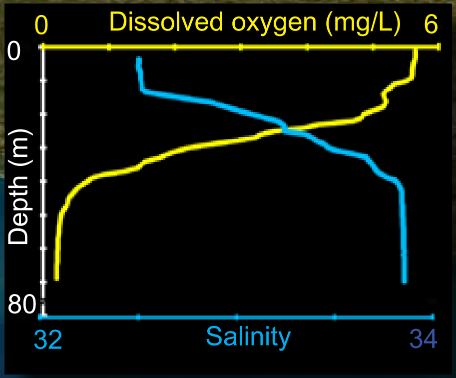
Scientific Assessment of Hypoxia in U.S. Coastal Waters



Interagency Working Group
on Harmful Algal Blooms, Hypoxia, and
Human Health
May 2010

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Many scientists and managers from Federal and state agencies, universities, and research institutions contributed to the knowledge base upon which this assessment depends. Many thanks to all who contributed to this report, and special thanks to John Wickham and Lynn Dancy of NOAA National Centers for Coastal Ocean Science for their editing work.

Cover and Sidebar Photos:

Background Cover and Sidebar: MODIS satellite image courtesy of the Ocean Biology Processing Group, NASA Goddard Space Flight Center.
Cover inset photos from top: 1) CTD rosette, EPA Gulf Ecology Division; 2) CTD profile taken off the Washington coast, project funded by Bonneville Power Administration and NOAA Fisheries; Joseph Fisher, OSU, was chief scientist on the FV Frosti; data were processed and provided by Cheryl Morgan, OSU); 3) Dead fish, Christopher Deacutis, Rhode Island Department of Environmental Management; 4) Shrimp boat, EPA.

Council on Environmental Quality
Office of Science and Technology Policy
Executive Office of the President

Dear Partners and Friends in our Ocean and Coastal Community,

We are pleased to transmit to you this report, *Scientific Assessment of Hypoxia in U.S. Coastal Waters.* This document assesses the problem of hypoxia (or low dissolved oxygen) in our Nation's coastal ocean and estuarine waters. It also describes recent advances made by Federal agencies to improve scientific understanding of hypoxia and our ability to manage and, ultimately, prevent these events.

In December 2004, Congress reauthorized the Harmful Algal Bloom and Hypoxia Research and Control Act (HABHRCA) by passing the Harmful Algal Bloom and Hypoxia Amendments Act of 2004. The reauthorization of HABHRCA acknowledged that hypoxia is one of the most scientifically complex and economically damaging coastal issues challenging our ability to safeguard the health of our Nation's coastal ecosystems.

This document was prepared by the Interagency Working Group on Harmful Algal Blooms, Hypoxia, and Human Health, which was chartered through the Joint Subcommittee on Ocean Science and Technology of the National Science and Technology Council and the Interagency Committee on Ocean Science and Resource Management Integration. This report complements and expands upon water quality-related priorities identified in *Charting the Course for Ocean Science in the United States for the Next Decade: An Ocean Research Priorities Plan and Implementation Strategy*, by the Joint Subcommittee on Ocean Science and Technology. It draws from the direct contributions of Federal agencies as well as previous reports and planning efforts that involved numerous experts and stakeholders from Federal, state, and local governments, academia, industry, and nongovernmental organizations.

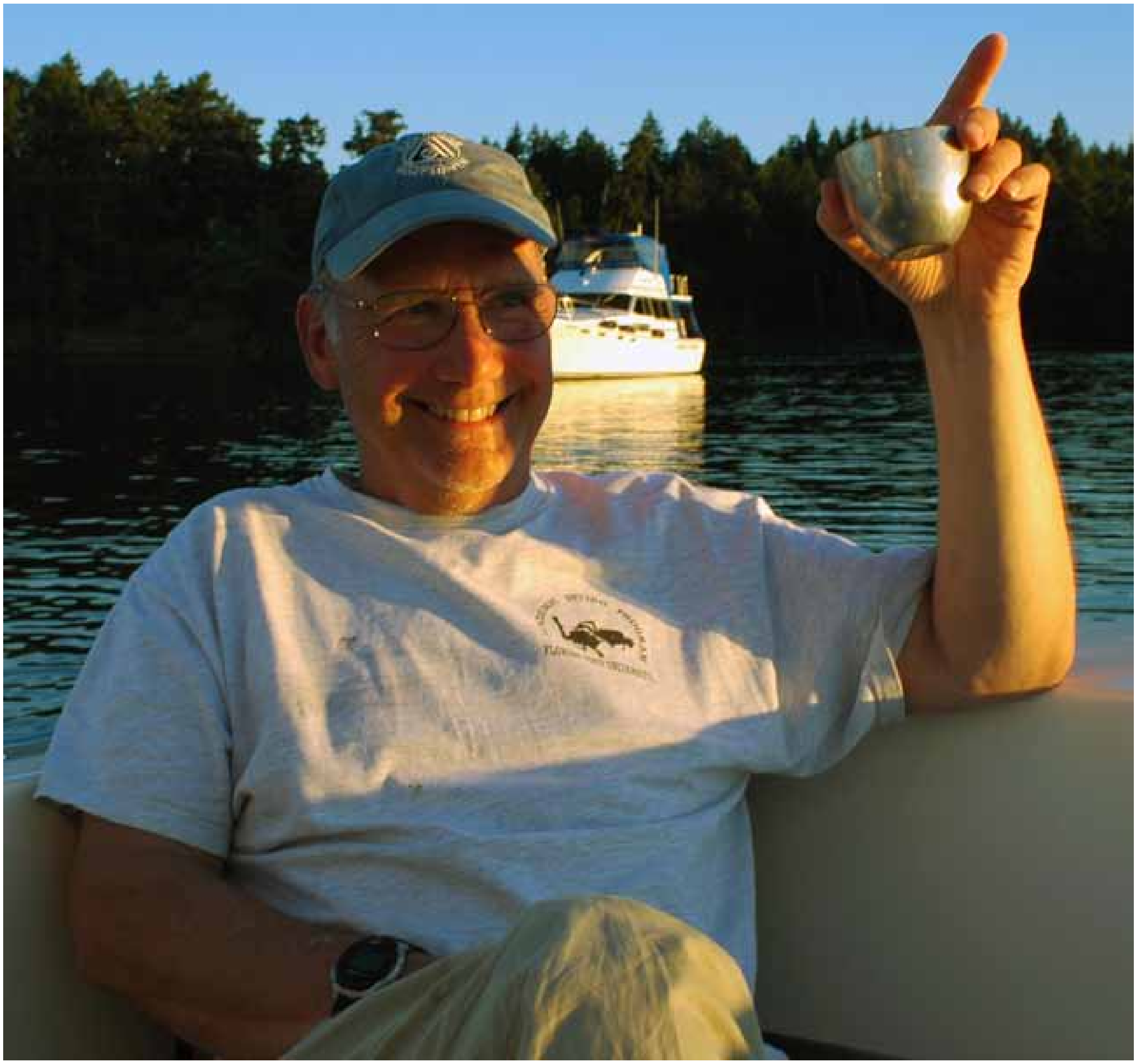
The Nation's coastal waters are vital to our quality of life, our culture, and the economy. Therefore, it is imperative that we move forward to better understand and prevent hypoxia events, which threaten all of our coasts. This report is an effort to assess the extent of efforts to understand and lessen hypoxia events and to identify opportunities for charting a way forward. We hope it will be useful to the Congress and a broad range of interested parties.

Sincerely,

Nancy H. Sutley
Chair
Council on Environmental Quality

Sincerely,

John Holdren
Director
Office of Science and Technology Policy



Peter Eldridge (1946 – 2008)

This report is dedicated to the memory of Dr. Peter Eldridge, who was a member of the hypoxia report writing team and a research scientist with the U.S. Environmental Protection Agency. Peter had a great love and passion for the ocean, the environment, and science. Among Peter's scientific contributions was the development of ecosystem models to address coastal environmental issues, such as coastal hypoxia, food web changes, and seagrass loss. Peter's friendship and enthusiasm for science will be greatly missed.

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Appendix II. Geographic Case Studies

Introduction and Background to Case Studies

The case studies presented here highlight selected coastal ecosystems that are geographically diverse and represent the spectrum of estuarine and coastal ocean ecosystems affected by hypoxia. The selected cases describe the range of circumstances, understanding, and scientific and management approaches across the United States (Figure A1). They provide examples of monitoring and research programs that have been or are being used to develop management plans. In some instances the outcomes of implemented management measures are also presented and should serve as encouragement that nutrient-related dissolved oxygen problems can be improved with proper management. The exception is hypoxia along the Oregon coast, which has occurred since 2002 and is more related to climate impacts on upwelling-favorable winds on the west coast. Yet, coastal management is still pertinent to the Oregon shelf which has thriving coastal fisheries negatively impacted by hypoxia. These case studies provide the basis for successful management approaches that may be used in other systems in the United States.

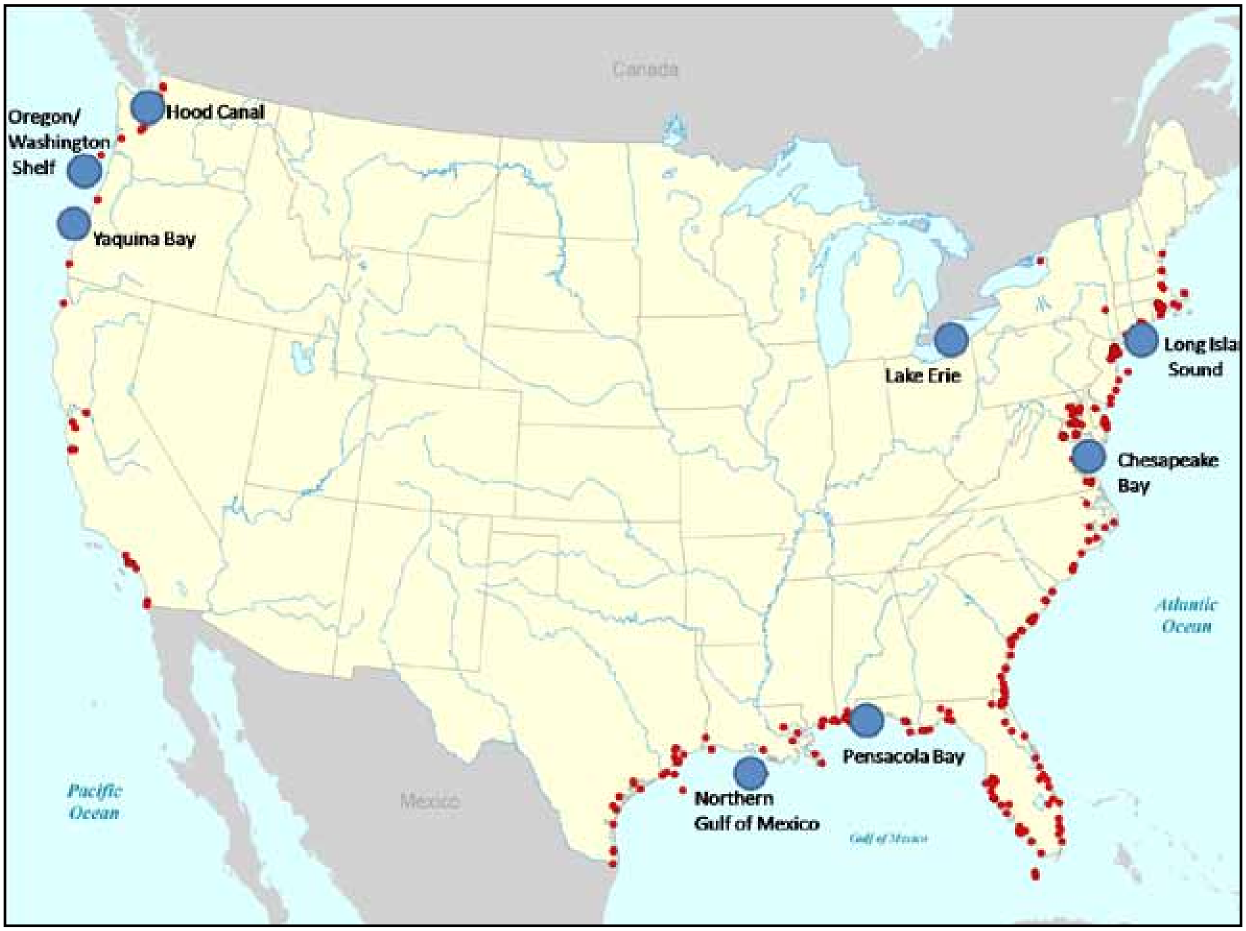

Figure A1. Geographic locations of hypoxia case studies. Large blue dots represent cases studies; red dots represent systems that have a documented hypoxia issue.

