water bodies with deep troughs, sluggish circulation and high natural inputs of organic matter. However, hypoxia is more typically associated with human activities that result in the input of untreated sewage or of the plant nutrients nitrogen and phosphorus. In the former case, organic matter in the sewage decomposes and consumes oxygen; in the latter case, organic matter produced by the overstimulation of algal growth decomposes and consumes oxygen. As human activities increase along the coast, so too can hypoxia. Controlling nutrient inputs from sewage and runoff is the only practical way to alleviate hypoxia, short of curtailing coastal development completely. The most promising controls are better land use, such as forest and riparian buffer preservation; "best management practices," such as reduction in fertilizer application and minimum tillage; and the implementation of nutrient removal at sewage treatment plants, such as biological nutrient removal.
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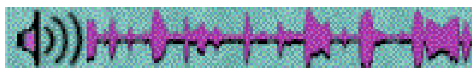
Question 2. What levels of reduction of nutrient loading, if any at all, will lead to an alleviation of hypoxia problems in U.S. estuaries and coastal regions?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The levels of reduction of nutrient loading necessary to reduce hypoxia problems, unfortunately, will have to be determined on a time- and place-specific basis. This is because estuaries differ in their circulation, shape and retention characteristics, and because the severity of overenrichment varies greatly. In the Chesapeake Bay, for example, the best estimates are that reducing hypoxia substantially will require at least a 40% total nutrient reduction.
(top)

Quay Dortch

Associate Professor, Phytoplankton Ecology, Louisiana Universities Marine Consortium

Dr. Dortch has been on the faculty at the Louisiana Universities Marine Consortium since 1986. She was a research scientist at Bigelow Laboratory for Ocean Sciences in Boothbay Harbor, Maine from 1981 to 1986, and, concurrently for several years, a senior oceanographer at the University of Washington from 1980 to 1984. Her research interests center around the processes by which algae in the ocean use nutrients. This research has evolved into studies of ways that nutrients stimulate phytoplankton growth and lead to hypoxia and harmful algal blooms.

Question 1. Is hypoxia a natural phenomenon? Is it affected by human activities? Have these human activities led to a worsening of hypoxia?

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Hypoxia and the more extreme anoxia are natural phenomena. They occur when organic matter produced at the surface sinks into deeper water and decomposes, using the oxygen in the deep water faster than it can be resupplied from the surface. In most cases of natural hypoxia/anoxia, the cause is not so much excess production of organic matter in the surface layers as it is the circulation patterns that trap the organic matter in a restricted area where oxygen resupply is slow. Naturally occurring hypoxia/anoxia is observed in the deep water of some fjords, the Cariaco Trench, at mid-depths below the coastal upwelling off of Peru, and the Black Sea.

In eutrophic coastal waters, hypoxia/anoxia is developing because high nutrient loading is stimulating excess surface production. Previously, these areas experienced little or no hypoxia/anoxia, because mixing was sufficient to resupply bottom water oxygen most of the time. However, increased surface production is tipping the balance between the utilization and supply of oxygen in the deeper water of many coastal areas, resulting in the increased incidence of hypoxia/anoxia.
(top)

Question 2. What levels of reduction of nutrient loading, if any at all, will lead to an alleviation of hypoxia problems in U.S. estuaries and coastal regions?

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Reducing nutrient loading will certainly decrease the incidence of hypoxia and other impacts of nutrient-enhanced eutrophication in many coastal estuaries. The necessary magnitudes of reduction must be determined for each individual estuary, because the balance between the physical and biological factors contributing to hypoxia differs between estuaries. While nutrient levels are being reduced, the ratios of nutrients must be balanced with respect to plant nutrient requirements in order to avoid the growth of unintended harmful algal species. Finally, a reasonable goal of nutrient reductions is often difficult to determine, because in most cases, the pristine state of the estuary is unknown. Although fertilizer use increased nutrient inputs starting in the 1950s, land clearing and the introduction of large quantities of untreated municipal waste occurred long before water-quality measurements were made. Data from cores suggest that the processes leading to eutrophication started long before the degradation became apparent to most observers. Thus, for each estuary, it is necessary to determine the desired level of water quality, the magnitude of nutrient reduction necessary to reach that level, and the nutrients that need to be reduced.
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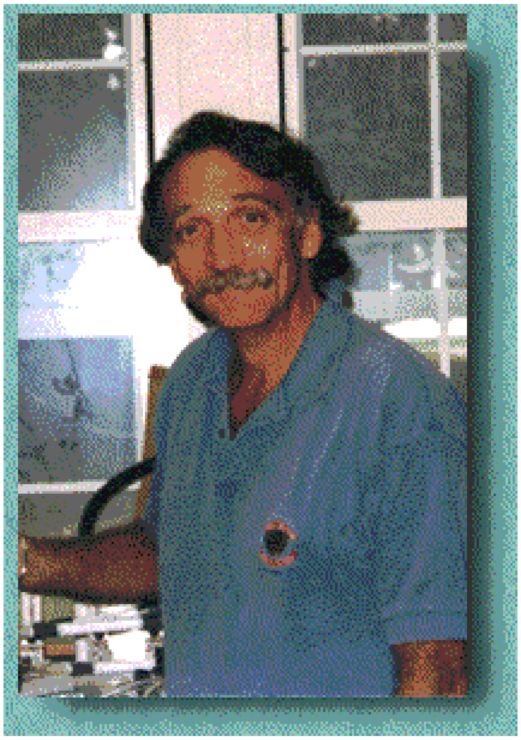

Thomas Torgersen

Professor of Marine Sciences, University of Connecticut

Dr. Torgersen was trained originally as a chemical engineer and geochemist. His research focuses on the coupled fluid transport and reaction processes of the environment, with particular attention to the use of tracers to quantify environmental processes that are beyond the range of experiment and observation. In addition to his extensive work in Long Island Sound, he has active research programs in groundwater and lakes.

Question 1. Is hypoxia a natural phenomenon? Is it affected by human activities? Have these human activities led to a worsening of hypoxia?

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Hypoxia can be a natural phenomenon. The deep waters of the Black Sea have been anoxic for thousands of years, and the oceans have experienced multiple hypoxic and/or anoxic events over geologic history. "Natural" is not necessarily a good thing, however. Oceanic anoxia has been a major cause of species extinction.

Man has contributed to both the creation and the worsening of hypoxia. To understand how man has affected this natural process, we must examine the root causes of hypoxia. The loss of oxygen from the water column (hypoxia) represents a competition between the processes that remove oxygen from the water (oxygen consumption by organic matter degradation and the sediments) and the processes that supply oxygen to the water column (gas exchange and mixing). We create conditions favorable for hypoxia by increasing oxygen consumption, or by decreasing oxygen supply, to the water. Nutrient-rich sewage effluent stimulates biologic productivity, which degrades and consumes oxygen. However, extensive channelization and dredging of major waterways could also reduce the rate of mixing and thereby contribute to hypoxia without the introduction of nutrients. We must also consider that anthropogenic climate change may alter the winds, the currents and the stratification of water bodies and, thus, significantly alter the gas exchange and mixing processes that govern the rate of oxygen resupply. While the time scale for climate change and increased hypoxia is longer, these are the very mechanisms by which oceanic anoxia was created in the geologic past.

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Question 2. What levels of reduction of nutrient loading, if any at all, will lead to an alleviation of hypoxia problems in U.S. estuaries and coastal regions?

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Because hypoxia is a competition between oxygen consumption processes and oxygen resupply processes, one cannot determine an adequate nutrient reduction level without knowing the climatically controlled physical mixing processes in the estuary/ocean. An appropriate answer to the question thus demands adequate research on the *local* mixing processes to quantify and, therefore, regulate an appropriate *local* nutrient loading level.

It is also important to realize that instant regulation will not lead to instant improvement. A great deal of undegraded organic matter can be sequestered in the sediment, and it can be a continuing oxygen sink until it is consumed, buried or lost from the system. Estimates of the recovery time scale for many bodies of water are in the range of 3 to 20 years. The moral of the story is that it took us a long time to become this harmful to the environment, and beneficial regulation will come primarily from good science and an educated public.

(top)

Barbara L. Welsh

Professor Emerita, Marine Sciences Department, University of Connecticut

Dr. Welsh has spent the last 30 years in scientific research on estuaries and coastal systems–the last 10 years investigating eutrophication and hypoxia in Long Island Sound. She specializes in the interactions of physics, geology and chemistry with biota. A member and past president of the Estuarine Research Federation and the New England Estuarine Research Society, Dr. Welsh has written a number of papers comparing estuarine systems in the United States and Europe.

Question 1. Is hypoxia a natural phenomenon? Is it affected by human activities? Have these human activities led to a worsening of hypoxia?

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Oxygen depletion occurs naturally in the bottom waters of systems that become stratified for extended periods of time. Although depletions also occur naturally in nonstratified systems, such periods are brief because mixing is frequent, usually controlled by day-night or tidal cycles. The severity of depletion under stratified conditions depends on combinations of factors that differ among systems. For instance, Long Island Sound has a series of deep basins separated by submarine sills, which make its bottom waters somewhat stagnant.

Oxygen depletion occurs when the basins become seasonally stratified by summer heating of the surface layer. Depletion to hypoxic levels (2-3 mg/l), however, is extremely unlikely under natural conditions. Historically, the large volumes of cold, oxygen-saturated (10-12 mg/l) bottom water sustained the Sound well above hypoxic levels from the onset of stratification in mid-June until fall mixing in August or September. Moreover, stratification provided natural controls on phytoplankton growth by reducing surface layer nutrients and, hence, reducing new carbon exports to the bottom waters for consumption.

Human activities have caused depletions to become more severe, mainly through the addition of organic carbon and nutrients. Organic carbon provides food for animals and bacteria, increasing oxygen consumption. Nutrients override natural stratification controls on phytoplankton growth, adding to organic carbon. Now, oxygen depletions reaching hypoxia or anoxia occur regularly in the Sound and in many other systems.
(top)

Question 2. What levels of reduction of nutrient loading, if any at all, will lead to an alleviation of hypoxia problems in U.S. estuaries and coastal regions?

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Computer models developed for Long Island Sound suggest that precolonial oxygen levels dipped naturally to about 5.5 mg/l, but human activity has more than doubled the nitrogen input. We need to remove about 55% of the added load to raise levels above 3 mg/l. Models provide simplistic initial estimates, but real systems are enormously variable. This model predicts just under 2 mg/l for present conditions, but field measurements between 0 and 1 are common. Difficulties arise because ecological systems make internal adjustments to changes, so effects may not be exactly as predicted. Biological responses, in particular, tend to be nonlinear and extremely difficult to incorporate into engineering models. Moreover, interannual variations in natural physical conditions, such as weather, may mask expected improvements, making changes apparent only when they are assessed over longer periods.

