Integrated Assessment of
Hypoxia in the northern Gulf of Mexico

DRAFT FOR PUBLIC COMMENT

Acknowledgments

Hundreds of scientists, from a wide array of different fields, contributed over the years to the extensive knowledge base on which this assessment depends. An intensive collaborative effort over the past two years has assembled and reviewed available information. Special thanks are due to all who participated, particularly the many peer reviewers and the editorial board, whose efforts have sharpened thinking and clarified presentation.

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Hypoxia Assessment Reports

As a foundation for the assessment, six interrelated reports that examine various aspects of the hypoxia issue were developed by six teams with experts from within and outside of government. The research teams were established not to conduct new research, but rather to analyze existing data and to apply existing models of the watershed-Gulf system. **This integrated assessment draws heavily from the results in these six reports.**

Each of the reports underwent extensive peer review by independent experts guided by an editorial board. Editorial Board members were Dr. Donald Boesch from the University of Maryland, Dr. Jerry Hatfield from the U. S. Department of Agriculture, Dr. George Hallberg from the Cadmus Group, Dr. Fred Bryan from Louisiana State University, Dr. Sandra Batie from Michigan State University, and Dr. Rodney Foil from Mississippi State University.

1. Characterization of hypoxia -- Describes the seasonal, interannual, and long-term variation of hypoxia in the northern Gulf of Mexico, and its relationship to nutrient loadings. It also documents the relative roles of natural and human-induced factors in determining the size and duration of the hypoxic zone.

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2. Ecological and economic consequences of hypoxia -- Presents an evaluation of the ecological and economic consequences of nutrient loading, including impacts on Gulf of Mexico fisheries and the regional and national economy.

Robert J. Diaz, Virginia Institute of Marine Science — Ecological co-lead
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with the assistance of many others

3. Flux and sources of nutrients in the Mississippi-Atchafalaya River Basin— Identifies the sources of nutrients within the Mississippi-Atchafalaya system and within the Gulf of Mexico, estimating both their location and the relative importance of specific human activities in contributing to these loads.

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4. Effects of reducing nutrient loads to surface waters within the Mississippi River Basin and Gulf of Mexico — Estimates the effects of nutrient source reductions in the Mississippi-Atchafalaya Basin on water quality in these waters and on primary productivity and hypoxia in the Gulf.

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David Mulla, University of Minnesota
Val Smith, University of Kansas
Clive Walker, Blackland Research Center
Terry Whitledge, University of Alaska
William J. Wiseman, Jr., Louisiana State University

5. Reducing nutrient loads, especially nitrate-nitrogen, to surface water, ground water, and the Gulf of Mexico — Identifies and evaluates methods to reduce nutrient loads to surface water, ground water, and the Gulf of Mexico.

William J. Mitsch, The Ohio State University -- Lead
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6. Evaluation of economic costs and benefits of methods for reducing nutrient loads to the Gulf of Mexico -- Evaluates the social and economic costs and benefits of the methods identified in Topic 5 for reducing nutrient loads, and assesses various incentive programs and any anticipated fiscal benefits generated for those attempting to reduce sources.

Otto C. Doering, Purdue University — Lead
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Executive Summary

Hypoxia is the condition in which dissolved oxygen levels are below those necessary to sustain most animal life. The largest zone of oxygen-depleted coastal waters in the U.S., and the entire western Atlantic Ocean, is found in the northern Gulf of Mexico on the Louisiana/Texas continental shelf. The area affected is about the size of the state of New Jersey. The extent of the mid-summer, bottom-water hypoxic zone varies but has increased since regular measurements began in 1985. Since 1993, it has been larger than 10,000 square kilometers (about 4,000 square miles) and the largest hypoxic zone measured to date was in 1999: 20,000 square kilometers (about 8,000 square miles).

This assessment summarizes the state of knowledge of the extent, characteristics, causes and effects of hypoxia in the northern Gulf of Mexico. It also identifies alternatives for reducing those effects and examines the costs and benefits associated with reduction actions. It is intended to make scientific information available to non-specialists. The information provides a basis for an action plan but this assessment is intended to describe options rather than make recommendations. This assessment also identifies additional research needed to reduce uncertainties in important aspects of our understanding.

CAUSES AND CONSEQUENCES

Hypoxia results when the rate of oxygen consumption mostly by bacteria-decomposing organic material in the water column exceeds the rate of oxygen production by photosynthesis and by replenishment at the air/water interface from the atmosphere. Organic matter is supplied either from external sources or produced within the system through biological processes stimulated by nutrient addition. Scientific investigations over the last several decades indicate overwhelmingly that hypoxia in the northern Gulf of Mexico is caused primarily by excess nutrients delivered to those waters from the Mississippi-Atchafalaya River Basin (the Basin), in combination with stratification of Gulf waters. Model analyses also confirm that river nutrient loads are highly significant in controlling hypoxia and that rates of algal production and oxygen depletion change significantly when modeled river loads are changed. Nutrients fuel accelerated growth of phytoplankton. Fecal pellets from grazing zooplankton and dead phytoplankton cells then sink, increasing the flux of organic material to bottom waters. Decomposition of this organic material consumes oxygen in the bottom water layers, and stratification of dense bottom water below warmer and frequently fresher surface water minimizes mixing. At dissolved oxygen levels of less than 2 milligrams per liter (2 mg/l), the general definition of hypoxia, mobile organisms leave and those remaining die off at varying rates depending on how low the oxygen level gets and for how long.

Very low levels of dissolved oxygen occur naturally but evidence from the Gulf of Mexico and around the world indicates that human activities are intensifying the natural phenomenon. Sediment cores collected in the hypoxic zone of the Gulf show that algal production and deposition, as well as oxygen stress, were much lower earlier in the century and that significant increases occurred in the latter half of the century. Over this period there have been three major changes in the drainage basin affecting the river flux to the Gulf: (1) channelization of the river for flood control and navigation, mostly completed prior to the 1950s (except the Atchafalaya modifications in the early 1980s); (2) alterations in the landscape (e.g., deforestation and artificial agricultural drainage) that removed much of the “buffer” for runoff into the Mississippi tributaries and main stem, with the greatest rates of change in the 50-year period straddling the turn of the last century and another burst in drainage development during 1945-1960; and (3) a dramatic increase in fertilizer nitrogen input into the Mississippi River drainage basin between the 1950s and 1980s.

Since 1980, the Mississippi and Atchafalaya Rivers have discharged, on average, about 1.6 million metric tons of total nitrogen to the Gulf each year. The most significant trend in nutrient loads has been in nitrate, which has almost tripled from 0.33 million metric tons per year during 1955-70 to 0.95 million metric tons per year during 1980-96. Other forms of nitrogen, as well as organic carbon and nutrients such as phosphorus, have not increased, and evidence indicates their fluxes have probably decreased over this century. About 90% of the nitrate comes from non-point sources, with the remainder coming from point sources. About 56% of the nitrate transported to the Gulf enters the Mississippi River above the Ohio River. The Ohio basin subsequently adds another 34% of the nitrate load. The principal sources of nitrate are river basins that drain agricultural land in southern Minnesota, Iowa, Illinois, Indiana and Ohio.

Fisheries are affected by this large hypoxic zone. Both abundance and biomass of fish and shrimp are significantly less where bottom water concentrations of oxygen fall below 2 mg/l. Comparison of the distribution of fishing effort shows that the industry has shifted shrimping efforts away from hypoxic zones. Yet, brown shrimp catch, the most economically important commercial fishery in the Gulf, declined from a record high in 1990 to below average during the years 1992-97, coinciding with years of greatly increased hypoxia. However, economic analysis of fisheries catch data did not demonstrate statistically significant effects attributable to hypoxia.

Significant changes in the ratios among the nutrients nitrogen, phosphorus and silica may also lead to important alterations in the types of algae present. Other components of the food chain and habitat are also affected. For example, copepods, the dominant zooplankton and important fish prey in the northern Gulf of Mexico, are lower in abundance or absent when dissolved oxygen is less than 1 mg/l. Bottom communities in the hypoxic zone consist of disturbance-adapted populations, compared to the late-successional stage “equilibrium”-type communities in less affected areas in Mississippi Sound. During hypoxia, significant amounts of the system’s energy are shunted from zooplankton and other invertebrates to bacteria, and energy flows through the ecosystem in pulses, favoring opportunistic species with shorter life cycles that can take advantage of the shortened time bottom habitats are available. The impact is an overall reduction in biodiversity, abundance and biomass.

Water quality in the drainage basin is also degraded by excess nutrients. Most states in the Basin have substantial numbers of river miles impaired by high nutrient conditions or not fully supporting the resource uses of aquatic life, fish consumption, swimming, and drinking water supply. Although state numeric nutrient standards are not established, some researchers considering eutrophication conditions have suggested an approximate boundary of 1.5 mg/l for total nitrogen and 0.075 mg/l for total phosphorus. About 30-55% of the Ohio, Lower Mississippi, and Tennessee sub-basins (defined as hydrologic cataloging units) exceed this suggested eutrophic criterion for total phosporus; 16-40% exceed the criterion suggested for total nitrogen. Even higher exceedance frequencies (70-75% for total nitrogen) were found in the Missouri, Upper Mississippi, and Arkansas-Red sub-basins.

REDUCTION EFFECTS AND APPROACHES

Potential futures if current activities are unchanged -- Nitrogen loading appears to have reached a plateau at the level of about 1.6 million metric tons/yr, which is the mean loading over the period 1980-96. If the set of activities which affect nutrient flux continues to prevent increasing trends, the current range of dimensions and severity of the hypoxic zone on the Louisiana shelf would most likely be maintained. Hypoxia would vary, depending on other factors, such as the timing and extent of spring and summer stratification, weather patterns, temperature, and precipitation in the Gulf and drainage basin. Thus, even if flux did not trend upward, natural variability could produce new extremes of hypoxia extent and impacts. Nutrient impairments to water quality in the Basin are unlikely to improve without some changes in current activities.

Under a “no action scenario,” it is important to recognize that other factors may increase nutrient loads. For example, efforts to reduce loads (e.g., ongoing improvements in farming practices, better targeting of riparian and wetland restoration, and improved river flow management) may be offset by increases in population growth, food production, and climate change that will tend to increase nutrient loss from land. If experiences in other systems are applicable to the Gulf of Mexico, then increased loads would lead to worsening hypoxic conditions and, at some point fisheries and other species would decline, perhaps precipitously. Spawning grounds, migratory pathways, feeding habitats, and fishing grounds of important species are all affected by the extent and severity of hypoxic waters. Thus, an expanding hypoxic zone could lead to further declines in productivity at higher levels of the food chain and loss of essential habitats.

Potential futures if loading is reduced -- Experience has demonstrated that large ecosystems do respond positively to nutrient reductions. Examples include Cheaspeake, Tampa and Sarasota Bays. There are also many examples of small-scale hypoxia reversals associated with improvements in treatment of sewage and pulp mill effluents. In the Gulf of Mexico, reductions in total nitrogen flux of about 40% are necessary to return to loads comparable to those before the large increases in the 1950-70 period. Model simulations indicate that nutrient load reductions of 20-30% would result in a 15 to 50% increase in bottom water dissolved oxygen concentrations and a 5 to 15% decrease in surface chlorophyll concentrations. Such increases in oxygen are significant in that they represent an overall average for the hypoxic zone and that any increase above the 2 mg/l threshold will have a significant effect on marine life.

Taking Effective Actions -- The two primary approaches to reduce, mitigate, and control hypoxia in the Gulf of Mexico are: (1) reducing inputs of nitrogen to streams and rivers in the Basin and (2) restoring and enhancing natural denitrification processes in the Basin.

In the first category, the most effective actions include improved management practices to retain nitrogen on fields, reducing application of nitrogen fertilizer (particularly above recommended rates), implementing alternative cropping systems, decreasing feedlot runoff, and reducing point sources. Other measures, such as reducing urban nonpoint sources and atmospheric deposition, could provide important contributions; but, on a Basin-wide scale, they are not as significant. Nitrogen trading among all sectors could offer opportunities to obtain least-cost reductions. Based on economic analysis, the cost of reducing edge-of-field nitrogen losses by 20% under economically optimum conditions was estimated to be $0.88 per kilogram reduction (about $0.40 per pound). To achieve an equal reduction through limits on fertilizer use would require 45% fertilizer reduction. However, edge-of-field nitrogen losses could be reduced by about 10% through a 20% reduction in fertilizer use at estimated costs of $0.69 per kilogram ($0.31 per pound). Costs of reductions of point sources and atmospheric deposition were estimated to be in the range of $10-100 per kilogram (about $5-50 per pound).

