A Science Strategy to Support Management Decisions Related to Hypoxia in the Northern Gulf of Mexico and Excess Nutrients in the Mississippi River Basin

Prepared by the
Monitoring, Modeling, and Research Workgroup,
Mississippi River/Gulf of Mexico Watershed Nutrient Task Force

Circular 1270

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FOREWORD

Every summer, hypoxia affects the northern Gulf of Mexico, an area where approximately 40 percent of U.S. fisheries are located. The hypoxic zone is characterized by reduced sunlight and decreased oxygen levels in bottom waters. These conditions can lead to the loss of shrimp, crabs, zooplankton, and other important fish. Scientific evidence indicates that excess nitrogen from the Mississippi and Atchafalaya River Basins drives the onset and duration of the hypoxic zone. Concerns increased in 1993, when the size of the hypoxic zone reached 17,600 square kilometers, more than twice the average of previous measurements made since 1985. The hypoxic zone reached its maximum extent in 2002, when it measured 22,000 square kilometers.

The **Mississippi River/Gulf of Mexico Watershed Nutrient Task Force** was formed in the fall of 1997 to determine the causes and effects of hypoxia in the Gulf of Mexico, and to coordinate activities to reduce the size, severity, duration, and effects of the hypoxic zone. These activities address management of nutrients from all sources, restoration of habitats to trap and assimilate nutrients, and other water-quality activities that relate to eutrophication and hypoxia in the Mississippi River and Gulf of Mexico watersheds. The Task Force is working to improve water-quality conditions in the Mississippi River Basin, to reduce hypoxia in the northern Gulf of Mexico, and to improve the communities and economic conditions, with particular attention to the agriculture, fisheries, and recreation sectors, across the Mississippi/Atchafalaya River Basins.

Since its inception, the Task Force has met about twice a year. Through its Coordination Committee, composed of senior managers from Task Force member agencies, the Task Force has worked continually to facilitate communication and planning for coordination of agency activities and to make recommendations to the Task Force for their action. Significant accomplishments of the Task Force include development of a science assessment of the causes and consequences of hypoxia in the Gulf of Mexico, which compiles and presents scientific information upon which management action can be based, and development of the *Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico*, which brought member agencies to consensus on a management strategy.

Management action to mitigate hypoxia in the northern Gulf of Mexico and to improve water-quality conditions in the Mississippi River Basin requires a base of scientific knowledge encompassing geographic scales and scientific disciplines that is required by few other national environmental challenges. This report is a product of the Monitoring, Modeling, and Research Workgroup of the Task Force. It describes a framework for implementing monitoring, modeling, and research activities that was formulated by an expert team of scientists and managers from universities, industry, private organizations, and the Task Force agencies and that will provide a sound scientific basis for future management actions.

Charles G. Groat, Director
U.S. Geological Survey

ACKNOWLEDGMENTS

The authors are grateful to the numerous scientists and managers from universities, industry, private organizations, and government who contributed to the gathering of information for this report, for their enthusiastic participation in the technical workshop held in St. Louis, Missouri, on October 16-18, 2002, and for the follow-up that assured that the scientific basis for the consensus achieved at that workshop was incorporated into this document. The participants in that workshop are identified in Appendix II at the end of this report.

Contents

EXECUTIVE SUMMARY

This Monitoring, Modeling, and Research (MMR) Strategy was developed under the auspices of the Mississippi River/Gulf of Mexico Watershed Nutrient Task Force. It describes a framework for monitoring, modeling, and research activities that will support management decisions related to achieving the three major goals: improving water-quality conditions in the Mississippi River Basin, reducing hypoxia in the northern Gulf of Mexico, and improving the communities and economic conditions, in particular the agriculture, fisheries and recreation sectors, across the Mississippi/Atchafalaya River Basins. The Strategy describes the scientific information needed to support management actions and defines the scope, interrelation, and framework of the activities needed to provide that information. It describes existing programs and activities that contribute to the needed framework, identifies gaps and limitations in those existing activities, and outlines actions and resources needed to overcome those gaps and limitations. This information is provided in three areas of activities for both the Mississippi River Basin, including the Deltaic Plain, and the Northern Gulf of Mexico:

- Basin Monitoring and Reporting,
- Basin Modeling and Research,
- Basin Social and Economic Research,
- Gulf Monitoring and Reporting,
- Gulf Modeling and Research, and
- Gulf Social and Economic Research.

The Strategy also outlines mechanisms of coordination that are necessary to insure complete and timely transfer of the needed scientific information to decisionmakers and identifies resource needs required to provide the scientific information necessary to implement the Task Force Action Plan in a manner that enables management actions to adapt to new and changing scientific information. This Strategy is not an implementation plan and does not include a schedule of actions and associated costs for implementing those actions. It does provide valuable guidance to such an implementation plan.

Priorities for each of the major areas of activity are summarized as follows.

Priorities for Basin Monitoring and Reporting

- Adopt a four-level watershed monitoring system based on varying spatial scale and led by different levels of government, thereby providing critical information for assessing watershed nutrient loads, the fate and transport of nutrients within the watershed, the efficacy of approaches to reduce the nutrient loads in the Basin, and the delivery of nutrients through the Delta to the Gulf.
- Supplement existing monitoring efforts as described. Although monitoring of the largest rivers is on-going through the U.S. Geological Survey (USGS), priority for additional monitoring should be on smaller rivers and streams to enable an understanding of the sources of nutrients, processes that affect nutrient loading, and ways to reduce nutrient loading.
- Coordinate monitoring and reporting through leadership at the federal level. The USGS and U.S. Environmental Protection Agency (USEPA) should take leading roles in providing assistance to state and local agencies and groups that monitor water quality.
- Link watershed monitoring to management actions being taken on the landscape and to modeling efforts. Coordination with U.S. Department of Agriculture (USDA) and other federal, state, tribal, and local management programs is essential to gaining an understanding of nutrient sources and impacts of management actions on those sources.

Priorities for Basin Modeling and Research

- Coordinate existing research and modeling activities with local and regional water-quality concerns, issues and initiatives through Task Force, Sub-basin Committee, and state and local management entities. This will provide a broad information base for effective adaptive management at all levels.
- Establish new research projects in small- and intermediate-sized watersheds (level-3 and level-4 monitoring). Broaden

the environmental settings and spatial and temporal scales of these projects to enable investigation of the effects of natural and cultural factors on nutrient and sediment flux and for demonstrating approaches for spatially integrating research and modeling.

- Develop an integrated system of field-, watershed-, and basin-scale models through use of data from the proposed four-level monitoring framework and through refinement of existing statistical and mechanistic models. These models will enhance understanding of nutrient cycling and transport, provide context for more efficient collection and analyses of monitoring data, and improve upon existing evaluations of the effects of management activities on water quality.
- Evaluate and improve the effectiveness of the broad range of management technologies and practices available for controlling excessive nutrient and sediment loads in streams. Studies should include controls on nutrient loss from fields (e.g., cropping systems, cover crops, tillage systems, fertilizer application rates), methods to intercept nutrients, water, and sediment (e.g., tile-line bioreactors, riparian systems, surface and subsurface drainage control, wetlands, drainage ditch controls) in various climate, soil, and land-use settings, and coastal diversions of river flows in coastal Louisiana for land restoration.
- Quantify the rates of nutrient cycling in terrestrial and aquatic ecosystems and how these rates vary in response to changes in physical and biochemical properties of watersheds. This effort should include estimates of net changes in soil phosphorus and nitrogen in agricultural watersheds, nitrogen fixation by leguminous crops, denitrification in soils, and nutrient transformations and removal in streams, wetlands, riparian zones, reservoirs of varying sizes, and coastal diversions.
- Quantify the potential for the Mississippi River Deltaic Plain to process and remove excess nitrogen from Mississippi River water. The Louisiana coastal restoration program has amassed considerable relevant research and experience on nutrient dynamics in the Deltaic Plain that can provide the basis for management opportunities to reduce and intercept excess nutrients before they reach the Gulf of Mexico hypoxic zone. Supporting the Louisiana coastal restoration program will thus help add new and innovative management tools to work with nutrient management programs up river to address the hypoxia problem.
- Expand knowledge of the magnitude and timing of lags between changes in anthropogenic nitrogen and phosphorus inputs to watersheds and the downstream delivery of these nutrients to streams and larger rivers, through the Mississippi Delta system, and ultimately to the Gulf. This research will enhance understanding of mechanisms responsible for temporal lags in nutrient transport and improve estimates of the time required to observe the effects of management actions on nutrient flux in the Basin.

Priorities for Basin Social and Economic Research

- Evaluate how current policies and programs shape the management decisions made by agricultural producers.
- Evaluate what methods of policy change, outreach, and education are most effective in getting alternative nutrient management practices adopted by farmers.
- Assure that the current information bases are adequate for informing landowners in any part of the Basin on the best alternative practices for reducing nutrient pollution. Research data and actual experience should be used to back up claims and to fill gaps.
- Estimate benefits and costs associated with improving water quality in the Basin. Consider all secondary environmental benefits, including improved habitat, recreation resources, fisheries, and coastal land restoration. Costs include those to individual producers, rural communities, and local governments. This should be linked to a study in the Gulf itself.
- Gather existing information and fill information needs to support evaluation of the effects of management decisions on improving communities and economic conditions in the Basin with respect to agriculture, fisheries, and recreation sectors.

Priorities for Gulf Monitoring and Reporting

- Maintain existing monitoring of hypoxia distribution and development (shelf-wide, bimonthly and monthly transects, and moored instrumentation in core of hypoxic zone), and supplement these efforts for better temporal and spatial resolution. Increased shelf-wide surveys between May and September, and additional moored instrumentation are required.

- Expand current hypoxia surveys by increasing resolution and by including additional physical, biological, and chemical parameters, process rates, and by extending spatial boundaries as needed for modeling efforts.
- Insure thorough quality control and analysis of data collected during each federal and state SEAMAP fisheries-assessment cruise, as well as from historical cruises. Archiving these data and dissemination of results will maximize use of information related to the distribution of hypoxia and its effects on living resources.
- Coordinate efforts among state and federal agencies collecting data relevant to the distribution and development of hypoxia to eliminate any redundancy.
- Create a portal to maximize accessibility to, and exchange of, hypoxia data and information.
- Develop a matrix of agencies and their previous and current data acquisition and activities. From this, identify gaps in data, additional needed parameters, additional spatial and temporal resolution needs, mechanisms of data integration and quality control, and the lead agencies for coordination of data collection efforts and for coordination of data accessibility.

Priorities for Gulf Modeling and Research

- Perform integrated research to better understand and quantify the rates of biological, chemical, and physical processes that contribute to development of hypoxia.
- Develop a suite of models focused on predicting the spatial and temporal extent of hypoxia over the Louisiana continental shelf given varying levels of nutrient inputs and physical forcing, including varying freshwater inputs.
- Determine the short- and long-term, individual- and population-level effects of different spatial and temporal extents of hypoxia on ecologically and commercially important aquatic species.

Priorities for Gulf Social and Economic Research

- Amass economic data for the entire breadth of commercial and recreational fisheries in the Gulf. Currently, archival data are insufficient for evaluating the economic impacts of changes in fish landings associated with hypoxia.
- Collect water-quality measurements at spatial and temporal scales that encompass the full range of fishing activity in the Gulf. The restricted spatial and temporal scope of existing data collection limits the precision of the estimated economic impacts associated with hypoxia.
- Define sufficiently the effects of hypoxia on marine species and ecosystems for incorporation in fisheries economic models.
- Guide priorities for filling monitoring, modeling, and research gaps related to Gulf fisheries by (a) the degree to which a fishery is known or believed to be affected by hypoxia, and (b) the economic and social importance of the fishery.
- Fill data gaps for assessing the economic impacts of hypoxia on fishing communities, non-harvest users, and those that receive existence value from a healthy Gulf of Mexico resource base. Social and economic methods are available for assessing these impacts should these information gaps be overcome.