Other paradoxes confound management efforts. When organic carbon was removed from New York City effluents, oxygen levels in the East River rose, but hypoxia worsened in the western Sound. Organically bound nutrients had been converted to inorganic forms that phytoplankton utilize; water clarity had increased, allowing better light penetration; and the western Sound was stratified, increasing its vulnerability to oxygen depletion. The East River is less stratified and flushes out too quickly for phytoplankton growth. Thus, our best efforts to reduce oxygen consumption locally actually increased oxygen consumption elsewhere, because nutrients were not removed along with organic carbon.

Ecological systems are inherently complex, so even our best models will continue to require "trial and error" refinement based on actual measurements of individual systems as we try to determine the reduction levels necessary to alleviate hypoxia.

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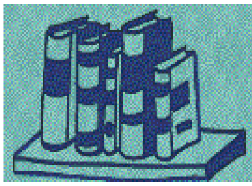

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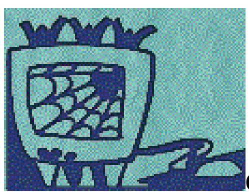

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Explains the Complexity and Stressors in Estuarine Systems (COASTES) program which, over a six year period of study within the Patuxent River estuary, will attempt to understand the effects of environmental stressors (nutrients, inorganic toxics, dissolved oxygen) on the ecological processes of coastal ecosystems.

Chesapeake Bay Information Network. Chesapeake Bay LMER: Trophic Interactions in Estuarine Systems.

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Provides information on the Trophic Interactions in Estuarine Systems (TIES) project, part of the Chesapeake Bay Land-Margin Ecosystems Research program, which studies secondary production within estuarine ecosystems. Includes an overview of the project, as well as some results on icthyoplankton, mid-water trawl tows, and sediment chlorophyll-a mapping. References to publications and presentations are provided.

George Mason University/Alliance for the Chesapeake Bay/Bay Journal. State-of-the-Bay: Nutrient Enrichment and Habitat Quality.

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Explains the causes of hypoxia and poor water quality within the

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University of Maryland/Maryland Sea Grant Program. Chesapeake Bay Facts.

http://www.mdsg.umd.edu/MDSG/CB.html

Provides access to a summary of quick facts about the Chesapeake Bay, a map of the watershed showing drainage into the Bay, general information and research reports and papers, sponsored by Maryland Sea Grant, on the Bay's ecosystem, and links to other Internet sites providing additional information about the Chesapeake.

U.S. Environmental Protection Agency. Chesapeake Bay Program.

http://www.chesapeakebay.net/bayprogram/pubs/87agree.htm

Presents the 1987 Chesapeake Bay Agreement to restore and protect the Chesapeake Bay that was accepted by the states of Virginia, Maryland, Pennsylvania, the District of Columbia, the Chesapeake Bay Commission, and the Federal government.

U.S. Environmental Protection Agency. Water Quality Monitoring Data, Graphics and Analysis, Chesapeake Bay Program.

http://www.chesapeakebay.net/bayprogram/infobase/infobase.htm

Provides numerous links to data on various physical, chemical and biological parameters measured within the Chesapeake Bay. Data for chlorophyll, salinity, dissolved oxygen, water temperature, nitrate and suspended solids are presented as figures, graphs and tables with explanations for current and past year periods. Offers on-line documents on environmental indicators of the Bay's environment and various biological, chemical, geochemical and physical parameters that have been monitored.

Gulf of Mexico

Gulf of Mexico Program Office. Hypoxia Conference Proceedings: List of Abstracts.

http://www.gmpo.gov/nutrient/front.html

Explains the Gulf of Mexico Program and the special topic of hypoxia. Presents abstracts of papers addressing the topic of hypoxia in Gulf of Mexico estuaries and coastal waters. Several abstracts provide links to the respective on-line papers.

Iowa State University. Agro-Oceanic Nutrient Flux Center.

http://www.public.iastate.edu/~turf2surf/

Supports a proposal to the U.S. Department of Agriculture's Fund for Rural America to establish a center where scientists, stakeholders and policy makers can create practical solutions to the hypoxia problem in the Gulf of Mexico that affects the strategic rural industries of farming and fishing. The site contains a questionnaire for stakeholders and its results, the grant proposal, and links to agriculture, hypoxia, and Fund for Rural America sites.

Rabalais, N.N. et al. 1995. Hypoxia in the Northern Gulf of Mexico: Past, Present and Future.

http://www.gmpo.gov/nutrient/P25.PDF

Presents information on hypoxia in the northern Gulf of Mexico, showing its distribution and dynamics (including present and historical conditions). Examines the history of hypoxia in the region as preserved in the sedimentary record. Shows changes to the ecosystem due to nutrient loading and provides a prediction of the future of the region under varying conditions of nitrogen nutrient influx.

U.S. Department of Commerce/NOAA. Nutrient Enhanced Coastal Ocean Productivity (NECOP) Program.

http://www.aoml.noaa.gov/ocd/necop/

Home page of NECOP, the NOAA program to examine the effects of eutrophication by the Mississippi River on the northern Gulf of Mexico marine environment and fisheries. Data were collected between 1990 and 1996. Provides several synopses on the collection and analyses of sediment, nutrient, phytoplankton and zooplankton. Raw data collected on the cruises during this time period are also available.

U.S. Department of the Interior/Minerals Management Service. Hypoxia Publications.

http://www.gomr.mms.gov/homepg/whatsnew/publicat/gomr/hypoxia.html

Presents a brief list of scientific papers focusing on hypoxia in the Gulf of Mexico continental shelf area.

U.S. Environmental Protection Agency. Oxygen Depletion, or Hypoxia, in the Nearshore Gulf of Mexico off the Louisiana Coast.

http://www.epa.gov/rgytgrnj/programs/wwpd/hypoxia.html

Presents information on the area of hypoxic waters ("the dead zone") found in northern near-shore waters of the Gulf of Mexico along the coast of Louisiana and Texas. Gives current thinking on the reasons for the hypoxia and its effects on Gulf of Mexico fisheries. Explains the role of the Gulf of Mexico Program, a cooperative effort among federal, state and local governments.

Long Island Sound

U.S. Environmental Protection Agency. Long Island Sound Study: Hypoxia.

http://www.epa.gov/region01/eco/lis/hypox.html

Presents the Hypoxia section of The Comprehensive Conservation and Management Plan for Long Island Sound, approved in September 1994, addressing the problem of low dissolved oxygen within the bottom waters of Long Island Sound and its impacts on the biota. Explains the chemical, physical, and biological synergisms leading to hypoxic conditions. Also, documents how two- and three-dimensional models of the Sound's dynamics are being used to better understand the causes of, and solutions to, hypoxia. Presents efforts by The Management Conference to ameliorate the current effects of human activities on the Sound and future plans to continue improvements.

New York Bight

Rutgers University. Rutgers IMC Remote Sensing Lab/New York Bight.

http://marine.rutgers.edu/mrs/upwelling/nybintro.html

Provides satellite map and brief discussion on upwelling along the New Jersey coastal region of the New York Bight. Indicates the mechanism by which upwelling transports nutrients inshore and leads to phytoplankton blooms that subsequently die and cause localized bottom water hypoxia/anoxia. Cites the 1976 hypoxic event and fish kill as an extreme example.

Neuse River

University of North Carolina at Chapel Hill/Institute of Marine Sciences. Neuse River Bloom Project Home Page.

http://www.marine.unc.edu/groups/Paerllab/NRBP.html

Provides information on the project's effort to study phytoplankton and nutrient interactions in the Neuse River estuary. Gives project background, objectives, sampling programs, and publications. Shows biweekly surface to bottom longitudinal (70 km) transects of oxygen and salinity for June and July 1997. It also shows longitudinal (40 km) time series profiles (1994-1996) of bottom dissolved oxygen concentrations. Times series show hypoxic and anoxic zones and areas of actual fish kills.

U.S. Department of the Interior/U.S. Geological Survey. Water Resources of North Carolina.

http://ser1dncrlg.er.usgs.gov/

Includes information on water resources (stream flow, water quality) of major riverine watersheds within North Carolina. The "Neuse River Water Quality–Current Data" link gives surface and bottom water temperature, salinity, pH and dissolved oxygen (mg/l and % saturation) from three near-real-time data stations in the Neuse River. Data taken every 15 minutes for the past week are available on-line for the same three stations. Graphs of the past week's data are on-line and updated frequently. The "Neuse River Water Quality–Historic Data" link gives archival data for the watershed.
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Appendix A.1