Table A1. Comparison of Physical Systems Represented by Case Studies in Appendix II

Site	Waterbody area (km^2)	Watershed area (km^2)	Average depth (m)	Tidal height (m)	Freshwater inflow m^3/d	Average salinity (psu)	Watershed population	NEEA Results*: Dissolved oxygen rating	
								Early 1990s	Early 2000s
Long Island Sound	3,259	12,773	20	1.9	1.55×10^7	28	4.91×10^6	Moderate	High
Lake Erie	25,744	---	19	0	---	0	---	---	---
Chesapeake Bay Mainstem	6,974	79584	7.3	0.45	1.05×10^8	16	6.41×10^6	High	High
Pensacola Bay	477	17650	3.0	0.42	2.58×10^7	18	3.71×10^5	Moderate	Low
Northern Gulf of Mexico	31,743	2,968,304	20	0.29	1.53×10^9	29	7.30×10^7	High	High
Yaquina Bay	14	634	2.1	1.9	6.60×10^5	22	6.03x103	Low	Low
Oregon Shelf	26,600	---	---	3 - 4 (nearshore)	5.6×10^8	32	---	---	---
Hood Canal	396	2768	70	2.2	7.45×10^6	26	3.49×10^4	Moderate	High

* from Bricker, S., B. Longstaff, W. Dennison, A. Jones, K. Boicourt, C. Wicks and J. Woerner. 2007. Effects of Nutrient Enrichment in the Nation's Estuaries: A Decade of Change, National Estuarine Eutrophication Assessment Update. NOAA Coastal Ocean Program Decision Analysis Series No. 26. National Centers for Coastal Ocean Science, Silver Spring, MD. 322 pp. http://ccma.nos.noaa.gov/news/feature/Eutroupdate.html

Long Island Sound

Physical Description of the System

Figure 1. Location of Long Island Sound (P. Stacey, CT DEP).

Long Island Sound is a large (3,056 km^2) glacial outwash estuary, shared by the States of Connecticut and New York (Figure 1). Its unique configuration connects it with the Atlantic Ocean via the Race in the east and via the East River in the west. The Connecticut River, very near the Sound's eastern terminus, contributes about two thirds of its freshwater input. The Housatonic and Thames Rivers also contribute significant volumes of fresh water to this system. The influence of the East River (a tidal strait) promotes a stratified salinity structure in the western sound especially in the spring runoff period when freshwater from the Hudson River basin is transported into western Long Island Sound. Salinity variability is less distinct in the eastern sound where salinities tend to be higher. Tidal amplitude ranges from about two meters in the west to less than one meter in the east. The Sound is moderately flushed, with mean residence times of two to three months. A highly developed watershed contributes to low dissolved oxygen problems (from Bricker et al. 1997, 2007).

History of Hypoxia (issue, causes, economic, and ecosystem impacts)

Long Island Sound has a large and highly developed watershed (Table A1). Nitrogen contributions from the watershed, combined with strong summer thermal stratification in its western half, renders Long Island Sound susceptible to seasonal hypoxia. Since 1985, the causes and effects of hypoxia have been the subject of intensive monitoring, modeling, and research through the Long Island Sound Study (LISS), part of the EPA National Estuary Program (see Appendix I, Interagency Efforts). Hypoxia most seriously affects the strongly stratified western half of the Sound where dissolved oxygen concentrations fall well below Connecticut and New York's water quality standards each summer (Figure 2). Dissolved oxygen levels below 3 mg/L are usually observed, levels below 2 mg/L are not uncommon, and during some years portions of the Sound's bottom waters become anoxic (<1 mg/L; Figures 2 and 3).

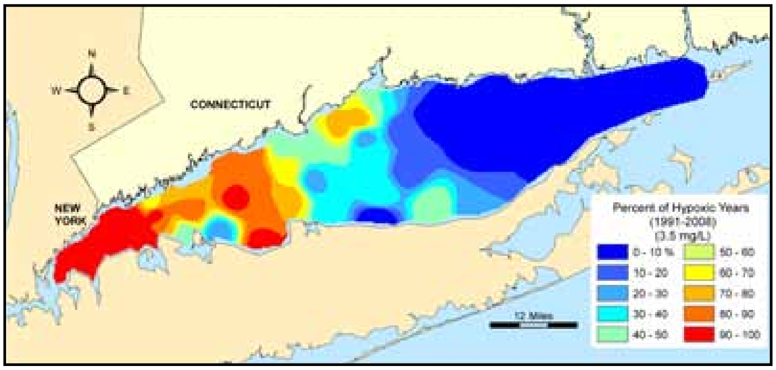

Figure 2. The frequency and location of hypoxia in Long Island Sound bottom waters from 1991-2008 (P. Stacey CT DEP).

Long Island Sound is surrounded by a highly urbanized landscape, including New York City in the west and large, sprawling populated areas in Long Island and Connecticut. Primary sources of nitrogen include sewage treatment plants, nonpoint source runoff, and atmospheric deposition, all driven by human influences in the watershed and airshed (Figure 4). Monitoring of Long Island Sound conducted by the Connecticut Department of Environmental Protection on behalf of the LISS has shown an annual recurrence and persistence of hypoxia over the last 15 years. Despite significant reductions in nitrogen loads by both Connecticut and New York under a total maximum daily load (TMDL) approved in 2001, dissolved oxygen improvements have been slow and masked by weather-driven variability and effects of climate change.

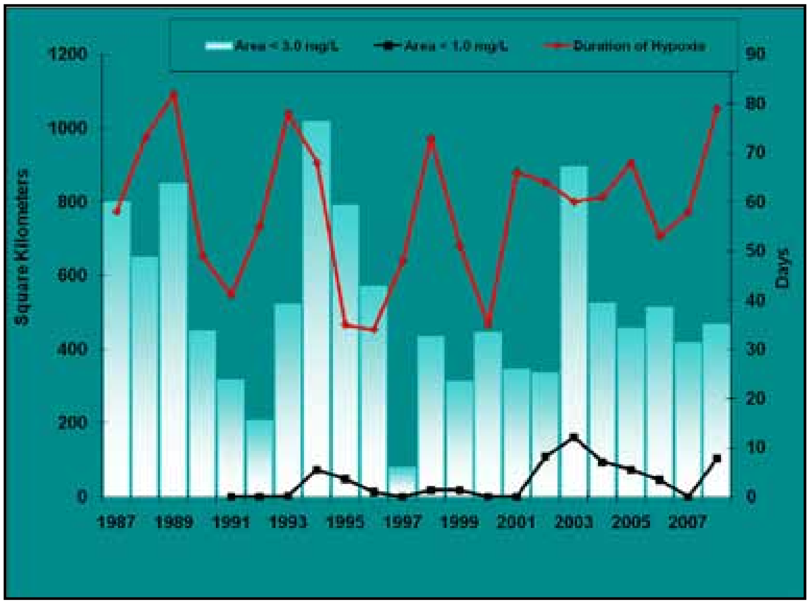

Figure 3. Areal extent and duration of Long Island Sound hypoxia, 1987-2007. The average areal extent is 521 km^2 and average duration is 58 days. (P. Stacey CT DEP).

Considering that nature contributes, at most, about 10,000 metric tons of nitrogen every year to the Sound from weathering and nitrogen fixation in the watershed, the nearly 38,000 metric tons per year added by more than 100 sewage treatment plants located along the coast and throughout the drainage basin have greatly enriched the ecosystem (Figure 5). Another 12,500 metric tons of nitrogen are contributed each year from nonpoint sources coming from excessive fertilizer added to lawns or agricultural crops, atmospheric emissions (from automobiles, power plants, and industry), and human and animal wastes (including home septic systems). Population continues to grow within the already densely populated Long Island Sound basin. This growth contributes to the nitrogen load through sewage treatment plants as well as through various nonpoint sources, and the impact is large. Since 1985, Connecticut's land conversion rate to developed uses was 11.3% for a population that had grown about 8.6%. Per capita consumption of land is outstripping population growth in Connecticut and throughout the basin.

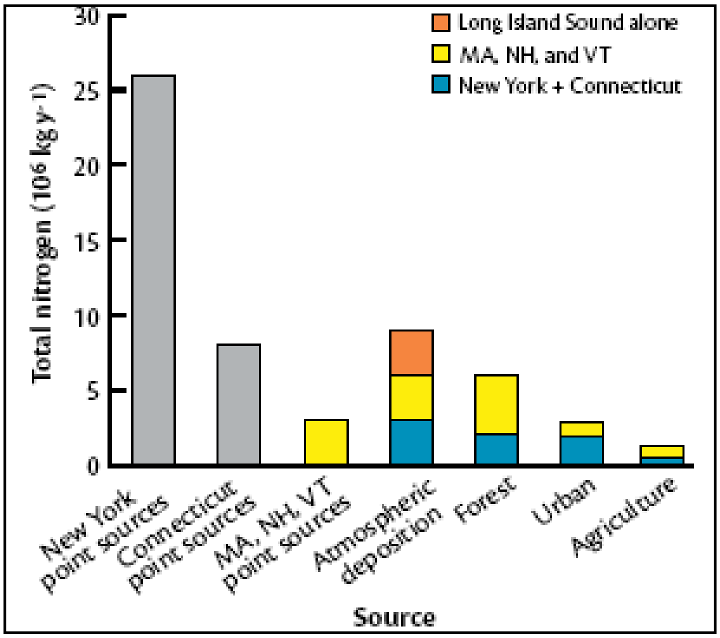

Figure 4. Sources of nitrogen to Long Island Sound – baseline condition (P.Stacey, CT DEP).

Nitrogen enrichment, coupled with the Sound's sensitivity to hypoxia due to relatively long residence time and seasonally strong stratification, leads to unhealthy conditions that are environmentally and economically costly for the Sound and its users. Furthermore, submerged aquatic vegetation (SAV) decline has been observed in many eastern Long Island Sound embayments and is

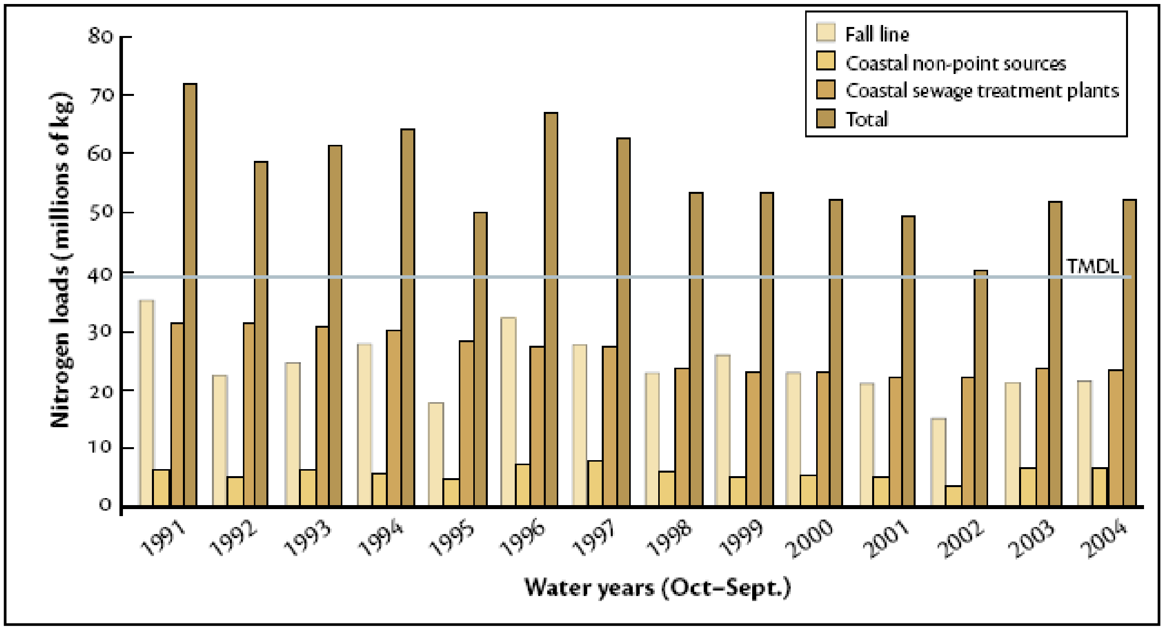

Figure 5. Estimated nitrogen loads to Long Island Sound, 1991-2004 (P. Stacey, CT DEP).

believed to be linked to nitrogen enrichment. Nitrogen reductions to protect SAV will be much more stringent and difficult to attain than for low dissolved oxygen (Stacey 2007).

Science and Management Actions (to date and planned)

Since 1985, the causes and effects of hypoxia have been the subject of intensive monitoring, modeling, and research through the LISS. Through the Long Island Sound partnership, a dissolved oxygen TMDL was completed by Connecticut and New York and approved by U.S. EPA in 2001. Both states have aggressively pursued sewage treatment plant nitrogen control using biological processes, and nitrogen loads are trending downward. New York has relied upon traditional permitting programs to limit individual sewage treatment plants while Connecticut has instituted a statewide nitrogen trading program, called Nitrogen Credit Exchange, for 79 municipal sewage treatment plants (CT DEP 2007). The trading program works as an economic engine, forcing action towards the most cost-effective and environmentally beneficial projects. Collectively, the two states have accomplished a 30% reduction in sewage treatment plant nitrogen loads towards the TMDL target of 60–65% by 2014. The nitrogen trading program has proven to be a viable alternative for improving dissolved oxygen conditions in Long Island Sound and has accelerated the schedule to meet the TMDL wasteload allocation deadline. Potential savings with nitrogen trading are in the $200-400 million range over individual permitting approaches. The Nitrogen Credit Exchange could serve as a working model for incentive-based trading in other states.

Connecticut and New York are also relying on stormwater permitting and nonpoint source programs to meet a 10% reduction target for urban and agricultural lands. However, the nonpoint sources are more difficult and costly to control, especially atmospheric deposition, much of which originates from jurisdictions outside of Connecticut and New York. If attained, promised reductions from Federal Clean Air Act initiatives will help Long Island Sound tremendously. The LISS is also working with Massachusetts, New Hampshire, and Vermont, states that share the Long Island Sound watershed, to ascertain what level of reduction might be achieved in a cost-effective manner by those states.