Priorities for Coordination and Information Needs

- Maintain coordination at the highest level, across all entities involved directly or indirectly in the Basin and the Gulf, management and scientific activities that support the Action Plan. It is the logical role of the Task Force to provide this coordination.
- Coordinate information needs between the Basin and the Gulf with respect to:
  - Monitoring activities and data,
  - Basin delivery to the Gulf, including the role of distributaries within the Delta,
  - Modeling activities, and
  - Social and economic considerations.

- Coordinate gathering of essential supplemental information from other Task Force Workgroups, including:
  - Inventories of implemented management actions, including key points of contact, from the Task Force's Management Response Workgroups;
  - Information on the specific approach and timing of the management implementation strategy from the Task Force's Management Implementation Workgroup;
  - Information on resource needs for coordinated management implementation and the associated science needs from the Task Force's Finance/Budget Workgroup; and
  - Information on new and effective management actions from the Task Force's Management Response Workgroups.

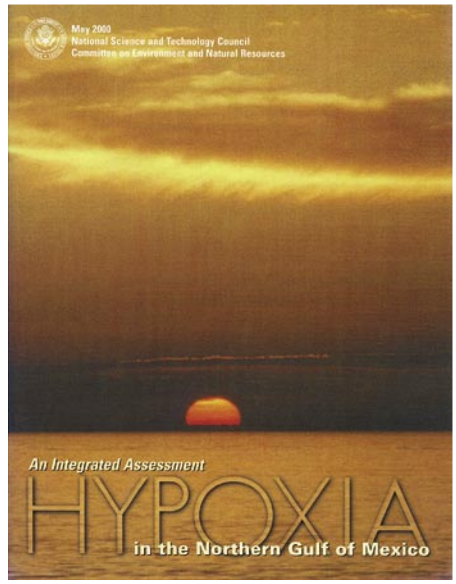
Priorities for Resource Needs

- New resources will be needed to plan, design, and implement the monitoring, modeling, and research activities outlined in this Strategy.
- Although the majority of new resources should be dedicated to incentive, restoration, and other management actions directed at improving environmental conditions, a proportionate fraction of new resources should be invested in monitoring, modeling, and research to develop new and improved scientific information that will enable continual improvement in management strategies and assure that specific resource investments are cost effective.
- Establish the minimal monitoring, modeling, and research activities required to develop a new baseline, analyze changes, and evaluate the efficacy of current management actions.
- Identify coordination and development of practical synergies among ongoing activities as a priority for new resources so as to avoid duplication of effort and maximize utility of existing programs.
- Refine long-term requirements for monitoring, modeling, and research frameworks.
- Develop a detailed implementation plan that identifies specific steps for implementing the monitoring, modeling, and research framework outlined herein, including the associated funding needs and anticipated benefits accruing to the proposed initiatives.

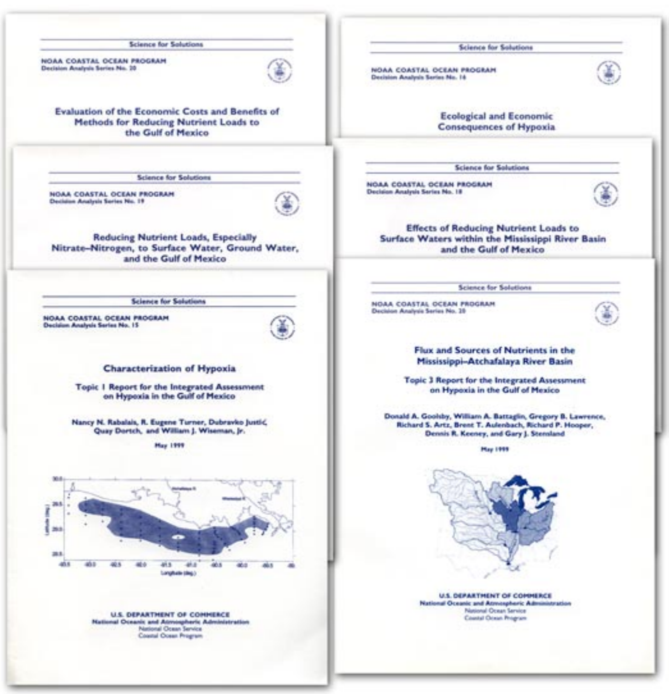
A SCIENCE STRATEGY TO SUPPORT MANAGEMENT DECISIONS RELATED TO HYPOXIA IN THE NORTHERN GULF OF MEXICO AND EXCESS NUTRIENTS IN THE MISSISSIPPI RIVER BASIN

INTRODUCTION

The activities undertaken to develop this Strategy have been conducted under the auspices of the Mississippi River/ Gulf of Mexico Watershed Nutrient Task Force (hereafter referred to as the Task Force). The Task Force was established in 1997 when representatives of states and tribes within the Mississippi River Basin joined the federal interagency working group considering options for responding to Gulf of Mexico hypoxia. A year later, on November 13, 1998, Congress enacted the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 ("HABHRCA," Title VI of P.L. 105-383, section 604(b)), which called for establishment of an interagency task force that would conduct a scientific assessment of causes and consequences of hypoxia in the Gulf of Mexico and develop a plan of action to reduce, mitigate, and control hypoxia. The Task Force responded to the charges of HABHRCA, and the National Science and Technology Council's Committee on Environment and Natural Resources (CENR) oversaw the assessment.



The Integrated Assessment



Technical Reports of the Science Assessment

The assessment was completed in May of 2000 when the report titled *An Integrated Assessment of Hypoxia in the Gulf of Mexico* (hereafter referred to as the Integrated Assessment) was published (CENR 2000). This report summarizes the findings of six peer-reviewed technical reports published as part of the assessment (Rabalais and others, 1999; Diaz and Solow, 1999; Goolsby and others, 1999; Brezonik and others, 1999; Mitsch and others, 1999; and Doering and others, 1999), as well as public comments. The Integrated Assessment describes the distribution, dynamics and causes of hypoxia; the sources and loads of nutrients transported by the Mississippi River to the Gulf of Mexico; the ecological and economic consequences of hypoxia; the effects of reducing nutrient loads; the methods for reducing nutrient loads; and the social and economic benefits of implementing such methods.

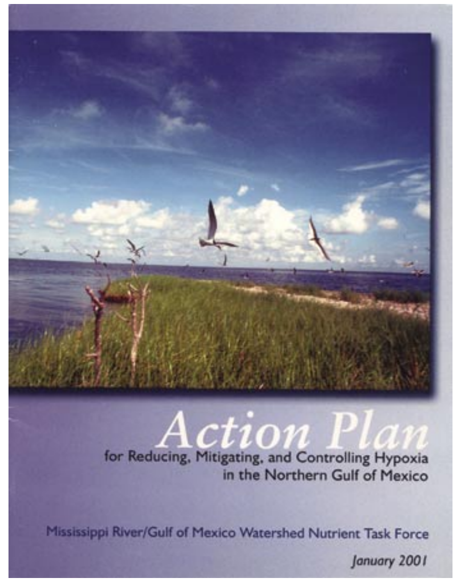
Utilizing the Integrated Assessment and several other reports, including *Gulf of Mexico Hypoxia: Land and Sea Interactions* (Council for Agricultural Science and Technology, 1999), *The Role of the Mississippi River in Gulf of Mexico Hypoxia* (Carey and others, 1999), and *Clean Coastal Waters: Understanding and Reducing the Effects of Nutrient Pollution* (National Research Council, 2000), the Task Force developed a plan to reduce the frequency, duration, size, and degree of the hypoxic zone in the northern Gulf of Mexico. The plan, titled *Action Plan for Reducing, Mitigating,* *and Controlling Hypoxia in the Northern Gulf of Mexico* (hereafter referred to as the Action Plan) was published in January of 2001. The Action Plan has three major goals: to improve water-quality conditions in the Mississippi River Basin, to reduce hypoxia in the northern Gulf of Mexico, and to improve the communities and economic conditions, in particular the agriculture, fisheries, and recreation sectors, across the Mississippi/Atchafalaya River Basins. These goals are based upon five principles: (1) Encourage actions that are voluntary, practical, and cost-effective; (2) Utilize existing programs, including existing state and federal regulatory mechanisms; (3) Follow adaptive management; (4) Base actions on “additional” appropriations beginning in Fiscal Year (FY) 2002; and, (5) Provide measurable outcomes as outlined below in the three goals and strategies.

The Action Plan also outlines 11 specific short-term actions, among which are actions calling for a comprehensive monitoring, modeling, and research strategy to guide proposed management actions. The strategy described herein, prepared by the Task Force’s Monitoring, Modeling, and Research (MMR) Workgroup, answers this call to develop a framework for implementing monitoring, modeling, and research in support of management actions related to the three goals of the Action Plan.

The MMR Workgroup (whose members are identified at the beginning of this report) is one of six workgroups established to guide implementation of the Action Plan. The MMR Workgroup gathered information for this Strategy from a broad range of technical and management specialists from state and federal governments, universities and other organizations. A key event in its development was a technical workshop held in St. Louis on October 16-18, 2002, which was organized around six major topical areas:

- Basin Monitoring and Reporting,
- Basin Modeling and Research,
- Basin Social and Economic Research,
- Gulf Monitoring and Reporting,
- Gulf Modeling and Research, and
- Gulf Social and Economic Research.

The discussion for each topical area was organized by a planning group that, prior to and during the workshop, developed information essential to their respective area. A writing team (also identified at the beginning of this report and comprised of the six planning group leaders and the workshop steering committee) drafted this Strategy based on the workshop proceedings. Global and specific management questions (Appendix I) for each of the three Action Plan Goals focused development of the Strategy on providing the scientific information that is most relevant to decisionmaking. The Task Force’s Management Implementation and Coordination Workgroup reviewed these questions, and additional revisions were made in response to discussions held during the workshop.



The Action Plan

Purpose of the Monitoring, Modeling, and Research Strategy

This report describes a framework for monitoring, modeling, and research activities that will support management decisionmaking related to achieving the three goals of the Task Force Action Plan and answer the associated global and specific management questions. This report inventories existing programs and activities that contribute to needed measures, identifies gaps and limitations in those existing activities, and outlines actions and resources needed to overcome those gaps and limitations.

The Strategy also outlines mechanisms of coordination that are necessary to insure complete and timely information transfer to decisionmakers and identifies resource needs. It identifies the means to coordinate activities of ongoing programs so as to minimize duplication of effort and increase

Task Force Workgroups

- Management Implementation and Coordination *
- Finance/Budget
- Monitoring, Modeling, and Research
- Management Response:
  - Point Sources
  - Nonpoint Sources
  - Restoration

* Also referred to as the Coordination Committee, which staffs the Task Force.

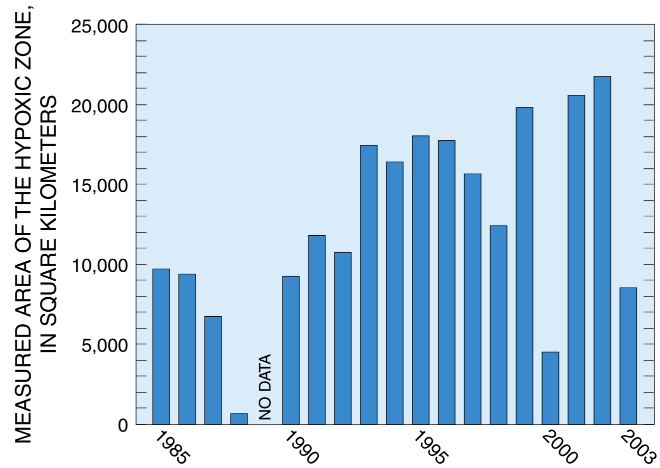
> **ACTION PLAN GOALS**
>
> *Coastal Goal:* By the year 2015, subject to the availability of additional resources, reduce the 5-year running average areal extent of the Gulf of Mexico hypoxic zone to less than 5,000 square kilometers through implementation of specific, practical, and cost effective voluntary actions.
>
> *Within Basin Goal:* To restore and protect the waters of the 31 states and tribal lands within the Mississippi/Atchafalaya River Basin through implementation of nutrient and sediment reduction actions to protect public health and aquatic life as well as reduce negative impacts of water pollution on the Gulf of Mexico.
>
> *Quality of Life Goal:* to improve the communities and economic conditions across the Mississippi/Atchafalaya River Basin, in particular the agriculture, fisheries and recreation sectors, through improved public and private land management and a cooperative, incentive based approach.

compatibility of information. It suggests practices for data handling and synthesis that facilitate information sharing and periodic reporting. This Strategy is not an implementation plan and does not include a schedule of actions and associated costs for implementing those actions. It does provide valuable guidance to such an implementation plan as well as guiding current activities and increasing coordination among agencies within existing resources.