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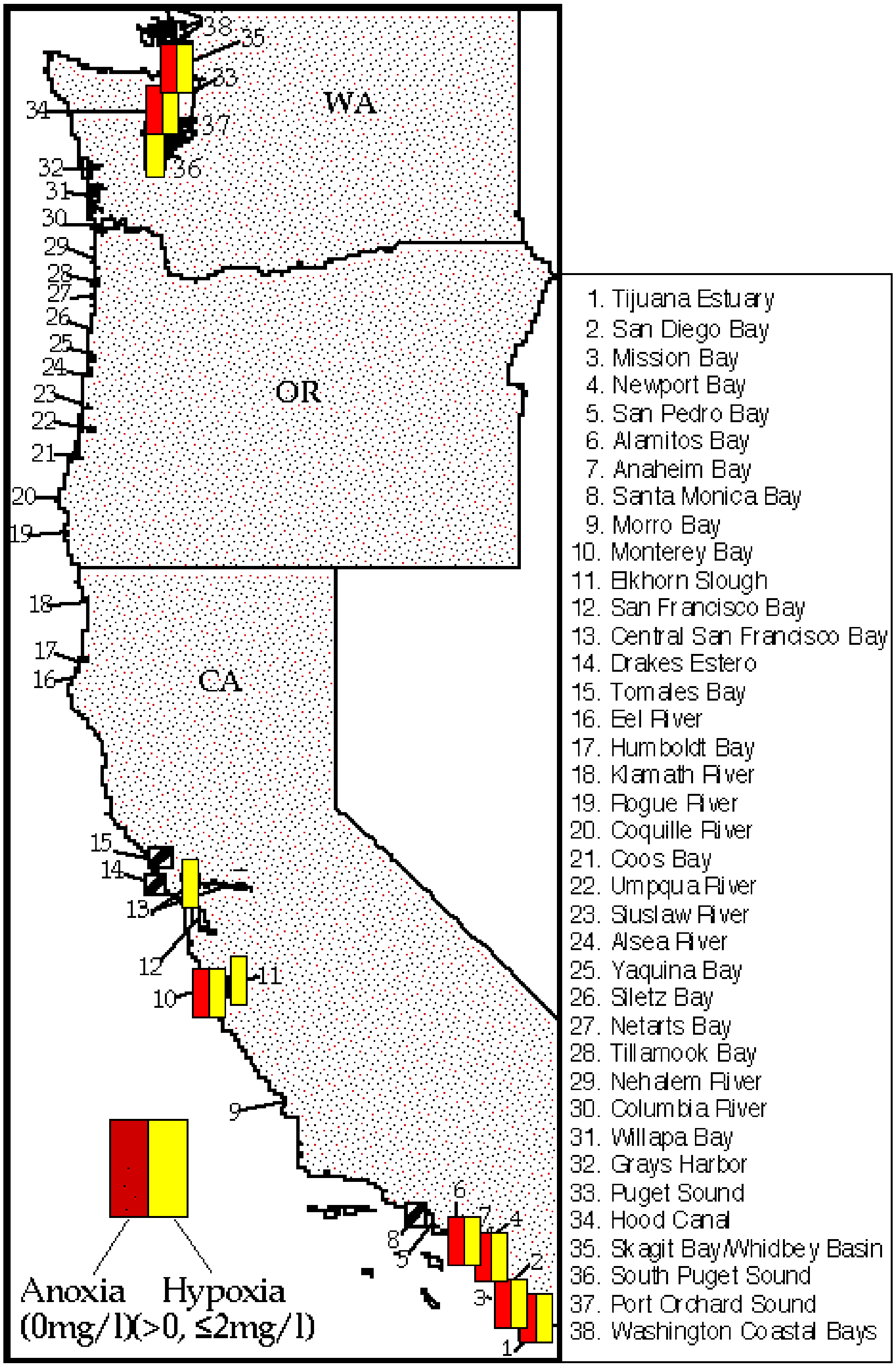
Existing Conditions for Oxygen Depletion, Pacific Region



Source: NOAA's Estuarine Eutrophication Survey, vol. 5: Pacific Coast region (NOAA, 1998)

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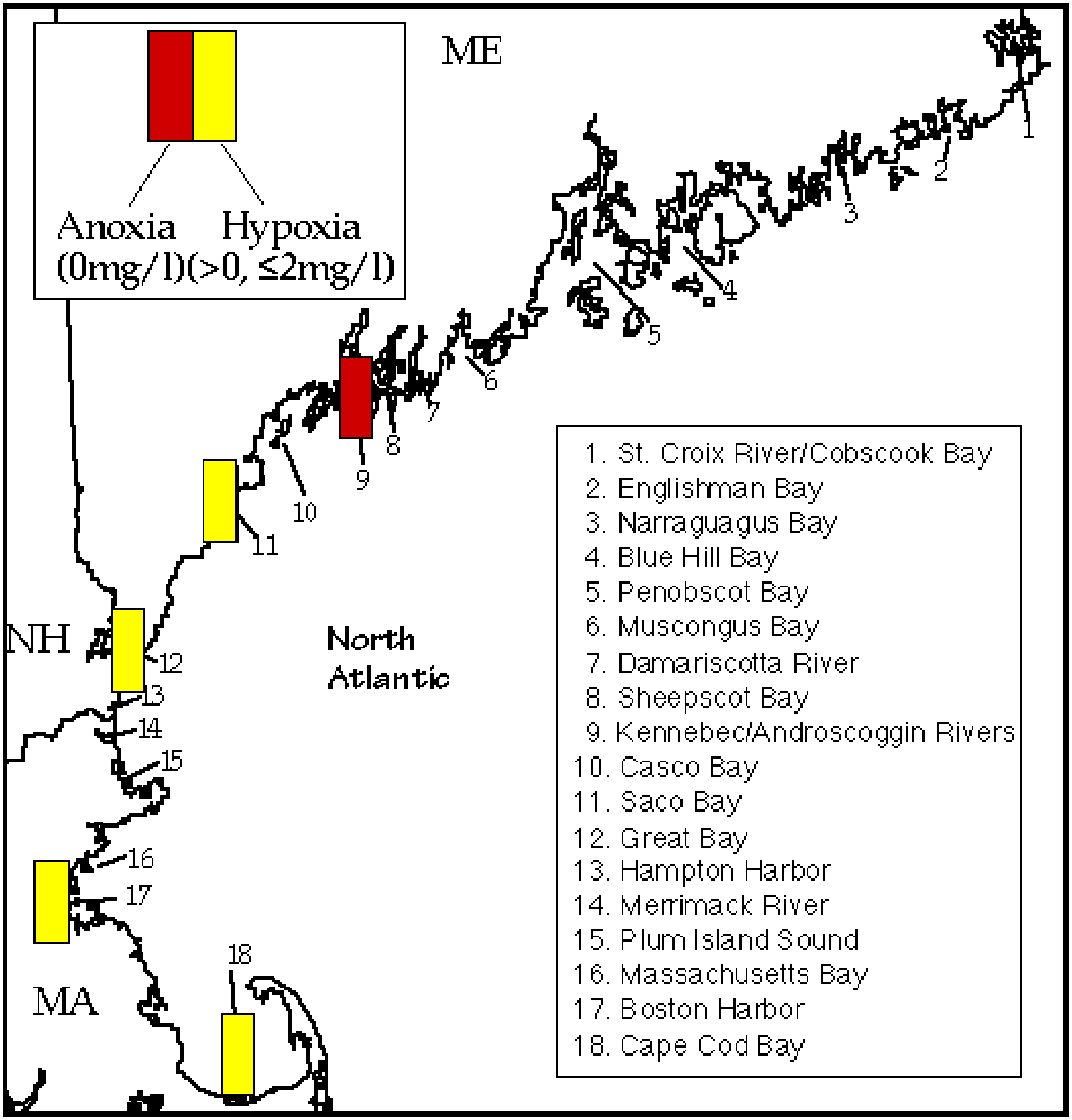
Existing Conditions for Oxygen Depletion, North Atlantic Region



Source: NOAA's Estuarine Eutrophication Survey, vol. 3: North Atlantic region (NOAA, 1997b)

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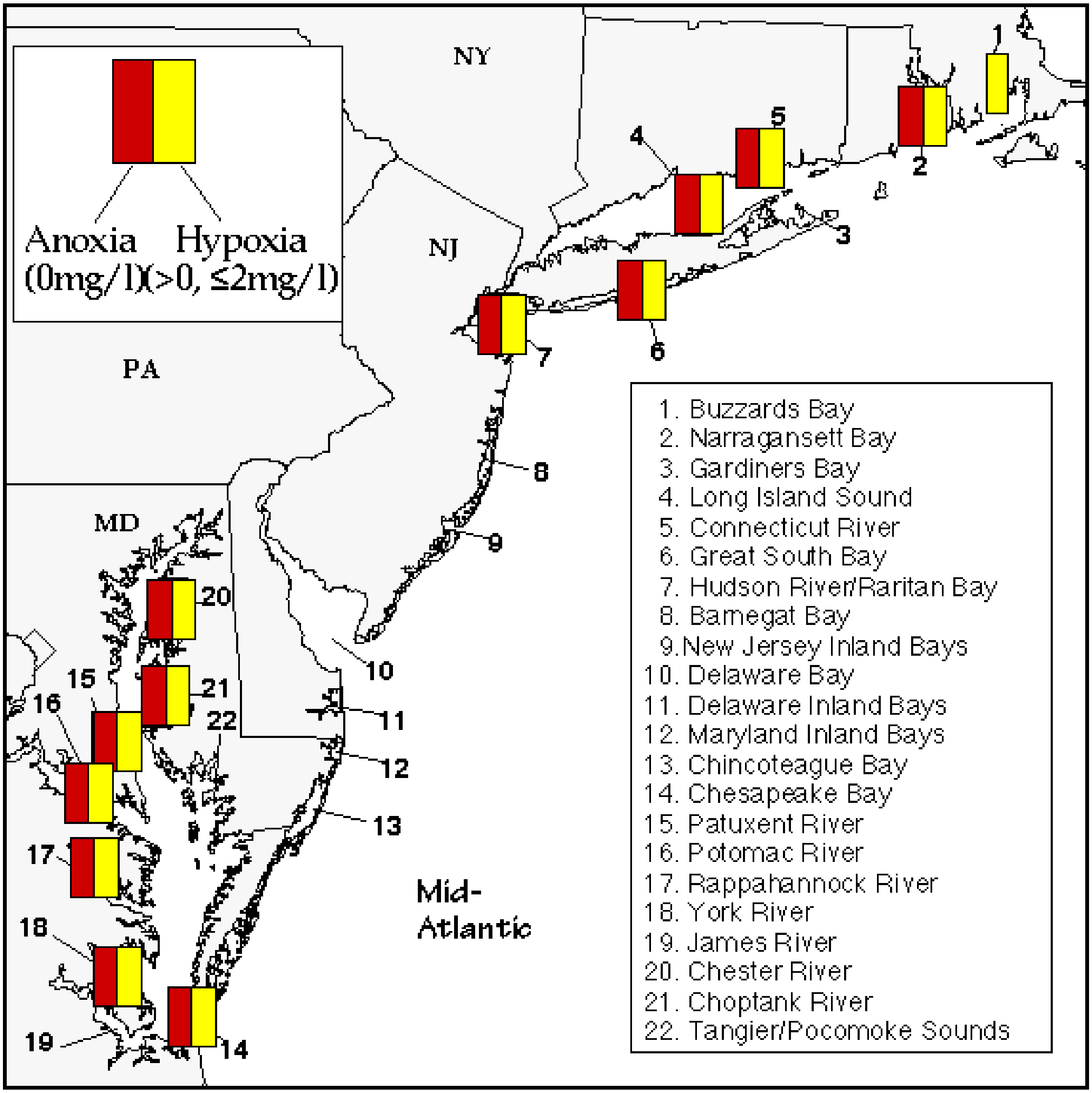
Existing Conditions for Oxygen Depletion, Mid-Atlantic Region



Source: NOAA's Estuarine Eutrophication Survey, vol. 2: Mid-Atlantic region (NOAA, 1997a)