Future Outlook

Population continues to grow within the already densely populated Long Island Sound basin. This growth contributes to the nitrogen load from sewage treatment plants as well as nonpoint sources. Despite the high land conversion rate since 1985, nitrogen loads have been reduced by some degree, largely through active management of sewage treatment. However, nutrient-related water quality problems have not improved as much as anticipated, in part, because of the high rate of per capita land consumption (sprawl) relative to population growth. As a result, management measures are offset by the increase in nutrient inputs related to population increases. In addition, the effects of climate change appear to have strengthened stratification in the Sound, exacerbating hypoxia.

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Lake Erie

Physical Description of the System

Lake Erie is the shallowest of the Great Lakes with an average depth of 19 meters. It has three identifiable sub-basins: the eastern, central, and western basins. Lake Erie is deepest in the eastern basin and becomes increasingly shallow towards the west. Because it is the shallowest of the Great Lakes, it warms more quickly in the summer and cools more rapidly in the fall. The shallow depth and warm temperatures lead to high productivity. Thermal stratification, caused by warming of the upper layer, occurs throughout the Lake every summer. However, vulnerability to hypoxia is not consistent basin to basin. Eighty percent of the Lake’s water inflow comes from the Detroit River, but most of the nutrient and sediment loading comes from other tributaries, notably the Maumee River. Lake Erie receives the highest sediment loads of all the Great Lakes (Letterhos 2007).

History of Hypoxia (issue, causes, economic and ecosystem impacts)

The central basin of Lake Erie is the most vulnerable to hypoxia because it is sufficiently deep to develop thermal stratification, but the volume of water below the thermocline (or temperature gradient) is small enough that oxygen is depleted quickly. The water below the thermocline is cut off from oxygen in the surface water due to the stratification. The bottom waters in the central basin frequently go hypoxic during late summer through early fall (Charlton 1980, Rosa and Burns 1987). In contrast, the much deeper eastern basin, which also develops thermal stratification, has a much higher water volume below the thermocline, so the oxygen is not depleted before the water column mixes when the cold weather returns in the fall. The shallower western basin experiences stronger wind-driven circulation that prevents stratification, and thus hypoxia, during most summers.

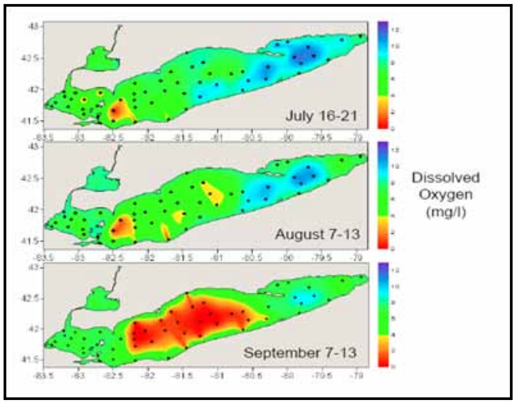

Figure 1. Hypoxia in Lake Erie in 2006. Source: IFYLE Program.

Although late summer hypoxia is a natural phenomena in Lake Erie probably dating back thousands of years (Delorme 1982), evidence suggests that the summer oxygen depletion rates increased during the 1950s and 1960s due to increased phosphorus loadings from point and nonpoint sources. Even the shallower western basin developed hypoxia during low wind periods (Hartman 1972, Leach and Nepszy 1976, Beeton 1963). Concerted phosphorus reduction programs led to improved conditions until late 1990s. However, the extent of bottom water hypoxia has returned to pre-action levels. The cause is much less clear, but likely related to increases in nutrient inputs from nonpoint sources (Richards, Unpublished Data) (Figure 1). Total phosphorous and soluble reactive phosphorous concentrations in the mainstem of the Lake have remained low, but levels in the nearshore areas are rising. Phosphorus, however, may no longer be the limiting nutrient; nitrogen and carbon may be playing greater roles (Letterhos 2007).

The effects of hypoxia on the Lake Erie ecosystem are not entirely clear. Some benthic species, such as burrowing mayflies (an important prey species), disappeared during periods of the most intense hypoxia (i.e., 1950s and 1980s) (Britt 1955, Carr and Hiltunen 1965, Krieger et al.1996). The loss of a thermal refuge due to low oxygen in the cooler bottom waters probably contributed to the decline of several commercially valuable benthic fishes (e.g., lake whitefish and burbot). The arrival of the zebra mussel in the 1980s caused tremendous ecological change and may be contributing to hypoxia. The effect on Lake Erie fisheries is currently an area of active research (see Appendix I, NOAA/GLERL International Field Years on Lake Erie).

Science and Management Actions (to date and planned)

The Great Lakes Water Quality Agreement of 1978 (http://www.epa.gov/glnpo/glwqa/1978/index.html) was a binational agreement between Canada and the United States which set strict limits on phosphorus loadings, a goal which was met in the 1980s (Hawley et al. 2006). The agreement targeted inputs from wastewater treatment plants, limited the use of phosphorus in detergents, and led to development of best management practices to reduce phosphorus from agricultural runoff. By the late 1980s, the goals outlined in the agreement were largely achieved and the incidence and extent of hypoxia significantly decreased (Hawley et al. 2006). However, the severity of hypoxia and levels of phosphorus in the lake began to increase in the 1990's, although the cause is relatively unknown (Hawley et al. 2006).

In 1987 the governments of Canada and the United States also made a commitment, as part of the Great Lakes Water Quality Agreement, to develop a Lakewide Management Plan for the Great Lakes. The Lakewide Management Plan (LaMP) for Lake Erie (http://www.epa.gov/greatlakes/erie.html) is coordinated by Federal, state, and provincial government agencies in the two countries. Under the guidance of these agencies, the LaMP unites a network of stakeholders in actions to restore and protect the Lake Erie ecosystem. The LaMP provides an opportunity to link efforts to work toward the common goal of restoring Lake Erie for future generations.

In 2005, the International Field Years on Lake Erie (IFYLE) was initiated by researchers from the United States and Canada to conduct comprehensive research in the Lake, with an initial focus on hypoxia and harmful algal blooms. The primary objectives of this effort focus on quantifying the spatial extent of hypoxia to enable the development of forecasts as well as to determine the ecological consequences of hypoxia to Lake Erie living resources.

Future Outlook

The IFYLE will hopefully elucidate the most important factors contributing to the increase in hypoxia since the mid-1990s. The impressive international cooperative effort, represented by the Great Lakes Water Quality Agreement, LaMP, and the recently signed Great Lakes Regional Collaboration (http://www.glrc.us/) of 2003, to identify and reduce stressors in Lake Erie and the other Great Lakes improves the chance of reducing hypoxia in the future. Management actions that reduce nutrient loadings in Lake Erie may have positive ramifications for both freshwater harmful algal blooms and hypoxia.

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Chesapeake Bay

Physical Description of the System

The Chesapeake Bay is a drowned river valley that is almost 300 km long with a relatively deep (20-30 m) and narrow (1-4 km) central channel (Kemp et al. 2005) (Figure 1). Broad shallow areas flank this central channel over its entire length (Boicourt et al. 1999), and the mean depth of the estuary is 6.5 m (Kemp et al. 2005). Typically, the Bay is stratified with the surface freshwater isolating the deep and saline channel waters and limiting vertical mixing. Although occasionally strong wind events may cause some vertical exchange, stratification quickly returns due to the north-south salinity gradient (Boicourt 1992). There is a natural tendency for oxygen depletion in the deeper waters of the Bay due to the narrow and deep channel, persistent stratification, wide and shallow (and productive) sills flanking the channel, and a long water residence time (Boicourt 1992).

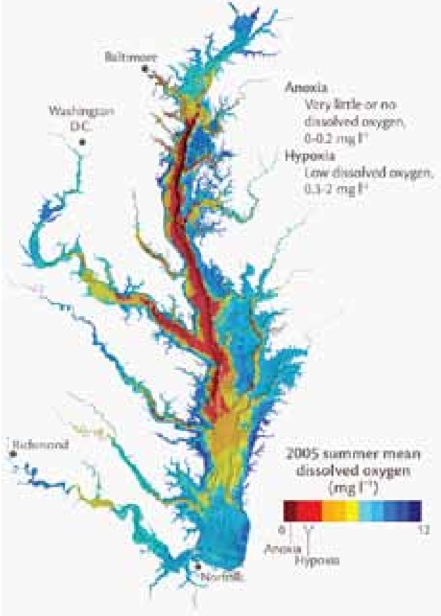

Figure 1. Dissolved oxygen conditions in the Chesapeake Bay in 2005
http://www.chesapeakebay.net/bayforecastspring2006.htm
www.eco-check.org

Relative to other estuaries, the Chesapeake Bay watershed is large (172,000 km^2) compared to the size and volume of the estuary (Bricker et al. 1999). The shoreline is long (18,800 km) and many rivers drain the watershed into the Bay. The largest tributary is the Susquehanna River which accounts for 41% of the watershed. The Bay is closely connected to its watershed which delivers freshwater to the Bay at an average rate of 2,300 m^3/s. Year-to-year fluctuations in river flow result in highly variable inputs of freshwater, nutrients, and sediment. The volume and nutrient composition of these flows influence stratification and productivity in the Bay (Kemp et al. 2005). This watershed is heavily populated, with an average density of 156 people per km^2. In addition to the major population centers surrounding and connecting Baltimore and Annapolis, Maryland; Washington D.C.; and Richmond, Virginia; agriculture is a prominent feature of the watershed's landscape (Bricker et al. 2007).

History of Hypoxia (issue, causes, economic and ecosystem impacts)

A recent assessment of eutrophic conditions in the Bay showed that it is among the most impacted estuaries in the United States. Nitrogen loads are high, and the Bay is susceptible to development of nutrient-related problems (Bricker et al. 2007). Eutrophic symptoms occur periodically or persistently and over extensive areas. These symptoms include high concentrations of chlorophyll-*a*, hypoxia, loss of submerged aquatic vegetation, nuisance and toxic algal blooms, and excessive growth of macroalgae. Throughout the Bay and its tributaries, symptoms have either worsened or not changed between 1999 and present (Bricker et al. 2007) (Figure 2). Primary sources of nutrients include agriculture, wastewater, and urban runoff. Other sources include septic tanks, sewer overflows, and atmospheric deposition. The sources of nutrient inputs and their transport have been described in detail by Boynton et al. (1995) who determined that nitrogen and phosphorus inputs from the watershed and atmosphere increased by six to eight fold and 13 to 24 fold, respectively, between pre-colonial times and the mid-1980s. About onefourth of the nitrogen and one-third of the phosphorus are from point sources, with the rest from nonpoint terrestrial and atmospheric sources (see Chapter 1, Figure 3).

Several seasonally varying factors influence the dynamics of oxygen depletion from bottom-waters of the Bay. The decline in dissolved oxygen in the spring appears to be controlled primarily by physical processes (e.g., stratification). Whereas, the late spring decline and the extent of summer hypoxia appear to be influenced by the level of phytoplankton production and by water temperature (Hagy et al. 2004), both of which influence the respiration rate. On an annual basis, the amount of freshwater inflow is a good predictor of bottom-water oxygen depletion, because it controls water column stratification and, therefore, the rate of oxygen replenishment through vertical mixing. Freshwater runoff also delivers nutrients, which fertilize phytoplankton growth. Year-to-year variations in runoff have also been correlated with production and sedimentation of organic matter (Boynton and Kemp 2000) and increased dissolved oxygen demand.

Evidence from sediment studies in the Chesapeake Bay suggests that hypoxia has increased in occurrence over many decades (Kemp et al. 2005). Geochemical and paleontological methods were used to interpret this indirect ecological history (Brush 1984), and results suggest that eutrophication increased starting in the 17th century, coinciding with settlement by Europeans. Eutrophication accelerated during the 20th century as indicated by a pronounced shift in the ratio of planktonic to, typically, benthic diatoms, reflecting a decline in both water clarity and benthic algal production (Cooper and Brush 1993). Increases in fossil abundance of hypoxia-tolerant species (Karlsen et al. 2000), iron pyrite (Cooper and Brush 1991, 1993), and geochemical changes (Zimmerman and Canuel 2002) provide additional sedimentary evidence for development of hypoxia in the 20th century.