Hypoxia in the Northern Gulf of Mexico and Water Quality in the Mississippi River Basin

Hypoxia occurs in the Gulf of Mexico when oxygen concentrations fall below the level necessary to sustain most animal life. Hypoxia results when oxygen consumption, caused by the decomposition of organic material, exceeds oxygen production through photosynthesis and replenishment from the atmosphere. While organic matter can be supplied from external sources, such as river inflow, hypoxia in the northern Gulf of Mexico is caused primarily by algal production stimulated by excess nitrogen delivered from the Mississippi-Atchafalaya River Basin and seasonal vertical stratification of incoming streamflow and Gulf waters, which restricts replenishment of oxygen from the atmosphere (CENR, 2000, p. 2).

Measured Area of the Hypoxic Zone (in square kilometers)

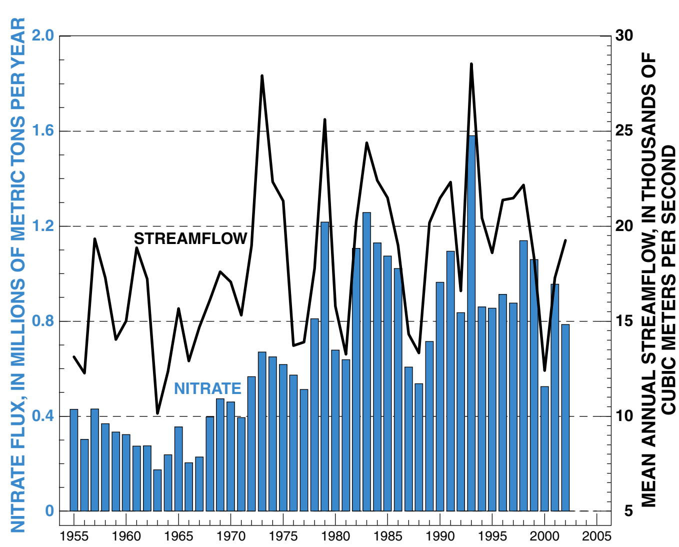


Source: Nancy Rablais, Louisiana Universities Marine Consortium

Since 1993, the average extent of mid-summer bottom-water hypoxia in the northern Gulf of Mexico has covered approximately 16,000 square kilometers, approximately twice the average size measured from 1985 (when measurement started) to 1992. The hypoxic zone attained a maximum measured extent in 2002, when it was about 22,000 square kilometers – larger than the size of the State of Massachusetts.

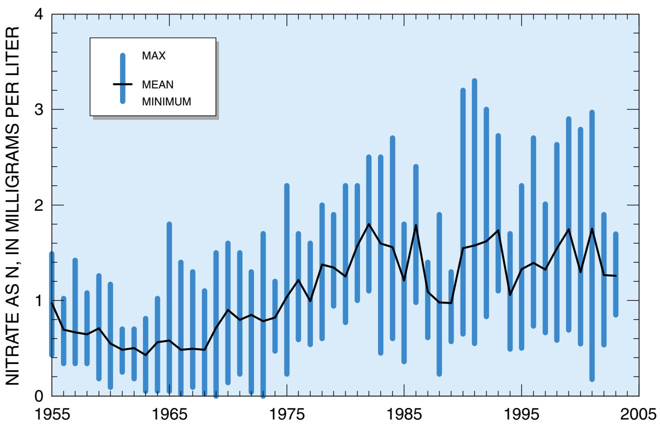
Excess nutrients enter stream waters within the Basin from a variety of sources, including municipal and industrial point-source discharges, atmospheric deposition, and a wide range of nonpoint sources, such as urban and agricultural runoff and drainage. Loss of Basin and Delta wetlands and riparian vegetation has substantially reduced the system’s potential to remove nutrients once they enter streams and the Mississippi River itself. Excess nutrients in stream waters can

Mississippi River Basin Nitrate Load and Streamflow Delivered to the Gulf of Mexico



Source: U.S. Geological Survey

Mississippi River Basin Nitrate Concentrations in Streamflow Delivered to the Gulf of Mexico



Source: U.S. Geological Survey

> **Short Term Action #2:** By Summer 2001, states and tribes in the Basin, in consultation with the Task Force, will establish sub-basin committees to coordinate implementation of the Action Plan by major sub-basins, including coordination among smaller watersheds, tribes, and states in each of those sub-basins;
>
> - *The Action Plan, p. 13.*

result in eutrophication. Excess algal growth threatens healthy wildlife habitat and recreational water use and increases water treatment costs. Nitrate loads at the mouth of the Mississippi River, which have increased approximately three-fold since about 1970, are an indicator of water-quality conditions within the Basin, as well as delivery to the Gulf. This increase in loads is attributed to both an increase in streamflow and an increase in the concentration of nitrate in streamflow. Streamflow has increased by approximately 15 percent since 1970, whereas nitrate concentrations have increased two-fold during the same period.

Relation to Management Action

The complex processes that affect the sources, transport, and cycling of nutrients within the Basin and Gulf make it difficult to design a single, specific course of action to achieve the desired improvements in water quality called for in the Action Plan. Although the current understanding of the causes and consequences of Gulf of Mexico hypoxia is drawn from substantial direct and indirect evidence collected and reported over many years of scientific inquiry, significant uncertainties remain. Furthermore, actions designed to improve water-quality conditions within the Basin, can take many forms and must be driven by varying local issues. Although environmental response to management actions in small watersheds where the actions are implemented may be observed in a relatively short timeframe, environmental responses in receiving waters that may be well downstream and that integrate large upstream areas likely will be substantially slower. Observed recovery of oxygen concentrations in the Gulf may take decades. Continued and improved monitoring, modeling, and research are needed to reduce uncertainties and to aid decisionmaking over time. For these reasons, the Action Plan called for an adaptive management approach, whereby management actions are continually evaluated and improved by analyzing and applying relevant, interdisciplinary, and timely scientific information. The adaptive management framework presented in the Action Plan involves ongoing feedback between interpretations of new information to reassess management performance, use of models to predict system response and design improved management actions, and implementation of indicated adaptive management actions. To support that approach, the Action Plan includes a specific action to develop this MMR Strategy.

> This plan describes an adaptive approach, based on implementation, monitoring, and research to address known problems, clarify scientific uncertainties, and evaluate the effectiveness of efforts to reduce hypoxia.
>
> - *The Action Plan, p. 4.*

A Hierarchy of Scales - The Action Plan set goals at the Basin-Gulf scale but based implementation on sub-basin management strategies by calling for states and tribes in the Basin, in consultation with the Task Force, to establish sub-basin committees within the Basin. These sub-basin committees will coordinate implementation among smaller watersheds, tribes, and states by using existing programs; by encouraging actions that are voluntary, practical, and cost-effective; and by providing measurable outcomes consistent with the major goals of the Action Plan. The MMR Strategy supports this hierarchy of approaches by recommending the development of necessary scientific information to support decisionmaking across an extreme range of scales from the Mississippi River and Gulf of Mexico watershed to the major sub-basins identified by the Task Force and to smaller watersheds at which state, tribal, and other entities implement management programs.

Other Publications

Other publications that served as resources, and provided context during development of this publication, and will provide insights for future monitoring, modeling and research activities to support the Task Force include an assessment of hypoxia in coastal waters conducted under the auspices of the National Science and Technology Council's Committee on Environment and Natural Resources (CENR 2003), titled *An Assessment of Coastal Hypoxia and Eutrophication in U.S. Waters*; a report compiled by National Oceanic and Atmospheric Administration, National Science Foundation, U.S. Department of Agriculture, and U.S. Geological Survey that identifies key research needs for better understanding and managing coastal nutrient pollution (Howarth and others 2003), titled *Nutrient Pollution in Coastal Waters: Priority Topics for an Integrated National Research Program for the United States*; and the Preliminary report of the U.S. Commission on Ocean Policy Governors' Draft, April 2004.

Other recent reports

MONITORING, MODELING, AND RESEARCH IN THE MISSISSIPPI RIVER BASIN

The strategy for science activities in the Mississippi River Basin is described in the following three sections: Basin Monitoring and Reporting, Basin Modeling and Research, and Basin Social and Economic Research. Issues related to coordination among Basin and Gulf activities and resource needs are discussed in the section *Coordination and Information Needs* near the end of this report.

Basin Monitoring and Reporting

Needed Framework for Monitoring and Reporting

A telescoping structure for monitoring, with four levels based on different geographic scales, is needed to provide the information across the broad range of spatial and temporal scales required to address management questions for the Basin. Spatial scales vary from basin-wide monitoring near the Mississippi and Atchafalaya River deltas to monitoring of individual watersheds where best management practices or other nutrient management actions would be implemented. Although annual basin-wide nutrient loads have been reported and monthly sampling occurs at the largest spatial scales, frequent sampling at all scales is critical to understanding nutrient sources, loadings and transport mechanisms, and sinks. Monitoring at different scales would provide data critical to the understanding of the physical, chemical, and biological processes that influence nutrient delivery to, transportation and alteration within, and export from the watersheds within the Mississippi–Atchafalaya River Basin. Understanding nutrient sources and loads and the effectiveness of management actions can be determined only by sampling at different geographic scales.

In recognition of the limited resources available to support monitoring, reliance on existing monitoring and the strategic enhancement of the monitoring that could be accomplished with modest additional resources and a greater level of partnerships and coordination must be stressed. The monitoring must include flow measurements along with measurement of nutrient concentrations and related parameters with sufficient frequency to enable seasonal loads to be determined accurately. The most successful approaches to modeling will build upon existing networks operated or supported by the USGS and state and local agencies, and will broaden the suite of monitored constituents to provide a greater understanding of nutrient sources and sinks within the Basin and the delivery of nutrients through the Delta to the Gulf of Mexico.

The responsibility for monitoring changes with spatial scale, from the federal agencies to state, tribal, and local agencies and non-governmental groups. Federal agencies have unique capabilities to monitor large rivers, whereas state and local groups do much of the monitoring of smaller rivers, streams, wetlands, and estuaries as part of their responsibilities related to the Clean Water Act. The increasing number of monitoring partners from the broadest to the smallest geographic scales increases the attendant challenges associated with coordination. In addition, the historical length and uniformity of baseline data are generally reduced when moving from large to small scales.

Coordination of data collection protocols and data sharing are critical to the success of any monitoring plan over an area the size of the Mississippi-Atchafalaya River Basin. Leadership by the USGS and USEPA is essential for coordinating the water-quality monitoring requirements among other federal agencies and the various state, tribal, local, and non-governmental organizations.

The needed monitoring framework should include four levels, distinguished largely by a range in spatial scale.

Level 1 - The broadest scale of monitoring provides the critical link between the Mississippi River Basin and the Gulf of Mexico by providing frequent data on the fluxes of nutrients and a broad suite of constituents from the Basin to the Gulf. The USGS currently provides this monitoring at the Mississippi River at St. Francisville, Louisiana, and the Atchafalaya River at Melville, Louisiana (a distributary of the Mississippi River). The data collected provide a measurement of nutrient load, discharge, and related parameters at least once a month, with more frequent monitoring during the spring when nutrient loading is most critical to primary productivity in the Gulf. Monitoring at these sites should provide the information needed to explain the relation between changing flows and nutrient loads from the Basin to the extent and duration of hypoxia in the Gulf. These data provide a major input to Gulf hypoxia models and support statistical modeling of the relation between nitrogen fluxes to the Gulf and the variables such as loads, nutrient concentrations, and other parameters.