In the second category, the most effective actions would be increasing the acreage of wetlands and riparian buffers within the Basin. Nitrogen transformations in wetlands and riparian soils, in surface water and in ground water involve several microbiological processes, some of which denitrify – that is, they make nitrogen effectively unavailable as a nutrient for plant uptake by removing it from the water as nitrogen gas. The most effective use of wetland restoration and creation would be in watersheds that discharge high amounts of nitrogen. At typical denitrification rates for flow-through wetlands, 5 million acres (0.7% of the Basin area) of constructed or restored wetlands would reduce nitrogen load to the Gulf by 20%. Riparian areas are vegetated areas, mostly forested, next to water resources. They are also effective in removing nitrates, but typical denitrification rates are less than those of wetlands. An estimated 19 million acres (2.7% of the basin) of additional riparian buffers would be needed to reduce nitrogen load to the Gulf by 20%. Reintroducing river water to the backwaters, coastal wetlands, and shallow inshore bodies of water on the delta could augment efforts to reduce nutrient inputs from the upstream sources and help reduce the rate of coastal land loss. Potential deleterious effects of diversions such as eutrophication of embayment estuaries receiving the flows should be avoided as much as possible. Direct costs of creating and restoring 5 million acres of wetlands were estimated to be $8.90 per kilogram reduction in nitrogen flux (about $4.05 per pound).

All of the nutrient-reduction approaches will also produce environmental benefits within the drainage basin. These include the values associated with restored wetlands, reduced soil erosion, reduced nutrient contamination of drinking water, reduced vulnerability to floods, better wildlife habitat, and improved water quality for recreational uses. Other potential benefits of nutrient reduction activities include more efficient use of organic and inorganic fertilizers and the energy associated with them, lower overall fertilizer costs, decreased health risk from contamination of public and private drinking-water supplies, and improved aquatic habitat in streams, lakes, rivers, and estuaries. Good estimates for the economic value of these benefits are only available for a few categories, such as wetlands and erosion. When these estimated benefits are factored in, the unit costs of wetlands and farm practices become close. With benefits included, reducing edge-of-field nitrogen loss by 20% was estimated to have a net cost of $0.80 per kilogram ($0.36 per pound), while equal reductions through restoration and creation of 5 million acres of wetlands would have net costs of $1.00 per kilogram ($0.45 per pound).

Based on analysis and modeling of broad aggregates across the Basin, one illustrative approach to reduce nitrogen loss by 20% would be through a program of 20% reduction in fertilizer use, and 5 million acres of wetlands construction or restoration. This combination would produce costs and acreage impacts that would be lower than for other combinations. However broader combinations of carefully refined, targeted, and flexible variations on the full array of alternatives, in synergy with other programs, could improve cost-effectiveness.

ADAPTIVE MANAGEMENT: ACTION, MONITORING AND RESEARCH

This assessment is based on assembly and peer review of a massive amount of direct and indirect evidence collected and reported over many years of scientific inquiry. A comprehensive, carefully targeted program of monitoring, modeling, and research to facilitate continual improvement in scientific knowledge and adjustments in management practices should be coupled to whatever initial nutrient management strategies are chosen. This adaptive management scheme involves continual feedback between interpretations of new information and improved management actions.

Monitoring, research, and decisions about taking action to reduce hypoxia should be integrated using holistic models that simulate our understanding of how the overall system functions and how actions can best be implemented. A comprehensive monitoring program requires measurement of the pressures and the environmental response both in the Gulf and in the Basin. Indicators of programmatic progress should also be established and periodically revisited.

Scientific understanding has been advanced significantly by the work on which this assessment is based. The conclusions provide a solid foundation on which to build an appropriate response strategy. There are, however, always uncertainties in scientific analysis. Immediate priorities for research to address these uncertainties include research on the ecological effects of hypoxia, watershed nutrient dynamics, and agricultural practices. Focused effort in these areas can provide near-term information to guide decisions about management actions. Longer-term priorities to fill critical gaps in understanding and guide future management strategies include research on nutrient cycling and carbon dynamics, long-term changes in hydrology and climate as well as economic and social impacts.

Introduction

The goal of this assessment is to document the state of knowledge of the extent, characteristics, causes and effects (both ecological and economic) of hypoxia in the northern Gulf of Mexico. This assessment also aims to identify alternatives to reduce those effects and to examine the costs and benefits associated with these alternatives.

The National Science and Technology Council's Committee on Environment and Natural Resources undertook the task to assess the state of scientific knowledge and understanding of Gulf of Mexico hypoxia in 1997. An assessment plan was developed in conjunction with the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force (MR/GM Task Force) and approved in March 1998. In October 1998, Congress passed the Harmful Algal Bloom and Hypoxia Research and Control Act, which was signed into law as P.L.105-383 by the President on November 13, 1998. This law calls for an "integrated assessment of hypoxia in the northern Gulf of Mexico that examines: the distribution, dynamics and causes; ecological and economic consequences; sources and loads of nutrients transported by the Mississippi River to the Gulf of Mexico; effects of reducing nutrient loads; methods for reducing nutrient loads; and the social and economic benefits of such methods."

As a foundation for this assessment, six reports that examine various interrelated aspects of the hypoxia issue were developed by six teams of experts from within and outside of government. The teams were not established to conduct new research, but rather to review and analyze existing data and apply existing models of the watershed-Gulf system. This integrated assessment draws heavily from the results in these six reports. Both the findings and the words of these reports have been used freely in this assessment. Explicit citations to the reports are included only when reference is made to specific information that a reader may want to examine in greater detail.

The six topic reports draw on a rich variety of work that preceeded them, including in-depth studies of oceanographic, hydrologic, agricultural, economic, and other questions related to the issue of hypoxia in the Gulf of Mexico. They underwent rigorous peer review with oversight by an independent editorial board. In addition, the six topic reports were available for a 90-day public comment period. The reports and the comments received on them are available at <http//www.nos.noaa.gov/products/pubs_hypox.html>. This draft assessment has been written with consideration of all that information and will also be available for a period of public comment before it is finalized.

This assessment is intended to be useful to non-specialists as well as specialists. It has been written attempting to use a minimum of specialized scientific terminology yet still precisely describe the state of knowledge. A glossary defining the scientific terms that are used is included at the back of this document.

In addition to this assessment, P.L. 105-383 calls for the development of a plan of action to reduce, mitigate and control hypoxia in the northern Gulf of Mexico. The Action Plan will be developed by the MR/GM Task Force. This integrated assessment is intended to provide scientific information as a basis for the Action Plan but it is not intended to make recommendations for action nor is it the only source of information which the MR/GM Task Force will consider in developing the Action Plan.

1. The Problem

Nearly all marine animals depend on oxygen dissolved in the water. Hypoxia is the condition in which there is so little dissolved oxygen that aquatic life is disrupted.

Hypoxia is generally defined by dissolved oxygen levels below 2 mg/l (or ppm) -- approximately 20% of the dissolved oxygen that northern Gulf of Mexico waters could hold in solution at typical summer temperatures and salinities. Mobile organisms leave, die, or are eaten as dissolved oxygen levels decrease below 2 mg/l. Trawlers in hypoxic areas usually do not capture any shrimp or demersal fish (fish that usually live near the bottom). Burrowing organisms first emerge from the sediments, then die, if oxygen concentrations remain near 0.5 mg/l for prolonged periods. In areas where the oxygen concentrations are below 0.2 mg/l, the sediment is typically black, and sulfur-oxidizing bacteria form mats on the seafloor. Toxic hydrogen sulfide may be found where bottom waters are completely devoid of oxygen (anoxic).

The largest zone of oxygen-depleted coastal waters in the US, and the entire western Atlantic Ocean, is found in the Northern Gulf of Mexico on the Louisiana/Texas continental shelf.

FIGURE 1.1 – Map of frequency of occurrence of mid-summer hypoxia
— based on data from Rabalais, Turner and Wiseman from the 60 to 80 station grid repeatedly sampled from 1985-1999

Hypoxic waters are most prevalent from late spring through late summer. Hypoxia is more widespread and persistent in some years than in others, depending on river flow, winds, and other environmental variables. Hypoxic waters are distributed from shallow depths near shore (4 to 5 meters) to as deep as 60 meters but more typically between 5 and 30 meters. Hypoxia occurs mostly in the lower water column but encompasses as much as the lower half to two-thirds of the entire column. Continuous time-series data for the bottom waters in the core of the hypoxia region show (1) the gradual decline in oxygen in the spring with interruptions due to wind-mixing events, (2) persistent hypoxia and often anoxia for extended parts of the record from May through September, (3) occasional summer upwelling of oxygenated water from the deeper shelf waters, and (4) the seasonal disruption of low oxygen in the fall by tropical storms or cold fronts.

Systematic study of the hypoxic zone, with regular repeated measurements, began in 1985. As shown in figure 1.2, the mid-summer bottom areal extent of hypoxic waters in 1985-92 averaged 8,000-9,000 km^2 (about 3,000-3,500 square miles) but increased to 16,000-18,000 km^2 (about 6,000- 6,500 square miles) in 1993-97. The estimated extent was 12,500 km^2 (about 4,800 square miles) in mid-summer of 1998 but increased to 20,000 km^2 (almost 8,000 square miles) at the end of July 1999, the largest ever recorded. The area affected is about the size of the state of New Jersey.

FIGURE 1.2 – Histogram of estimated areal extent of bottom water hypoxia for mid-summer cruises 1985-99 --- based on data from N. Rabalais, Louisiana Universities Marine Consortium

2. Causes of Gulf of Mexico Hypoxia

This chapter examines the scientific evidence concerning the causes of the formation of hypoxic bottom waters in the northern Gulf of Mexico. While information gaps still exist and several factors discussed below may contribute to hypoxia, the overwhelming scientific evidence indicates that inputs of nitrogen from the Mississippi River drainage basin is the primary factor driving hypoxia. Although hydrologic and climatic factors influence the onset and duration of hypoxia, it is this nitrogen flux that fuels the annual event. This evidence, described in the detailed technical reports and the scientific literature upon which this assessment is based, is summarized in the following section. Analysis of nutrient trends and sources, and the relative importance of specific human activities in contributing to these trends, are then described, providing the basis for the chapters that follow.

COASTAL EUTROPHICATION

Development of hypoxia in northern Gulf of Mexico bottom waters, as well as in most ocean and freshwater systems, is described best by the eutrophication paradigm. Eutrophication is defined as an increase in the rate of supply of organic matter in an ecosystem (Nixon 1995). This increase in organic matter can be due to flux from external sources or production within the system through biological processes stimulated by nutrient addition. Controlling or reversing the effects of eutrophication necessitates understanding the relative roles of externally supplied and internally produced organic carbon. Externally supplied organic carbon most often comes from wetlands or uplands via rivers. Internally produced organic carbon comes from the growth of algae.

FIGURE 2.1 - The "Eutrophication Process" (modified from Downing et al. 1999) – Eutrophication occurs when organic matter increases in an ecosystem. Eutrophication can lead to hypoxia when decaying organic matter on the bottom depletes oxygen and replenishment is blocked by stratification. The flux of organic matter tothe bottom is fueled by nutrients carried by riverflow or, possibly, from upwelling that stimulate growth of phytoplankton algae. This flux consists of dead algal cells together with fecal pellets from grazing zooplankton. Organic carbon from the river can also contribute to the flux of organic matter.

As shown in figure 2.1, nutrients stimulate production of phytoplankton algae. Algae that are not incorporated into the food web, fecal products, and other debris from zooplankton feeding on algae, together with externally supplied particulate organic carbon, sink into bottom waters as "excess" organic material. Decomposition of this organic material by bacteria and other organisms consumes oxygen, and when the consumption rate is faster than its replenishment, oxygen concentrations decrease.

Excess organic carbon and subsequent oxygen consumption alone do not necessarily lead to hypoxia -- stratification is also necessary for the development of hypoxia in bottom waters. In most saltwater systems, the water stratifies (creating horizontal layers), with cold and/or saltier water at the bottom and warmer and/or fresher water at the surface. This layering separates bottom waters from the atmosphere and prevents re-supply of oxygen from the surface to replenish deficits created by the decomposing organic matter in the deeper waters. Thus, the extent of hypoxia is determined by the balance between the rate of delivery and decomposition of algae and other organic matter and the rate of oxygen re-supply, which is inversely related to the strength of stratification.

Hypoxia, and other symptoms of eutrophication, such as growth of nusiance or toxic algae and loss of submerged aquatic vegetation, are major stresses in many coastal ecosystems. Over half of the nation's estuaries experience low oxygen and other symptoms of eutrophication (Bricker et al. 1999). Almost all of these problems are caused or exacerbated by the increased flow of nutrients from land due to human activities. There is growing evidence around the world that low oxygen is having pervasive effects on shallow coastal and estuarine areas (Diaz and Rosenberg 1995). While hypoxia can occur naturally and has existed throughout geologic time, its occurrence in shallow coastal and estuarine areas appears to be increasing and is most likely accelerated by human activities (Vitousek et al. 1997; Jickells 1998).

Role of Nutrients

Nitrogen is the most significant nutrient controlling algal growth in coastal waters, while phosphorus is the most significant nutrient in fresh water (NRC 1993). Silicon also plays an important role in that it regulates the production of diatoms which are algae that are an important food for fish and invertebrates. Diatoms, unlike other phytoplankton species, require silicon to build their cell walls and are the dominant biomass component of many marine and estuarine phytoplankton communities, particularly in the spring. If silicon supply is limited relative to the other nutrients, then non-siliceous algae, such as dinoflagellates and cyanobacteria, may become proportionately more important in the phytoplankton community. Some of these forms are harmful or toxic. The ratios among dissolved silica, nitrogen, and phosphorus in the lower Mississippi River now closely approximates the typical ratio of these nutrients in diatoms. Thus, while nitrogen is the nutrient that controls the quantity of coastal algal production, significant changes in the relative composition of nutrient supplies may also lead to important alterations in the type of algae present.