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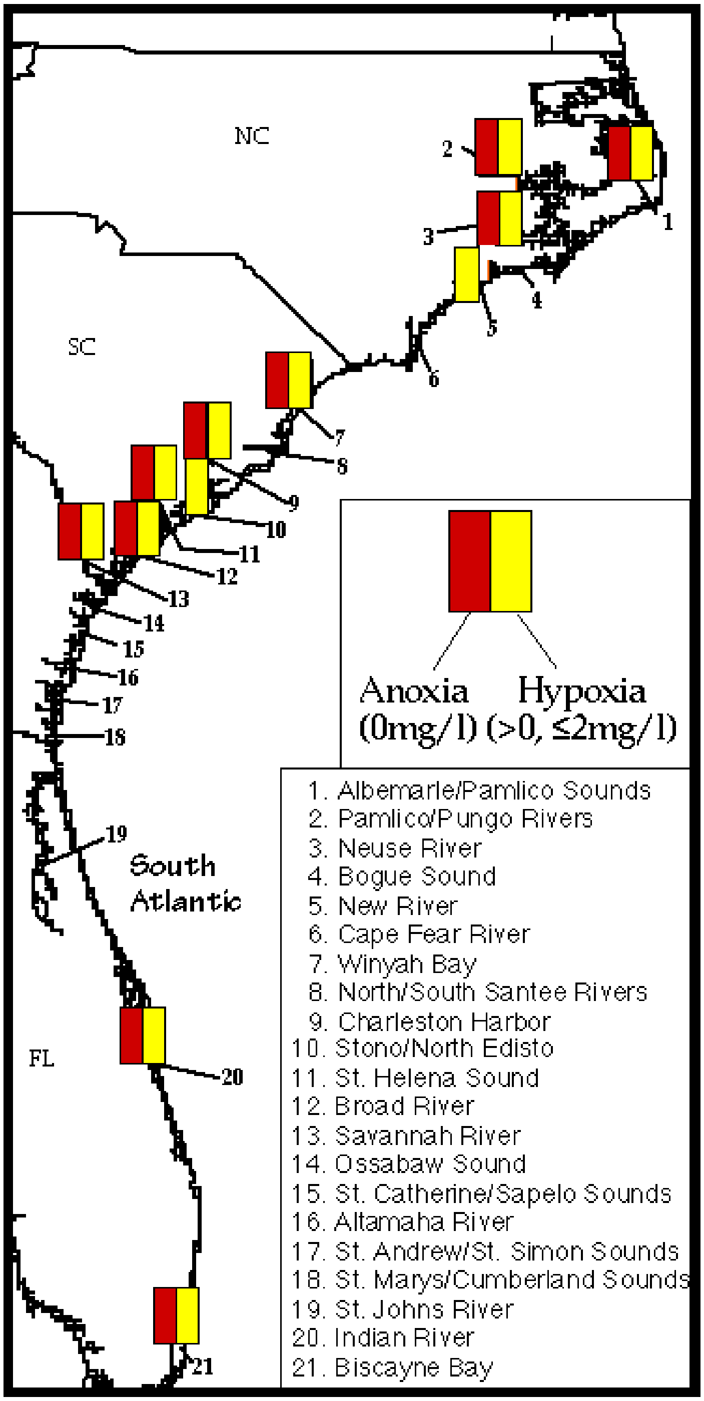
Existing Conditions for Oxygen Depletion, South Atlantic Region



Source: NOAA's Estuarine Eutrophication Survey, vol. 1: South Atlantic region (NOAA, 1996)
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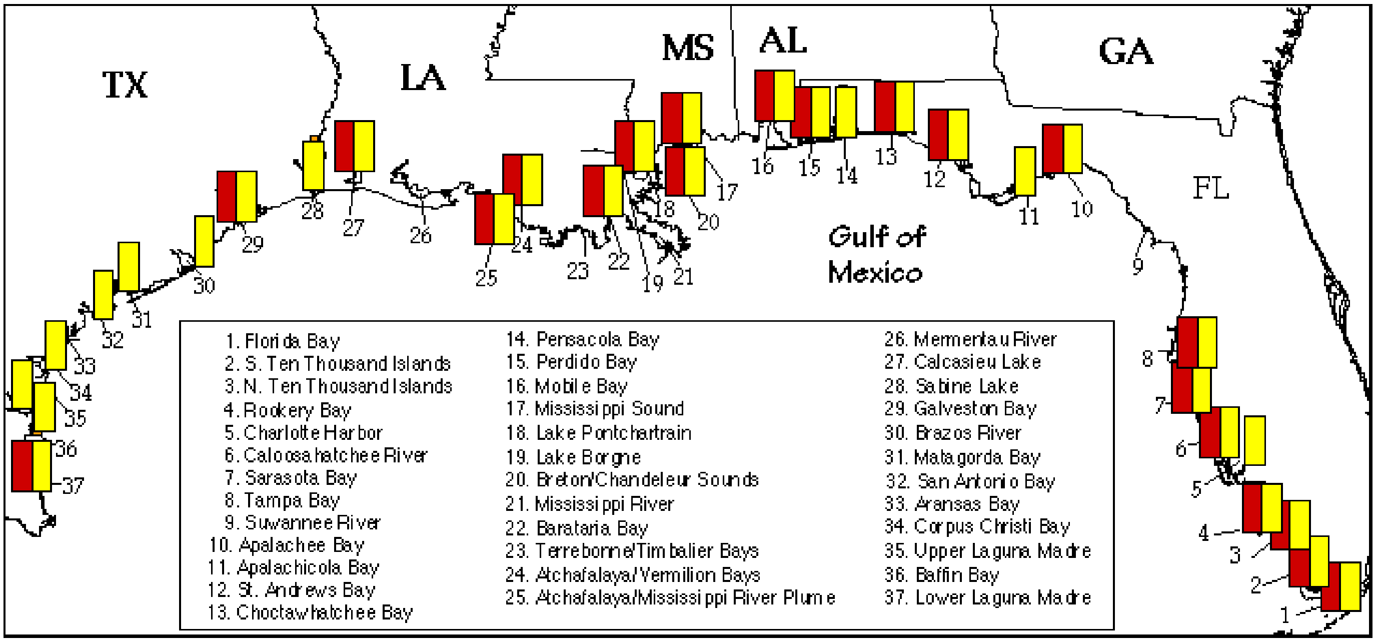
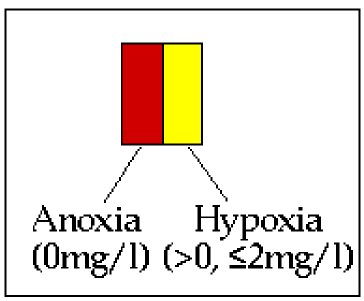
Existing Conditions for Oxygen Depletion, Gulf of Mexico Region





Source: NOAA's Estuarine Eutrophication Survey, vol. 4: Gulf of Mexico region (NOAA, 1997c)

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Appendix Preview

Click here to view the complete Appendix B (45 K).

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Trends (1970 - present) in Chl *a*, Anoxia, SAV by Estuary

	Chlorophyll a (µg/l)	Anoxia (frequency)	SAV (Spatial coverage)
North Atlantic			
St. Croix River/Cobscook Bay	●	●	↑
Englishman Bay	?	?	?
Narraguagus Bay	?	?	?
Blue Hill Bay	●	●	●*
Penobscot Bay	?	●	?
Muscongus Bay	●	?	?
Damariscotta River	●	●	●*
Sheepscot Bay	●	●	?
Kennebec/Androscoggin Rivers	?	?	●*
Casco Bay	●	↓	↓
Saco Bay	●	?	?
Great Bay	↑*	●	↑
Hampton Harbor	?	?	↑
Merrimack River	?	?	↓
Plum Island Sound	●	●	●
Massachusetts Bay	●	●	↓
Boston Harbor	●	●	↓
Cape Cod Bay	●	●	?

Key:
- * = speculative
- ? = unknown
- ● = no trend
- ↑ = increasing
- ↓ = decreasing

Note: Trends shown here represent the largest salinity zone in the estuary (for most estuaries this is the mixing zone). They do not represent conditions throughout the entire estuary.

Abbreviation: SAV, submerged aquatic vegetation

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Comparison of Northern Gulf of Mexico, Chesapeake Bay and Long Island Sound

	Northern Gulf of Mexico	Chesapeake Bay	Long Island Sound
Physical Characteristics			
Surface area	32,000 km^{2a}	4,400 km^2	3,400 km^2
Freshwater supply	14,000 m^3/s	2,800 m^3/s	850 m^3/s
Mean water depth	15 m	7 m	20 m
Water volume	$5*10^{11}$ m^{3a}	$74*10^9$ m^3	$64*10^9$ m^3
Watershed area	$3,317*10^3$ km^2	$166*10^3$ km^2	$44*10^3$ km^2
Population	$67*10^6$	$12.7*10^6$	$8.8*10^6$
Total	(Watershed)	(Watershed)	(Coast counties)
Density	15-106 people/mi^2	404 people/mi^2	1,008 people/mi^2
Critical processes	River discharge, nutrient loading	River discharge, nutrient loading, estuarine circulation	Sewage discharge, nutrient loading, deep water circulation
Hypoxia Frequency	Annual	Annual	Annual
Extent	8,000-18,000 km^2	2,000 km^2	200-400 km^2
Volume	1 to $3*10^{11}$ m^{3b}	2 to $8*10^9$ m^3	$700*10^7$ m^3
Duration	6 months	3 months	1.5 months
Bottom depth	5-30 m	5-20 m	5-20 m
Depth of pycnocline	10 m	8-10 m	5-10 m
Principal cause stratification	Salinity, additionally temp in summer	Salinity, additionally temp in summer	Temperature
Carbon source	Spring phytoplankton, additional in summer	Spring phytoplankton, additional in summer	Spring phytoplankton

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[a] Arbitrary boundaries of area on Louisiana continental shelf most directly influenced by the Mississippi/Atchafalaya River Plume.
[b] Estimate

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GLOSSARY

algae: a group of chiefly aquatic plants (e.g., seaweed, pond scum, stonewort, phytoplankton) that contain chlorophyll and may passively drift, weakly swim, grow on a substrate or take root in a water body.

anoxia: the absence of dissolved oxygen.

benthic organisms: organisms living in or on the bottom of aquatic environments (e.g., polychaetes, clams, snails).

chlorophyll: pigments found in plant cells that are active in harnessing energy during photosynthesis.