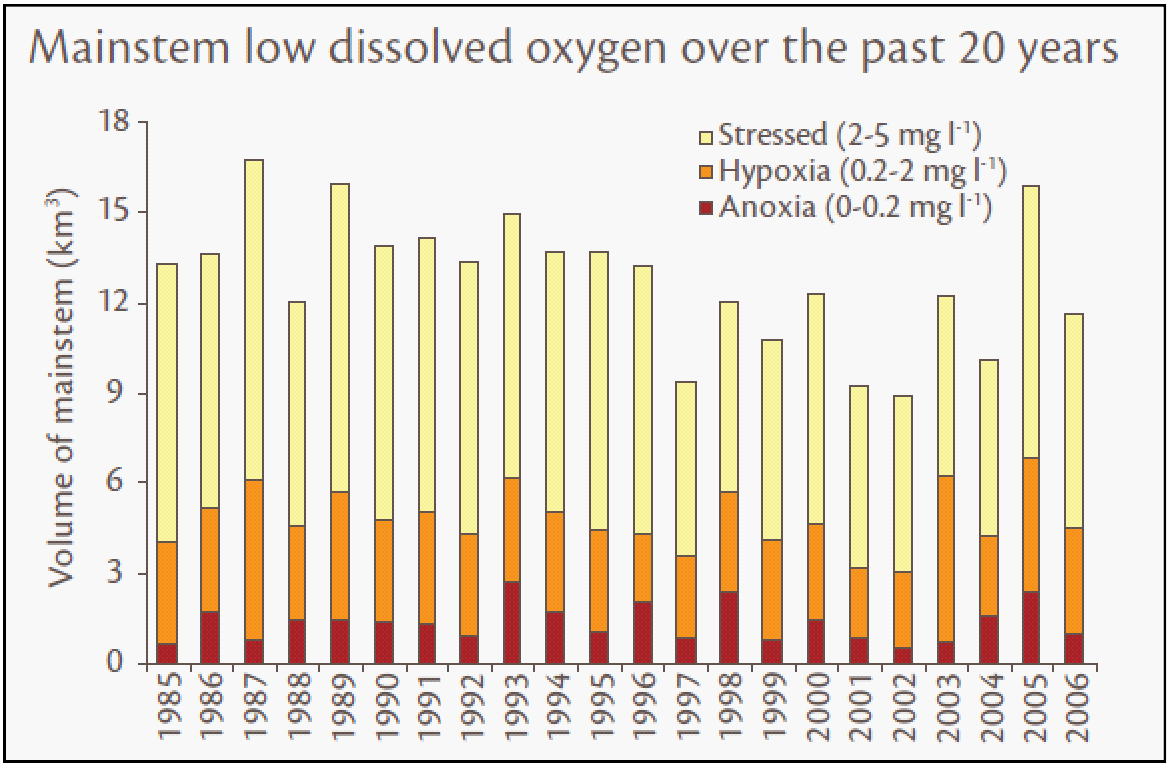

Figure 2. Volume of Chesapeake Bay affected by hypoxia/anoxia by year.
http://www.chesapeakebay.net/bayforecastspring2006.htm
www.eco-check.org

Year-to-year variations in hypoxia extent and intensity are correlated with the amount of nitrogen entering the Bay. The amount of hypoxia generated from a given level of nitrogen loading has, however, been more severe in recent years relative to the past (Hagy et al. 2004). Since the early 1990s, the volume of hypoxic water has increased, while nitrogen loading has leveled or declined (Boesch et al. 2001, Hagy et al. 2004, Langland et al. 2006)). In the mid-1980s, there was a shift in the relationship between hypoxia and nitrogen loading, suggesting that the Bay has passed an ecological threshold and is now more susceptible to eutrophication processes. This shift may have reduced the capacity of natural processes to both oxygenate the water column and trap nutrients in the sediments (Kemp et al. 2005).

Further compounding the effects of eutrophication has been the dramatic loss of oyster beds (currently biomass is approximately 1% of the 19th century levels, Newell 1988). Oysters strongly influence the Bay ecosystems through an ability to assimilate nutrients and rebound from hypoxic events (Kemp et al. 2005). Oysters reduce concentrations of phytoplankton and other suspended particles through filter-feeding, thereby increasing light levels reaching the sediment (e.g., Cohen et al. 1984, Newell and Koch 2004). The loss of oysters has reduced water clarity, which in turn has negatively impacted the growth of vital submerged aquatic vegetation. It has been estimated that at the height of ecosystem health, Bay waters were filtered once every four days, but the depleted filter feeder populations now require more than a year to filter the same volume (Newell 1988).

Although heavy fishing pressure and other stressors in Chesapeake Bay make it difficult to isolate effects of eutrophication on fish, an increased ratio of pelagic (water column-dwelling) to demersal (bottom-dwelling) fish species documented for the Chesapeake Bay (Kemp et al. 2005) is indicative of increased eutrophication. Some of the most noticeable changes were the increase in pelagic Atlantic Menhaden, and the decline in demersal blue crab and oyster landings. This shift from demersal-dominated to pelagic-dominated fisheries has been observed for other coastal systems and is attributed, in part, to bottom-water hypoxia (e.g., Caddy 1993). It is not clear how hypoxia influences the habitat requirements of particular fish and invertebrates, but some species, such as sturgeons, can no longer reproduce or rear young in the Bay due to the lack of habitat with adequate oxygen and temperature levels (Niklitschek 2001, as cited in Kemp et al. 2005).

Whereas impacts to fisheries have been difficult to determine, impacts of hypoxia on benthic animals have been well documented. The diversity, abundance, and productivity of many benthic animals is affected by seasonal hypoxia in the Bay, particularly in deeper water (Holland et al. 1987, Diaz and Rosenberg 1995), and the effective loss of habitat and fauna as a result of hypoxia can have profound effects on ecosystem energetics (Diaz and Rosenberg 2008). Estimates of biomass lost due to hypoxia are approximately 10,000 megatons of carbon per year, or 5% of the Bay's total secondary production. Under healthy circumstances, an estimated 60% of benthic energy would be passed up the food chain in the Bay; therefore, it is estimated that hypoxic conditions in the Bay result in 6,000 megatons of carbon being lost as food energy for fisheries (Diaz and Rosenberg 2008).

Science and Management Actions (to date and planned)

Eutrophication and its influence on hypoxia have been studied extensively in the Chesapeake Bay in an effort to produce information useful for effective management of water quality and critical habitats (Boesch et al. 2001, Kemp et al. 2005). For example, Bay research has demonstrated that nitrogen and phosphorus limitation for phytoplankton growth vary seasonally and regionally (Fisher et al. 1999, Malone et al. 1986), underscoring the need to regulate both nitrogen and phosphorus inputs to the Bay. In addition, studies in this system have shown that nitrogen removal from Chesapeake Bay through denitrification appears to be inhibited compared with estimates for other coastal ecosystems that do not experience seasonal hypoxia (Kemp et al. 1990). The Chesapeake Bay has also been subjected to long-term water quality monitoring, as well as a long-term benthic monitoring program that has been a key metric for assessing progress towards nutrient- and hypoxia-related goals.

Historically, nutrient dynamics within the watershed have received less attention than in the Bay proper (Boesch et al. 2001), but there has recently been an increasing focus on the watershed processes. For example, it is clear that riparian zones, even in urban areas, are 'hotspots' of ecological function and can be effective at sequestering nutrients from runoff (Groffman et al. 2003). However, riparian zones can contribute to nitrogen loading in the Bay watershed when they undergo the "urban stream syndrome" (Groffman et al. 2004), which occurs where impermeable surfaces increase runoff leading to channel incision and lower water tables, thereby reducing denitrification potential in the watershed. This information has contributed to ongoing water quality improvement efforts.

A reduction in eutrophication has been a top priority for management of the Chesapeake Bay in the last few decades (Boesch et al. 2001). Scientific research has improved public awareness and political interest in reversing eutrophication in the Chesapeake Bay (Malone et al. 1993), and a series of policies and adaptive management plans have evolved (Boesch et al. 2001). The Chesapeake Bay became the first estuary in the United States to be targeted by Congress for restoration and protection. An outgrowth of this recognition was the formation of a regional partnership of Bay states, the District of Columbia, and Federal agencies. An agreement to cooperatively work together to protect the Bay was codified in The Chesapeake Bay Agreement of 1983 (http://www.chesapeakebay.net/content/publications/cbp_12512.pdf). This agreement was signed by what would become the Chesapeake Executive Council, a group comprised of the governors of Maryland, Virginia, and Pennsylvania; the mayor of the District of Columbia; the administrator of the EPA; and the chair of the Chesapeake Bay Commission. In support of this agreement and the Chesapeake Bay Program, a Scientific and Technical Advisory Committee was formed to provide the most recent and accurate information. In 1987, a second agreement was signed, pledging to reduce nitrogen and phosphorus inputs into the Bay by 40% by the year 2000. In 1992, amendments were added, reaffirming the original goals of the 1987 agreement, but also pledging the development of tributary-specific strategies to reduce nutrient inputs.

Recognizing a lack of progress towards restoration of the Bay, members of the Chesapeake Bay Program drafted and signed the Chesapeake 2000 Agreement (C2K; http://www.chesapeakebay.net/content/publications/cbp_12081.pdf), which provided comprehensive and specific direction for improving the water quality in the Bay, particularly related to nutrients. Recognizing the need to address Bay water quality within the watershed, the governors of Delaware, New York, and West Virginia entered into an agreement with the Chesapeake Executive Council to meet the goals of the C2K. This agreement was more aggressive than the previous one and called for, based on 1985 levels, a 48% reduction in nitrogen and 53% in phosphorus inputs. In 2003 and 2004, 36 tributary strategies were completed that outlined specific measures for each tributary to reduce the inputs of nutrients into the Bay. A history of Chesapeake Bay eutrophication and the evolution of public policy and awareness are available in Boesch et al. (2001).

Research on nutrient cycling in soil-water systems of the Chesapeake Bay watershed provides fundamental insight into the movement of nutrients in agricultural systems and their impact on water resources. This research has led to the development of models for better predictions of nutrient transport via runoff as well as practical tools, such as the "Phosphorus Index" (adopted by all states in the Bay watershed), to guide nutrient management decisions on agricultural fields. The advent of Comprehensive Nutrient Management Planning has resulted in the development and implementation of best management practices (BMPs) for water and air quality protection. These BMPs range from traditional conservation practices—such as cover crops, riparian buffers, and constructed wetlands—to new technologies for precision application of fertilizers and manures to new practices for controlling and filtering drainage waters. Some of these BMPs can be transferred to nonagricultural uses, and ongoing research promises to deliver another generation of BMPs that immobilize nutrients and sediment.

A recent assessment of water quality trends in rivers feeding the Bay showed significant improvements in loadings of nitrogen (72% of sites showed downward trends), total phosphorus (81% of sites), and sediment (43% of sites), indicating that management actions are having some effect in reducing nutrients and sediments (Langland et al. 2006). However, to date, lower nutrient input has not improved dissolved oxygen levels overall in the Chesapeake Bay, although it has caused small-scale reversals in hypoxia (Diaz and Rosenburg 2008). Clearly, there are complex and poorly understood mechanisms that are acting to delay recovery of some ecosystem components (e.g., seagrass beds), and these mechanisms are priorities for scientific attention. Restoration of seagrass, oyster, and marsh habitats are expected to help the Bay's recovery from eutrophication and hypoxia by priming key ecological processes that will enhance recovery through biological positive-feedback mechanisms (Kemp et al. 2005).

Future Outlook

Small improvements in dissolved oxygen conditions are expected for the mainstem of the Chesapeake Bay, and the outlook for rivers draining into the Bay ranges from slight deterioration to slight improvement (Bricker et al. 2007). This projection is an improvement from the last eutrophication outlook presented in 1999 (Bricker et al. 1999), when the Bay and its tributaries were expected to experience small to large levels of deterioration. These projections are based on the prediction of expected nutrient load increases from wastewater treatment, septic tanks, agriculture, and urban runoff.

Current potential management concerns include increasing nutrient loads from sources such as wastewater treatment, agriculture, urban runoff, atmospheric deposition, on-site septic tanks, and combined sewer overflow, particularly because an increase in population is expected in the watershed. To mitigate these potential problems, Bricker et al. (2007) suggests changes in land use policies that could limit urban sprawl and concentrate development, which could lead to more efficient treatment of runoff and waste.

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Pensacola Bay

Physical Description of the System

The Pensacola Bay system is a network of estuarine bays located in the far western panhandle of Florida. The Bay system is arranged in two major arms that combine to form Pensacola Bay proper. The component bays include Escambia Bay, Blackwater Bay, East Bay, and Pensacola Bay (Figure 1). Santa Rosa Sound is relatively distinct shallow back-bay that joins the lower reach of Pensacola Bay and separates Santa Rosa Island from the mainland eastward to Destin, Florida, and Choctawhatchee Bay, Florida. The combined Pensacola Bay system, excluding Santa Rosa Sound, is medium sized (370 km^2) and shallow (mean depth is 3 m). Tides occur once per day and are relatively small, 15 to 65 centimeters. Three major watersheds drain into the Bay via the Escambia, Blackwater, and Yellow Rivers (Figure 1).

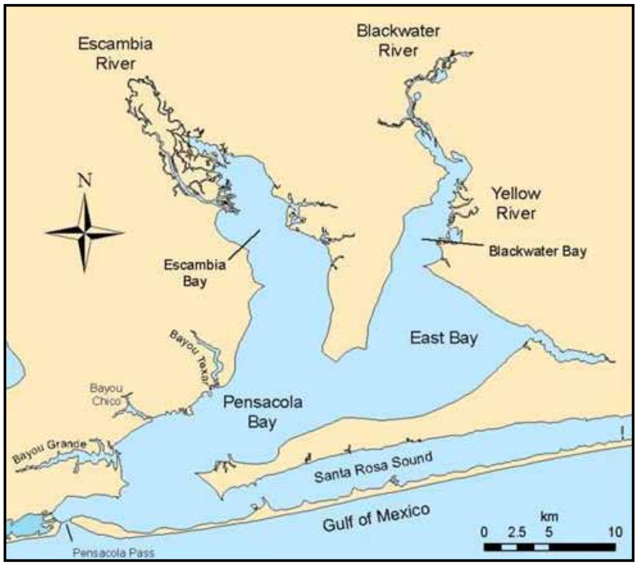

Figure 1. Map of Pensacola Bay, Florida.