Potentially Contributing Factors

Among the potential factors contributing to Gulf hypoxia, only increased nutrient loads from the Mississippi/Atchafalaya River system can account for the magnitude of the hypoxic zone and its increase over time in a non-contradictory manner. While other factors may contribute to the growth, dynamics, and decay of the hypoxic zone, none of them, alone or in combination, can explain its overall size and persistence.

Internally produced organic carbon, stimulated by nutrients (from the land, air, or sea), externally supplied organic carbon, horizontal stratification, ocean circulation, and river hydrology are not competing hypotheses, but rather interacting factors within the eutrophication paradigm applied to the Gulf of Mexico. These factors have been discussed in the six technical background papers, in the comments on those papers, in recent reports on this subject sponsored by the Fertilizer Institute and the Council for Agricultural Science and Technology (Carey et al. 1999 and Downing et al. 1999), as well as the wide range of previous work summarized in volumes such as the *1995 Gulf of Mexico Hypoxia Management Conference* (EPA 1997) and the December 1994 and June 1996 special issues of *Estuaries*. The most significant potential contributing factors for the Gulf of Mexico and its drainage basin are described in the box on the next page.

Factors Potentially Contributing to Hypoxia in the Gulf

Landscape changes in the drainage basin -- Wetlands and riparian zones can improve water quality and reduce nitrogen flux down the Mississippi River by enhancing denitrification (the conversion of nitrate to nitrogen gas, with subsequent loss from the aquatic system) and incorporating nitrogen into vegetation. However, the natural capacity of the river basin to remove nutrients has diminished. Many of the original freshwater wetlands and riparian zones that were connected to streams and rivers are gone. Ohio, Indiana, Illinois, and Iowa have had over 80% of their wetlands drained. Indiana, Illinois, Iowa, Minnesota, Missouri, and Wisconsin collectively have lost the equivalent of 14.1 million ha (35 million acres) of wetlands over the past 200 years.

Organic loading from the Mississippi River -- Externally supplied organic carbon from the Mississippi River has been proposed as a cause for the formation of hypoxia in the Gulf. For river-borne organic carbon to be an important contributor to the increase in hypoxia since the 1950s, significantly increasing quantities would have to be delivered to the bottom waters of the hypoxic zone and be decomposed by bacteria. Only the particulate organic carbon (POC) fraction of the total organic carbon load could contribute directly to hypoxia because only that fraction would be delivered to the bottom waters. The dissolved fraction would remain in the river-freshened surface waters and would have to be biologically assimilated and deposited as newly formed POC, with large attendant respiratory losses, to reach hypoxic zones extending 100-200 km from the river discharges. Suspended sediment in the river has declined by about half since the 1950s, so the POC load that can settle on the Louisiana shelf has also most likely decreased since then. Also, nutrient cycling affords nitrogen the ability to stimulate production of organic carbon at rates that far surpass that supplied by the river. Whereas decomposition of river-supplied organic carbon consumes oxygen only once, river-supplied nitrogen can be recycled and thus provides a continuous source of comparatively easily decomposed organic carbon (Ryther and Dunstan 1969).

Channelization of the delta and loss of coastal wetlands -- Although in some years over-bank flow has been significant, flooding through coastal wetlands has been reduced since the 1927 flood, but geochemical and biological indicators show that hypoxia has intensified only since the 1950s. Coastal wetland loss rates exceeded 100 km^2 (about 40 square miles) per year between 1950 and 1980. Recent wetlands protection and restoration programs helped reduce losses in the 1990s to 65-90 km^2 (about 25-35 square miles) per year. Both the loss of wetland filtering capacity and the direct contribution of organic matter eroded from wetlands and carried to the Gulf may contribute to the problems of hypoxia; however, the total contribution is relatively small compared with the nitrogen-related factors.

Intrusion of deeper offshore waters -- Some have suggested that flow of low-oxygen water from water layers in the deeper Gulf on to the continental shelf was the source of shelf hypoxia. However, these features are always physically distinct, with the shelf hypoxic zone at depths of less than 60 meters, and the deep low-oxygen layer at depths of 400 to 700 meters. Further, oxygen concentrations and consumption rates, salinity, and temperature of the deep low-oxygen layer differ considerably from the waters of the hypoxic zone. Flow of nitrate from deeper waters may be important at the shelf edge (at depths of approximately 100 meters); however, all data indicate that the Mississippi and Atchafalaya Rivers contribute substantially more nutrients to the inner shelf and hypoxic region.

Short- or long-term climate changes -- River discharge and nitrate concentrations, and sediment core data, provide almost 100 years of record for this system. On that time scale, there is no indication that climate factors override the impacts of human activities in the basin. Average annual flow in the Mississippi River increased 30% between 1955-70 and 1980-96, compared to the 300% increase in nitrate flux over this period. Episodic events, such as the 1993 flood, can nearly double the nitrate flux to the Gulf in a given year as a result of both higher-volume flow and increased leaching of nitrate from the drainage basin. There are indications that the future climate for this basin may be wetter and may include more extreme events, leading potentially to increased water and nitrate fluxes (Kunkel et al. 1999).

NUTRIENT OVER-ENRICHMENT

The evidence of nutrient over-enriched production in the northern Gulf of Mexico and its linkage with oxygen depletion in the lower water column is consistent with the eutrophication paradigm, with data and experiences world wide, and with Gulf- and basin-specific information on a variety of scales.

> ***Scientific investigations over the last several decades indicate overwhelmingly that oxygen stress in the northern Gulf of Mexico is caused primarily by excess nutrients delivered to Gulf waters from the Mississippi-Atchafalaya River drainage basin, in combination with the stratification of Gulf waters.***

The scientific evidence supporting river nutrient loads as the primary factor fueling hypoxia in the Gulf of Mexico through over-enrichment is outlined in this section. It is supported by analysis of the sources and loads, as described in the next section.

Stratification

If Louisiana shelf waters did not stratify, hypoxia would be unlikely. However the river and Gulf oceanography create a strongly stratified system each year, characterized by relatively warm and fresher water that forms a high-production lens over the deeper salty, colder waters. The greater the density difference (related to temperature and salinity) between layers, the more stable the stratification. Very strongly stratified systems require a lot of wind energy – sometimes a tropical storm – in order to mix. If storms do not mix the waters, they will remain in layers, isolating bottom waters from aeration until fall brings cooler surface temperatures and the density of the surface water approaches that of the bottom water.

Trends in Indicators of Production, Low-Oxygen Stress, and River Nutrient Flux

Analysis of river discharge data and sediment cores from the Louisiana shelf in the Mississippi River delta bight indicate that eutrophication and hypoxia in the northern Gulf increased coincidently with increases in nutrient loads from the Mississippi River. The data exhibit both long-term trends and short-term variations. One particularly important factor is that peak river flows have increased over the past 150 years due to flood control and navigation projects in the river and climate (precipitation) changes.

--- Long-term records – Gulf ecosystem changes. Since there are no comprehensive, direct measurements of oxygen in the northern Gulf of Mexico prior to 1985, evidence for long-term changes in hypoxia is based on indirect analysis from sediment records. While it is possible to explore temporal changes in water-column production, oxygen-relevant geochemistry, and biology because such properties are preserved sequentially down a sediment core, it is important to recognize that bottom mixing and sediment reworking limits the resolution of temporal change to scales approaching decades, as opposed to years.

FIGURE 2.2 – Long-term records of Gulf ecosystem change -- These are profiles from cores taken in the Mississippi River bight in an area of persistent seasonal bottom water hypoxic conditions. The top profile shows a decrease in the Shannon-Wiener Diversity Index (SWDI) of ostracods, a family of minute shelled organisms. The next profile shows increasing glauconite grain abundance, indicating low oxygen conditions. The third profile shows increasing average concentration of biologically-bound silica, indicating changes in the algal community composition. The bottom profile shows increasing organic carbon accumulation rates.

The data shown in figure 2.2 are from cores collected within one area of the current hypoxic zone, and therefore do not necessarily represent the timing of the transitions for the entire contemporary hypoxic zone. They do, however, clearly show that increased algal production and deposition, as well as oxygen stress, were much lower earlier in the century and that significant changes have occurred in the latter half of the century.

The sediment record clearly shows significant increase in algal production beginning near the 1950s. Accumulation of organic carbon and biogenic silica (a measure of diatom abundance) both increased significantly after that time period. Because there have been no significant increasing trends in either the organic carbon or silica river loads, it is reasonable to infer that these increases in the sediment record since the 1950s are due to production of marine algae.

The sediment geochemistry record indicates that while there was likely some oxygen stress on the Louisiana shelf as early as the turn of the century, there was a striking increase in that stress starting roughly during the 1940s and 1950s. Because the mineral glauconite forms only under reducing conditions, its presence in the sediment is an indication of low oxygen conditions. Sediment cores show the history of glauconite formation from sediments as they were deposited on the bottom. As shown in the core profile in figure 2.2, glauconite abundance was relatively low in the early 1900s, but increased dramatically in the 1940s-1950s, indicating increased low oxygen stress.

Another indirect indicator of a significant change in the relative magnitude of hypoxia during this same transition period is the biodiversity of benthic foraminifera and ostracods preserved in the sediments. These single-celled organisms and metazoans, respectively, produce carbonate shells which remain intact in buried sediments. After a transition period in the 1940s-1950s, the diversity of these organisms decreased significantly, which is typical of stressed environments. Also, the types of organisms that remained after the transition period were those that are more tolerant of low oxygen conditions.

-- Long-term records – drainage basin changes. Three key historical trends are important to consider in relationship to the above long-term trends in hypoxia. First, most of the significant flood-control and navigation channelization occurred prior to the 1950s. Second, significant alterations in the landscape (e.g., deforestation and expansion of artificial agricultural drainage) that removed much of the "buffer" for runoff into the Mississippi tributaries and main stem occurred with the greatest rates of change in the 50-year period straddling the turn of the last century and another burst in drainage development during 1945 to 1960. Third, there was a dramatic increase in nitrogen input into the Mississippi River drainage basin, primarily from fertilizer applications, between the 1950s and 1980s. This increase in human activity in the drainage basin has led to significant increases in the flux of nitrogen from the Mississippi River system to the Gulf.

FIGURE 2.3 – Long-term records of drainage basin changes – annual amount of fertilizer application and area artificially drained (see #5 figure 1.2 and #3 page 44 for details)

-- Shorter-term records. Extensive monitoring of the hypoxic zone did not begin until 1985, and areal estimates (see figure 1.2) since then have been primarily from a single shelf-wide survey taken during mid-summer each year. Thus, for any given year, the maximum extent of hypoxia could have been significantly greater. Despite this limitation, three significant extreme events illustrate the nature of the variation in this record. First, during the summer of 1988, following a severe regional drought and subsequent low nutrient load (see Figure 2.4), the hypoxic zone covered only 40 square kilometers, compared to 5,000-20,000 square kilometers in other years (15 square miles, compared to 2,000-8,000 square miles). The hypoxic zone had developed in the spring but was not maintained into the summer because of reduced flow of freshwater and resulting lack of stratification. Second, the size of the hypoxic zone nearly doubled during the summer following the 100-year flood of 1993. While it is not clear why this larger area has persisted in years following 1993, nutrient recycling and resuspension of recently deposited, algal-produced organic material are likely important factors. The record large extent observed in 1999 may be related to abnormally wet conditions producing high nitrate concentrations in rivers draining the upper Basin.

Model Simulations

Model analyses provide further evidence connecting the extent of the hypoxic zone to river nutrient flux. Computer models have been constructed to simulate algal dynamics, nutrient cycles, sedimentation, organic carbon production and decay, and oxygen dynamics as functions of river nutrient loads and other environmental factors, such as variations in sunlight and ocean currents (Bierman et al. 1994; Justic et al. 1996; Justic et al. 1997)**.** These models were designed to examine the relative roles of various factors on hypoxia, such as ocean circulation, vertical stratification, light variation, nutrient loads, and climate change. These analyses show that river nutrient load is a highly significant factor in controlling hypoxia and that rates of algal production and oxygen depletion change significantly when modeled river loads were changed.

SOURCES, LOADS, AND TRENDS OF RIVER NUTRIENTS

Nutrient Trends

River-borne nutrients and water-column stratification are the major factors controlling hypoxia in the northern Gulf of Mexico. The key nutrients in this process are nitrogen, phosphorus, and silica. Of these, nitrogen is the most important nutrient leading to the production of excess algae and subsequent hypoxia in the Gulf and elsewhere (NRC 1993). Nitrogen is also the only nutrient that has increased significantly in concentration and loads in the Mississippi River in recent decades. Phosphorus loads have not changed significantly since the early 1970s when records began. Silica loads decreased between the 1950s and 1970s, and have not changed significantly since.

Nitrogen is present primarily in three forms in the Mississippi River and its tributaries -- nitrate, ammonium, and organic nitrogen. On average, 61% of the nitrogen load is nitrate; 24% is dissolved organic nitrogen; 13% is particulate organic nitrogen associated with suspended material; and the remaining 2% is ammonium. There has been no significant trend in the organic nitrogen load since 1973 when it was first measured. However, indirect evidence suggests that the particulate organic nitrogen load in the suspended sediment may have been as much as 50% larger before completion of the Missouri River reservoirs in 1950s and 1960s. These reservoirs now trap about half the sediment that the Mississippi River once discharged to the Gulf of Mexico (Meade 1995).