cyanobacteria: formerly known as blue-green algae.

demersal organisms: organisms associated with the bottom of aquatic environments, but capable of moving away from it (e.g., blue crabs, shrimp, red drum).

diatom: a major phytoplankton group characterized by cells enclosed in silicon frustules, or shells.

eutrophication: an increase in the rate of supply of organic matter to an ecosystem, usually involving overenrichment by nutrients.

hydrogen sulfide: a toxic chemical that diffuses into the water as the oxygen levels above the seabed sediments become zero.

hypoxia: very low dissolved oxygen concentrations, usually ranging between 0 and 2 milligrams per liter.

nonpoint: a diffuse source of chemical and/or nutrient inputs not attributable to any single discharge (e.g., agricultural runoff, urban runoff, atmospheric deposition).

nutrients: inorganic chemicals (particularly nitrogen, phosphorus and silicon) required for the growth of phytoplankton.

phytoplankton: minute plant life (e.g., algae), usually containing chlorophyll, that passively drifts or weakly swims in a water body.

productivity: the conversion of light energy and carbon dioxide into living organic material by phytoplankton.

pycnocline: the region of the water column characterized by the strongest vertical gradient in density, attributable to temperature, salinity or both.

respiration: the consumption of oxygen during energy utilization by cells and organisms.

stratification: a multilayered water column, delineated by pycnoclines.
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Suzanne Bricker of NOAA's Office of Ocean Resources Conservation and Assessment contributed extensive results from NOAA's National Estuarine Eutrophication Survey and helped in the development and review of the document. Tom Malone, Horn Point Environmental Laboratory; Tom Torgersen, University of Connecticut, Avery Point; Jon Pennock, Dauphin Island Sea Lab; and Gene Turner, Louisiana State University; reviewed a draft of the document and provided helpful suggestions. Ben Cole, LUMCON, and Mary DiGiacomo-Cohen, University of Connecticut, assisted with graphics. Several individuals contributed photographs.
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Many of the photos were gathered from NOAA archives or were generously provided from the personal collections of NOAA staff members.

Others were contributed from outside of NOAA, and we gratefully thank the following institutions and individuals:

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About the Author

Nancy N. Rabalais is a professor at the Louisiana Universities Marine Consortium, where she has been working for the last 15 years. She earned a Ph.D. in zoology from The University of Texas at Austin in 1983, and her B.S. and M.S. from Texas A&I University, Kingsville, in 1972 and 1975. Before she joined LUMCON, Dr. Rabalais was a research associate, then graduate student, at the U.T. Marine Science Institute, Port Aransas Marine Laboratory. She teaches marine science courses at LUMCON and in the Department of Oceanography and Coastal Sciences at Louisiana State University. Dr. Rabalais' research interests include the dynamics of hypoxic environments, interactions of large rivers with the coastal ocean, estuarine and coastal eutrophication, benthic ecology, and the environmental effects of habitat alterations and contaminants. Dr. Rabalais is a Fellow of the American Association for the Advancement of Science and President of the Estuarine Research Federation.

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Table 1. U.S. estuaries with hypoxia

Region	% Ests.[1]	% Ests.[2]	Area	Months[3]	Frequency	Depth	Zone[4]
North Atlantic	6%	22%	0-2%	7-9	Periodic	Bottom	SW
Mid-Atlantic	50%	59%	9-22%	6-9	Periodic	Bottom	MX
South Atlantic	16%	62%	4-12%	5-9	Periodic	Bottom/Through	MX/SW
Gulf of Mexico	66%	84%[5] 86%[6]	12-27%[5] 32-66%[6]	6-10 4-10	Periodic Periodic	Bottom Bottom	MX/SW/TF
Pacific Coast	21%	26%	1-2%	8-10	Periodic	Bottom	MX/SW
Nation	37%	52%[5] 53%[6]	8-19%[5] 21-43%[6]	5-10	Periodic	Bottom	MX/SW

[1] Based on Whitledge (1985), number of estuaries reporting as % of total.

[2] Based on NOAA's National Estuarine Eutrophication Survey, estuaries with hypoxia in part or all of the estuary, number of estuaries reporting as % total. Of all responses, 6 are speculative; 3 in South Atlantic, 2 in Gulf of Mexico and 1 in Pacific.

[3] Months are referred to by number with 1 = January, 2 = February, . . . 12=December.

[4] TF = tidal fresh zone (<0.5 ppt), MX = mixing zone (0.5-25 ppt), SW = seawater zone (>25 ppt).

[5] Does not include the Mississippi/Atchafalaya River Plume.

[6] Includes the Mississippi/Atchafalaya River Plume.

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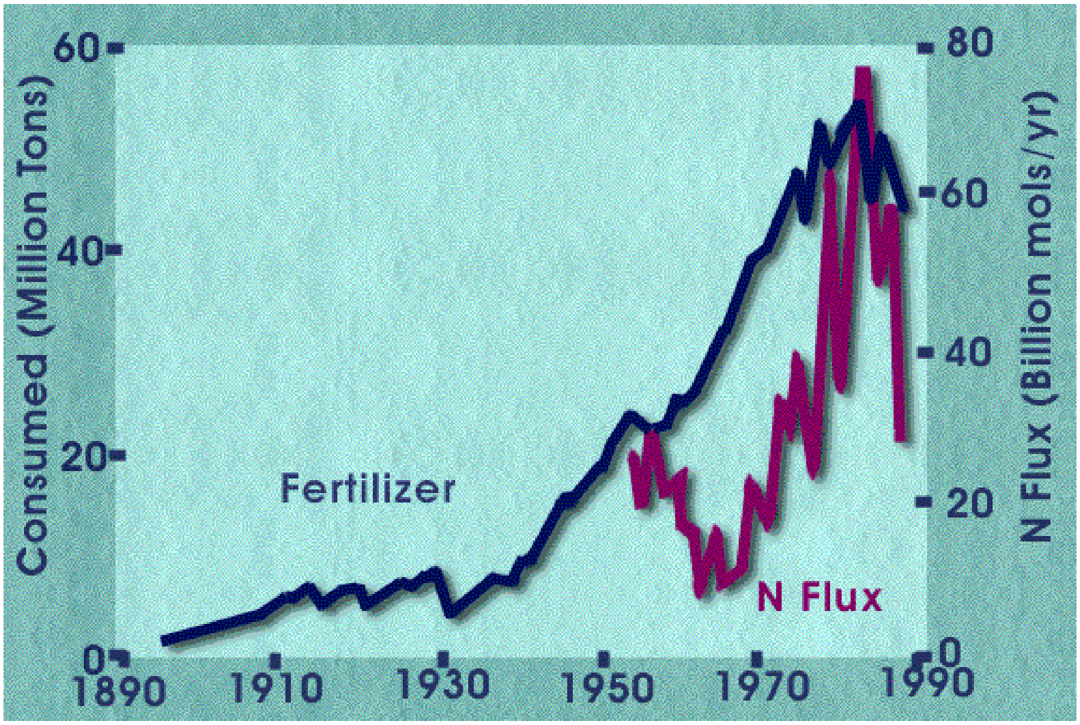

Figure 1. Commercial fertilizer consumption in the United States and nitrogen flux from the Mississippi River

Note: Although fertilizer was used prior to 1895, substantial increases begin around 1930 (from Eadie et al., 1992).

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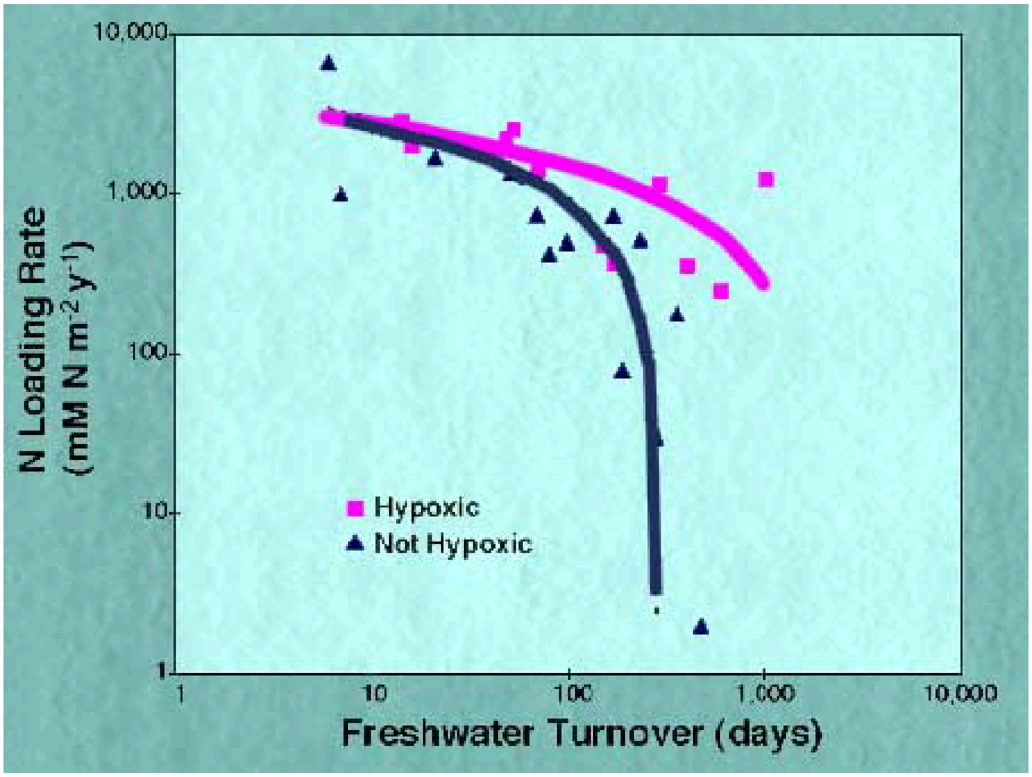

Figure 2. Nitrogen loading per estuarine surface area and turnover of freshwater in northern Gulf of Mexico estuaries

Note: Estuaries with evidence of hypoxia (from surveys) are distinguished from those estuaries without a record of hypoxia. A regression of the untransformed data is shown. Source: Turner and Rabalais, 1998 (in press)

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Figures 3a-c.