History of Hypoxia (issue, causes, economic and ecosystem impacts)

The condition of the Pensacola Bay system, particularly that of Escambia Bay, became a matter of public concern as early as the late 1960s after significant industrial point source discharges began and extensive fish kills and hypoxia were observed (Olinger et al. 1975). The large fish kills prompted actions that ultimately led to elimination of the point source loadings by the mid-1970s. Olinger et al. (1975) provides a remarkable early compilation of ecological conditions in the Bay, intended principally to document the recovery of the system following reductions in industrial waste loads. These reports indicate that hypoxia was present in the Bays in the early 1970s, but does not provide enough data to evaluate the average extent or severity.

EPA monitored the Bay quarterly from 1996-2001 (U.S. EPA 2005) and monthly from 2002-2004 (Hagy and Murrell 2007). Whereas differences in survey methodology and data reporting mostly preclude quantitative analysis of ecological changes since the early 1970s, comparison with the most recent data suggests that neither recovery nor further degradation has occurred. The major ecological concerns of the early 1970s persist today: bottom water hypoxia, loss of seagrass habitats, toxic contamination, and degradation of biotic communities (Hagy et al. 2008).

Hypoxia occurs frequently and extensively in bottom waters of Pensacola Bay (Hagy and Murrell 2007). An average of 25% of the Bay bottom is affected during the summer. Moderate river flow conditions create the highest potential for hypoxia in the Bay. In 2004, nearly 40% of the Bay bottom was hypoxic for two consecutive months (Hagy et al. 2008). Strong winds can bring hypoxic water onto shallow shoals, giving hypoxia the potential to degrade nearly all habitats in the Bay. Hypoxia has not been observed in the lower Bay, south and west of Bayou Texar, where tidal exchange with the Gulf of Mexico appears to be adequate to prevent hypoxia.

The causes of hypoxia in Pensacola Bay include strong salinity stratification, low tidal mixing energy, and sluggish estuarine circulation, which create an optimal physical environment for hypoxia (Hagy and Murrell 2007). On the other hand, water clarity in the Bay is often relatively high, chlorophyll-*a* concentrations are low to moderate, and phytoplankton production is moderate (Murrell et al. 2007). Correspondingly, rates of oxygen consumption in the water and sediments are relatively low (Murrell et al. 2009). These reflect low to moderate rates of nutrient loading, which can be related to low population density and minimal nutrient-intensive uses of much of the watershed (Hagy et al. 2008). The simultaneously low level of anthropogenic nutrient enrichment and eutrophication and high degree of hypoxia and seagrass loss suggests that the Bay has not been able to recover from earlier impacts.

The impact of hypoxia on biological communities in Pensacola Bay has not been well documented, but one can infer from the extent, frequency, and severity of hypoxia that affected habitats are almost certainly in a poor ecological condition. Limited data from the Florida Inshore Monitoring and Assessment Program show that the numbers of benthic macrofauna in Pensacola Bay in 2003 were only 5 to 10% of numbers in healthier regions of the Florida west coast. Livingston (1999) found that substantial biomass of infaunal animals occurred in only a narrow zone around the perimeter of the Bay, beyond the reach of persistent hypoxia. It has also been shown that chronic exposure to hypoxia imposed physiological stress on fish in Pensacola Bay, preventing them from reproducing (Thomas et al. 2007). Although the massive seagrass loss in Pensacola Bay has not been linked directly to hypoxia, it could reduce the abundance of animals that graze on algae growing on seagrasses, thus inhibiting their recovery. For example, grass shrimp enhanced growth of *Ruppia maritima*, a seagrass that was once abundant in Pensacola Bay (McCall and Rakocinski 2007). Conceivably, the massive loss of seagrasses that has occurred and the extensive recurrent hypoxia could be mutually reinforcing, promoting persistence of these conditions despite currently unremarkable rates of nutrient loading.

Science and Management Actions (to date and planned)

The record of scientific research addressing water quality and ecological condition in Pensacola Bay began in earnest with the Olinger et al. (1975) studies. These studies documented many of the key features of the ecology of the Bay, including the incidence of hypoxia and some of its physical causes. Papers by EPA scientists, mostly since 2000, provide more detail on many aspects of the physical and biological conditions that control hypoxia in the Bay (see Hagy et al. 2008). EPA will continue studies of Pensacola Bay as part of a regional research program in the northeast Gulf of Mexico. The project will focus on providing data and methods to develop numeric water quality criteria for nutrients and nutrient-related water quality parameters.

Because Pensacola Bay is a relatively small estuary, no management programs have been created specifically to manage and improve its water quality (e.g., such as those created for Chesapeake Bay or the Gulf of Mexico). Florida's Impaired Waters Rule provides some numeric guidelines for listing estuaries as impaired for chlorophyll-*a* and dissolved oxygen, but there are no enforceable water quality standards for nutrients or dissolved oxygen for the Bay.

On the other hand, the state of Florida has recently increased its focus on developing water quality criteria for nutrients in its estuaries and coastal waters. Portions of Escambia Bay have been listed as impaired for an excessive increase in chlorophyll-*a*. Establishing levels for total maximum daily loads has been proposed and would call for significant reductions in both nitrogen and phosphorus loading to upper Escambia Bay. These actions signal an increase in regulatory attention to nutrients in Pensacola Bay. A continuation of scientific research by EPA and others could provide an improved scientific basis for these actions. Presently, the best hope for improved management of water quality in the Bay seems to be the likely prospect that the State of Florida will soon develop and adopt numeric nutrient criteria for

Pensacola Bay. EPA is collaborating with the Florida Department of Environmental Protection to support its efforts to achieve this objective for Pensacola Bay and other estuaries in Florida.

Future Outlook

The relatively undeveloped status of a large portion of the watershed of Pensacola Bay is one of its best assets. Arguably, low population density in the watershed has prevented eutrophication and hypoxia from becoming much worse. However, the population of the coastal counties surrounding the Bay, especially Santa Rosa County, Florida, is projected to grow nearly 3.5-fold by 2060 (Zwick and Carr 2006), most likely increasing nutrient loading to this sensitive system. A regulatory approach utilizing the authority of the Clean Water Act and based on numeric nutrient criteria will be the best way of ensuring that this growth occurs in a manner that does not further degrade the Bay. Although the available research clearly indicates that increased nutrients could harm water quality in the Bay, it is less clear that nutrient reductions alone will be sufficient to restore the Bay. A more active restoration program may be needed. Research is needed to determine the best methods for restoring ecological function in the Bay in order to simultaneously increase the extent of seagrass habitats, reduce hypoxia, and promote better biological condition overall.

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Northern Gulf of Mexico

Physical Description of the System

The largest zone of oxygen-depleted coastal waters in the United States and arguably the second largest on Earth is in the northern Gulf of Mexico on the Louisiana continental shelf (Figure 1). The Gulf hypoxic zone typically occurs in waters 5-60 m in depth up to 125 km offshore from west of the Mississippi River Delta and occasionally extending to the upper Texas coast.

The dominant sources of freshwater, sediments, and nutrients to the northern Gulf of Mexico are the Mississippi and Atchafalaya Rivers. The watershed for these rivers (commonly referred to as the Mississippi Atchafalaya River Basin ,or MARB) encompasses 41% of the contiguous United States (Figure 2). The average annual streamflow delivered from the MARB to the Gulf of Mexico during the period from 1981 to 2005 was 21,700 cubic meters per second (m^3/s); the average annual flux of total nitrogen and total phosphorus during that period was 1.47 and 0.14 million metric tons, respectively (Aulenbach et al. 2007). Streamflow from the MARB enters the Gulf of Mexico through two deltas—about two thirds of the flow enters via the Mississippi River Birdfoot Delta (southeast of New Orleans, Louisiana), and one third via the Atchafalaya River Delta (200 km west on the central Louisiana coast). The freshwater discharge is carried predominantly westward along the Louisiana/Texas inner to mid-continental shelf, especially during peak spring discharge. This coastal ocean margin is characterized as a relatively shallow, open coastline with complex circulation patterns, weak tidal energies, generally high water temperatures, seasonally varying stratification strength, and large inputs of freshwater that effectively result in an unbounded estuary, stratified for much of the year. Water column density stratification, which is critical to bottom water oxygen depletion, is dominated by vertical salinity gradients, but thermal warming of surface waters intensifies summer stratification strength. Water column structure is also highly influenced by wind stress, frontal weather bands, hurricanes, and mixing of buoyant river plumes.

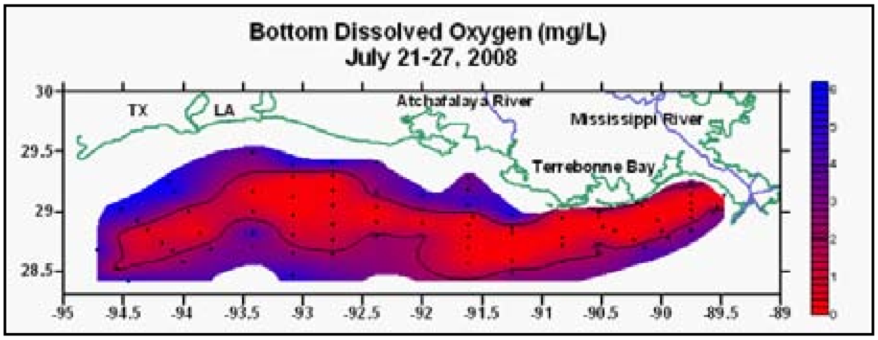

Figure 1. Map of bottom water oxygen levels in mg/L. Black line is less then 2 mg/L (hypoxic).
Data source: N. Rabalais, Louisiana Universities Marine Consortium, NOAA, map by B. Babin.

History of Hypoxia (issue, causes, economic and ecosystem impacts)

Extensive bottom water hypoxia forms each year between May and September. Since 1985 (when systematic mapping was started), the hypoxic area has averaged 13,808 km^2 and achieved its maximum size in 2002 at 22,000 km^2 (Figure 3). While low dissolved oxygen is commonly considered a bottom-water condition, oxygen-depleted waters often extend up into the lower half to two-thirds of the water column. Long-term increases in nutrient loads from the MARB, coupled with water column stratification, have been implicated as the primary causes of hypoxia (CENR 2000, U.S. EPA 2007). However, the complex physical, chemical, and biological processes along the coastal ocean margin—which consume, transform, and remineralize riverine nutrients and organic matter and ultimately result in bottom water oxygen depletion—remain poorly resolved in space and time.

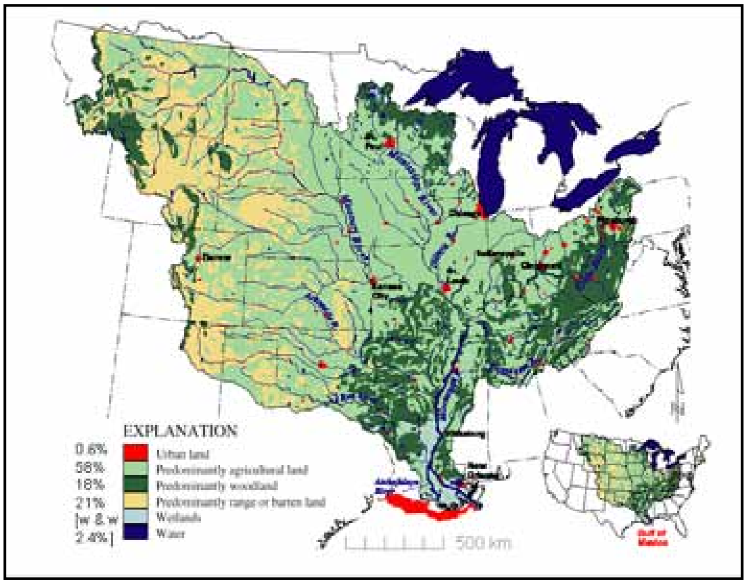

Figure 2 Mississippi River Watershed with Dead Zone shown in Red (modified from Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2004).

The nutrients delivered with freshwater inputs support primary productivity within the immediate vicinity of the river discharges as well as across the broader continental shelf. The settling of fixed carbon to the lower water column and seabed in the form of senescent phytoplankton, zooplankton fecal pellets, or aggregates provides a large carbon source for decomposition by aerobic bacteria, which in turn leads to hypoxia. Tropical storms, hurricanes, and cold front passages disrupt the hypoxia until stratification reestablishes and oxygen depletion processes continue.

Low oxygen events on the Louisiana-Texas continental shelf have been reconstructed over the past centuries using the relative abundance of low oxygen tolerant benthic foraminifera in sediment cores (Osterman et al. 2005). These records show that low oxygen events have increased over the past 50 years. Additionally, regression model hindcasts using historical Mississippi River discharge and nitrate concentrations indicated that large-scale hypoxia has likely been present along the continental shelf since the mid-1950s (Greene et al. 2009). More recently, the areal extent of the hypoxic zone increased from an average of 6,900 km^2 during 1985-1992 to 17,100 km^2 during 2004-2008 (Rabalais and Turner 2006, LUMCON 2008) (Figure 3).