The most significant nutrient trend has been nitrate loads, which have almost tripled from 0.33 million metric tons per year during 1955-70 to 0.95 million metric tons per year during 1980-96. Most of this increase has occurred north of the convergence of the Mississippi and Ohio Rivers.

FIGURE 2.4 – Annual loads of nitrate, organic nitrogen and annual streamflow from the Mississippi River Basin to the Gulf of Mexico 1955-98

Longer-term records indicate that nitrate concentrations increased even more over the last 100 years**.** For example, concentrations in the Lower Illinois River averaged 1.01 mg/l in 1906-07, but averaged 4.12 mg/l between 1980 and 1996. Average concentrations increased from 0.7 mg/l in 1906-07 to 4.67 mg/l in 1980-96 in the Cedar River, IA; from 0.75 to 4.12 mg/l in the Des Moines River, from 0.32 to 4.19 mg/l in the Minnesota River; from 0.36 to 1.43 mg/l in the Muskingum River, OH and from 0.14 to 1.45 mg/l in the Lower Mississippi River, LA over the same time period (see #3 for additional comparisons).

Figure 2.5 shows trends in annual nitrogen inputs to and outputs from the basin. The most significant changes in both inputs and outputs occurred between the 1950s and 1980s, when fertilizer input more than tripled and crop harvest and pasture production increased about 2.4 times. Total nitrogen inputs increased from about 13 to nearly 22 million metric tons per year, an increase of about 9 million metric tons per year. Outputs increased by about 11 million metric tons per year.

FIGURE 2.5A – Annual Nitrogen Inputs to the Mississippi/Atchafalaya River Basin

FIGURE 2.5B – Annual Nitrogen Outputs from the Mississippi/Atchafalaya River Basin

The difference between these inputs and outputs (the residuals) represents nitrogen available for leaching to the river system (see figure 2.6). The rapid decline in residuals corresponds to the period of rapid change in fertilizer application and crop harvests and may represent increased efficiency in the use of nitrogen in crop production. Residuals since around 1980 have exhibited no trend, although they have become highly variable from year to year. The leveling off of nitrogen fertilizer, crop outputs of nitrogen, and the nitrogen residuals may indicate that a new steady-state condition was established about 1980.

FIGURE 2.6 – Annual Nitrogen Inputs, Outputs and Residuals (inputs minus outputs) from Nitrogen Mass Balance for 1951-96

Seasonal Variability

Nitrogen concentrations and loads vary seasonally. Loads and freshwater discharge are usually highest during the late winter, spring, and early summer when runoff is highest. The seasonal and annual cycles of nitrate transport are illustrated in figure 2.7**.**

FIGURE 2.7 – Flux of Nitrate from the Mississippi River Basin to the Gulf of Mexico 1980 to August-1999

Precipitation leaches the highly soluble nitrate from the soil into streams via overland runoff, ground-water discharge, and agricultural drains. Nitrate is subsequently transported into the Mississippi River and eventually discharges to the Gulf of Mexico.

Nitrogen Sources

The principal sources of nitrate are river basins that drain agricultural land in southern Minnesota, Iowa, Illinois, Indiana, and Ohio**.** This is an area of intensive corn and soybean agriculture. Large amounts of nitrogen from fertilizer and manure are applied to soils in this region each year. Legumes and atmospheric deposition add nitrogen. Also, soils in this region contain large amounts of nitrogen, some of which is converted to soluble nitrate each year. The nitrate accumulated from all sources and not utilized by crops or removed by biochemical processes is subject to being leached to streams and ground water by precipitation. Extensive use of tile drains in this region can intercept water with high levels of nitrate and accelerate its transport directly to ditches and streams. In addition, in some basins sewage treatment plants and industrial sources add nitrogen directly to streams. All of these sources contribute to the nitrogen load transported by the Mississippi River to the Gulf of Mexico. About 56% of the nitrate transported to the Gulf enters the Mississippi River above the Ohio River. The Ohio basin subsequently adds another 34% of the nitrate load.

FIGURE 2.8 -- Average annual nitrate yields (1980-96) for 42 basins within the Mississippi-Atchafalaya River Basin

Since 1980, the Mississippi and Atchafalaya Rivers have discharged, on average, about 1.6 million metric tons of total nitrogen to the Gulf each year; 0.95 million metric tons of that is in the form of nitrate. About 90% of the nitrogen comes from non-point sources, with the remainder coming from point sources. Table 2.1 presents the estimated contributions of nitrate and total nitrogen from the predominant sources in the basin.

TABLE 2.1 – Estimated Contributions of Nitrogen Input Sources to the Total Nitrogen and Nitrate Nitrogen Yield of the Mississippi/Atchafalaya River Basin and Flux to the Gulf of Mexico

Source of Nitrogen Transported to the Gulf	Percent of Nitrate	Percent of Total Nitrogen
NON-POINT SOURCES		
Fertilizer and mineralized soil nitrogen	58	50
Animal manure	16	15
Atmospheric deposition and unmeasured inputs	16	24
POINT SOURCES		
Municipal and industrial point sources	9	11

3. Consequences of Hypoxia in the Northern Gulf of Mexico

The consequences of hypoxia in the Gulf of Mexico are not fully known. This chapter examines what is known about the direct effect on fisheries and the structure of the marine ecosystem in the Gulf. It also describes the consequences of excess nutrients, the probable primary cause of hypoxia, for water quality and ecosystem functioning within the Mississippi-Atchafalaya River Basin (MARB).

CONSEQUENCES IN THE GULF

The shallow continental shelf area in the Gulf of Mexico that is affected by hypoxia shows signs of hypoxia-related stress -- low abundance of fish and shrimp and distinctly different benthic communities in hypoxic areas. While current ecological conditions are a response to a variety of stressors, the most obvious effects of hypoxia are that many bottom-dwelling, or benthic, organisms die; larger, long-lived species are eliminated; and productivity is shifted to nonhypoxic periods (energy pulsing).

The effects of hypoxia on fishery resources could include direct mortality of both fish and their food base, as well as such indirect effects as altered migration patterns, reduction in suitable habitats, increased susceptibility to predation, and disruption of spawning and recruitment.

Trawl data from the fishery-independent SEAMAP database showed a very consistent pattern that whenever dissolved oxygen approached 1-3 mg/l, catch of shrimp and fish rapidly declined to zero. Laboratory experiements have shown that both white and brown shrimp are able to detect and attempt to avoid hypoxic waters. Both abundance and biomass of fish and shrimp are significantly less where bottom-water concentrations of oxygen decline below 2 mg/l. Geographic comparison of the distribution of fishing effort around the Gulf show that the industry has shifted shrimping efforts away from hypoxic zones (Downing et al. 1999)

Overall, fisheries landings statistics for at least the last few decades have been relatively constant. However, the brown shrimp catch, the most important commercial fishery (by dollar value) in the Gulf, declined from a record high in 1990 to below average during 1992-97, coinciding with years of greatly increased hypoxia. Catch per unit effort for brown shrimp, while variable, has trended down since the late 1970s. Near-shore zones, away from hypoxic waters, are the usual habitat for white shrimp, which have not shown as great a decline.

FIGURE 3.1 -- Trends in shrimp yield recorded by the National Marine Fisheries Service for Louisiana and Texas, 1979-98 -- The lines indicate 3-year moving averages. The data are available at <www.st.nmfs.gov/st1/commercial/landings/index.html>

An economic analysis sought to examine the relationship between the estimates of the hypoxic zone area and available fisheries data, primarily on the two main shrimp species in the Gulf because they are part of the benthic community and are commercially important. Since data on the area of the hypoxic zone are only single annual estimates and not available before 1985, the time series was judged too short to establish a credible relationship and the analysis resorted to an extrapolation back to 1960 (see #2, pp. 19-20, for details). Fisheries variables examined included catch per unit effort, depth of landings, and shrimp size. This economic assessment based on fisheries data failed to detect effects attributable to hypoxia (i.e. correlations between the extrapolated time series and fisheries data were below levels usually considered statistically significant). However, the failure to identify hypoxic effects does not necessarily mean that they are absent, only that the data available for analysis were inadequate to identify the reasons for variability.

Fisheries data are highly variable and affected by many factors. Fisheries productivity, particularly in pelagic or near-surface species, may increase as a result of nutrient enrichment, but enrichment can fuel bottom hypoxia, thereby decreasing productivity of bottom-dwelling (or benthic) species. In the food chain, the documented responses of zooplankton to hypoxia include direct mortality, avoidance behavior in adults, interference with vertical migration, and changes in species composition toward smaller species that carry their eggs. Copepods, the dominant zooplankton in the northern Gulf of Mexico, are lower in abundance or absent when dissolved oxygen was less than 1 mg/l.

Comparison of benthic communities between the area affected by hypoxia with those unaffected in nearby Mississippi Sound shows distinct differences. On the Louisiana shelf, benthic communities consist of disturbance-adapted populations, whereas the Mississippi Sound contains more fully developed, late-successional stage “equilibrium”-type communities.

In addition to the loss of bottom and near-bottom habitat, hypoxia alters energy flows in the ecosystem. During hypoxia, significant amounts of the system’s energy are diverted from invertebrates to microbial decomposition. Energy flows through the ecosystem in pulses, favoring opportunistic species with shorter life cycles that can take advantage of the abbreviated time bottom habitats are available. A reduction in overall biodiversity, abundance and biomass of the ecosystem is associated with pulsed energy systems, since longer-lived species tend to be eliminated.

CONSEQUENCES IN THE MISSISSIPPI-ATCHAFALAYA RIVER BASIN

Nutrient concentrations affect many aspects of ecosystem and water quality in the Basin, including plankton composition and production, nuisance algal blooms, macrophyte communities and fish communities, as well as the suitability of waters for swimming and drinking and, ultimately, to violations of water quality standards.

Review of state assessments submitted to the U.S. Environmental Protection Agency under section 305b of the Clean Water Act indicates that most MARB states have substantial numbers of river miles that do not fully support three resource uses (aquatic life support, fish consumption, and swimming) because of nutrient conditions. Elevated nutrient concentrations, primarily nitrogen and phosphorus, can result in excessive growth of algae and other nuisance aquatic plants, disrupting the ecological balance, clogging pipes, and interfering with recreational activities. Subsequent decay of algae can result in foul odors, bad taste, and further ecological disruption through oxygen depletion.

Legally binding numeric standards have not been established in any state for nutrients in flowing- water systems or lakes, but efforts have been directed at the development of such standards for many years. At present, many states have a non-numeric (narrative) standard that in essence says nutrients must not be added to a water body to the extent that they cause an imbalance in the natural flora and fauna. Although science-based numerical criteria for nutrient concentrations to classify lake ecosystems according to trophic state have been available for many years, few classification methods exist in the literature to evaluate the trophic status of stream ecosystems in quantitative terms. One simple classification scheme developed by researchers (Dodds et al. 1998) for streams would use nutrient concentrations at the boundary approximately defining mesotrophic and eutrophic conditions, which is 1.5 mg/l for total nitrogen and 0.075 mg/l for total phosphorus. Using this scheme, about 30-55% of the hydrologic cataloging units (HCUs) of the Ohio, Lower Mississippi, and Tennessee sub-basins exceed this proposed eutrophic criterion for total phosphorus in flowing waters, and 16-40% of the HCUs in these regions exceed the proposed flowing-water criterion for total nitrogen. Higher exceedance frequencies were found in the Missouri, Upper Mississippi, and Arkansas-Red sub basins (~80% of the HCUs for total phosphorus and 70-75% for total nitrogen) (see #4 for details).

Excessive nitrate in drinking water can result in “blue baby syndrome” (methemoglobinemia), which causes oxygen levels in the blood of infants to be low, sometimes fatally. About 15% of all shallow ground water beneath agricultural and urban areas that has been sampled by the USGS exceeded the 10 mg/l drinking-water standard for nitrate (USGS 1999). Contamination of shallow ground water may be a warning to alert populations to potential future risks from consumption of water from deeper wells in these aquifers.

4. Effects of Changing Nutrient Loads

Evidence described in the previous chapter indicates that high nutrient loads, particularly nitrogen, from the Mississippi-Atchafalaya River Basin is a primary cause of hypoxia in the Gulf of Mexico. Actions to reduce these nutrient loads will cause changes in both the hypoxic conditions in the Gulf and water quality and land-use conditions within the Basin. This chapter presents projected effects over the next 10-20 years both in the Gulf and in the watershed:

- if there are no major changes in current activities or practices related to nitrogen loads, and
- if additional efforts are undertaken to reduce, mitigate, and control hypoxia in the Gulf.

EFFECTS IF CURRENT ACTIVITIES REMAIN UNCHANGED

Analyses supporting this assessment were based on data that were generally complete through the mid-1990s. Thus, the assessment of "current" activities is up-to-date only to about 1995 or 1996.