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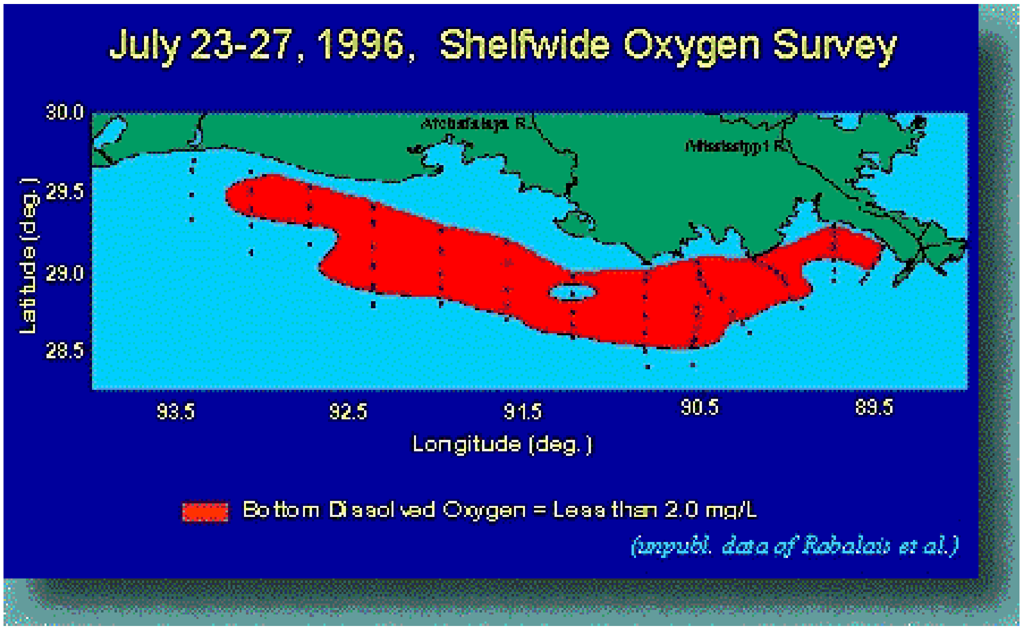

Figure 3a. Bottom water dissolved oxygen from Shelfwide Oxygen Survey, July 23-27, 1996 (from Rabalais et al., press release, July 1996).

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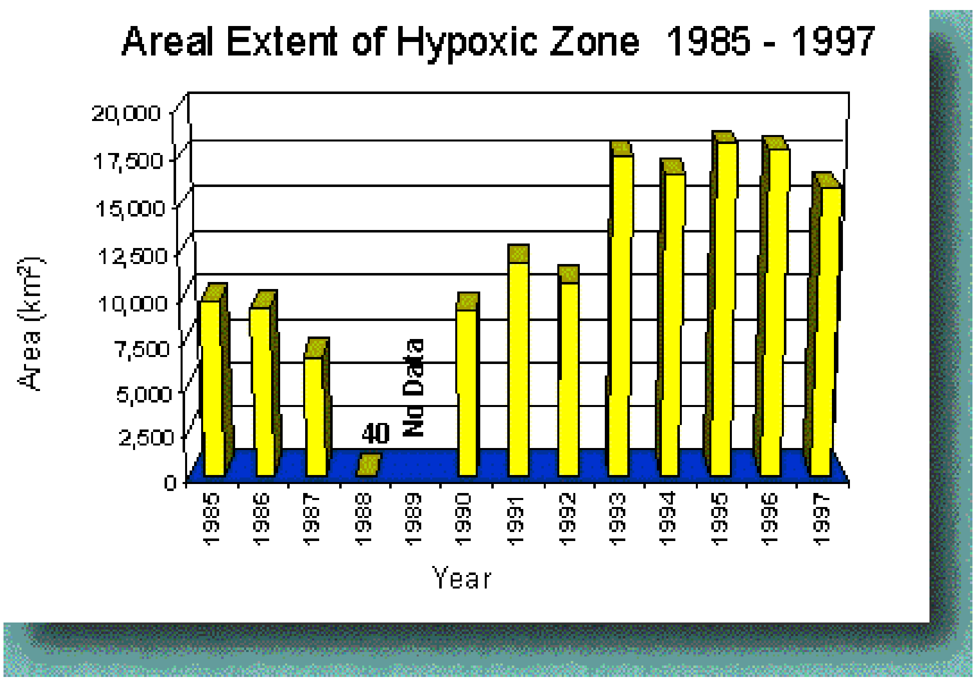

Figure 3b. Areal extent of hypoxic zone, 1985-1997 (adapted from Rabalais et al., 1998, in press).

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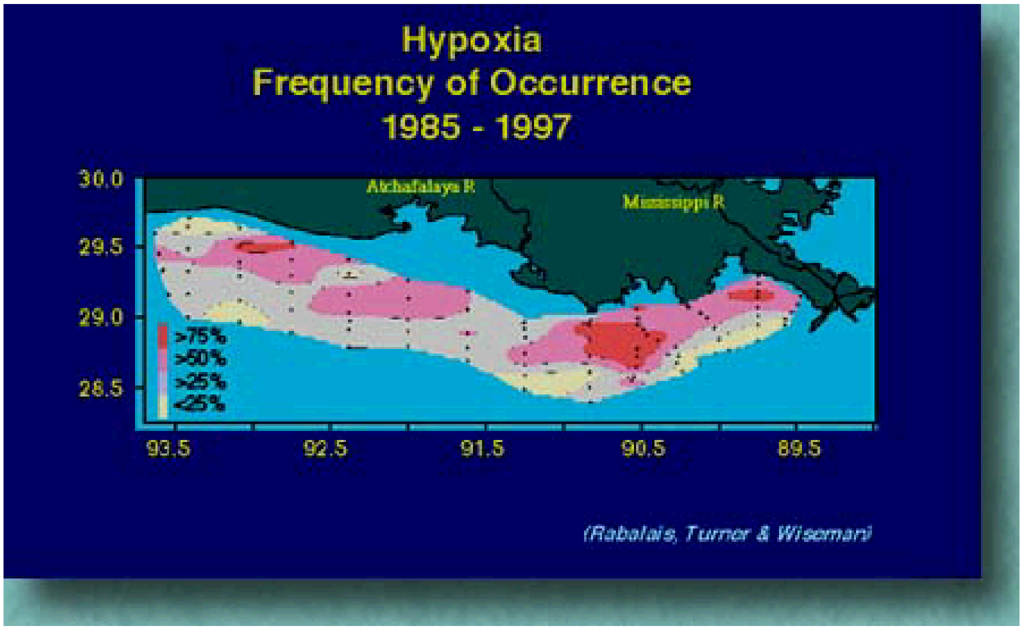

Figure 3c. Frequency of occurrence of mid-summer hypoxia, 1985-1997 (from Rabalais et al., unpublished report).

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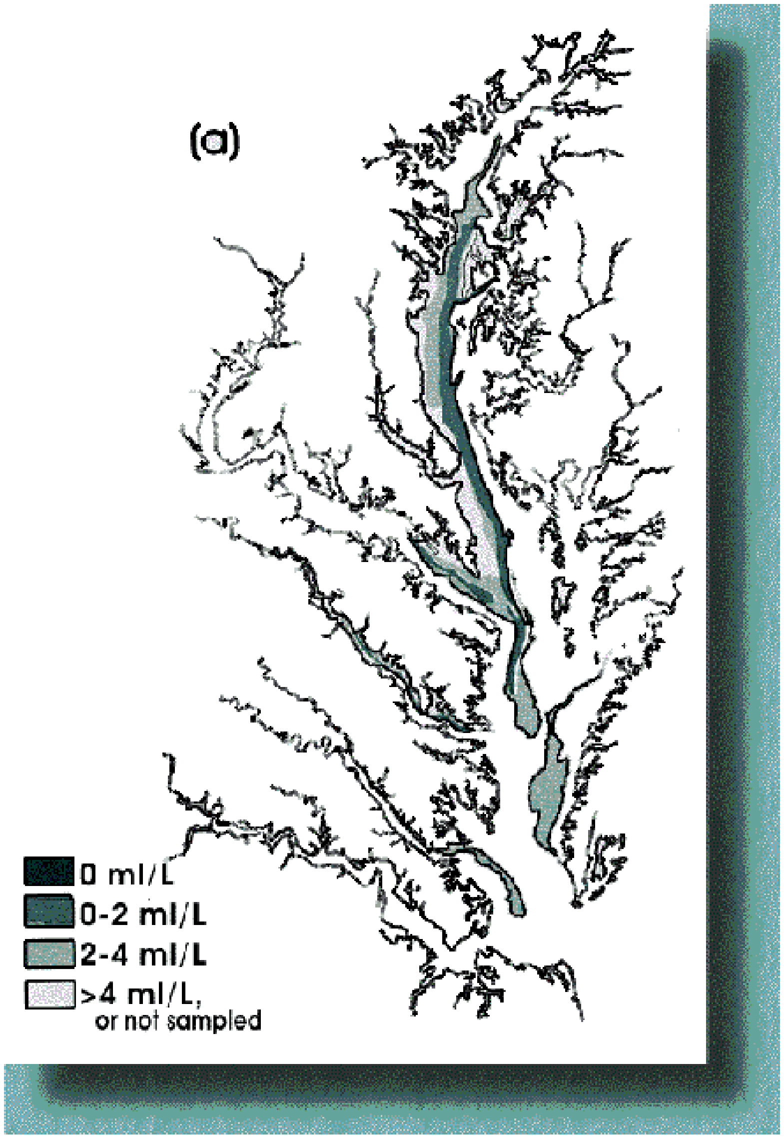

Figure 4a. Comparison of dissolved oxygen levels in Chesapeake Bay in 1950 (from U.S. EPA, 1983).