The increased prevalence of Gulf hypoxia over recent decades has been related to increases in nutrient loads (CENR 2000, U.S. EPA 2007). However, it has been demonstrated that hypoxia events have occurred for centuries driven by high streamflow events that flush nutrients from wetland ecosystems and stratify ocean waters (Osterman et al. 2005, Swarzenski et al. 2008). Alterations of the Mississippi and Atchafalaya Rivers for transportation and flood control over two centuries have significantly lessened the assimilation of nutrients in the watershed and changed the pattern of freshwater discharge to the coastal ocean margin (U.S. EPA 2007). Concurrent increases in anthropogenic inputs of nutrients to the watershed have contributed to increased eutrophication and hypoxia (from Bricker et al. 1998, Rabalais in Bricker et al. 2007).

The region supports some of the most valuable commercial and recreational fisheries in the United States (Diaz and Solow 1999, Chesney et al. 2000, Zimmerman and Nance 2001). For example, Texas and Louisiana lead all states in catches of shrimp, which is the largest U.S. commercial fishery (NOAA 2007). However, partitioning the impacts of hypoxia on living resources from other ecosystem stressors (e.g., climate change and overfishing) has proven difficult and significant knowledge gaps remain. Fish kills are occasionally reported and significant impacts to benthic fauna have been well documented (e.g., Rabalais et al. 2001). Zimmerman and Nance (2001) suggest that severe hypoxic conditions may block the migration of shrimp from nearshore to offshore habitats. Additionally, brown shrimp are subjected to a significant amount of habitat loss due to hypoxia (Craig et al. 2005), congregating in suboptimal environments along the hypoxic zone edge, possibly causing a reduction in growth (Craig and Crowder 2005). Recent advancements in biomarker techniques have suggested that hypoxia may be causing reproductive impacts in croaker as well (Thomas et al. 2007).

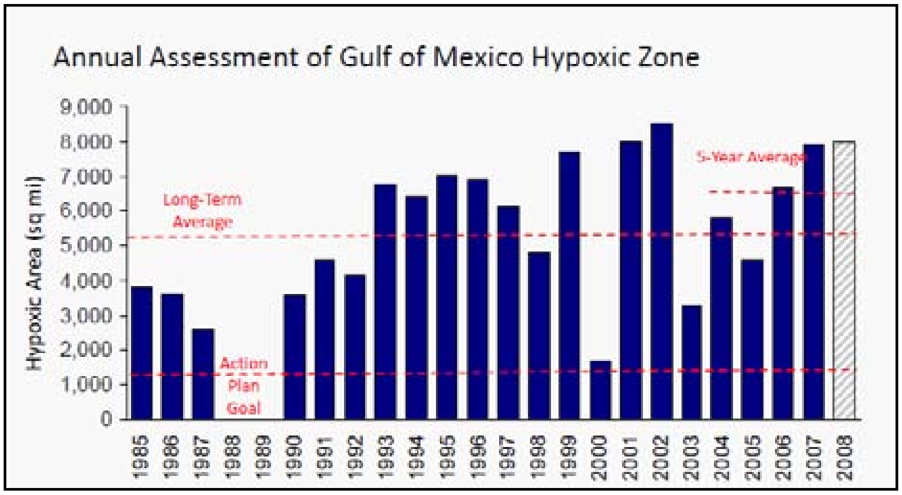

Figure 3. Northern Gulf of Mexico hypoxic area by year, including 5 year running and long-term averages. Action Plan Goal is 5000 km^2.

Science and Management Actions (to date and planned)

In 1998, the EPA established the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. The Task Force brought together Federal agencies, states, and tribes to consider options for reducing, mitigating, and controlling hypoxia in the northern Gulf of Mexico. In 1999 and 2000, the results of an integrated science assessment, requested by the Task Force and conducted under the auspices of the National Science and Technology Council, was published (CENR 2000, Brezonik et al. 1999, Diaz and Solow 1999, Doering et al. 1999, Goolsby et al. 1999, Mitsch et al. 1999, and Rabalais et al. 1999) (http://oceanservice.noaa.gov/products/pubs_hypox.html). Using this science assessment, the Task Force published its first "Action Plan", entitled *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico* (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2001), which was endorsed by Federal agencies, states, and tribal governments. The 2001 Action Plan coastal goal was to reduce the five-year running average size of the hypoxic zone to 5,000 km^2 by 2015 (Figure 3). It estimated that an overall reduction in nitrogen load of 30–45% would be required. The 2008 Plan identifies the requirement that phosphorus as well as nitrogen loads be reduced and increases the required reduction to at least 45%. The 2008 Plan also notes that reductions in nitrogen loads from 2001-2005 were from nitrogen forms other than nitrate, which is the primary form fueling spring primary production that leads to hypoxia. The Action Plan was based on a series of voluntary and incentive-based activities that address both reducing nutrient inputs and increasing assimilation in aquatic ecosystems, including proper timing and amount of fertilizer applications, best management practices on agricultural lands, restoration and creation of wetlands, river hydrology remediation, riparian buffer strips, nutrient removal from stormwater and wastewater, and coastal diversions.

In 2007, an updated science assessment was conducted by the EPA Science Advisory Board under the oversight of the Task Force (U.S. EPA 2007). This update science assessment was used by the Task Force to develop the *Gulf Hypoxia Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico and Improving Water Quality in the Mississippi River Basin* (Mississippi River/ Gulf of Mexico Watershed Nutrient Task Force 2008) (see Box 4 in Chapter 2). This plan retains the coastal goal of reducing the hypoxic zone to less than 5,000 km^2 by 2015, but understands the difficulty of meeting the goal. In this regard, the Task Force accepts the advice of the EPA Science Advisory Board on this issue: "The 5,000 km^2 target remains a reasonable endpoint for continued use in an adaptive management context; however, it may no longer be possible to achieve this goal by 2015… it is even more important to proceed in a directionally correct fashion to manage factors affecting hypoxia than to wait for greater precision in setting the goal for the size of the zone. Much can be learned by implementing management plans, documenting practices, and measuring their effects with appropriate monitoring programs" (U.S. EPA 2007). The 2008 Action Plan, also like the 2001 Action Plan, calls for a reassessment after five years. The next reassessment will be conducted in 2013.

Future Outlook

Although overall total annual nutrient loads to the northern Gulf from 2001–2005 suggests a decline in nitrogen inputs relative to the previous 24-year average (Mississippi River/Gulf of Mexico Watershed Nutrient Task Force 2008), reductions in nitrate during the critical spring period have not occurred. Further, the five-year running average (2004–2008) of the hypoxic zone is 17,071 km^2, is more than three times the Action Plan goal of 5,000 km^2. The adaptive management approach put forth in the Action Plans of 2008 and 2001 commits to a reliance on sound science and continual feedback between the interpretation of new information and improved management actions as the key to targeting actions within watersheds where they will be most effective. Significant variability in nutrient export rates, hypoxic zone size, and other parameters resulting from anthropogenic and/or climate change will make it difficult to assess the outcome of nutrient management actions. However, targeted monitoring on representative watersheds, continued monitoring of streamflow and nutrient flux, and research that addresses biogeochemical processes and improved model application will provide the most effective means of measuring results and providing feedback on performance.

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Northeast Pacific Continental Shelf (Oregon/Washington)

Physical Description of the System

The Oregon and Washington Shelf out to 200 meters water depth encompasses approximately 26,600 square kilometers (km^2) and has an average width of approximately 40 km. Generally, the shelf narrows from north to south, with a shelf width of more than 60 km off Washington and less than 20 km along southern Oregon. The exception to this general trend is a region called Heceta Bank in the central region of Oregon (43.8° to 44.6° N) which extends out to 65 km.

The shelf is part of the Northern California Current system. This system has strong seasonal variability, with northerly (from the north) winds dominating from April to October, and southerly winds dominating through the winter. The strong northerly winds induce coastal upwelling which brings nutrient-rich, low-oxygen waters onto the shelf (Figure 1).

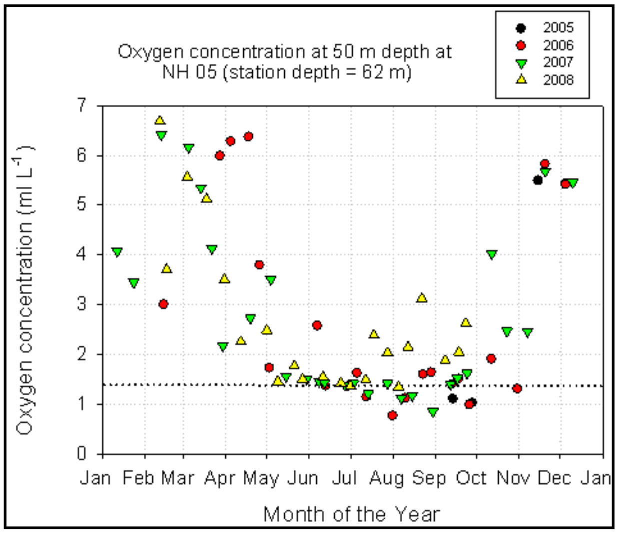

Figure 1. Seasonal change in bottom water oxygen concentration at a station 5 miles from shore off Newport, OR. The horizontal line at 1.4 ml/L represents hypoxic waters. Note that hypoxic waters appear only during the upwelling season (May-October). Source: Bill Peterson, NOAA NWFSC.

The major source of terrestrial input to the system is from the Columbia River, with an annual mean outflow of 6484 cubic meters per second (m^3/s, 15 year mean from 1992 – 2006). River outflow tends to be low during the summer growing season and the input of nutrients from the river is negligible compared to contributions from upwelled waters (Hickey and Banas 2003). Thus, hypoxia off Washington and Oregon is unique in that it is due to natural sources rather than anthropogenic sources.

Economically, upwelling-induced productivity in Oregon-Washington Shelf waters supports a $50 million fishery for dungeness crabs. This is a pot fishery, so crabs trapped in the pot fishing gear are killed during summertime hypoxic events. The value of the salmon fishery is on the order of $10-20 million; however, the impact of hypoxia on the landings of the crabs and salmon has not yet been evaluated economically.

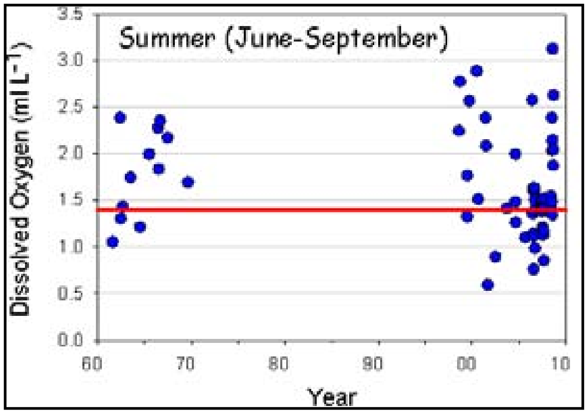

Figure 2. Oxygen concentration (ml/L) within 10m of the bottom at a station 5 miles offshore of Newport, OR. The thick, red line indicates hypoxic waters (1.4 ml/L). Although hypoxia was observed in the 1960s, it has been observed more frequently in this century. Source: Bill Peterson, NOAA NWFSC.

History of Hypoxia (issue, causes, economic and ecosystem impacts)

Evidence of hypoxia on the Oregon-Washington continental shelf indicates that it is a seasonal occurrence (Figure 1) that has been present since at least the 1960s (Figure 2). However, there has not been a consistent sampling program developed to assess the degree and magnitude of hypoxia over time (note the lack of any data between 1970 and 1998 in Figure 2). Data have been collected three to four times per year since 1998 during broad-scale surveys of zooplankton and salmon and biweekly since late 2005 (Figure 1).

Cross-shelf transects (Figure 3) show that the hypoxic bottom waters can extend at least 20 to 30 meters off the bottom and occupy up to 30% of the water column. Low oxygen water moves onto the shelf in early spring (April or May) during the onset of upwelling. Throughout the summer, the oxygen level of bottom waters is reduced through the biological degradation of organic matter.

Wider regions of the shelf, where circulation patterns retain water for longer periods of time, tend to have more persistent and severe oxygen depletion (Figure 4). In September 2007, 8,600 km^2 of the shelf had hypoxic bottom waters, covering 63% of the shelf area surveyed (Figure 4). This makes the Oregon-Washington shelf the second largest hypoxic region in the continental United States, second only to the Gulf of Mexico (which averages roughly 14,000 km^2).

Severe hypoxia events were observed in 2002 (Grantham et al. 2004) and 2006 (Chan et al. 2008). From these events, it is clear that in some areas, such as Heceta Bank (just south of Newport), oxygen concentrations fall to very low values and can persist through much of the summer, ultimately killing or displacing nearly all of the bottom-dwelling organisms. Recent work on the impacts of hypoxic waters on the development of copepods indicate that oxygen concentrations below 1 ml/L (or 1.43 mg/L) greatly reduces the hatching rate of copepod eggs (Peterson unpublished). In instances where copepods are not able to move out of hypoxic zones, the reduced hatching rate may also be accompanied by reduced egg production (Marcus 2001, Sedlacek and Marcus 2005), severely impacting recruitment of species critical to the food web of many commercially important fish species.