“No Loading Change” Scenario

Analyses presented earlier in this assessment show that Mississippi River nutrient concentrations and loadings, particularly nitrogen, to the northern Gulf of Mexico have changed dramatically this century, with an acceleration of these changes in the last four decades. However, nitrogen loading appears to have reached a plateau at the level of about 1.6 million metric tons/yr, which is the mean loading over the period 1980-96. If the set of activities that affect nutrient flux continues to prevent increasing trends, the current range of dimensions and severity of the hypoxic zone on the Louisiana shelf may be maintained. Hypoxia would vary depending on other factors, such as spring and summer stratification caused by fresh river water flowing over marine waters, weather patterns, temperature, and other physical factors in the Gulf and the Basin. However, even under these conditions natural variability could produce new extremes of hypoxia extent and impacts.

Nitrogen fertilizer use (together with mineralized soil nitrogen) constitutes about 58% of the input of nitrate to the MARB. Nitrogen fertilizer use in the Basin appears to have reached a plateau beginning in the 1980s, while phosphorus fertilizer use stabilized in 1980 and then dropped slightly. At the same time, both the rise in river nitrate concentration and the fall in silicate concentration ceased.

Agricultural policies and practices have changed over the last two decades so that both crop production and efficiency has increased. Average fertilizer use per acre of corn in the U.S. has been essentially constant since the late 1970s; however, corn yields have continued to climb, resulting in an increase in the bushels of corn produced per unit of fertilizer applied. According to comments from the Fertilizer Institute, farmers have also increased the amount of grain produced from 0.76 bushels per pound of nitrogen in the late 1970s to approximately 1.0 bushel per pound of nitrogen today -- a 32% increase in efficiency. A mass balance of nitrogen inputs and outputs to the Basin indicates that these have been approximately equal and at a steady state since about 1980 and may indicate that levels of nitrogen stored in the Basin ecosystem are no longer increasing as they did between 1955 and 1980 (see figure 4.1). However, even if pressures driving hypoxia do not increase, it is not known if significant changes in species abundance and composition or ecosystem function will result as a consequence of prolonged maintenance of the existing levels of hypoxia in the Gulf of Mexico.

FIGURE 4.1 – Cumulative residual (nitrogen inputs minus outputs) from nitrogen mass balance for the MARB

Under the "no loading change" scenario, if the Gulf of Mexico continues to experience a large zone of hypoxia each summer, then the area affected will continue to suffer from annual losses of biodiversity, abundance and biomass. The loss of harvest from the hypoxic region may, or may not, be offset by harvests from nonhypoxic waters. It is not known whether the northern Gulf can sustain this level of impact without observable reductions in overall fisheries production.

Not all nutrients entering tributaries within the Basin are transported to the Gulf. Substantial processing of nutrients occurs in the rivers and streams. Excess nutrients there can over-stimulate primary production, which commonly leads to impaired water quality. Most states in the Basin have substantial numbers of river miles that suffer use-impairment related to nutrient conditions or do not fully support the resource uses of aquatic life, fish consumption, swimming, and drinking-water supply. This situation is unlikely to improve without some changes in nutrient loading.

Increased Loading Scenario

Any "no loading change" scenario must assume that the anticipated increases in population growth, food production and fertilizer use, and changes in climate that will tend to exacerbate Gulf hypoxia will be offset by changes that tend to mitigate hypoxia (e.g., ongoing improvements in farming practices, better targeting of riparian and wetland restoration, and improved river flow management).

Pressures that drive hypoxic conditions are likely to increase. U.S. population and food demand are projected to continue to increase. Although yields may increase, it may be difficult to meet food demand without increased use of nitrogen fertilizer. Over the past decade the U.S. population has increased by 10% (Statistical Abstract 1998); middle series projections predict an 8% increase by 2010; and 17% by 2020. World population is expected to grow at 1.2% per year through 2010 according to the World Bank (World Development Indicators 1998), and the U.S. has provided a large percentage of the world's food, particularly grain.

The northern Gulf of Mexico is a coastal area that may experience increased freshwater runoff or greater extremes of influx as a result of global climate change. Streamflow was approximately 30% higher during 1980-96 than during 1955-70. Part of this increase may be due to long-term climatic variation, and some may be driven by shorter-term climatic cycles. The higher flows in the later half of the century are attributed to increased precipitation throughout the year and, in particular, to warmer, wetter springs. However the 30% increase in streamflow is small compared to the 300% increase in nitrate flux over this period.

The higher precipitation and streamflow in the later half of this century could influence nitrate flux in several ways. More nitrate would be transported with the larger volume of flow unless concentrations decreased more readily than flow volume increased. The higher precipitation could leach more accumulated nitrate from soils in the basin into tile drains and ditches, resulting in higher nitrate concentrations in streams. Higher streamflow would decrease the residence time of water in the river, reducing the rates of denitrification, burial, and uptake by aquatic plants and riparian vegetation. The resulting higher runoff in summer would most likely affect water column stability, surface productivity and oxygen cycling, leading perhaps to an expanded extent of the hypoxic zone.

Understanding the effects of hypoxia in other areas can aid in projecting effects in the Gulf of Mexico. Experience with other hypoxic zones around the globe shows that both the ecological and fisheries effects become progressively more severe as hypoxia worsens. Several large systems around the globe have suffered serious ecological and economic consequences from seasonal hypoxia. Most notable are the Kattegat, the Baltic and Adriatic Seas, and the northwestern shelf of the Black Sea. The consequences range from localized loss of target fish catch and recruitment failure (low numbers joining a population, generally due to low reproduction rates) to complete system-wide loss of fishery species. Where oxygen depletion is severe, the food web that supports bottom feeders such as shrimp and drum is disrupted, as well as the natural processing of organic matter, nutrients, and pollutants.

At first, the higher nutrient concentrations lead to increased production of both organic matter and fisheries. However, as organic matter production increases, changes occur in the food web that lead to different endpoints. These changes have followed the same path in many marine ecosystems.

FIGURE 4.2 -- Comparative evaluation of fishery response to nutrients based on data from around the world (redrawn from Caddy, 1993) -- Each curve represents a general guild of species and their reaction to increasing nutrient supplies. The top part of the figure lists recent trends for various systems around the world. Vertical dashed lines separate general categories of organic production that result from different levels of nutrients.

In the Gulf of Mexico region, Louisiana leads in production and landings of commercial and recreational marine fisheries which are dependent on conditions in the Gulf. The fishery resources of the Gulf are among the most valuable in the United States, generating $2.8 billion annually. Catch per unit effort for brown shrimp, one of the most commercially valuable species in the Gulf, has trended down since the late 1970s.

Other areas that have experienced severe hypoxia, with near-anoxic conditions, experienced greater mortality and had fewer species and lower biomass than areas with intermittent or less severe hypoxia. If experiences in other systems are applicable to the Gulf of Mexico, projections are that, in the face of worsening hypoxic conditions, at some point fisheries and other species will decline, perhaps precipitously.

The degree of ecological and economic effects related to hypoxia varies from system to system. For example, both ecological and economic effects of the combined problems of eutrophication and hypoxia have been seen in the Black Sea and Baltic Sea, where demersal trawl fisheries have been either eliminated or severely stressed. Initially in the Kattegat, hypoxia caused mass mortality of commercial and noncommercial species. Now large-scale migrations and/or mortality among demersal fish and the Norway lobster (*Nephrops*) continue, resulting in a changed species composition and reduced growth and biomass. Hypoxia in the Kattegat is believed to be partly responsible for the overall decline in stock size, recruitment, and landings of commercial fish over the last two decades.

Louisiana's commercial and recreational fisheries depend on species that have part of their life cycles within shallow continental shelf waters that often overlap the hypoxic zone. This is true not only for shrimp but also for the benthic organisms that form the forage base for valuable commercial and recreational species. Because shrimp must move from inshore wetland nurseries to offshore feeding and spawning grounds, hypoxia can block their migration. Spawning grounds, migratory pathways, feeding habitats, and fishing grounds of important species are affected by the extent and severity of hypoxic waters. Expansion of the hypoxic zone could lead to further decreases in productivity at higher levels of the food chain and loss of essential habitats.

Increasing nitrogen loads have decreased the silica- to- nitrogen ratio. Decreased silica availability in relation to increasing availability of other nutrients could stimulate blooms of harmful algae, such as dinoflagellates. On the other hand, *Pseudo-nitzschia* spp., a group of toxic diatoms that require silica, have increased in abundance in spite of silica decreases, likely in response to increasing nitrogen inputs from the Mississippi River.

EFFECTS IF REDUCTION MEASURES ARE UNDERTAKEN

Reducing sources of nutrients from the MARB may have as a primary goal decreasing the hypoxia problem in the Gulf of Mexico, but also will affect water quality conditions in the Basin itself. Although there are distinct differences between the nature of the responses to such reductions in the two systems, not surprisingly, there are also substantial similarities. In both the Gulf and the freshwater Basin area response variables of interest include various nutrient forms, chlorophyll, dissolved oxygen, water clarity, and planktonic and benthic biota, and higher organisms. However, the response variable of primary interest for hypoxia is dissolved oxygen in the bottom waters in the Gulf of Mexico.

Depending on the suite of techniques used to reduce loads (i.e., the mix of source controls, wetland restoration, and river management), a number of costs would be incurred, including those associated with higher material, equipment, and management costs of improved farming practices; loss of productive farmland; and increased treatment costs for municipalities and industry (air and wastewater controls). These costs would be offset by a number of benefits, including: improved water and habitat quality within the basin; reduced soil erosion; reduced contamination of drinking water by nitrates; improved water quality for recreational use; improved recreational fisheries and wildlife; cost-effective flood control improvements; restoration of critical coastal wetlands in Louisiana; and reduced risk to Gulf fisheries from catastrophic hypoxic/anoxic conditions.

Changes in the Gulf of Mexico

Simulations with a quantitative water quality model indicate that dissolved oxygen and chlorophyll concentrations on the Louisiana Inner Shelf do appear to be responsive to reductions in nutrient loadings from the MARB. However, there are large uncertainties in the magnitudes of these responses for a given nutrient loading reduction. For nutrient loading reductions of 20-30%, bottom-water dissolved oxygen concentrations were estimated to increase by 15-50% and surface chlorophyll concentrations were estimated to decrease by 5-10%. The ranges correspond to different assumptions for sediment responses and large-scale Gulf of Mexico water quality, and to different hydrometeorological conditions among different years. Both nitrogen and phosphorus loading reductions produced responses although, particularly for dissolved oxygen, the response was somewhat greater for nitrogen reductions.

There has been no statistically significant long-term trend in phosphorus flux to the Gulf for the period 1972-96. Over the past half century, phosphorus flux, a large portion of which is associated with sediments, has probably decreased. Nitrogen is the only component of nutrient flux that has increased. For nitrogen loading reductions of 30-50% (returning to the levels that existed in 1955-70), the model estimates that dissolved oxygen concentrations would increase by 20-75%.

There appears to be no evidence that the ecological changes related to hypoxia in the northern Gulf of Mexico at this point are irreversible. Experience has demonstrated that large ecosystems respond positively to nutrient reductions. Examples include Cheaspeake, Tampa, and Sarasota Bays. There are many examples of small-scale hypoxia reversals associated with improvements in treatment of sewage and pulp mill effluents. In the U.S., the improved water quality in Lake Erie is a good example of positive response to nutrient reductions but also a demonstration that the time interval for achieving noticeable improvements may be long, on the order of five to ten years after nutrients are reduced. Substantial nutrient reduction targets are being proposed for the drainage area of the Baltic Sea in order to control eutrophication (Jansson and Dahlberg 1999).

Changes in the Watershed

The most direct effect of actions to reduce nutrient loading to surface waters in the MARB will be to decrease concentrations and shift the composition of nutrients in its rivers and streams. The changes in nutrient concentrations and composition will induce other changes in trophic conditions and should result in Basin-wide improvements in surface-water quality. The extent of reductions achieved (and subsequently the effects) will depend on site-specific characteristics (climate, soils, cropping history), the types of improvements in management, and the baseline conditions to which the management improvements are being compared.

Aquatic macrophytes (such as duckweed, water lilies, and sedges) have important effects on water quality in shallow waters throughout the Basin. If reductions in nitrogen and phosphorus levels cause an increase in underwater light, submersed aquatic macrophyte distribution will expand in the Upper Mississippi River. The effects on water quality will be beneficial, both locally and system-wide. Increased macrophyte abundance may enhance nutrient retention significantly, leading to lower delivery rates of nutrients to the Gulf of Mexico than would otherwise be predicted for direct effects of source reductions.

Reductions in nutrient concentrations would not strongly affect sport fisheries because the rivers and streams in the Basin would most likely continue to be highly productive systems. Any decline that might occur in total biomass production would likely be more than compensated for by habitat and other improvements that would promote game fish over rough fish populations.

All the nutrient-reduction approaches considered, including steps to reduce nutrient losses from farmlands, reduce nutrient discharges from point sources, and increase natural processes to remove excess nutrients from surface waters, are expected to produce environmental benefits within the Basin. These include the values associated with restored wetlands, reduced soil erosion, reduced nutrient contamination of drinking water, reduced vulnerability to floods, better wildlife habitat, and improved recreational water quality. Other potential benefits of nutrient-reduction activities include more efficient use of organic and inorganic fertilizers and the energy associated with them, lower overall fertilizer costs, decreased health risk from contamination of public and private drinking-water supplies, and improved aquatic habitat in streams, lakes, rivers, and estuaries. All the approaches considered will also have associated costs, including costs for changes in land use; introduction of new technologies, such as precision agriculture and biological nitrogen removal; and implementation of improved management practices. The estimated economic costs of the various approaches to reduce nutrients are described in the next chapter.