Monitoring at this level should occur at least monthly, with additional measurements in the spring when nutrient loading to the Gulf is most critical to the formation of hypoxia. These measurements should be flow-weighted, provide adequate representation of periods of both low and high flow, and include sampling for analysis of major dissolved and whole-water constituents. At a minimum, constituents monitored should include nitrogen, phosphorus (both organic and inorganic forms), organic carbon, and dissolved silica. If key correlations between parameters can be determined, a surrogate constituent could be identified and its sampling frequency could be increased, yielding an overall reduction of the total individual constituents monitored. Such sampling could provide more temporal information to modeling efforts in both the Mississippi River Basin and the Gulf.

The capability to implement real-time monitoring should be evaluated. Substantial value can be gained from characterizing detailed temporal variations in loads to the Gulf and using these data during the periods immediately preceding seasonal expansion of the hypoxic zone to develop model predictions of the size of the hypoxic zone and cause-and-effect relations.

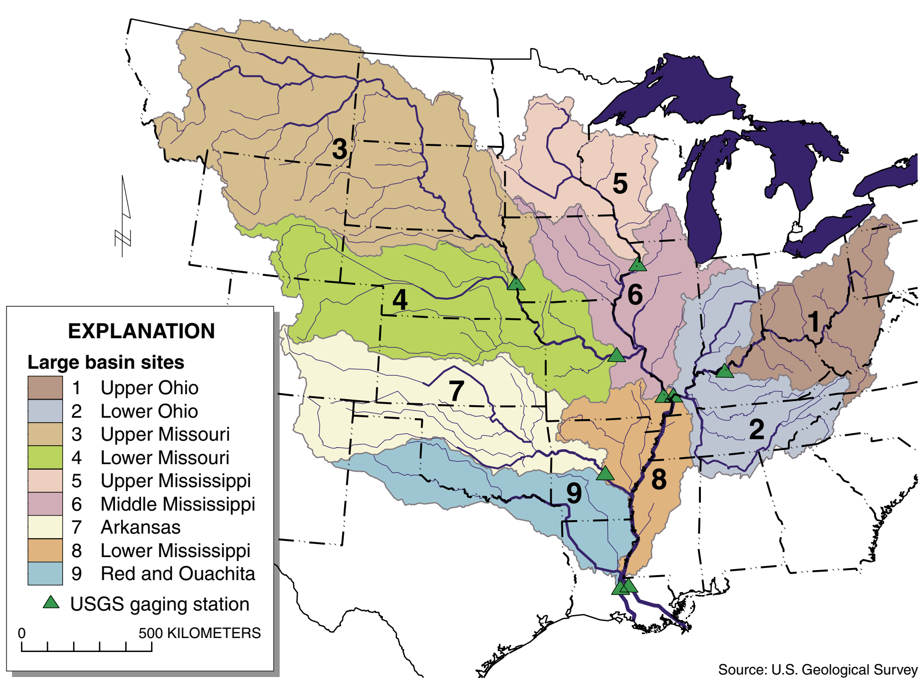
The monitoring stations at St. Francisville, Louisiana, and the Atchafalaya River at Melville, Louisiana, are located far upstream from where streamflow enters the Gulf. As a result, there is the potential to incorrectly estimate the actual nutrient loading to the Gulf. For example, on the main channel of the Mississippi River downstream from St. Francisville, there are large municipal and industrial point-source dischargers of nutrients to the river, and on the Atchafalaya River, the Atchafalaya Swamp, which may account for considerable nutrient uptake and transformation, is downstream from Melville. In addition, the beneficial effects of future efforts downstream from St. Francisville to restore coastal land losses, including large-scale river diversions into coastal wetlands and estuaries, and voluntary industrial nutrient pollution prevention, will not be accounted for in the St. Francisville data. Although some monitoring has been conducted downstream from these long-term monitoring stations, no systematic monitoring system is in place to assure that the delivery of nutrient loads to the Gulf are accurately characterized.

Monitoring within the Delta is discussed in level 4, primarily because state and local diversion programs drive this monitoring.

Level 2 - The next level of monitoring consists of measurements of nutrient and other fluxes in major sub-basins within the Mississippi River Basin. These measurements address questions about the variations in loads observed at the mouths of the Mississippi and Atchafalaya Rivers and support the sub-basin planning and management activities proposed in the Action Plan. This monitoring is best accomplished by the federal agencies because of the challenges of collecting data on such large rivers. Current monitoring at seven additional sites, conducted by the USGS, fulfills this requirement. Because of the need to study trends and to understand the roles and processes that affect nutrient loads, this monitoring must also include a broad range of physical and chemical water-quality parameters. Loads are required on both annual and shorter time frames. Stream gages are required at these sites. The measurements made and the frequency and schedule of measurements at this level should correspond to that of level 1 so that the linkages between levels 1 and 2 can be explained.

Level 3 - The Mississippi-Atchafalaya Basin consists of approximately 130 smaller sub-basins (roughly corresponding to six-digit Hydrologic Unit Codes). Not all of these basins must be monitored, but a sufficient number of representative basins should be monitored to address questions related to climatic variation, land use and land-use changes, sources of nutrients, ecological variations, varying types of management actions, and factors that affect the time lags related to nutrient movement and management action. This monitoring needs to provide broad geographic coverage of representative sites within the Basin to allow resolution of these issues and to provide baseline data against which to measure change at both larger (level 2) and smaller scales. Monitoring at this spatial scale is currently inadequate, but significant synergies could be realized by federal coordination of state and tribal programs, through augmentation of existing activities to satisfy data-collection frequencies and protocols. The adoption of water-quality standards for nutrients to prevent eutrophication

Nine Large Sub-Basins Monitored Currently by USGS



Source: U.S. Geological Survey

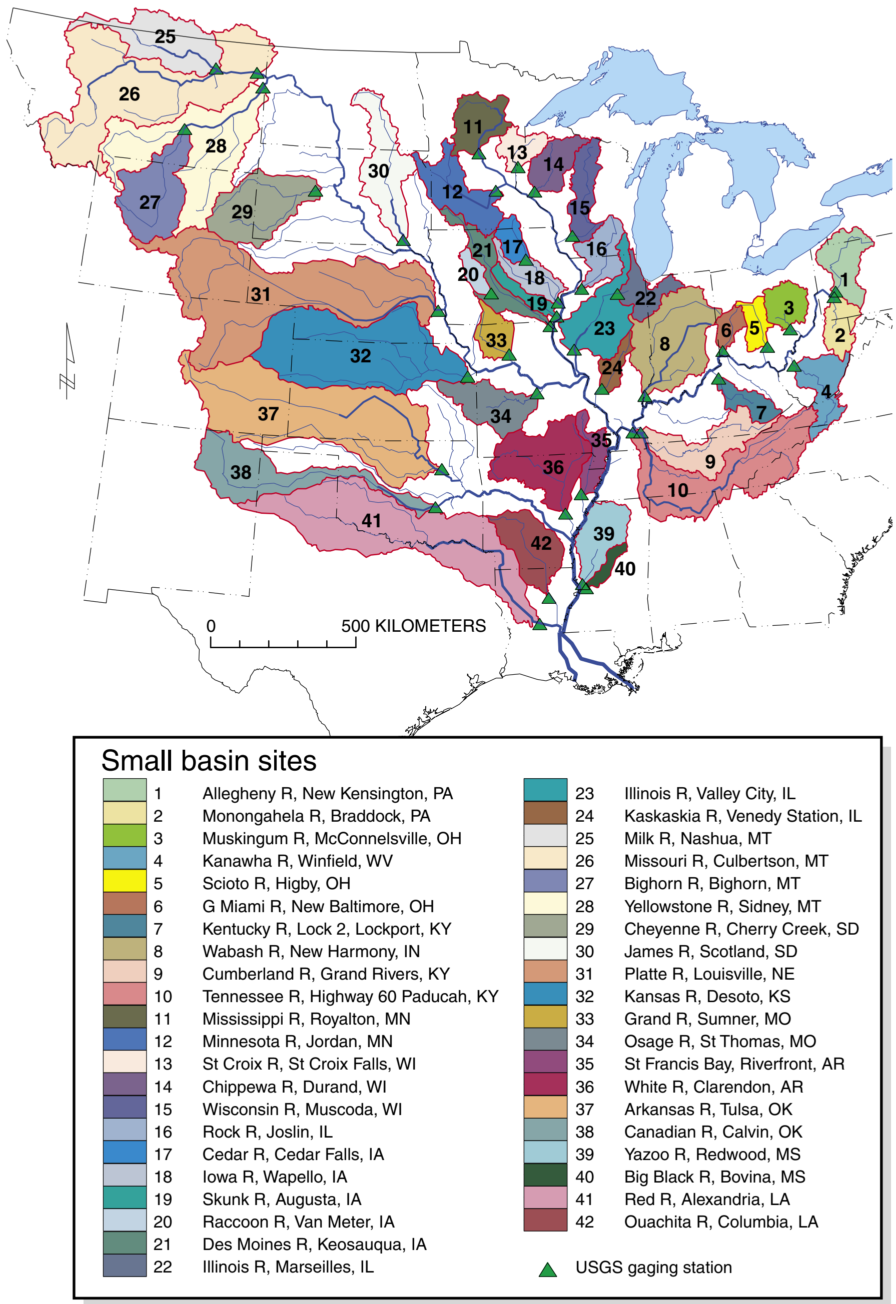
could provide added incentives for monitoring of nutrients within states. Streamflow data should be collected along with water-quality data at these sites to enable determination of loads as well as concentrations. Although both dissolved and whole water analyses are desired, this may be the level at which compromises in the completeness of the suite of parameters measured may be desirable in order to collect data at more sites.

Ideally, total nitrogen and phosphorus species including dissolved and particulate, and organic and inorganic species should be determined. In addition, silica and dissolved and suspended organic carbon should be determined. Such a broad analysis of species present in water is desirable because it can reveal much about the source and transport mechanisms of nutrient loads.

The federal lead agencies should coordinate efforts to standardize protocols for data collections with the state and tribal water-quality agencies. A group such as the Association of State and Interstate Water Pollution Control Administrators (ASIWPCA) could provide a forum for review and approval of these protocols. In addition, data from groups such as the Ohio Tributary Monitoring Program at Heidelberg College should be included in the analyses. Such programs offer insight into interpreting data from less frequently sampled sites, and may offer very high frequency measurements at critical times.

Level 4 - The final scale of required monitoring is at the smallest geographic scale and presents the greatest challenges. The purpose of monitoring at this level is to evaluate the effectiveness of specific management actions and to improve understanding of the processes that affect downstream transport to the larger basins. Generally, monitoring at this scale has been driven by local requirements of the federal Clean Water Act, which requires that states report to Congress on the quality of the Nation's waters and impaired resources. Also included are monitoring of pilot or demonstration projects, such

During 1980-96, USGS Measured Nutrients on 42 of 133 Small Mississippi Basin Sub-Basins



as watershed management projects or coastal diversion projects, and monitoring to address Total Maximum Daily Load (TMDL) calculations on impaired watersheds. There is a need to expand the applicability of existing monitoring at this scale to enable analysis in aggregate. Similarly, monitoring within the Delta will need to be coordinated to provided a comprehensive assessment of nutrient losses and gains and the spatial and temporal distributions of delivery to the marine environment. The challenges, however, to creating useful information from monitoring at this scale are significant. Coordination among monitors, modelers, and those implementing management actions is important and will likely require coordination at the state or federal level. Another challenge will be collecting the monitoring information in a computer or data system in order to make the data available to all studying nutrient loading.