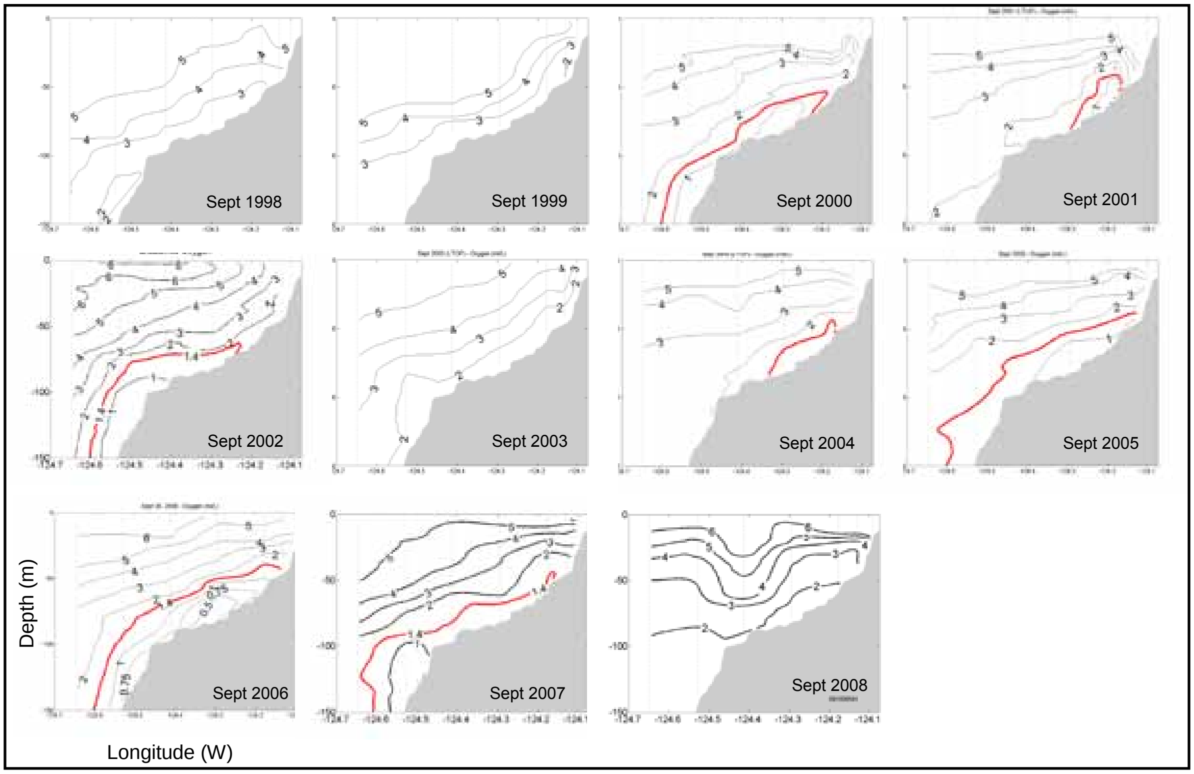

Figure 3. Oxygen concentration along a 46 km (25 mile) transect across the Oregon shelf (NH Line off Newport, Oregon). The thick, red contour indicates the region of hypoxia (1.4 ml/L). The gray shaded area is the bottom bathymetry. Source: Jay Peterson, NOAA/OSU CIMRS.

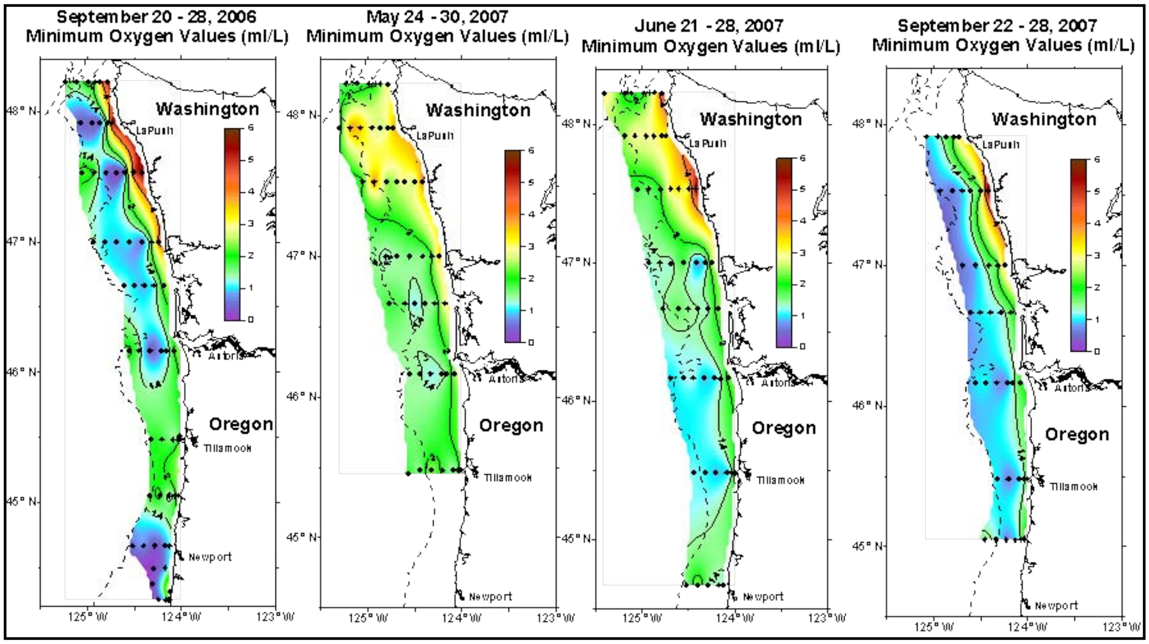

Figure 4. Distribution and extent of hypoxic waters (bold 1.4 ml/L contour) along the Oregon-Washington shelf. Shown is the minimum oxygen value regardless of the depth it occurred (but the minimum values was almost always at the deepest sampling). Panels show the extent in September 2006 (far left), and the seasonal progression during 2007 (May, June and Sept). The dashed line along the coast represents the 200 m isobath. Data Source: Cheryl Morgan (OSU and CIMRS) and Bill Peterson (NOAA NWFSC), project supported by Bonneville Power Administration.

The cause of the hypoxia is driven primarily by an interaction between circulation and biological activity. The typical upwelling season extends from April to October. During this time, periods of strong winds from the north bring nutrient-rich, low-oxygen waters onto the shelf. The nutrient-rich waters are mixed into the surface layer and fuel a highly productive planktonic food chain. However, vertical transport of fecal pellets of grazers and sinking of nutrient-depleted phytoplankton blooms results in the degradation of massive amounts of organic matter on the sea floor. Depending on the vertical flux and on the retention time of the water mass, the oxygen consumption can rapidly lead to hypoxic and even anoxic conditions.

Science and Management Actions (to date and planned)

To date, no specific scientific programs have been established to monitor the status of hypoxic zones along the Oregon-Washington shelf. The development of hypoxic regions along the coast is primarily driven by naturally occurring physical and biological processes. Changes in the amount of nutrients upwelled to surface waters, water temperatures, and retention of water masses on the shelf likely contribute to the persistence, size, and severity of hypoxic zones. The low oxygen zones have been shown to greatly impact bottom-dwelling fishes, shellfish, and other organisms inhabiting the shallow banks (i.e., Heceta Bank).

Future Outlook

A coordinated research and monitoring effort aimed at informing resource managers is needed. The combination of increased awareness of the spatial extent of hypoxia, its impact on the shelf ecosystem, and the availability of instruments that can easily be integrated into current scientific programs will provide additional data on the timing and extent of hypoxia along the Oregon-Washington shelf. This improved understanding may also lead to an ability to forecast the extent and severity of low dissolved oxygen along the shelf which could be a useful tool for fishery managers.

Research programs—such as those carried out through the Pacific Coastal Ocean Observing System (NOAA), the Partnership for Interdisciplinary Studies of Coastal Oceans (Oregon State University, et al.), the Oregon Coastal Ocean Observing System (Oregon State University), the Olympic Coast National Marine Sanctuary (NOAA/National Marine Sanctuaries), and the Bonneville Power Administration (Oregon State University, NOAA)—collect hydrographic data, including dissolved oxygen, physical, and biological data along the Oregon-Washington shelf. Combined with regional and broad-scale hydrographic data, it will be possible to gain a better understanding of the potential mechanisms driving the variability of the hypoxic zone. Understanding how natural versus anthropogenically induced changes in climate influence the spatial extent and severity of hypoxic zones along the shelf requires consistent, long-term observations across the entire region of interest.

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Yaquina Bay

Physical Description of the System

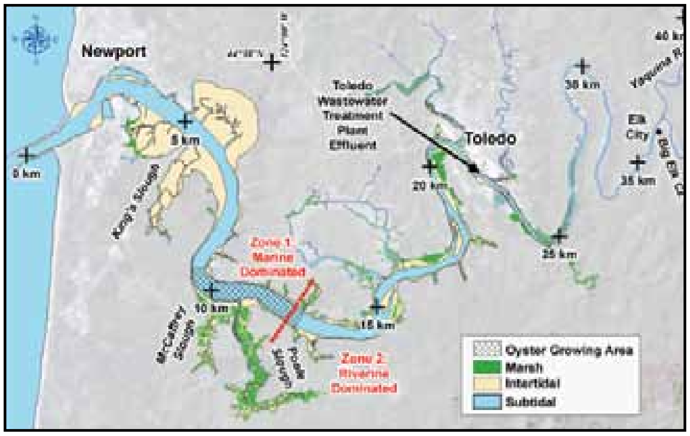

Figure 1. Location map of Yaquina Estuary in Oregon. The estuary is divided into "marine dominated" (Zone 1) and "riverine dominated" (Zone 2) segments (Lee et al. 2006) based on the relative proportion of oceanic-derived nutrients versus terrestrially derived nutrients (from Brown et al. 2007).

Yaquina Estuary is a small, drowned, river valley estuary located along the central Oregon coast of the United States (Figure 1) with an estuarine surface area of 19 square kilometers (km^2) and a watershed area of 650 km^2 (Lee et al. 2006). Approximately 48% of the estuarine area is intertidal. November through April (wet season) is a period of high precipitation along the Oregon coast when the estuary is river dominated. From May through October (dry season) the estuary switches from riverine to marine dominance and a saltwedge extends fairly far upriver. Two tributaries, the Yaquina River and Big Elk Creek, with similarly sized drainage areas, contribute approximately equally to the long-term median freshwater inflow of 7.5 cubic meters per second (m^3/s). The estuary is well mixed under low flow conditions, and partially- to well-mixed during winter high inflow conditions. Tides are semidiurnal with a mean tidal range of approximately 1.9 m (Shirzad et al. 1989). The estuary is divided into two zones, one of which is dominated by ocean input (Zone 1) and the other which is more influenced by watershed and point source inputs (Zone 2).

Due to the small volume of the estuary and the strong tidal forcing, there is close coupling between the estuary and the coastal ocean. Approximately 70% of the volume of the estuary is exchanged with the coastal ocean during each tidal cycle (from Brown et al. 2007, Bricker et al. 1998). Like other estuaries in the Pacific Northwest that are adjacent to the California Current System, Yaquina Estuary is influenced by seasonal wind-driven upwelling which moves relatively cool, nutrient-rich water into the estuary during April through September.

History of Hypoxia (issue, causes, economic and ecosystem impacts)

The Yaquina watershed is heavily forested with deciduous, evergreen, and shrub land-use classes constituting 85% of the watershed (Lee et al. 2006, based on NOAA 2001 Coastal Change Analysis Program data). Although primarily forested and showing little "urban footprint," the watershed has been impacted by a variety of disturbances, including logging which began in the mid-1800s and continues to the present. In addition to the direct effects of logging on erosion and water quality, rafting of logs can also affect aquatic habitats by physical disturbance, alteration of flow regimes, and accumulation of wood and bark debris and sawdust which can smother the benthos and result in low dissolved oxygen and/or elevated hydrogen sulfide (Sedell et al. 1991). There are three other nutrient sources influencing low dissolved oxygen in the Yaquina Estuary: sewage from municipal discharges, industrial discharges, and nonpoint sewage inputs specifically from septic systems. The Yaquina Estuary watershed contains the cities of Toledo and Newport; however, only the "Bay Front" of Newport lies within the watershed boundaries.

Although the recent *National Estuarine Eutrophication Assessment* (Bricker et al. 2007) reports that Yaquina has only low level problems with dissolved oxygen, there are strong seasonal patterns within the estuary (Figure 2). Oxygen levels in the estuary are comparatively stable during the wet season, but show a decline during the dry season. The wet season dissolved oxygen values have an overall mean of 9.7 mg/L, which is well above the threshold considered to be hypoxic, indicating no significant problems. The dry season data show a decline to an overall mean value of 5.8 mg/L but it increases again to wet season values. Zone 1 (marine-dominated) and Zone 2 (riverine-dominated) follow the same pattern, but Zone 2 appears to have the lower values overall. The lowest values during the dry season are approaching hypoxic conditions (< 2 mg/L). However, even during the dry season, most values are above the threshold considered to be hypoxic, indicating minimal problems with dissolved oxygen in this system.

During 1960–1984, there was a noted improvement in dissolved oxygen concentrations in Zone 2 (riverine-dominated), but it is not clear if the cause of the observed trend was from the decrease in logging or the improved sewage treatment. Recent (2002-2006) dissolved oxygen levels in Zone 2 are similar to dissolved oxygen levels during the mid-1980s, suggesting that there have been no recent changes in dissolved oxygen levels.