5. Approaches for Reducing Nutrient Loads

This chapter deals with methods for reducing nutrient loads and their social and economic costs and benefits. Analysis of the causes of hypoxia in the Gulf of Mexico, as reported in chapter 3, indicates that nitrogen is the principal nutrient fueling excess organic matter sedimentation which, when stratified conditions exist, results in hypoxia. Thus, the primary approaches to reduce, mitigate, and control hypoxia in the Gulf of Mexico are:

- reducing inputs of nitrogen from farmlands, point sources, atmospheric deposition and other sources to streams and rivers in the Basin, and
- restoring and enhancing natural denitrification and nitrogen-retention processes to reduce nitrogen loads from the Mississippi and Atchafalaya Rivers to the Gulf.

Analyses of these options are organized around two levels of potential impact:

- reduction of total nitrogen loads to the Gulf of Mexico by 40% (approximately 625,000 metric tons/yr), to the average level that existed in the period 1955-70, and
- reduction of nutrient loads by approximately 20% as a middle option between reduction to historical levels and no reduction.

Precise estimates are difficult due to the complexity of the issues compounded by natural variability. For many aspects, available models offer only rough approximations.

REDUCING INPUTS

After a period of marked increase in nitrogen flux to the Gulf between 1970 and 1983, loadings have remained variable but without statistically significant trends, despite increasing agricultural production, increasing population, and other pressures in the Mississippi River Basin. Improved agricultural practices are probably the major contributors to keeping nitrogen loads from significantly increasing since the 1980s. Innovations by researchers, industry, and individual farmers have reduced nitrogen losses, in part to reduce fertilizer expenditures. Agricultural fertilizer's share of the nitrogen loading to the Gulf is estimated to represent a loss of $410 million annually (Downing et al. 1999).

Some reduction in nitrogen loads from municipalities could be achieved by the elimination of combined sewer overflows and the installation of biological nutrient control processes in new sewage treatment plants. While such sources are not the major contributor to the total nitrogen load from the Basin, they discharge directly to major streams, with little opportunity for natural treatment.

Reduction in discharges of nitrogen from farms to streams and rivers could be achieved by implementing a wide variety of changes in management practices, such as:

- limiting the application of nitrogen fertilizer and manure to agronomically recommended rates;
- switching from fall to spring application of fertilizer;
- better management of livestock manures, whether stored or applied to the land;
- changing from row-cropping to perennial-cropping systems;
- planting cover crops for fall and winter nutrient absorption;
- switching from conventional to ridge-tilling or other reduced tillage practices;

- increasing the lateral spacing of subsurface tile drainage to 20 meters, rather than the usual 5-10 meters;
- controlling water tables to promote denitrification within the soil column; and
- routing soil drainage effluent through wetlands, grass buffer strips, or riparian forest buffers.

Nitrification inhibitors for fertilizers, amino acid feed supplements, and other measures have also been suggested. For some of the above improved management practices, reduction in nitrogen losses to streams are on the order of 10-20% of baseline conditions, but others have been shown to reduce losses by as much as 90% in specific field studies (see #4 and #5 for details).

Of these measures, the three with greatest estimated potential to reduce nitrogen sources to streams and rivers are:

- Reduced application of nitrogen fertilizer -- This is estimated to offer the greatest potential reduction of nitrogen loading. By reducing “insurance” rates of nitrogen fertilizer[1], improving management of manure, applying appropriate credits for previous crops and manure, and using improved soil nitrogen testing methods, nitrogen losses at the edge of fields could be reduced by 10-15%, or about 0.9 to 1.0 million metric tons per year[2].

- Alternative cropping systems — If 10% of the corn-soybean farms in the Basin were changed to include alfalfa or alfalfa-grass mixes as crops, edge-of-field nitrogen losses could be decreased by an estimated 0.5 million metric tons per year.

- Improved management of feedlot runoff — A 20% decrease in feedlot runoff could decrease edge-of-field nitrogen losses by 0.5 million metric tons/year.

Measures to reduce nutrient loads would generally have net costs. Assuming constant levels of efficiency, large decreases in nutrient use below agronomic rates would lead to reduced agricultural productivity in the Mississippi Basin and reduced total production as marginally fertile land is retired. The agriculture sector’s response to these alternative management strategies was simulated with the U.S. Mathematical Programming Model for Agriculture (see box). The model predicts both the economic effects and the changes in nitrogen loading under the various scenarios examined**.**

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[1] Data on “insurance” application of nitrogen fertilizer, application at rates above agronomic recommendations, are sparse. “Insurance” application is an economic wager — in a good year, on a per acre basis, an extra 10-20 pounds of nitrogen fertilizer may result in 10-15 more bushels, worth $20-30. In practice, the Potash and Phosphate Institute reported nitrogen use on corn in Iowa in 1996 was within the range of agronomic recommendations when manure was not used but exceeded agronomic recommendations by more than 30%, or about 33 kg of nitrogen/ha (30 lb/acre) when manure was used.

[2] Note that these estimates of the impacts of changes in agricultural practices are for reductions at the “edge of field”; reduction of loadings to the Gulf of Mexico could be less, depending on the denitrification between the field edge and major rivers.

This model predicts that edge-of-field nitrogen losses can be reduced by 20% (941,000 metric tons/yr) at a total societal cost under economically optimum conditions of $831 million/yr, or $0.88 per kg reduction in edge-of-field nitrogen flux. Reduction in fertilizer use is less than optimum economically but less difficult, in concept, to implement. Achieving a 20% reduction in edge-of-field nitrogen loss would require a 45% reduction in fertilizer use, resulting in costs of $2.85 per kg of nitrogen reduction. However, smaller reductions would be more attractive on a per kg basis: 20% reduction in fertilizer would reduce edge-of-field losses by 503,000 metric tons/yr (about 10%) at a total societal cost of $347 million or $0.69 per kg. Fertilizer taxes were predicted to be economically inefficient, with a 500% tax required to reduce edge-of-field losses by 20%.

US Mathematical Programming Model for Agriculture (USMP)

Both the economic and environmental effects of agricultural changes were estimated using the USMP, a model developed by the USDA Economic Research Service for analysis of government commodity programs. The model calculates commodity prices and quantities, net returns to producers, net social benefits, and environmental emissions recognizing spatial variation and explicitly representing various management practices used by farmers. Adjustments to crop production can be estimated in response to restrictions placed on nitrogen or land use by altering any or all of the following: acreage planted, crop mix, rotations used, tillage practices, and fertilizer application rates (see #4, p. 27ff for details).

Nonagricultural, nonpoint sources of nitrogen also contribute to the total nitrogen load to the Gulf. Nitrate concentration in urban nonpoint sources are generally not high compared to urban point sources or cornbelt cropland. Urban areas constitute only 0.6% of the Basin, but improved management practices could provide cost-effective reductions in nitrogen load. Biological nitrogen removal from urban point sources typically costs $40/kg of nitrogen removed.

Reductions of atmospheric nitrogen emissions beyond those now being implemented are probably not warranted from the perspective of hypoxia in the Gulf of Mexico. Atmospheric deposition of nitrogen is estimated to be less than 1% of the nitrogen input to the Gulf from the Mississippi-Atchafalaya River Basin. The costs of reducing atmospheric deposition of nitrogen are estimated to be $20-100/kg of nitrogen.

Nitrogen trading among all sectors could offer opportunities to obtain least-cost reductions.

TABLE 5.1 – Potential Approaches to Reducing Nitrogen Inputs

Approach	Potential Nitrogen Reduction (Thousands of metric tons/yr)
1. Changing Farm Practices	
Nitrogen management (reduction in “insurance” rates of N fertilizer application, improved manure management, crediting of nonfertilizer nitrogen)	900 - 1,400[3]
Alternative cropping systems (Perennial crops in lieu of corn and soybeans on 10% of acreage)	500[4]
Decrease feedlot runoff by 20%	500[5]
2. Reduction in Point Sources	
Tertiary treatment of domestic wastewater	20

RESTORING AND ENHANCING DENITRIFICATION AND NITROGEN RETENTION PROCESSES

A second general approach to reducing nitrogen flux to the Gulf of Mexico is to place or restore ecosystems that are effective nitrogen sinks along the paths of nitrogen flow from sources to the Gulf. Nitrogen transformations in wetlands and riparian soils, surface water, and groundwater involve several microbiological processes, some of which denitrify, that is, make the nutrients effectively unavailable for plant uptake. Wetlands also serve as traps for phosphorus, which limits primary production within the Basin and, under some conditions, on the shelf in the Gulf.

High rates of denitrification are possible but wetlands and riparian zones can also act as sources of nitrogen under some conditions. Loading rates (flow times concentration of inflowing water) dictate the effectiveness of wetlands in reducing nitrogen. The most effective use of wetland restoration and creation would be in watersheds that discharge high amounts of nitrogen. Retention time is also important. Storm events, if significant enough, can cause nitrogen to shoot through the system, bypassing effective retention.

Extensive experience with flow-through wetlands suggests a narrow range centered around 10-25 g N/m^2/yr as a reasonable target for denitrification by wetlands. Assuming denitrification at 15 g N/m^2/yr, 2.1 million hectares (5 million acres, or 0.7% of the Mississippi River Basin area) of constructed or restored wetlands would reduce nitrogen load to the Gulf of Mexico by 20%. The current national goal is to restore wetlands at a rate of 100,000 acres/yr (about 40,000 ha/yr). The total direct costs for permanent easements and restoration of wetlands to reduce nitrogen load by 20% when selected at least cost was estimated to be $4.7 billion. Annual costs,

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[3] Note that these estimates of the impacts of changes in agricultural practices are for reductions at the “edge of field”; reductions of loadings to the Gulf of Mexico could be less depending on the denitrification between the field edge and major rivers.

including changes to consumer and producer surpluses plus annualized wetlands restoration costs, were estimated to be \$3.1 billion, or about \$8.90 per kg reduction in nitrogen flux per year. There would be ecological and wildlife benefits in addition to those that might accrue in the Gulf from using this approach.

Riparian areas are vegetated areas, mostly forested, next to water resources. They have been shown to be effective in removing nitrates from ground water as it passes beneath the vegetated buffer. Typically denitrification rates are 2-6 g N/m^2/yr. Assuming denitrification at 4 g N/m^2/yr, 7.8 million hectares (19 million acres, or 2.7% of the basin) of additional riparian buffers would be needed to reduce nitrogen load to the Gulf by 20%. A current national goal is to establish two million miles of conservation buffers on agricultural lands. Total direct costs for permanent easements and restoration of riparian buffers to reduce nitrogen load by 20% were estimated to be \$46.3 billion equating to \$18.0 billion annually in changes to consumer and producer surpluses plus annualized restoration costs, or about \$26 per kg reduction in nitrogen flux per year.

FIGURE 5.1 – Role of forested riparian buffers in trapping nutrients before entering streams

Separation of the Mississippi River from its deltaic plain may be an important factor in supplying nutrients to the Gulf. The river once spread out over the delta during flood periods. Today, however, with the exception of such locations as the Bonne Carre Spillway and the Atchafalaya Basin, the river is now mostly shunted directly to the sea. Through enhanced water management strategies, it may be possible to increase the amount of water reaching these coastal wetlands and thereby increase nitrate removal from the water and reduce coastal land loss. Using a denitrification rate of 10 g N/m^2/yr based on studies at Caernarvon, Louisiana, and other locations, diverting 13% of the total river flow over 500,000 hectares would remove 50,000 metric tons of nitrate per year. However, without upstream controls, the deltaic system might become nitrogen-saturated, or it might release nitrogen in a different form, in a different season, or in a different location. A recent study (Turner 1999) compared nutrient concentrations entering and leaving the Atchafalaya River basin, a major floodway used to divert floodwaters from the Mississippi and Red Rivers to the Gulf during the annual high-water season. This study found that nitrate concentrations remained essentially unchanged from upstream to downstream monitoring stations. Other studies have shown that harmful algal blooms may result when large quantities of Mississippi River water are diverted into coastal areas.

The construction and restoration of wetlands and riparian zones in the Basin to reduce nutrients would contribute to several important national goals, including those for drinking-water protection, adding to the nation's disappearing wetland habitat, improving river ecosystems, enhancing terrestrial wildlife in river corridors, and mitigating the effects of floods. This restoration of wetlands is in keeping with recommendations by the National Research Council's Committee on the Restoration of Aquatic Ecosystems (NRC 1992), which called for a national program of wetland restoration that would contribute to an overall gain of 10 million acres by the year 2010. Well-placed wetlands and riparian buffers generally support larger populations of wildlife because of the diverse habitats they provide. The restoration of riparian vegetation improves the ecological condition of streams and rivers and protects the aquatic communities that depend on them. Roots of riparian vegetation stabilize the stream bank and prevent both bank erosion and downstream sedimentation. The National Research Council also called for restoration of about 640,000 km (400,000 miles) of streams, rivers, and floodplains across the nation (NRC 1992).