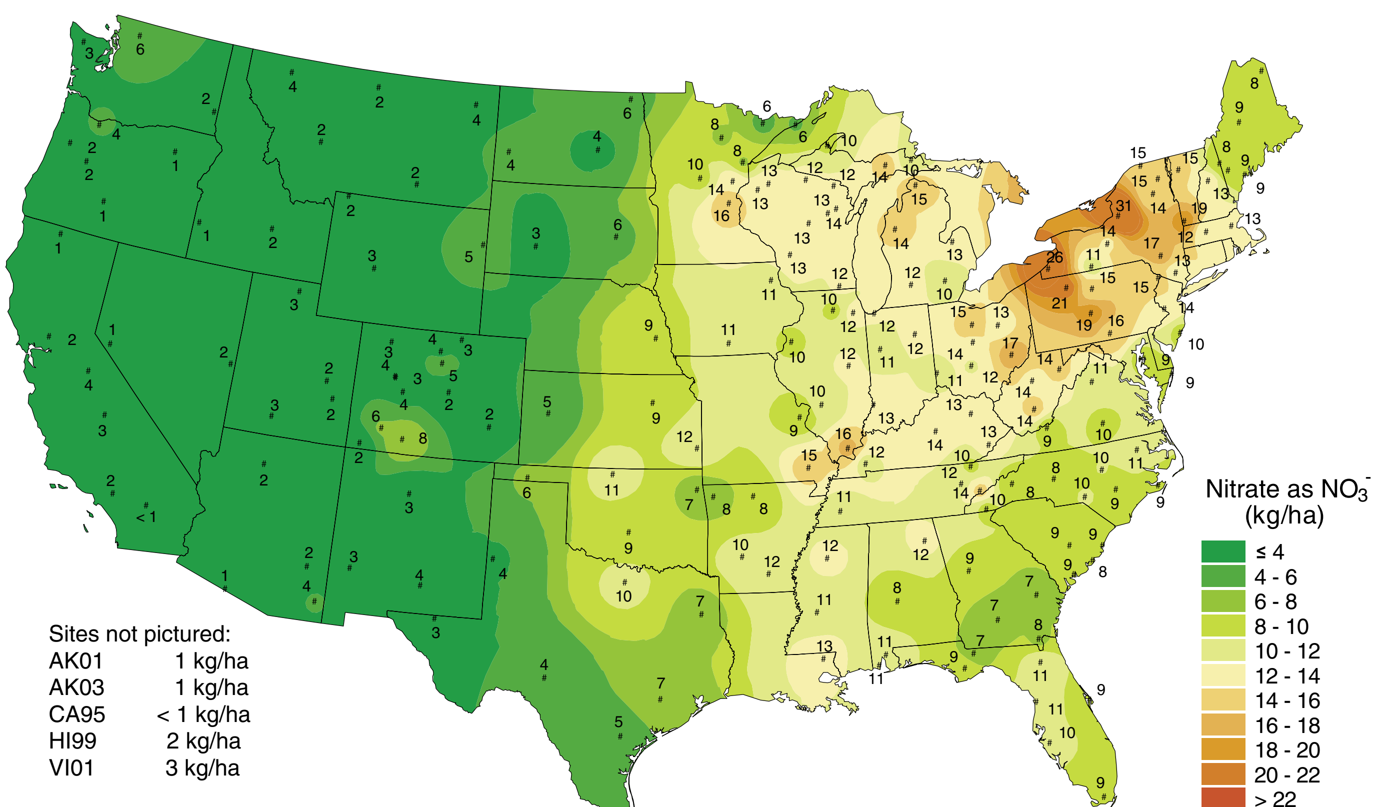
Long time series of measurements at this scale are extremely valuable for understanding long-term trends and the anthropogenic and natural factors that account for the variations observed. However, long-term measurements from watersheds at this scale are rare. In the absence of long monitoring histories, analyses on selected sub-watersheds (experimental and control) may provide the opportunity to observe natural variations and to determine the effectiveness of specific best management practices (BMPs) or other management actions. Concentrating BMPs or management actions within a single watershed would allow for a more robust assessment of their performance. Such an approach should not be used, however, to discourage the use of BMPs in any watershed.

It is probably unreasonable to expect that all data at this level will be collected according to a single protocol and include identical constituents. It is critical, however, that the protocols be clearly documented and available to those who wish to use these data in combination with data collected at other scales or in similar watersheds. Although it is unlikely that all, or even most, of these monitoring activities will be as comprehensive as those conducted at levels 1 and 2, sampling must occur frequently enough to discern trends and the relation between discharge and nutrient movement. Smaller watersheds are subject to more highly variable conditions and are likely to have greater variations between watersheds. Thus the frequency of sampling on small watersheds must be very high to provide a high level of confidence in understanding the natural and anthropogenic factors that affect loads and their variability or trends at this scale.

Issues of Scale and Time – The relation between scale and monitoring frequencies needs to be considered carefully across all scales of monitoring. At the large-basin scales, information on nutrient load as a function of time is required. In contrast, at the management project level, the changes in loading before and after project completion are more important. Secondly, multiple time scales need to be examined, including monthly, seasonal, annual and multi-year averages. The need to detect meaningful change in nutrient loading and to identify the corresponding cause in the presence of multiple, large natural variations places significant demands on monitoring and reporting of nutrient loads, stream discharges, and other important variables. As an example, a 30 percent reduction in nitrogen load to the Gulf is thought to be needed to meet the Gulf of Mexico goal of the Action Plan; therefore, a combination of monitoring and modeling must provide resolution of critical variables to some level greater than 30 percent.

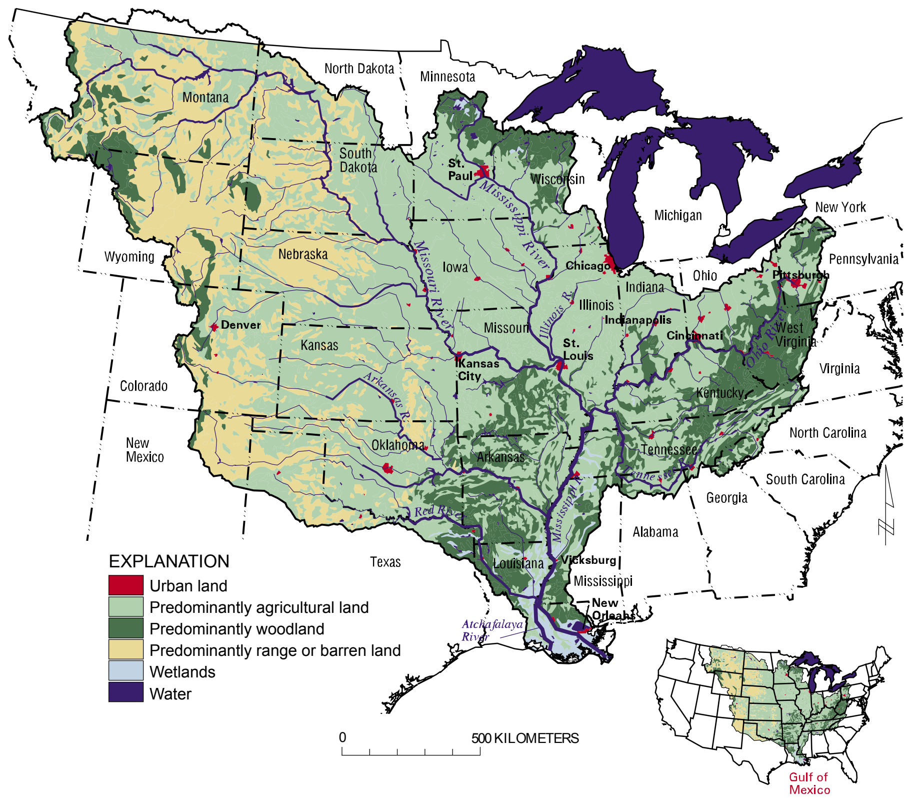
Other Monitoring - Estimates of the magnitude of nutrient contributions from point sources should be improved

Nitrate Ion Wet Deposition, 2002



National Atmospheric Deposition Program/National Trends Network
http://nadp.sws.uiuc.edu

Drainage and Land Use in the Mississippi-Atchfalaya River Basin



by use of additional measurements of actual effluent nutrient concentrations and flow. Previous estimates suffer from a lack of these data. Atmospheric sources, from automobile and truck traffic, animal wastewater lagoons, and fertilizer, need to be quantified better, and the transport, transformation, and deposition of the nitrogen species produced by these sources in the atmosphere needs to be better understood. As both large- and small-scale coastal diversions are implemented, inventories are needed to track the cumulative diversion of water and the estimated consumption of nutrients before ultimate discharge to the Gulf. The National Atmospheric Deposition Network (NADP)/ National Trends Network (NTN) provides a long-term record of wet deposition of nitrogen from nitrate and ammonium, but little is known of the organic nitrogen precipitation in the watershed. The Clean Air Status and Trends Network provides dry deposition measurements of nitrogen from nitrate, but these measurements are sparse and point measurements cannot be generalized to the vast area of the Mississippi River Basin. Also little is known about the dry deposition of ammonia or organic nitrogen in the watershed. To fully understand the sources of nutrients to the Gulf, more information on urban nonpoint sources is needed. This last source may prove to be the most difficult to assess accurately and should be a focus of increased monitoring and modeling.

In addition to stream and river monitoring, measurements of soils nutrients and edge-of-field nutrient losses are necessary to understand the effectiveness of management actions. Many of the soils in the watershed are rich in organic matter containing nitrogen. The nutrient content of the soils is generally assumed to be in a quasi-steady state, although interannual variations in mineralized nitrogen are a large potential source of nitrate. A greater understanding is needed of the processes that occur between the application of nutrients to the soil and their uptake by plants, their binding to soils, their volatilization into the atmosphere, or their loss to ground or surface waters. Thus, linked soil and stream nutrient measurements are critical. The lack of a standard soil nitrogen measurement that is simple, accurate, and inexpensive hinders our knowledge of processes acting at this scale.

Finally, land-use and chemical-use changes have a huge potential to change the sources and sinks of nitrogen. Thus, land use and chemical use should be monitored, especially at small basin scales where management actions occur. Because nitrogen losses from agricultural lands, particularly from cropland with subsurface drainage flows, have been identified as a major contributor to nitrogen loads, areas with substantial subsurface drainage should be the focus of additional monitoring. Design and management changes currently recommended for surface and subsurface drainage systems, such as controlled drainage, water-table management systems, and shallower subsurface drainage systems where replacements are required need to be considered in future monitoring activities.

Data reporting and availability ranges from superb to poor. While many federal and state monitoring data are readily available in standardized format via the Internet, other data are much more difficult to locate. The Internet could make reporting much easier and allow for easier access to a wide range of pertinent data. The use of the USEPA's Storage and Retrieval (STORET) system would greatly facilitate the exchange of information critical to understanding nutrient loading and its impacts throughout the Basin. Organizations and individuals collecting data should be expected to share their data and provide a clear explanation of the sampling techniques and analysis methodologies used. This will provide the user with the necessary understanding to make full and informed use of the data.

The use of Geographic Information Systems (GIS) to help analyze the data collected also can provide a convenient, well understood and widely used method of sharing data and information about water quality within the Basin. Maps produced using GIS can show a multitude of variables including soil types, land use, management practices, and their influence on nutrient loss to local streams. GIS may provide the most useful method of informing decisionmakers given that simple, information-intensive maps can be easily produced and shared. Such systems make it easy to show changes and trends and to compare results from across the Basin and to relate changes within the Basin to those observed in the Gulf.

Existing Monitoring and Reporting Activities

Currently, the four levels of required water-quality monitoring all exist, at least in part. The completeness of the monitoring and reporting efforts, however, drops off substantially from the broadest scales of monitoring to the scales at which nutrient sources and management action effectiveness can be assessed.

Level 1 - The USGS currently monitors both discharge and a broad range of water-quality parameters near where the Mississippi and Atchafalaya Rivers flow into the Gulf of Mexico. Maintaining this effort is critical to addressing fundamental questions related to nutrient loading and Gulf hypoxia. The data collected are readily available to those studying nutrient loading and Gulf hypoxia.

Level 2 - Similarly, the USGS is currently conducting the level 2 monitoring identified in this section. The challenges of monitoring at these sites (and the Level 1 site) on major rivers are significant and it is unlikely that any state or local entity could meet those challenges. It is important that the USGS continues to fulfill this role. The seven sites currently monitored using the same protocols as the sites near the Gulf (level 1) provide a robust set of data for examining the processes acting on the very large scales and provide support for smaller scale monitoring.