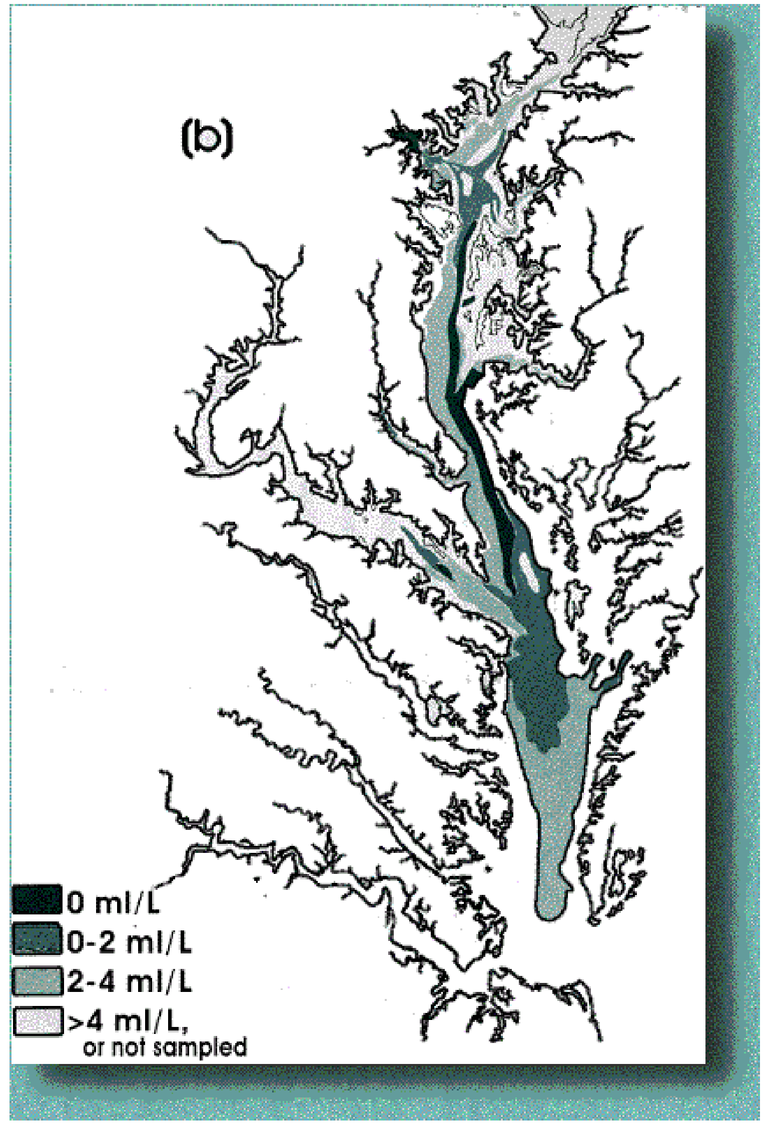

Figure 4b. Comparison of dissolved oxygen levels in Chesapeake Bay in 1980 (from U.S. EPA, 1983).

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Click on the image or the figure title to view the full size image.

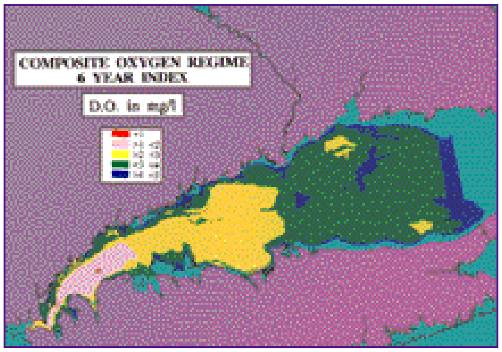

Figure 5a. Six year (1986-1991) composite bottom water dissolved oxygen (D.O.) concentrations in Long Island Sound

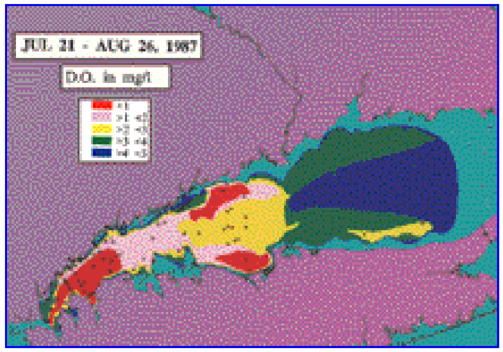

Figure 5b. Bottom water dissolved oxygen (D.O.) concentrations in Long Island Sound from Jul 21-Aug 26, 1987

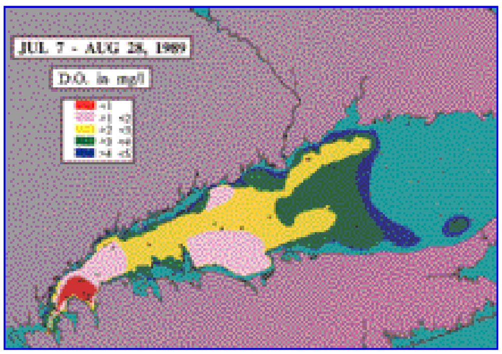

Figure 5c. Bottom water dissolved oxygen (D.O.) concentration in Long Island Sound from Jul 7-Aug 28, 1989

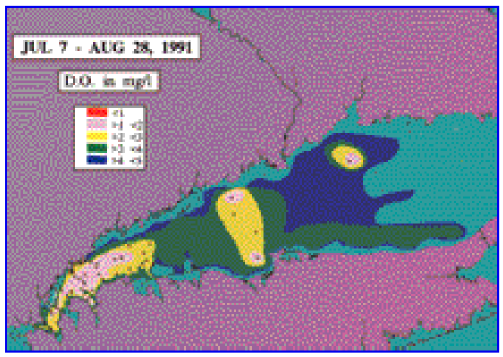

Figure 5d. Bottom water dissolved oxygen (D.O.) concentrations in Long Island Sound from Jul 7-Aug 28, 1991

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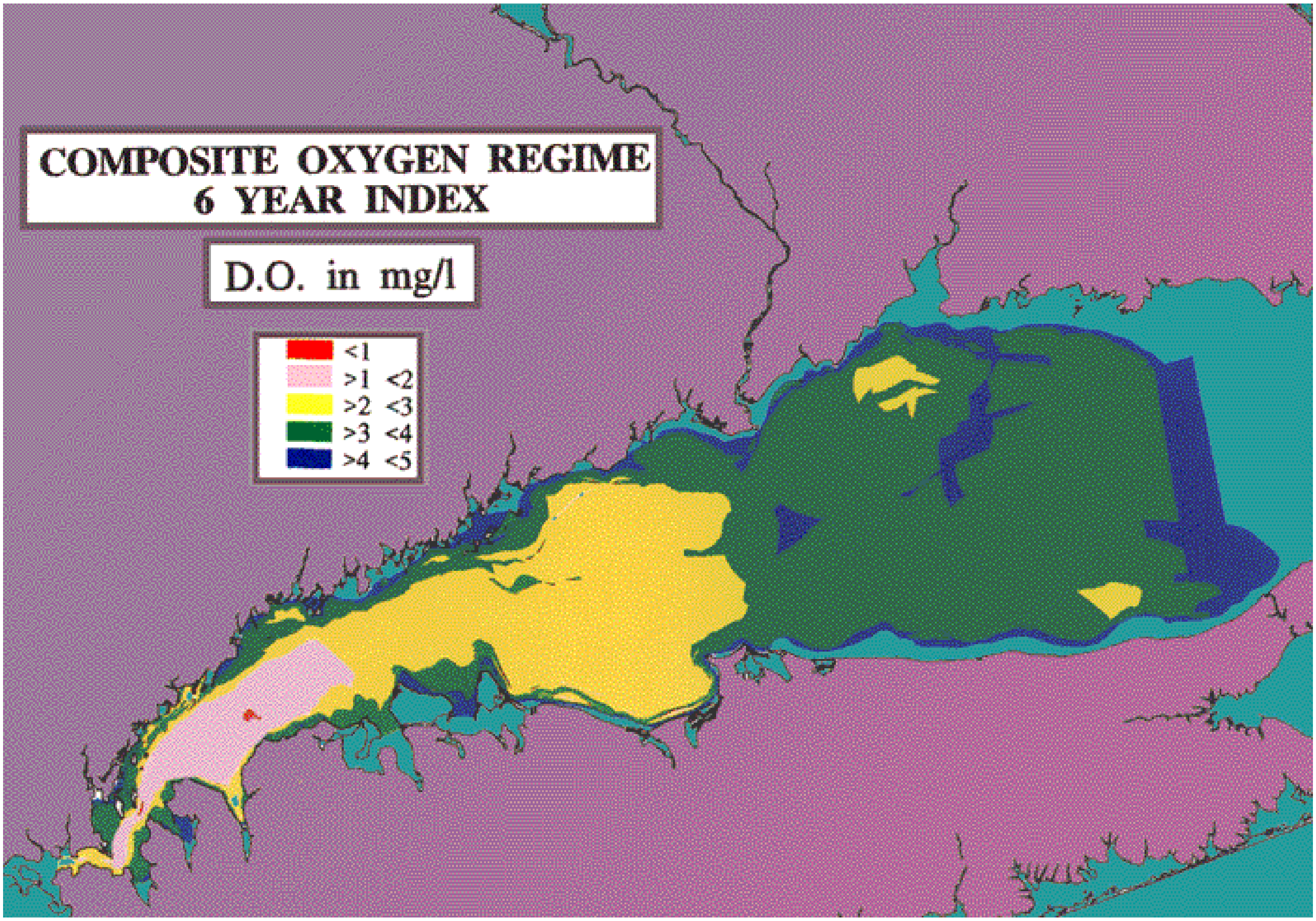

Figure 5a. Six year (1986-1991) composite bottom water dissolved oxygen (D.O.) concentrations in Long Island Sound (from Barbara Welsh, personal communication)

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Figure 5b.