FIGURE 5.2 – The role of riparian wetlands in capturing nutrients during flood events

TABLE 5.2 – Potential Approaches to Increasing Denitrification

Approach	Potential Nitrogen Reduction (Thousands of metric tons/yr)
1. Creating and Restoring Wetlands (Create and restore 5 to 13 million acres of new wetlands)	300 - 800
2. Creating and Restoring Riparian Buffers (Restore 19 to 48 million acres of riparian bottomland hardwood forest)	300 - 800
3. Diverting Rivers in Coastal Louisiana	50 - 100

COST- EFFECTIVE STRATEGIES

Various potential components of a program to reduce nitrogen loadings to the Gulf via the MARB system were analyzed to develop cost-effective strategies to achieve various levels of reduction, considering impacts upon the economy, farmers and consumers, and the reductions in loadings.

Direct costs, including changes in consumer and producer surpluses and easement and restoration costs for wetlands, were estimated using the USMP. All of the nutrient-reduction approaches will also produce environmental benefits within the drainage basin. These include the values associated with restored wetlands, reduced soil erosion, reduced nutrient contamination of drinking water, reduced vulnerability to floods, better wildlife habitat and improved recreational water quality. Other potential benefits of nutrient-reduction activities include more efficient use of organic and inorganic fertilizers and the energy associated with them, lower overall fertilizer costs, decreased health risk from contamination of public and private drinking-water supplies, and improved aquatic habitat in streams, lakes, rivers, and estuaries. Good estimates for the economic value of these benefits are only available for a few categories, such as wetlands and erosion. When these estimated benefits are factored in, the net costs of wetlands and farm practices become close. 20% edge-of-field nitrogen-loss reduction was estimated to have a net cost of $0.80 per kilogram ($0.36 per pound), while 5 million acres of wetlands would have a net cost of $1.00 per kilogram ($0.45 per pound).

TABLE 5.3 – Summary of Economic Costs of N-loss Reduction Actions

Scenario		N-loss Reduction (Thousand metric tons/yr)	Unit Cost ($/kg N-loss)	Net Cost ($/kg N-loss)
edge-of-field N-loss reductions				
20%		941	0.88	0.80
30%		1,412	1.90	1.80
40%		1,882	3.37	3.25
50%		2,352	5.20	5.08
60%		2,822	7.48	7.37
fertilizer reductions:	20%	503	0.69	0.67
	45%	1,027	2.85	2.81
500% fertilizer tax		1,027	14.54	14.50
wetlands	1M acres	67	6.06	- 2.19
	5M acres	350	8.90	1.00
	10M acres	713	10.57	2.81
	18M acres	1,300	11.93	4.27
riparian buffers (19M acres)		692	26.03	
river diversions to coastal wetlands		75	~6	
tertiary treatment of waste water		20	~40	

An optimal strategy would take appropriate advantage of the full range of possible measures to deal with hypoxia in the Gulf, including modification of farm practices, creation and restoration of wetlands and riparian ecosystems, implementation of nitrogen control on wastewater plants, and diversion of floodwaters to backwaters and marshlands of the Mississippi River delta and adjacent coastal wetlands.

Based on analysis and modeling of broad aggregates across the Basin, one illustrative approach to reduce nitrogen loss by 20% would be through a program of:

- 20% fertilizer use reduction, and
- 5 million acres of wetlands construction or restoration

This combination would produce costs and acreage impacts that would be relatively low, requiring smaller adjustments both inside and outside the MARB. However, broader combinations of carefully refined, targeted, and flexible variations on the full array of alternatives, in synergy with other programs, could improve cost-effectiveness.

The benefits of a program to reduce nitrogen loadings to the Gulf are difficult to calculate. Economic analysis failed to show direct effects on Gulf fisheries based on past data. The information is not available to estimate the benefit value for such actions as restoring the ecological communities in the Gulf or improving water quality in the Basin.

An effective program will require adaptive management. Hypoxia is a complex phenomenon, incompletely understood with numerous interacting variables, many of which are not controllable. Increases in population, with associated increases in food requirements, and domestic, commercial and industrial waste production changes would necessitate continued adjustments in programs.

Substantial time lags may also complicate management measures. Such time lags have two policy implications. First, observed ambient water quality conditions may be the result of past management practices or of sources that are no longer discharging. Second, the results of a program may not be immediately apparent, making it difficult to assess its actual effectiveness, and potentially difficult to maintain a consensus to sustain the program. Many people may suffer modest inconvenience or cost to try to improve the situation in the Gulf and may not see clear improvements for several years or longer.

6. Adaptive Management: Action, Monitoring and Research

This assessment of the causes and consequences of Gulf of Mexico hypoxia, and its analysis of options for dealing with it, are drawn from the assembly and peer review of a massive amount of direct and indirect evidence collected and reported over many years of scientific inquiry. The conclusions presented are thus well founded and grounded in those research and monitoring results. There are, however, always uncertainties in scientific analysis. This section identifies areas of further monitoring and research that are needed to reduce those uncertainties in future assessments and to aid decision making in an adaptive management framework

The complex nature of nutrient cycling and transport within the MARB and Gulf of Mexico make it difficult to predict specific improvements in water quality that will occur for a given reduction in nutrient inputs. Nutrient cycling is affected by atmospheric, watershed, riverine, and marine processes. Many of these processes, such as nitrogen transformations in river reaches, are not fully understood at the local scale at which they occur. Large-scale, multidisciplinary interpretations that integrate knowledge across these hydrologic compartments are difficult.

Further, it is clear that environmental responses to management actions in the MARB likely will be slow, possibly requiring decades of data to demonstrate statistically that remedial actions have helped the recovery of oxygen concentrations in the Gulf and have improved water quality in the Basin. For example, the nitrogen balance in the soil zone and ground water will adjust relatively slowly to changes in nitrogen inputs and outputs, slowing any change in the flux of nitrogen to the Gulf. At the same time, the flux of nutrients to the Gulf most likely will respond quickly and dramatically to large variations in precipitation and runoff -- further complicating measurement of reductions in nutrient flux.

A comprehensive program of monitoring, interpretation, modeling, and research to facilitate continual improvement in scientific knowledge and adjustments in management practices should be coupled to whatever initial nutrient management strategies are chosen. This adaptive management scheme involves continual feedback between interpretation of new information and improved management actions.

FIGURE 6.1 -- Adaptive Management Feedback Loop -- connecting the following 4 steps in a continuous process:

1. Monitor System Response;
2. Data Interpretation, Model Analysis and Improvement;
3. Model Prediction and Management Plan Improvement;
4. Implement Management Strategy)

MONITORING AND RESEARCH IN A MODELING FRAMEWORK

The adaptive management framework includes monitoring programs that use integrated models of the hydrologic and ecological systems for interpretation of system change. Whole-system monitoring will enable comprehensive interpretation of processes and linkages that affect nutrient concentrations and transport within the MARB and development of hypoxia in the Gulf. These coordinated monitoring efforts must be able to:

- Detect environmental trends to evaluate the effectiveness of management actions, to enable effective adaptation of strategies over time;
- Observe physical, chemical, and biological processes and their roles in the cause-and-effect relationships between nutrient inputs and resulting environmental quality; and
- Differentiate among trends caused by changes in climate, streamflow, nutrient and landscape management measures, and other concurrent factors.

An effective research strategy is also integral to the adaptive management framework. Coordinated research efforts improve monitoring designs, support the interpretation of monitoring output, and increase the predictive power of models and other assessment tools used in the management process.

For a system as large and complex as the Mississippi-Atchafalaya River drainage basin and the northern Gulf of Mexico, monitoring and research should be integrated using holistic models that simulate our understanding of how the overall system functions and how management practices can best be implemented. Such holistic models include a suite of conceptual, functional, and numerical formulations; integrate research findings; and are tied to monitoring programs designed to both provide input variables and verify model outputs. An effective modeling framework would include models that simulate:

- Transport and transformation of nutrients (nitrogen, phosphorus and silica) from natural, urban, and agricultural landscapes to ground water and surface waters;
- Inputs and outputs of nutrient flow throughout the landscape to improve estimates of nutrient mass balances;
- Biogeochemical cycling and water quality effects of those nutrients on river ecosystems within the drainage basin;
- Oceanographic and climate influences on those nutrients and their impacts on Gulf productivity as they leave the Mississippi and Atchafalaya River system; and
- Impact of increased nutrient flux on productivity in the northern Gulf of Mexico ecosystems, including commercially and recreationally important fisheries.

- Three dimensional coupling of biological and physical processes in the Gulf ecosystem influenced by the Mississippi River discharge.

Within this larger modeling framework, research and monitoring needs have emerged from this assessment. Monitoring gaps are found in environmental programs of the MARB and Gulf, as well as programs to monitor management measures. Research needs include improving the quantitative understanding of the biogeochemical cycling of nutrients within the watershed and the Gulf and its relationship to the dynamics of organic carbon flux in the Gulf; the roles of long-term change in climate, hydrology, and population in year-to-year and long-term trends in nutrient loads and hypoxia; and the social and economic impacts of various management and policy alternative strategies.

MONITORING NEEDS

A comprehensive monitoring program requires both measurement of environmental response in the MARB and the Gulf of Mexico and tracking indicators of programmatic progress toward mitigating excessive nutrients.

Environmental Responses in the Gulf - Essential components of an environmental monitoring program in the Gulf of Mexico include efforts to:

- Document the temporal and spatial extent of shelf hypoxia, and to collect basic hydrographic, chemical, and biological data related to the development and maintenance of hypoxia over seasonal cycles. A triad of mid-summer shelf-wide hypoxia surveys, monthly transects off Terrebone Bay, and instrumented arrays at stations in the core of the hypoxic zone would provide an optimal combination of spatial and temporal scales of measurement and be consistent with the existing long-term data. Establishing multiple vertical and horizontal instrument arrays oriented cross-shelf and along-shelf will better define processes that control the temporal and spatial development of hypoxia.

- Improve the collection of ecological, production, and economic information related to fishery and nonfishery species; and

- Facilitate synthesis and interpretation of these data through an integrated database.

Environmental Responses in the MARB - Essential components of an environmental monitoring program in the MARB include efforts to:

- Document the flux of nutrients, carbon, and selected other water quality constituents from the MARB to the Gulf of Mexico systematically on at least a monthly basis and more frequently at high flows -- at least 25-30 times annually. Additional monitoring sites in the main channel of the Mississippi River are needed to evaluate the extent of nutrient retention/loss within the lock-and-dam system, and to clarify the extent of nutrient retention in the Lower Mississippi.

There is a need to re-establish monitoring of nutrients, carbon, and selected other water quality constituents in the major sub-basins (the 42 interior basins) throughout the MARB and to establish monitoring in selected small basins within some of the 42 interior basins where the effects of changes in land management practices on nutrient concentrations and yields will be easiest to detect and quantify.

- Monitor nutrients from atmospheric wet deposition in the MARB, and expand the current limited monitoring of nutrients in atmospheric dry deposition. This information is needed to determine if nutrient management strategies affect precipitation chemistry.
- Establish a periodic inventory of effluent reporting conducted through the National Pollution Discharge Elimination System (NPDES) to systematically improve current estimates of nitrogen and phosphorus loads discharged to streams from municipal and industrial point sources.
- Improve measurements for soil nitrogen and nitrogen loss.

***Programmatic Measures* -** Ongoing programs are taking action to improve water quality conditions within the MARB and Gulf of Mexico. The following describes major measures of progress of those programs. Coordination of these and future programmatic actions to improve water and ecological conditions can increase their overall effectiveness in achieving goals.

- Inventory changing patterns in other nutrient inputs to the Basin, such as fertilizer use and manure application and disposal.
- Inventory acres of land leased through the Conservation Reserve Program and the Conservation Reserve Enhancement Program annually.
- Inventory acres of restored wetlands implemented through the Wetlands Reserve Program and the Emergency Wetlands Reserve Program.
- Inventory acres of riparian buffers implemented through the Conservation Buffer Initiative.
- Inventory acres of created or restored wetlands implemented through the various environmental restoration and related authorities, such as the Coastal Wetlands Planning, Protection and Restoration Act and the Partners for Fish and Wildlife Program.
- Inventory farmers' actions to reduce nutrient runoff stimulated by the Environmental Quality Incentive Program.

RESEARCH NEEDS

The research needs outlined below fall into two categories: (1) immediate priorities that are essential for designing near-term management actions, and (2) longer-term priorities that fill critical gaps in understanding as well as guide efforts to mitigate and control the effects of hypoxia and excess nutrients. These are outlined below and provided in the accompanying boxes.

Immediate Priorities

***Ecological Effects of Hypoxia* -** A better definition of past, current, and potential impacts from hypoxia on both commercially and ecologically important species and ecosystems is needed. New retrospective analyses over longer temporal and spatial scales, based on data from marine sediment cores should improve the historical perspective.

***Watershed Nutrient Dynamics* -** There is a need to better understand the dynamics and timing of movement of nitrogen and other nutrients from the "edge of field" in agricultural landscapes to small streams and tributaries. Additional information is also needed on the geographic distribution and design criteria for targeting wetlands creation and restoration efforts and to determine if other strategies (e.g., riparian buffers) and mixtures provide the best nitrate reduction for the least cost.