Level 3 - The current monitoring at level 3 is insufficient to address critical questions related to water quality in general and the topics of this report in particular. Also, the lack of monitoring at this scale prevents the connection from being made between the watershed-scale measurements and sub-basin scales (Level 2). Of the 42 basins analyzed as part of the Integrated Assessment and the six associated technical reports published in 1999, only 12 basins are currently producing nutrient data collected by the USGS. A handful of other basins may be monitored by states or other, local entities. An important aspect to this monitoring is the continued operation of the USGS streamgaging network. Without the flow data collected at streamgages, load calculations will not be possible, and our ability to resolve many of the remaining questions regarding hypoxia and the effectiveness of management actions at reasonable spatial and temporal scales will be severely compromised.

Level 4 - Abundant monitoring is being done at level 4. Knowledge of this monitoring is anecdotal, however, and it remains unclear whether the data being collected are useful for nutrient-load determinations on time scales useful to this effort. While much of this monitoring does follow a defined protocol, the methodologies are likely to be highly variable and may not include important parameters. Most prominently, many of these sampling efforts are not conducted in the vicinity of streamgaging stations, and therefore, do not have the benefit of stream discharge data, which makes the calculation of nutrient and other loads difficult. Ongoing monitoring of nutrient loads and related parameters in the Delta system is generally limited to specific project activities, such as the Caernarvon Diversion project. The Caernarvon project has been studied intensively but suffers from the difficulties associated with estimating discharge in tidal channels.

Other Monitoring - Measurements of key parameters from wastewater-treatment plants, taken to fulfill permit requirements, provide some estimates of the role of these facilities in nutrient loading in inland waters. The National Atmospheric Deposition Program, National Trends Network (NADP/NTN) provides data to support the assessment of the wet deposition of nitrogen, and Clean Air Status and Trends Network (CASTNet) provides limited measurement of the dry deposition of nitrate and particulate ammonium. USDA Management Systems Evaluation Areas (MSEA) studies and watershed research and state experiment station studies provide BMP-related information and should be encouraged to collect the requisite data and report it through the USDA National Agricultural Library’s Water Quality Information Center with retrieval capabilities that facilitate use of the information in water-quality studies.

Limitations in Existing Activities and Related Science Needs

A modest increase in existing resources and a focus on partnerships would significantly enhance the current monitoring framework and standardize reporting such that more information could be brought to bear on reducing the current uncertainties about nutrient loading within the Basin.

Level 1 – Ongoing monitoring and reporting at this level has provided important information on loads leaving the Basin. There is a need for continued support for ongoing USGS activities. There are, however, questions related to the need for additional monitoring to provide daily load data during the periods that most affect the seasonal expansion of the hypoxic zone. A major issue related to monitoring at the Mississippi River mouth is the change in nutrients below St. Francisville, Louisiana. This poses significant challenges, because no continuously operated streamgaging station exists below Tarbert’s Landing near St. Francisville, Louisiana, or below Melville, Louisiana, on the Atchafalaya River.

Level 2 - Monitoring and reporting at this level is largely sufficient. The main need is for continued support for USGS monitoring efforts. There are questions related to the need for implementing real-time monitoring at this scale to provide daily load data during the periods that most affect the seasonal expansion of the hypoxic zone.

Level 3 - Level 3 monitoring is currently woefully inadequate. Only 12 sites currently are being monitored by the USGS as of late 2002, as opposed to 42 during the early 1990's. The most critical sites to be re-established are those within the areas of greatest nitrogen loading. These sites will provide the greatest value in determining nutrient loads. In addition, a group of sites from other parts of the Basin are required to prevent bias in interpretations and models. The specific sites should be determined in consultation with the states and tribes and those modeling nutrient loss in the Basin.

Three methods of providing for a reasonable monitoring network at level 3 should be considered. First, the USGS funding shortfalls, which resulted in the reduction from the 42 sites measured in the early 1900's and utilized in the baseline analysis presented by Goolsby et al. (1999), could be restored. Second, the USGS and the USEPA, in combination with the states and tribes, could seek modest funding increases to allow states to assume this monitoring effort as part of their existing water-quality monitoring. Finally, states could be given increased flexibility in monitoring requirements in exchange for assuming monitoring efforts at the USGS monitoring sites. This last option is the least likely to be successful because other local factors drive state monitoring priorities.

A separate issue arises at level 3 as well. Nutrient sources in the Lower Mississippi Basin are being estimated through subtraction (i.e., a mass balance approach). Additional sites within the lower Basin, at locations such as the mouth of the White River, are needed to enable direct measurements for selected watersheds.

Level 4 - The greatest needs at this level are coordination and communication of results. Although the process for preparation of this report could not examine all the local efforts at small-watershed and field-scale monitoring, anecdotal information clearly indicates that small-scale monitoring is widespread. USDA should increase efforts to have the information gathered under their auspices made available for use. A survey of monitoring currently supported at this level would provide a basis for coordination and inform those who are currently monitoring about the Task Force's work. Because such a wide range of groups conducts this monitoring, the need to make the data useful for comparison between geographic areas being monitored is a major challenge. Federal and state agencies that fund such efforts should clearly state their expectations for data sharing through USEPA's STORET database and other linked or related systems. There is a need to accommodate the privacy concerns of individual landowners. Aggregating data may provide some help in resolving these concerns.

The nature of monitoring at level 4 indicates that more variation in measurement protocols is needed to meet the more variable goals of monitoring at this scale. Basic protocols for data collection and reduction should be coordinated, however, by a group led by the federal agencies in coordination with states and tribes. The usefulness of discharge data collected concurrently with water-quality data, even at this scale, should not be understated; however, it is recognized that reliable discharge data are less likely to accompany water-quality data at this scale.

Other Monitoring - Wastewater treatment plants provide useful data on their discharges. USEPA and the states should closely examine these data to determine more accurately the importance of nutrient loading from wastewater treatment plants and the potential for cost-effective nutrient reductions.

Urban nonpoint source, atmospheric, and soils monitoring all suffer from a combination of incompleteness and a lack of straightforward measurement. Additional information is needed on urban nonpoint source contamination as well as information on the effectiveness of approaches taken to reduce urban nonpoint sources. Data on dry deposition of nitrogen and other airborne chemical species is needed to provide the basis for a better overall nutrient budget. Increases in atmospheric nitrogen, in multiple chemical forms, from vehicles and from confined animal feeding operations (CAFO) needs to be examined.

Although soil monitoring is widespread, the timing of this sampling and its relation to longer-term soil nitrogen budgets and nutrient loss from the soils is poorly understood. Monitoring the effectiveness of best management practices and other innovative approaches will require coordinated water and soils monitoring. There is a need for an end-of-season nitrate-N test for use in refining nitrogen management. In addition, monitoring phosphorus in soils, particularly in sensitive watersheds, should be expanded to look at water-quality impairment risks, investigate the effects of management practices on phosphorus, and examine the relation between soil nitrogen and phosphorus levels for better nutrient management.

Needed Coordination, Information Sharing, Synthesis, and Reporting

The need for coordination increases dramatically from the broader spatial scales (levels 1 and 2), where the USGS is solely responsible, to the smaller scales (levels 3 and 4) where federal, state and local organizations are all active. The demands for coordination at the two smaller scales differ somewhat.

At level 3, the greatest need is for coordination of sampling between the two main federal water-quality agencies (USEPA and USGS) and the states, tribes, and local entities. This should focus on providing necessary monitoring capabilities and to ensure standardization of procedures for data collection and reduction to provide a robust data set.

At level 4, the need is greatest for information sharing, including data, the procedures followed, and common storage of the data. USEPA is the most likely common depository for data using the STORET system already in place. Federal and state agencies should begin to include a requirement for information sharing for their grant and contract-supported organizations.

If a greater understanding of critical parameters could be determined, the ability to use a wide assortment of data collected on small watersheds and individual projects would be greatly enhanced. Easily and widely measured parameters that provide at least a partial view of the physical, chemical and biological processes at work at the small-watershed and field scales need to be identified. Although this represents a compromise in data completeness, the gains in information quantity at the smallest scales justify this approach.

Data collected at all levels should be subject to rigorous Quality Assurance/Quality Control (QA/QC) procedures before use. For level-4 monitoring, in which the sharing of data from a wide range of sources is encouraged, sufficient information on data protocols and QA/QC should be associated with the data so that informed decisions on the suitability for various uses can be made. Coherent nitrogen and phosphorus values are needed to examine the relation between these two nutrients. In particular, some actions to reduce phosphorus loss to streams (the major nutrient impairment within the Basin) may exacerbate nitrogen loading. The time lag associated with nutrient transport and delivery to the Gulf is poorly known. As a result, monitoring is required for long periods, with the capability to detect subtle responses in environmental conditions. Similarly, modeling activities must include simulation of processes occurring over long periods of time rather than focusing solely on the short-term response to specific management projects.

Central to many of the most important questions facing both the science and the managerial efforts to improve water quality is the need to closely coordinate the monitoring and modeling efforts. The need for improved coordination is illustrated by the need to extrapolate data across spatial scales, to model locations of data scarcity, and the lack of simple, defined time lags for many of the processes at work within the Basin. Monitors and modelers need to work closely together to define the data needs of the models and to examine the trade-offs between the numbers of monitoring sites, the frequency of sampling, and completeness of the constituents monitored.

This integrated program of research and modeling will need to provide information in each of three topical areas:

- Nutrient cycling in terrestrial and aquatic ecosystems;
- Management activities affecting nutrient sources, transport, and removal; and
- Watershed models of nutrient dynamics and management activities.

Monitoring at all levels needs to be responsive to the needs of both deterministic and empirical models. The demands of determining changes over time across spatial and temporal scales that vary by orders of magnitude will require periodic review of current procedures. To ensure that monitoring is meeting the needs of those who use the data to support both scientific analysis and management-level decisionmaking, a conference at which information, technologies, and experiences can be exchanged should be convened on a periodic basis.

One of the challenges of monitoring is to determine the effectiveness of management actions at different locations and temporal and spatial scales. By concentrating management actions geographically, one can increase the likelihood that the effects of those actions will be discernable above the natural variations in climate, streamflow, and practices.

Periodic reporting of management actions and monitoring results are critical to the assessment of hypoxia and the nutrient loading of inland rivers and streams. Although the Action Plan notes a requirement for assessment on a 5-year cycle, more frequent reporting will be necessary to allow scientists to examine the efficacy of monitoring and modeling efforts and to assess management actions within the Basin. Annual scientific workshops that provide the opportunity to exchange information and ideas would promote understanding of the major factors that influence nutrient loading and progress toward improving water quality throughout the Basin.

Basin Modeling and Research

Needed Framework for Modeling and Research

Nutrient transport within the Mississippi River Basin, through the Mississippi Delta system, and ultimate delivery to the Gulf of Mexico is governed by a complex interaction of atmospheric, terrestrial, and aquatic processes and human activities. These processes and activities affect the cycling and transformation of nutrients over a wide range of spatial and temporal scales. An improved understanding of these complexities is needed to better explain and predict the specific improvements in water quality and habitat that can be expected in the aquatic ecosystems of the Mississippi River Basin and Delta, and in the northern Gulf of Mexico as a result of the nutrient reductions called for in the Action Plan. This understanding will need to be developed from a combination of observational research and modeling to further identify the role of existing processes and human activities and to predict the response of ecosystems in the Mississippi River Basin to future changes in nutrient management.

A comprehensive, integrated modeling and research program is needed to collect and analyze data regularly and report information to support assessments of the water-quality effects of management activities over a range of spatial and temporal scales in the Mississippi River Basin. The modeling and research program has three objectives:

1. Improved knowledge of nutrient cycling in terrestrial and aquatic ecosystems; the natural physical, chemical, and biological processes; and human activities governing the relations between nutrient inputs to the Mississippi River Basin and changes in the environmental quality of Mississippi River Basin and coastal Gulf waters.
2. Improved understanding of the effectiveness of the broad range of management technologies and practices in controlling nutrient flux in different environmental settings over field and watershed scales.
3. An integrated system of models with the supporting research that explains and predicts spatial and temporal variations in nutrient flux in response to natural factors and human activities over a wide range of spatial scales.