Since 2002, there has been an increase in the incidence of hypoxic events on the Oregon shelf (Grantham et al. 2004) that have the potential to influence dissolved oxygen levels within the estuary, especially during periods of low oxygen water upwelling (and particularly in Zone 1). Data collected 3.7 km from the mouth of the estuary show that hypoxic shelf water is imported into Yaquina Estuary during flood tides. A time series of dissolved oxygen and salinity data measured during July 9-19, 2002,

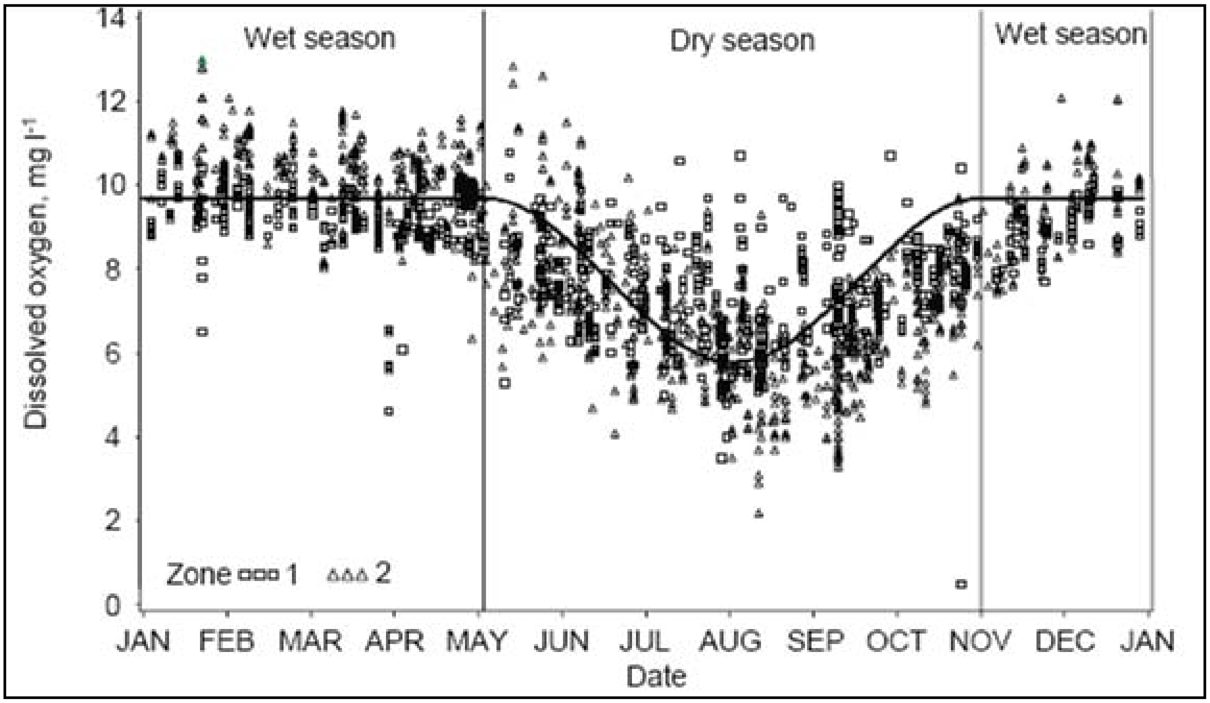

Figure 2. Seasonal pattern (1960-1984) of dissolved oxygen at all locations in the Yaquina Estuary and River with squares and triangles representing samples from Zones 1 (oceanic dominated) and 2 (river dominated), respectively. Solid line is nonlinear least-squares fit to data, which was modeled as a constant during wet season and a cosine function of date during the dry season (n = 869; from Brown et al. 2007).

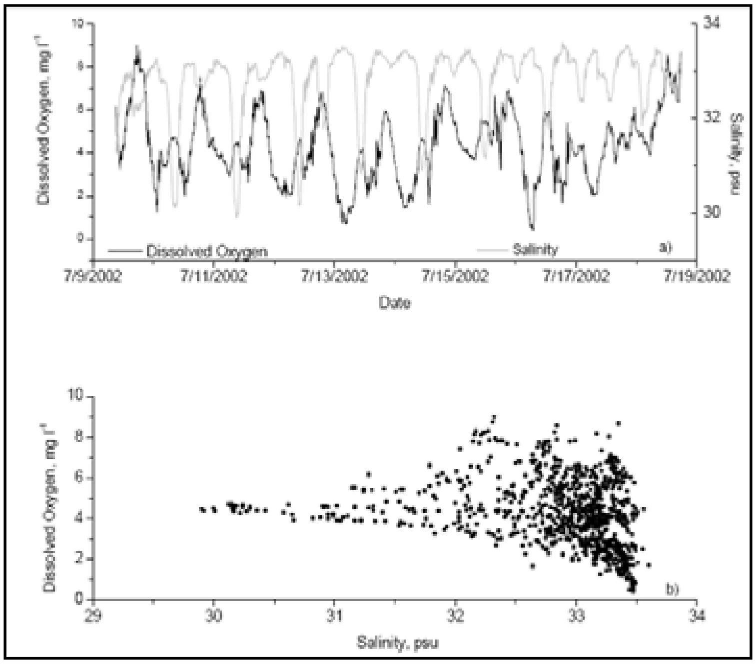

Figure 3. a) Time-series of dissolved oxygen and salinity and b) salinity versus dissolved oxygen showing import of hypoxic ocean water at a station 3.7 km from mouth of estuary (from Brown et al. 2007).

coinciding with a documented hypoxic event on the Oregon shelf off of Newport, Oregon (Grantham et al. 2004), shows the import of hypoxic shelf water into the estuary (Figure 3a). Minimum dissolved oxygen levels occurred during maximum salinities, coincident with flooding tides. In addition, minimum dissolved oxygen levels occur during minimum water temperatures (~ 9 degrees C), which is indicative of recently upwelled water.

These results show that, like other Pacific Coast estuaries, dissolved oxygen conditions in the lower portion of the estuary are strongly influenced by ocean conditions due to close coupling between the shelf and the estuary resulting from strong tidal forcing and upwelling during the wet season. Although this has been reported with increasing frequency recently, it is not a new phenomenon. A study of the Yaquina Estuary attributed low dissolved oxygen concentrations (5 mg/L) in the lower estuary to coastal upwelling during July 1968 (Gibson 1974).

Science and Management Actions (to date and planned)

In response to observed problems with sewage in the early 1900s, a combined stormwater/sewage system that discharged raw sewage into the Yaquina River was constructed in Toledo in 1926, and then upgraded in 1954 to a primary treatment facility to handle the municipal waste from the city of Toledo. This facility, which discharges into the Yaquina Estuary (about 22 km from the mouth of the estuary), was upgraded to secondary treatment in 1981. In the late 1980s and early 1990s, the city of Toledo made improvements to their stormwater collection system, reducing the bypassing of the treatment plant during high flow periods. In 1996, the Toledo plant had a discharge of 0.979 million gallons per day with a design capacity of 3.5 million gallons per day (www.epa.gov/OW-OWM.html/mtb/cwns/1996report2/or.htm).

In addition to the Toledo municipal discharge, a number of houses along the Yaquina Estuary and River have on-site septic systems, some which were previously failing. The primary environmental impact of these septic systems appears to be microbial contamination and they have all been repaired. A combined sewage discharge with a pump station was constructed for Newport in the mid-1950s, which eliminated the direct discharge of sewage from Newport into Yaquina Estuary (Brown et al. 2007). A municipal sewage system with primary treatment and an offshore discharge was constructed in Newport in 1964, which has since been upgraded to secondary treatment.

Addressing issues associated with ocean input of nutrients and the seasonal shift in dominance of riverine and oceanic loading is critical in the process of developing nutrient criteria for estuaries in the Pacific Northwest region. Several studies have been conducted to try to understand sources and variability in order to develop appropriate nutrient criteria and management measures.

Future Outlook

Although presently hypoxia is not a significant problem in this estuary, it may worsen in the future since the population of Lincoln County, where Toledo and Newport are located, is predicted to increase by 12% by 2020. It is possible that conditions will remain the same, if wastewater treatment and other land-based nutrient management measures are maintained and improved. However, hypoxia and other nutrient-related problems may worsen due to the additional nutrient loads associated with the population increase if nutrient management infrastructures are overloaded. This is particularly true in Zone 2 (riverine-dominated), since this zone is more influenced by land-based sources of nutrients than Zone 1. Historical reduction of dissolved oxygen in Zone 2 suggests that this system can be impacted by watershed activities even in the presence of strong flushing. However, if the population of Newport increases, water quality in the lower estuary may also worsen as a result. The import of low dissolved oxygen water into the estuary from the coastal ocean may result in this system being susceptible to hypoxia in the future.

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Hood Canal

Physical Description of the System

Despite its name, Hood Canal is a natural formation which has experienced hypoxia periodically dating back centuries (Brandenberger et al. 2009). It is a sub-basin of Puget Sound, Washington, with a fjord-like structure (Figure 1), including a natural sill at the mouth which restricts circulation with greater Puget Sound; it has a surface area of 386 square kilometers (km^2) (King County 2001). Restricted and slow circulation coupled with a strong salinity stratification and high productivity make it conducive to low dissolved oxygen conditions (Newton 2007).

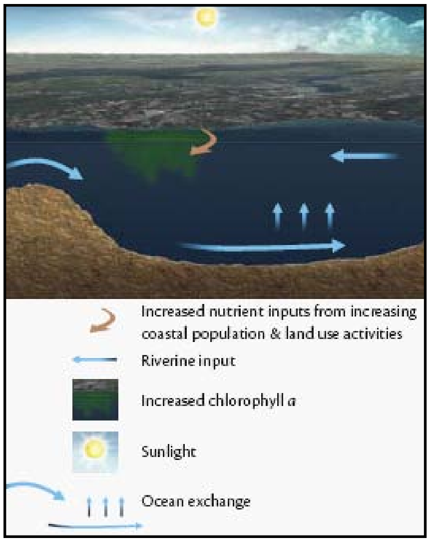

Figure 1. Diagram of Cross Section of Hood Canal with prevailing geography and physical conditions (Newton 2007).

History of Hypoxia (issue, causes, economic and ecosystem impacts)

Hypoxic events have increased in intensity, duration, and spatial extent since the 1990s, causing fish kills that prompted the Washington State Department of Fish and Wildlife to close many fisheries in Hood Canal in 2003. Southern Hood Canal, towards Lynch Cove (Figure 2), has experienced more hypoxia than the rest of the canal, and the measured dissolved oxygen concentrations are now lower in this area than they were in the 1950s and 1960s (Newton 2007). Hypoxia also develops seasonally along the main stem of Hood Canal, and transient upwelling of these waters caused by wind events has caused fish kills that garnered considerable public attention. Mortality events of living resources have been reported back to the 1920s (Fagergren et al. 2004). Ecosystem impacts such as these, however, have increased in frequency since 2002 including an extensive event in September 2006 (Newton 2007). Nitrogen inputs, especially from the Lynch Cove area, have been implicated, but nitrate from inflowing seawater (Paulson et al. 2006), changes in circulation and flushing (e.g., modified river flows), stratification, and algal blooms are also important (HCDOP 2007).

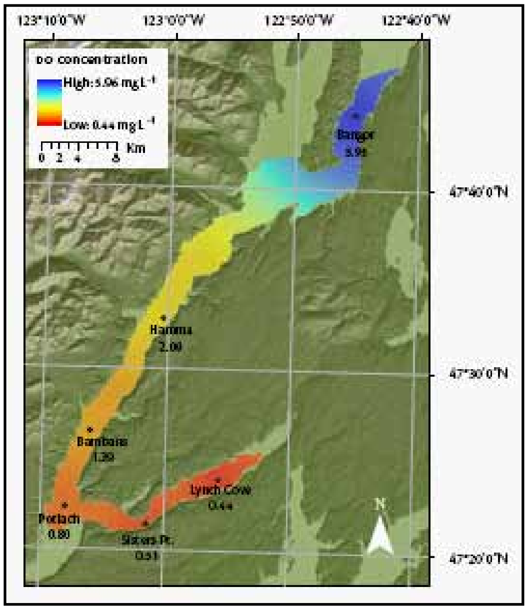

Figure 2. August 2006 interpolation reflecting typical pattern of low DO concentrations in Hood Canal (Newton 2007).

Science and Management Actions (to date and planned)

As a result of heightened attention to Hood Canal environmental deterioration, two significant developments may lead to improvements in hypoxia in the future. First, the Hood Canal Dissolved Oxygen Program (http://www.hoodcanal.washington.edu/index.jsp), a partnership of 28 organizations, including NOAA, EPA, USGS, USACE, and the U.S. Navy, was created in 2005 to study oxygen dynamics through broad-scale community involvement, concerted assessments, and development of models. In addition to the Hood Canal Dissolved Oxygen Program, but operating on a larger scale, the Puget Sound Partnership (http://www.psp.wa.gov/), a new state agency, was established in 2007 to develop a coordinated, region-wide response to the deterioration of the Sound. The group adopted an ambitious action plan in 2008.

Future Outlook

The factors driving hypoxia in Hood Canal are still being clarified, especially the role of nutrients derived from human activities. Creation of the Puget Sound Partnership in 2007—which represents a broad coalition of citizen, Federal, state, and tribal agencies and interests—should allow development of deliberate protection actions for Puget Sound, and Hood Canal specifically. It is important to develop a comprehensive management plan before the situation worsens given the expected growth in the coastal population around Puget Sound.

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