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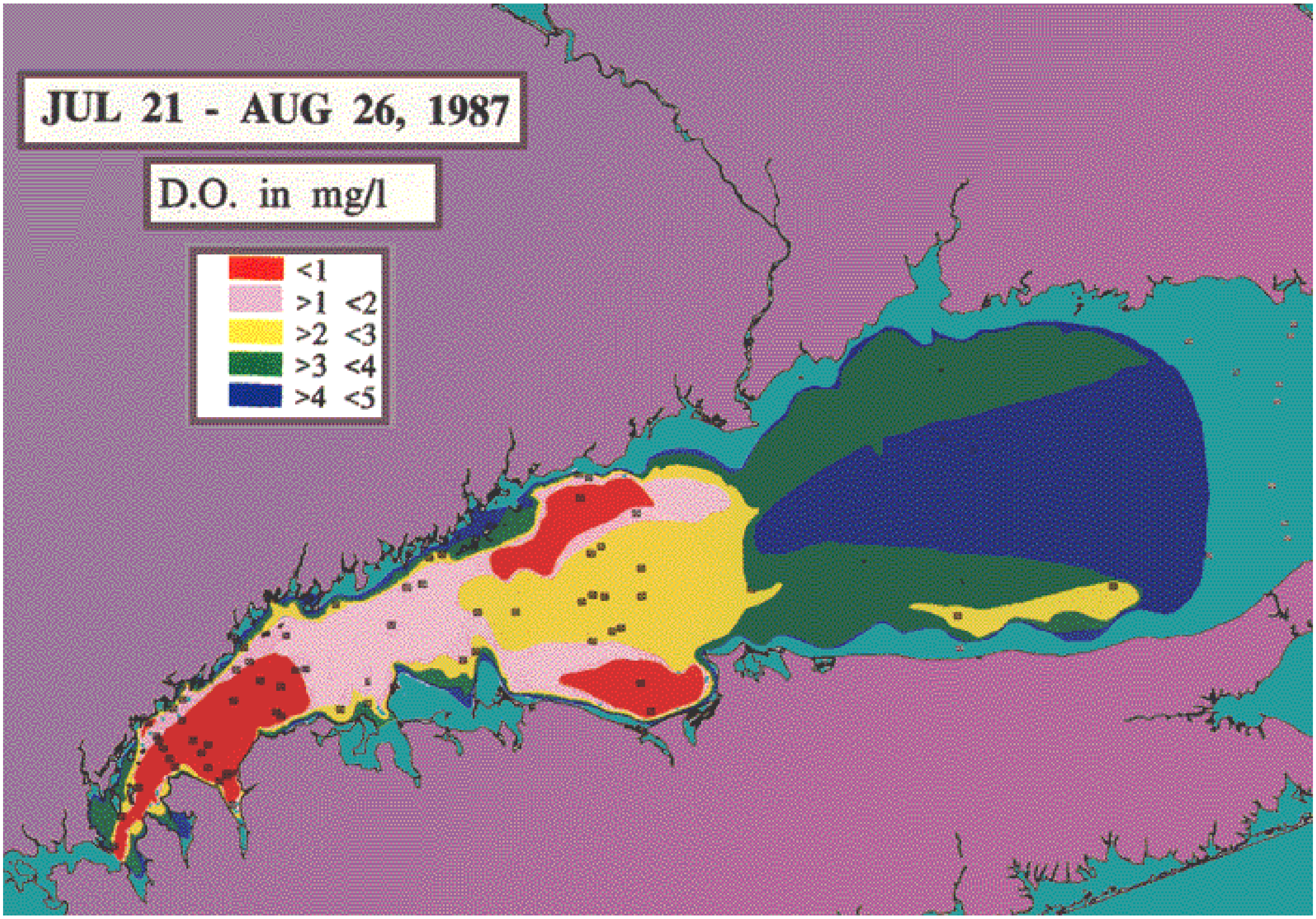

Figure 5b. Bottom water dissolved oxygen (D.O.) concentrations in Long Island Sound July 21-August 26, 1987 (from Barbara Welsh, personal communication)

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Figure 5c.

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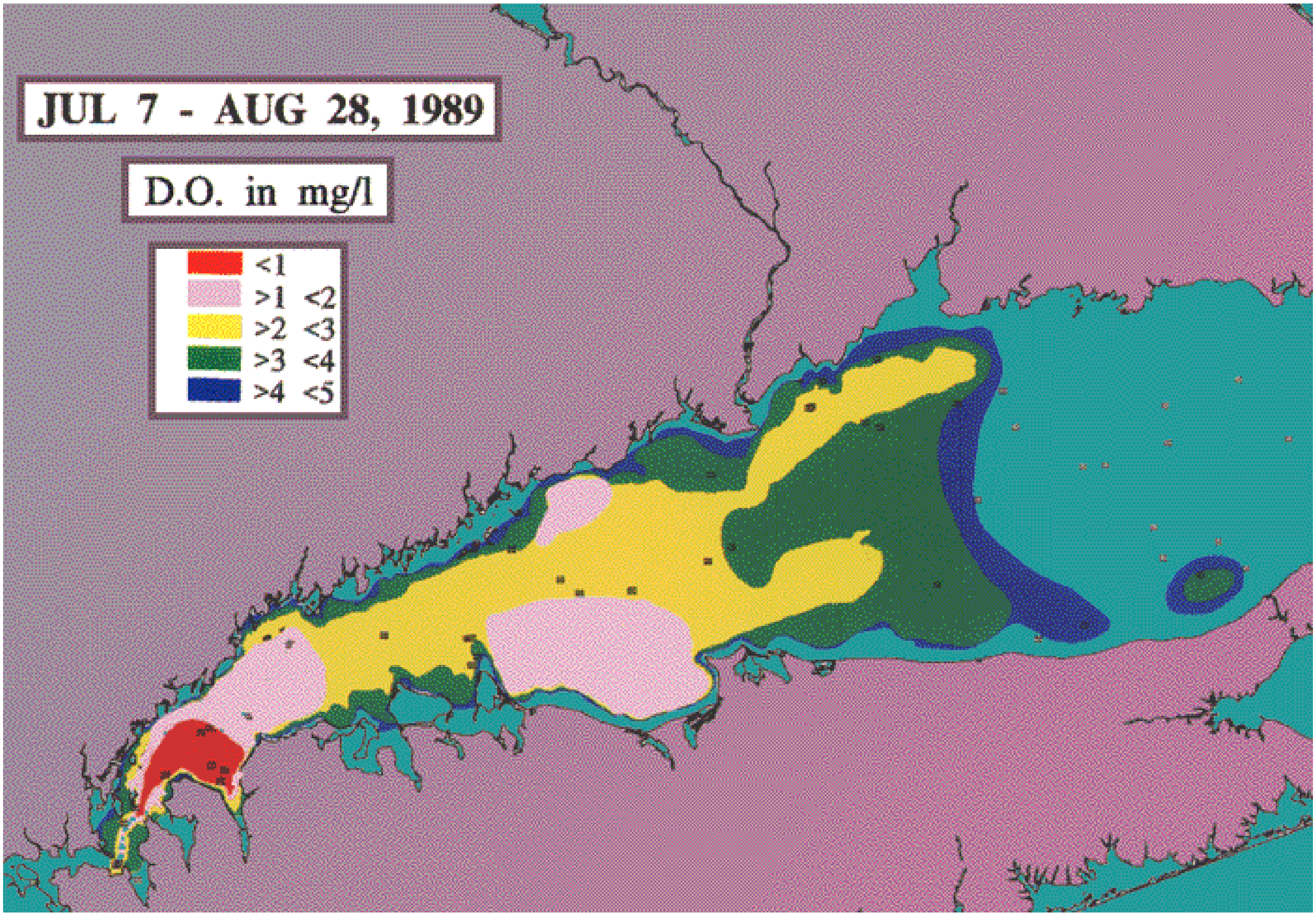

Figure 5c. Bottom water dissolved oxygen (D.O.) concentrations in Long Island Sound July 7-August 28, 1987 (from Barbara Welsh, personal communication)

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Figure 5d.

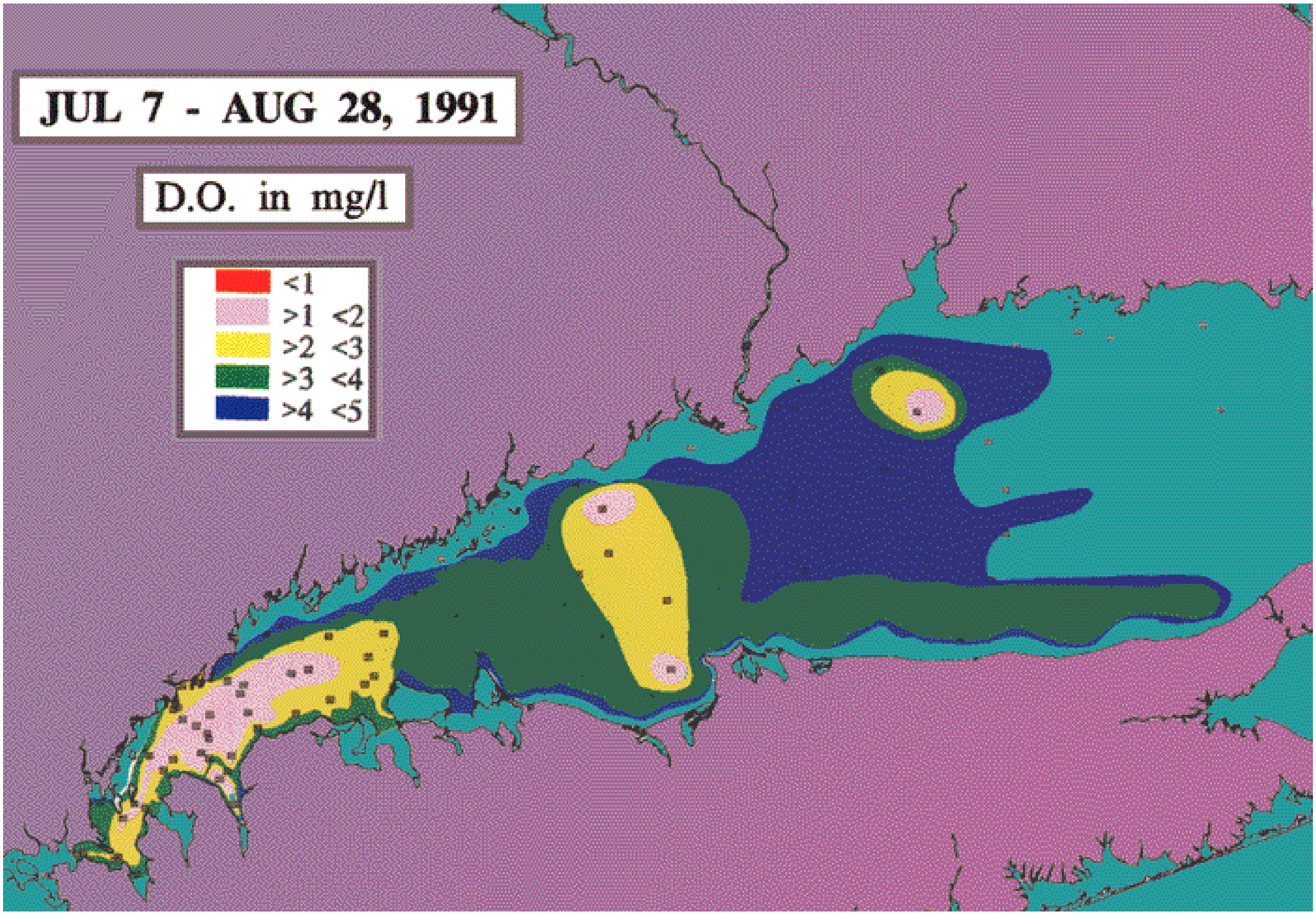

Figure 5d. Bottom water dissolved oxygen (D.O.) concentrations in Long Island Sound July 7-August 28, 1991 (from Barbara Welsh, personal communication)