Understanding the controlling processes and the effects of human and management activities on nutrient dynamics and transport over multiple spatial and temporal scales is central to effectively implementing an adaptive management framework and achieving the Action Plan goals in the Mississippi River Basin. Nutrient loading to the Gulf of Mexico is the cumulative result of the nutrient inputs from numerous local activities that occur at very small spatial scales (e.g., crop management in individual fields, discharges from particular municipal wastewater treatment plants) and their interactions with biogeochemical processes in soils, air, and water during transport over a broad range of spatial and temporal scales. No single model or research program can provide the process understanding that is needed to support effective management action. Instead, a nested or hierarchical framework will be required in which local- and basin-scale monitoring, modeling, and research collectively interact to inform and validate the methods for predicting nutrient transport and delivery to streams, rivers, alluvial and riparian wetlands, Delta wetlands and estuaries, and the Gulf of Mexico.

This integrated program of research and modeling will need to provide information in each of three topical areas: (1) nutrient cycling in terrestrial and aquatic ecosystems; (2) management activities affecting nutrient sources, transport, and removal; and (3) methods to refine existing models of nutrient dynamics and management activities and to develop new integrated watershed models.

Nutrient Cycling

Biogeochemical transformations and processes that affect movement within the hydrologic cycle are responsible for the removal and storage of large quantities of nutrients in terrestrial and aquatic ecosystems of the Mississippi River Basin. Improved understanding of these processes is needed to better predict the effects of future management activities on the transport of nutrients from their points of application to downstream locations where water-quality monitoring and various ecosystem effects occur. Research and modeling efforts will need to focus on nitrogen, phosphorus, and sediment to improve this process understanding and to accommodate the broad range of water-quality issues and management interests in the Mississippi River Basin. Sediment provides an important mechanism for the terrestrial and aquatic transport of phosphorus and organic nitrogen. Research and modeling also will need to provide information on the intra-annual processes and human activities that control nutrient transport during spring runoff events, which are critical to the seasonal occurrence of Gulf hypoxia. The processes affecting sources, transport, and transformation of nitrogen and phosphorus, and the effectiveness of various management actions will need to be evaluated comparatively to assure that management actions achieve the greatest benefit for problems resulting from both nutrients.

In terrestrial ecosystems, estimates of the rates of nutrient cycling need to include net changes in soil phosphorus and nitrogen in agricultural watersheds, nitrogen fixation by leguminous crops, and denitrification in soils. Research is needed to describe how these rates vary geographically in response to climate and the physical and biochemical properties of terrestrial ecosystems. Moreover, information is needed on the spatial distribution of these terrestrial properties along surface and subsurface flow paths to support the use of models to simulate and predict the flux of nutrients in a range of watershed sizes in the Mississippi River Basin. Of particular need are measurements of the rates of nitrogen and phosphorus transformations and cycling in soils (i.e., immobilization, mineralization, denitrification, volatilization) for a range of cropping systems, soil properties, and cultivation histories to improve understanding of the factors affecting the spatial and temporal dynamics of nutrient leaching to surface and ground waters.

In aquatic ecosystems, estimates of the rates of nutrient processing and transformations are needed for a wide range of ecosystem types: streams of various sizes, river pool reaches, lakes reservoirs, wetlands, and estuaries. Knowledge is needed of how these rates vary in response to changes in physical, biochemical, and hydrologic properties of the water bodies. To support efforts to model and predict the flux of nutrients over multiple spatial scales, particular emphasis is needed on improving understanding of how nutrient losses vary with readily measured physical and chemical environmental factors, such as channel depth and flow, water-column concentration, and the water residence times of impoundments. Moreover, improved understanding is needed of the temporal scales (i.e., intra- and inter-annual) over which nitrogen is transformed, cycled, and permanently removed via denitrification. This includes evaluations of the short- and long-term effects of the biological uptake and cycling of nutrients (e.g., settling and burial of particulates, mineralization) in streams, floodplains and deltaic environments on the fate of nitrogen and phosphorus over watershed scales.

Research is needed over a broad range of spatial scales to quantify the magnitude and timing of lags between changes in net anthropogenic nitrogen and phosphorus inputs to watersheds and the delivery of these nutrients to streams of the Mississippi River Basin and the Gulf of Mexico. This research will aim to improve understanding of the mechanisms responsible for time lags in nutrient flux so that more accurate predictions can be made of the time required to observe the benefits of management actions in streams of the Mississippi River Basin. Various mechanisms need to be investigated, including farm-scale management of cropping systems, nutrient cycling and transformations in soils, precipitation and runoff effects, surface and subsurface drainage systems, and nutrient storage and transport in ground and surface waters.

Research is needed to improve knowledge of the trophic response of streams to nutrient enrichment and changes in stream habitat and other physical characteristics of streams and riparian areas. This research is important for assessing the effects of nutrients on ecosystem health in streams, rivers and reservoirs in the Mississippi River Basin, and the effects of biological uptake and nutrient cycling on the quantities of nutrients transported in streams and delivered to the Gulf of Mexico. Studies of trophic conditions in Mississippi River Basin streams and rivers are needed to improve estimates of the response of algal biomass and composition to historical and future changes in nutrient concentrations. Improved understanding is especially needed on the topic of phosphorus-algae relations in agricultural streams, where much of the sediment-bound phosphorus may be biologically unavailable.

Monitoring and modeling are needed to improve the spatial and temporal resolution and accuracy of estimates of nutrient inputs to watersheds from the atmosphere, municipal and industrial wastewater treatment facilities, fertilizer application, and livestock wastes. More accurate and spatially detailed estimates are needed of atmospheric deposition sources of nutrients, including phosphorus deposition and dry and organic fractions of the reduced and oxidized forms of nitrogen.

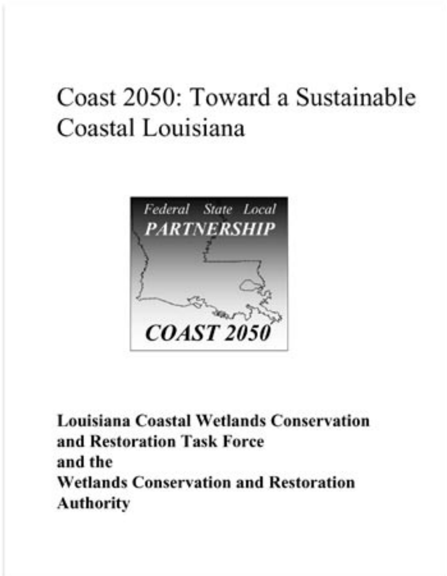
Management Practices Affecting Nutrient Transport in Watersheds

A wide variety of management technologies are available for controlling the supply of nutrients and intercepting nutrients during transport. A coordinated set of research and modeling efforts is needed to broaden the spatial and temporal scales and environmental settings in which the effectiveness of these technologies is evaluated.

Research related to the control of nutrient supply is needed on selected watersheds to improve understanding and to quantify the effects of conservation buffers, irrigation and drainage systems, cover crops, rotational cropping practices, tillage systems, and the placement, time, and rate of nutrient application on losses of water and nutrients (nitrogen and phosphorus) from farm fields. A systematic understanding is required of how these losses vary geographically within the Mississippi River Basin, especially in relation to changes in precipitation, climate, soil properties, and land-use patterns. Studies also are needed to quantify the degree of nonlinearity of the fertilizer application-nutrient loss relation over field and watershed scales. This information should address whether the previous field-scale observations and relations extend to larger scales and whether disproportionately larger reductions in nutrient flux could be expected to occur over watershed scales in response to fertilizer reductions on fields.

Research on the methods for intercepting nutrients is needed to quantify the comparative technical and cost effectiveness of the wide range of BMPs currently available to control water, sediment, and nutrient losses to streams via surface and subsurface drainage. The research needs to comprehensively evaluate the effectiveness of such practices as tile-line bioreactors, riparian systems, surface runoff controls, subsurface drainage control, wetlands, in-stream and edge-of-stream storage, drainage ditch controls, and stream restoration. The investigations need to quantify differences in the nutrient removal efficiency of these BMPs for various forms of nitrogen and phosphorus as well as other water-quality contaminants such as sediment and pesticides. The studies should also quantify the effects of BMPs on nutrient and contaminant flux in both surface and ground waters. Evaluations of tile drains should assess the effect of drainage architecture (location, intensity) on nutrient and water flux. Research is also needed on the effectiveness of wetlands in removing nutrients from surface and ground waters over large watershed scales. These studies need to quantify removal efficiency over short and long time periods as a function of various wetland properties including influent nutrient concentrations, site characteristics, water residence time, temperature, biological activity, and the location of wetlands in relation to streams. Evaluation of the relative effectiveness of various management practices must consider seasonality and their ability to mitigate the adverse effects of excess nutrients during the most sensitive times of the year.

Of special and unique importance to reducing nutrients in the watershed is the considerable relevant research on nutrient dynamics (uptake, burial, and denitrification) in the Mississippi River Deltaic Plain being developed under Louisiana's coastal restoration program. Ongoing research on the effects of diverting nutrient-rich river water into Louisiana's deteriorating coastal wetlands and the considerable extant data on nitrogen dynamics in both riparian and coastal wetlands provide a wealth of management opportunities to reducing and intercepting nutrients before they reach the Gulf of Mexico hypoxic zone (Day and others, 2003; Mitsch and others, 2001; and Lane and Day, 1999). Continued support of Louisiana's coastal restoration program in this regard is critical to the overall hypoxia solution. The Mississippi River Deltaic Plain in Louisiana represents a "distributary zone" that serves as the transitional, estuarine, wetland interface between the continental basin and the ocean. And the Deltaic Plain is not trivial in size; at about 5,000 square miles, it is roughly the same area as the recent average


Coast 2050: Toward a Sustainable Coastal Louisiana

Federal State Local
PARTNERSHIP
COAST 2050

Louisiana Coastal Wetlands Conservation and Restoration Task Force and the Wetlands Conservation and Restoration Authority

State of Louisiana Coastal Plan

zone of Gulf hypoxia. Based on recent studies, the Deltaic Plain distributary zone has the potential to process and remove a highly significant amount of excess nitrogen in river water before it reaches the Gulf. Further effort and research remains to be done to quantify this potential. The explicit connection between hypoxia reduction and Louisiana's coastal restoration program is described in several documents produced under the restoration program. The State of Louisiana's Coastal 2050 Plan: titled, *Coast 2050: Toward a Sustainable Coastal Louisiana* and the ongoing Louisiana Coastal Area (LCA), Louisiana Comprehensive Coastwide Ecosystem Restoration Study being developed with the U. S. Army Corps of Engineers describe these connections in greater detail. The latter study will connect delta and water-quality management and Gulf hypoxia reduction with the Louisiana coastal restoration program. Another important publication that also connects Deltaic Plain restoration with hypoxia reduction is the recently released preliminary report by the U.S. Commission on Ocean Policy (U.S. Ocean Commission, 2004). Given all these considerations, it is vital that research efforts conducted under the Louisiana coastal restoration program be supported and coordinated with programs under the Hypoxia Action Plan.

Watershed Models of Nutrient Dynamics and Management Activities

An integrated system of field- and watershed-scale and whole-basin models is needed to support research and monitoring objectives in the Mississippi River Basin. This involves the use of existing statistical and mechanistic models, the refinement and integration of these models, and the development of new models as needed, to improve their representation of nutrient sources, processes, and management activities. The models will serve the following five functions:

1. Improved estimation of stream water-quality loads and concentrations over space and time - Stream monitoring data serve a prominent role in describing the movement of nutrients and water at specific locations and times on small streams, major tributaries, and the main stem of the Mississippi River Basin. There are, however, inherent limits on resources for collecting data. Models are needed to reliably extend monitoring information in time and space to allow a more detailed description of nutrient concentrations and flux.

2. Research to improve understanding of nutrient sources, transformations, and cycling over multiple spatial scales - Models are an integral part of experimental research and monitoring. The measurements collected at fine scales and as part of larger scale stream monitoring networks describe the physical and chemical conditions of the system. Models are needed to interpret these measurements and to infer the types of sources and processes that may explain temporal and spatial variability in the observations. The understanding of processes that models provide is critical to explaining and predicting the response of nutrient flux to spatial and temporal variability in climatic conditions and to a broad range of changes in human activities. This includes the use of models to improve understanding of the influences of streamflow and natural and anthropogenic sources on the seasonal delivery of nutrients to the Gulf of Mexico.