***Agricultural Practices* -** While improvements in agricultural practices have been achieved in recent years and the efficiency of nitrogen use has increased substantially, there is a need to better quantify the effects of on-farm practices and methods that intercept agricultural nutrients between the field and ground water and adjacent streams. There is also a need to better quantify and understand the economics associated with current and proposed policies (e.g., nutrient trading, fertilizer-use insurance) that increase incentives to reduce nitrogen loss.

Longer-term Priorities

Nutrient Cycling and Carbon Dynamics - Research is needed to better understand mineralization and immobilization processes, to develop better means for measuring the amount and forms of nitrogen in the soil reservoir, and to develop strategies to minimize leaching of nitrate from the soils to the streams. There is a need to better quantify denitrification and phosphorus retention rates in small and large streams and in Gulf sediments, and to compare these rates to those achieved in riparian buffers and wetlands. Further refinements of the relationships among nutrient fluxes, nutrient ratios, nutrient cycling, and organic carbon on the continental shelf in the Gulf are necessary.

Long-term Changes in Hydrology, Climate, and Population - The relationship between large-scale climate patterns and their potential impacts on river flows, nutrient flux, and flow dynamics on the continental shelf need further evaluation. Studies are needed to evaluate the potential role of flood prevention and control methods that seek to distribute and retain more floodwater within the basin and thus increase nitrogen retention, while protecting against flood damage. Future changes in management activities within the deltaic plain, such as the diversion of floodwaters to delta backwaters and coastal wetlands restoration, should be understood in the context of potential changes (both decreases and increases) in nutrient flux to the shelf.

Economics and Social Impacts - There is a growing need for an aggregated analysis of both direct (e.g., drinking-water protection) and indirect (increased recreation) improvements in water quality, for the basin as a whole. Additional work needs to be done to explore a broader range of ecological impacts, including potential impacts to biodiversity and to nonmarket- valued ecosystem goods and services. Better estimates of cost savings to agricultural producers from reduced fertilizer nutrient inputs are needed.

Immediate Priorities

Ecological Effects of Hypoxia

Contemporary effects - A better definition of past, current, and potential impacts from hypoxia on both commercially and ecologically important species and ecosystems is needed. Additional data sources have yet to be examined exhaustively, most notably the SEAMAP database, which includes long-term fishery-independent data on nektonic species' composition in the northern Gulf of Mexico ecosystem. Model analyses of trophic structure and ecosystem dynamics -- which will help identify affected fishery resources, and assess potential future impacts -- are also needed.

Historical perspective - The northern Gulf of Mexico ecosystem may have already undergone significant ecological change prior to initiation of the first in-depth scientific investigation in the mid-1980s. Thus, the system is likely in a transitional state as nutrient loading approaches new plateaus. Further research and assessment of these longer-term trends are needed. New retrospective analysis over longer temporal and spatial scales, based on data from marine sediment cores should improve the historical perspective.

Watershed Nutrient Dynamics

From "edge of field" to streams - There is a need to better understand the dynamics and timing of movement of nitrogen and other nutrients from the "edge of field" in agricultural landscapes to small streams and tributaries. This is especially true as it relates to tile drains and other practices that move nitrogen and other plant nutrients through the soil drainage system.

Wetlands creation - Additional information is needed on the geographic distribution and design criteria for targeting wetlands creation and restoration efforts. There is also a need to determine which other strategies (e.g., riparian buffers) and mixtures provide the best nitrate reduction for the least cost. It is important to understand and quantify the potential for changes in the production of the greenhouse gas N2O that could occur from wetland creation and restoration efforts.

Agricultural Practices

While dramatic improvements in agricultural practices have been achieved in recent years and the efficiency of nitrogen use has increased substantially, there is still room for continued improvement in these systems.

Watershed/farm-scale studies - There is a critical need to scale up from experimental plots to watershed/farm-scale studies falling into two classes. The first class includes studies to better quantify and demonstrate the effects of on-farm practices, such as "precision farming", altered lateral spacing of drainage tiles, controlled water table levels, use of fall and winter cover crops, altered timing of fertilizer application, and exploring alternatives to traditional crop rotations. The second class includes studies on better means to intercept agricultural nutrients between the field and ground water and adjacent streams through riparian buffers, wetlands, and other means.

Experimental policies and practices - Measuring and quantifying the effectiveness of recent policies and voluntary actions to reduce nutrient inputs should be coordinated on a basin scale. There is a need to better quantify and understand the impacts of current and proposed policies (e.g., nutrient trading, fertilizer-use insurance) that increase incentives to reduce nitrogen loss. Additionally, there is a need to evaluate how future policies or practices might best be implemented and administered under various institutional frameworks.

Longer-term Priorities

Nutrient Cycling and Carbon Dynamics

Soil organic nitrogen - Scientific investigations indicate that the soil zone is a huge storage reservoir of nitrogen. Both inputs to and outputs from this reservoir have increased dramatically in recent decades. Research is needed to better understand mineralization and immobilization processes, to develop better means to measure the amount and forms of nitrogen in the soil reservoir, and to develop strategies to minimize leaching of nitrate from the soils to the streams.

In-stream, in-river, and Gulf sediment denitrification - There is a need to better quantify denitrification and phosphorus retention rates in small and large streams and in Gulf sediments, and to compare these rates to those achieved in riparian buffers and wetlands.

Nutrient cycling in the northern Gulf of Mexico - Further refinements of the relationships among nutrient fluxes, nutrient ratios, and nutrient cycling on the continental shelf in the Gulf are necessary. Such refinements would improve simulations of subsequent effects on primary productivity, species composition, development of hypoxia, and higher trophic-level productivity in the Gulf ecosystem.

Organic carbon - There is a need to improve upon the characterization and potential role of both particulate and dissolved organic carbon, and to more fully quantify the relationship between this carbon and trends in river discharge which drive carbon transport to the bottom waters of the northern Gulf of Mexico. The subsequent comparison of this information with carbon from marine production (stimulated by river nutrients) will clarify the relative roles of river-borne nutrients and organic matter in the formulation of hypoxia.

Atmospheric Deposition - Additional research on atmospheric deposition of nitrogen in the Gulf is also needed to examine hypotheses that suggest this may be a larger input factor than presently estimated.

Long-term Changes in Hydrology, Climate, and Population

Large-scale climate effects - The relationship between large-scale climate patterns (e.g., long-term trends and changes in variability of precipitation) and their potential impacts on river flows, nutrient flux, and flow dynamics on the continental shelf need further evaluation. Changes in precipitation, temperature, and flow patterns may have significant long-term influence on the rate and pattern of nitrate flux within the basin, and on the physical constraints of nitrate assimilation in the northern Gulf. The potential effects of future global climate change on such large-scale climate patterns should also be taken into consideration.

Flood events - Episodic events, such as the Great Mississippi River Flood of 1993 have not only caused significant damage to life and property, but have also transported abnormally high quantities of nitrogen and phosphorus to the Gulf. Studies are needed to evaluate the potential role of flood prevention and control methods that seek to distribute and retain more floodwater within the basin and thus increase nitrogen retention, while protecting against flood damage.

Mississippi-Atchafalaya River delta management and restoration - Studies are needed to improve understanding of nutrient cycling in the deltaic plain in order to guide possible changes in management activities, such as the diversion of floodwaters to delta backwaters and coastal wetlands restoration.

Point-source and urban nonpoint source controls - The cost of nitrogen reduction from point sources and from urban nonpoint sources has been analyzed on the basis of existing technologies and human population densities. The potential for additional population and landscape changes to offset reductions achieved in nitrogen loading from the basin should be carefully evaluated.

Longer-term Priorities
(continued)

Economics and Social Impacts

Economic values of river and lake water-quality improvements - The benefits of reducing nutrient loads in the freshwater system are considered significant. A great deal of research into these benefits has been conducted. Most studies, however, have been site-specific and performed for selected watersheds or water uses. There is a growing need for an aggregated analysis of both direct (e.g., drinking-water protection) and indirect (increased recreation) improvements in water quality, for the basin as a whole.

Economic values of Gulf water quality improvements - To date only the potential direct economic effects of Gulf hypoxia on commercial fish catch have been attempted. Additional work needs to be done to explore a broader range of ecological impacts, including potential impacts to biodiversity and to nonmarket-valued ecosystem goods and services.

Economic Trade-offs in Agricultural Systems - Better estimates of cost savings to agricultural producers from reduced fertilizer nutrient inputs are needed. Similarly, better estimates of the social costs that could result from nitrogen management or reduction strategies (e.g., from dislocation in land use, agribusiness infrastructure, and farm communities) are needed.

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.

copepod: zooplankton whose bodies are covered with a hard shell or crust.

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).

denitrification: nitrogen transformations in water and soil that make nitrogen nutrients effectively unavailable for plant uptake, usually returning it to the atmosphere as nitrogen gas.

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

eutrophic: waters or soils that are high in nutrients; in aquatic systems, associated with wide swings in dissolved oxygen concentrations and frequent algal blooms.

eutrophication: an increase in the rate of supply of organic matter to an ecosystem.

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, generally less than 2 milligrams per liter.

mesotrophic: intermediate between oligotrophic (low nutrient) and eutrophic (high nutrient) systems.

nitrate: inorganic form of nitrogen; chemically NO_3

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 plants, including crops and phytoplankton.

oligotrophic: waters or soils that are poor in nutrients and have low primary productivity.

pelagic: living or growing near the surface of the ocean.

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

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

recruitment: the influx of new members into a population by reproduction or immigration.

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

riparian areas: vegetated areas, mostly forested, next to water resources.

senescence: the aging process in mature individuals; in plants, the process that occurs before the shedding of leaves

stratification: a multilayered water column, delineated by pycnoclines.

zooplankton: minute animal life that passively drifts or weakly swims in a water body, often feeding on phytoplankton.

References

Bierman, Victor J. et al 1994, A Preliminary Mass Balance Model of Primary Productivity and Dissolved Oxygen in the Mississippi River Plume/Inner Gulf Shelf Region, Estuaries 17(4) 886-899

Bricker, S. B. et al 1999, National Eutrophication Assessment: Effects of Nutrient Enrichment in the Nation's Estuaries, NOAA National Ocean Service, Silver Spring, MD, 71 pp.

Caddy, J. F. 1993, Toward a Comparative Evaluation of Human Impacts on Fishery Ecosystems of Enclosed and Semi-Enclosed Seas, Reviews in Fisheries Science 1(1) 57-95

Carey, Anne E. et al 1999, The Role of The Mississippi River in Gulf of Mexico Hypoxia, Report Number 70, Environmental Institute, University of Alabama, Tuscaloosa, AL

Diaz, R. J., and R. Rosenberg 1995, Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna, *Oceanography and Marine Biology: An Annual Review*. Vol. 33:245-303.

Dodds, W. K. et al 1998, Suggested Classification of Stream Trophic State: Distribution of Temperate Stream Types by Chlorophyll, Total Nitrogen, and Phosphorus, Water Research 32(5) 1455-1462

Downing, John A et al 1999, Gulf of Mexico Hypoxia: Land and Sea Interaction, Task Force Report No. 134, Council for Agricultural Science and Technology, Ames IA

EPA 1997, Proceedings of the First Gulf of Mexico Hypoxia Management Conference, December 1995, Gulf of Mexico Program Office, Stennis Space Center, MS

Jansson, Bengt-Owe and Kristina Dahlberg 1999, The environmental status of the Baltic Sea in the 1940s, today, and in the future, Ambio 28(4) 312-319

Jickells, T.D. 1998, Nutrient Biogeochemistry of the Coastal Zone, Science 281, 217-221

Justic, Dubravko et al. 1996, Effects of Climate Change on Hypoxia in Coastal Waters: A Doubled CO_2 Scenario for the Northern Gulf of Mexico, Limnology and Oceanography 41(5) 992- 1003

Justic, Dubravko et al. 1997, Impacts of Climate Change on Net Productivity of Coastal Waters: Implications for Carbon Budgets and Hypoxia, Climate Research 8, 225-237

Kunkel, Kenneth E. et al 1999, Long Term Trends in Extreme Precipitation Events over the Conterminous United States and Canada, Journal of Climate 12, 2515-2527

Meade, R. H. (ed) 1995, Contaminants in the Mississippi River, US Geological Survey Circular 1133, 140 pp

National Research Council 1992, Restoration of Aquatic Ecosystems, National Academy Press, Washington DC, 552 pp.

National Research Council 1993, Managing Wastewater in Coastal Urban Areas, National Academy Press, Washington DC

Nixon, Scott W. 1995, Coastal Marine Eutrophication: A Definition, Social Causes, and Future Concerns, Ophelia 41, 199-219

Ryther, J. H. and W. M. Dunstan 1969, Nitrogen, Phosphorus and Eutrophication in the Coastal Marine Environment, Science 171, 375-380

Statistical Abstract 1998

Turner, R. Eugene 1999, A Comparative Mass Balance Budget (C, N, P and suspended solids) for a Natural Swamp and Overland Flow Systems, pp. 61-71 in J. Vymazal (ed), Nutrient Cycling and Retention in Natural and Constructed Wetlands

USGS 1999, The Quality of Our Nation’s Waters: Nutrients and Pesticides, U. S. Geological Survey Circular 1225, 82 p.

Vitousek, Peter M. et al 1997, Human Alteration of the Global Nitrogen Cycle: Sources and Consequences, Ecological Applications 7(3) 737-750

World Development Indicators 1998, World Bank, Washington, DC