3. Assessment of the effects of management activities on water quality - Statistical and mechanistic models are needed to detect and simulate changes in water-quality conditions in response to observed and proposed changes in management practices at small and large spatial scales. Such information can support evaluations of the effectiveness of alternative management practices for purposes of policy evaluations and assist local managers and producers in making decisions about the implementation of effective nutrient control and cropping technologies. Models also are needed to evaluate whether observed changes in water quality at stream monitoring locations can be explained by management activities. In these evaluations, models are needed to control for the exogenous effects of climatic factors, such as streamflow and temperature, and account for the multi-scale effects of terrestrial and aquatic processes on nutrient delivery to streams and the Gulf of Mexico.

4. Quantification of uncertainties in model predictions and process understanding - Uncertainties are an intrinsic characteristic of the information generated

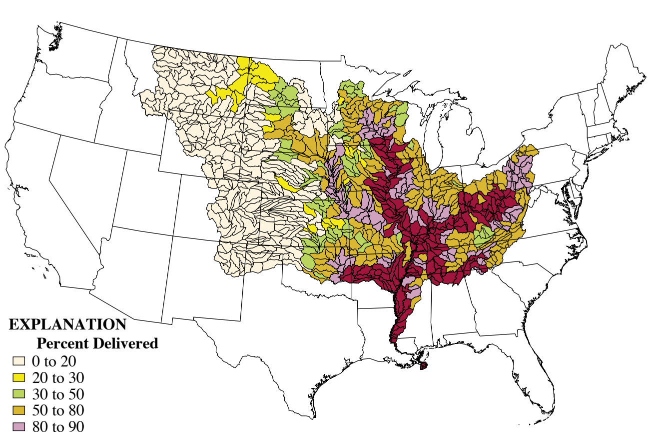
by research and modeling activities and need to be evaluated as part of nutrient management decisions. Watershed models will provide information for assessing the limits of current understanding of processes and methods for quantifying the effects of uncertainty on predictions of the response of water-quality and ecosystem conditions to management actions.

5. Evaluation of the information content and costs of alternative stream monitoring designs - Watershed models are helpful in making management decisions about the monitoring locations and sampling frequencies that provide the most cost-effective and accurate predictions of water quality. These monitoring decisions are inherently complex because monitoring data are used in models to satisfy a large number of (and sometimes competing) water-quality objectives of interest to stakeholders (e.g., prediction of nutrient concentrations and flux in Mississippi River Basin streams, prediction of nutrient delivery to the Gulf of Mexico). Watershed models provide a tool for systematically evaluating alternative monitoring designs in relation to individual management objectives.

Existing Modeling and Research Activities

Existing nutrient research and modeling activities in the Mississippi River Basin collectively address a broad range of nutrient cycling and management issues. Federal and state agencies, academic institutions, and industry groups are currently conducting nutrient research and modeling activities. Various governmental and non-governmental institutions are actively applying watershed models to small catchments within the Mississippi River Basin related to work on TMDLs and other regulatory interests. State and local governmental modeling efforts are frequently focused on phosphorus rather than nitrogen because inland streams, lakes, and reservoirs are typically phosphorus limited. Most of the modeling activities in the Mississippi River Basin are conducted at relatively small spatial scales ranging from farm plots to small catchments of less than a few hundred square kilometers in size. Field- and catchment-scale models that simulate the effects of climate and the management of agricultural cropping systems on nutrient and sediment transport at these scales include EPIC (Erosion-Productivity Impact Calculator), AGNPS (Agricultural Non-Point Source Pollution Model), and CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems). Only a small number of large watershed-scale (several thousands of square kilometers) studies are conducted by these organizations in the Mississippi River Basin (e.g., Minnesota River; statistical modeling of larger interior watersheds). Even fewer modeling efforts are focused on the investigation of nutrient sources and transport processes at the regional- and whole-basin scale in the Mississippi River Basin; examples are SWAT (Soil and Water Assessment Tool), HSPF (Hydrological Simulation Program-Fortran), and SPARROW (SPAtially Referenced Regressions On Watershed attributes). (See Singh, 1995 and NRC, 2000 for summaries of selected watershed models.)

SPARROW Model Estimate of In-Stream Nitrogen Delivered to the Gulf of Mexico



Source: U.S. Geological Survey

Limitations in Existing Activities and Related Science Needs

The lack of sufficient coordination of existing research activities and programs makes it difficult to define fully the limitations and gaps in that research. Gaps exist in the spatial and temporal coverage of scientific and management issues, which limits how effectively current research and modeling efforts can support adaptive management in the Mississippi River Basin. Much of the research and modeling is conducted at the field- and plot-level and in small watersheds. The measurements and research findings from these studies reflect only a fraction of the wide variability in the watershed properties that control nutrient generation, transport, storage, and removal. Studies also are frequently conducted independently with little sharing of methodologies and information and without making broader spatial connections to the fate of nutrients and their effects on downstream ecosystems. Thus, it is difficult to reliably generalize and extrapolate available information to new environmental settings and to predict the response of ecosystems to nutrient management activities over large watershed scales. Moreover, this lack of information and coordination hampers efforts to make recommendations to agricultural producers and resource managers as to how best to select and use the wide range of technologies and practices currently available to control nutrients both on and off farm fields.

A program to coordinate and modify existing programmatic efforts and to develop new research efforts spanning multiple spatial scales is needed to achieve an integrated system of data collection and analysis to support an effective adaptive management framework in the Mississippi River Basin. The research and modeling program will need to coordinate extensively with the existing activities of governmental, academic, industry, and other non-governmental organizations. This includes existing monitoring efforts and experimental and modeling studies conducted by these institutions from field to watershed scales. The research and modeling program will need to be effectively integrated with local and regional water-quality concerns and issues of stakeholder groups, including TMDLs, best management practices (BMPs), nutrient standards setting, biological integrity, and stream restoration. Commonly, many of the stakeholders in the Mississippi River Basin are more focused on local water-quality, habitat or other issues, such as the control of sediment and phosphorus, restoration of the integrity of aquatic ecosystems, or coastal restoration, than on the control of nitrogen per se. To provide an effective information base for adaptive management, experimental and modeling research must consider the broader effects of management technologies on nitrogen, phosphorus, sediment, and other measures of water quality and their relation to ecosystem functioning and health.

Initial actions to coordinate existing stakeholder research and modeling activities will synthesize current understanding of the sources of nutrients in the Mississippi River Basin and how nutrient flux responds to natural processes and management activities from field to broader watershed scales. This includes developing a centralized inventory of existing watershed projects and conducting meta-analyses of historical and recently collected experimental data available from existing farm- and watershed-scale research projects in the Mississippi River Basin (e.g., Management Systems Evaluation Area projects). Synthesis efforts also should analyze and make available to stakeholders the variety of existing research and modeling tools and information currently available that can provide immediate support for the adaptive management framework. This includes existing model predictions of nutrient sources and flux that are available for streams and rivers throughout the Mississippi River Basin. Complementary to these tasks is a coordinated effort to begin the integration of existing small- and large-scale watershed models that will be required to effectively explain and predict changes in water quality in response to natural processes and management activities.

The initial synthesis activities will provide important baseline information needed to establish new research sites and modeling locations that will broaden the environmental settings in which to develop an improved understanding of how natural and cultural factors affect nutrient processing and transport in watersheds. The new investigations should include a representative set of small- and intermediate-sized watershed projects to demonstrate the integration of research and modeling over multiple spatial scales. The environmental settings should reflect a broad array of cropping systems, climate and soil conditions, stream and catchment sizes, and surface and subsurface drainage systems located in the various ecoregions of the Mississippi River Basin. The monitoring and research in these projects need to be highly coordinated with the modeling tools and have the objective of collecting data to support the refinement of simulation models and additional integration of small- and large-scale watershed models. These projects generally can be classified as level-4 type watershed monitoring as described by the monitoring section of this report, but would also be highly coordinated with the location of new and existing level-3 monitoring efforts in the six-digit Hydrologic Accounting Units.

Initial actions are needed to conduct inter-model and inter-data comparisons to promote understanding of model accuracy and the level of process complexity supported by existing models. The centralized inventory of existing watershed projects can be used to identify models and geographic areas for these initial comparisons. Common criteria need to be established for reporting and validating model components (input data and parameters) and predictions of nutrient and water flux. Measures of model performance and accuracy may include the reporting of parameter sensitivities and uncertainties in model coefficients and predictions. Evaluations may also include the use of parameter estimation methods and comparisons with trial-and-error fitting procedures to quantify model uncertainties and to identify additional stream monitoring needs and potential improvements in model specification.

Subsequent actions are needed to refine the capability of existing models to describe temporal and spatial variability in nutrient flux. These refinements should be coordinated with the new watershed demonstration projects established in small- and intermediate-sized watersheds. Methods to expand the spatial scale of mechanistic models should be investigated to provide a broader understanding and predictive capability of nutrient transport from field and sub-basin levels to regional scales. The addition of more spatially distributed features in these models is needed to improve their ability to evaluate geographic differences in biogeochemical processes affecting nutrient flux. Large-scale statistical models should be refined to include dynamic hydrologic components to improve spatial and temporal interpretations of regional and sub-basin stream monitoring data (as described by monitoring levels 1 through 3). The development and testing of novel methods for linking statistical and deterministic watershed models should be investigated to potentially aid in broadening the applicable geographic scales of the models. Research also needs to focus on ways to refine watershed models to account for temporal lags in nutrient storage in soils and ground waters, the effects of surface and subsurface drainage systems, and the effects on nutrient riverine flux of future changes in climate, land use, population, and other human factors. Methods to provide a more comprehensive treatment of agricultural management practices in small watershed-scale models also should be investigated.

There is increasing interest at the state level in adopting conservation measures related to biodiversity and the generation of greenhouse gases and excess carbon dioxide. Research needs to evaluate the consequences of increased denitrification from BMPs on nitrogen fluxes to the atmosphere and the generation of greenhouse gases. Research also should include assessments of the effect of expanding biodiversity on the landscape and carbon sequestration on water and nutrient flux to streams and rivers.

New efforts will be required to build on existing programs and encourage new directions for research and modeling. The research and modeling plans call for establishing new small-watershed demonstration projects in each ecosystem to broaden the environmental settings in which to develop an improved understanding of how natural and cultural factors affect nutrient processing and transport in watersheds. These projects will need to be highly integrated with the modeling tools and have the objective of refining existing simulation models and integrating small- and large-scale watershed models. This will require that the modeling and experimental research communities work together closely.

Major actions will be required to upgrade the watershed data infrastructure to support multi-scale research and modeling in the Mississippi River Basin. Improvements are required in the availability and accuracy of a broad range of watershed data, including nutrient sources (e.g., fertilizer application rates, municipal wastewater treatment plant effluent, urban runoff and atmospheric nitrogen), biogeochemical factors affecting nutrient processing (e.g., soil properties, stream geomorphology, hydrologic flow paths, reservoirs, and connectivity of the river with floodplain and Delta wetlands), and management technologies and practices (e.g., location and intensity of tile drains and other drainage controls, conservation tillage, wetland restoration and coastal diversions). Historical data on nutrient sources (e.g., fertilizer, livestock wastes, point-source effluent discharges) are especially needed for Mississippi River Basin watersheds to support the modeling of temporal lags in the storage and transport of nitrogen and phosphorus. This information is needed to improve understanding of the time required to observe the benefits of management activities on nutrient conditions and ecosystem health of downstream water bodies. Evaluations also are needed to determine the suitability of the existing and proposed stream monitoring data (e.g., station location, sampling frequency, constituent coverage) for satisfying modeling and research objectives related to the adaptive management framework.

Finally, the challenges of the program design and analysis of the data collected in the multi-scale monitoring and research efforts may also require the creation of a temporary or permanent data management and analysis team to ensure continuity in the work among all stakeholders. The USEPA Chesapeake Bay Program office has used this approach effectively to organize stakeholders, to make monitoring and modeling decisions, and to communicate information in support of their adaptive management efforts.

Needed Coordination, Information Sharing, Synthesis, and Reporting

The proposed research and modeling program will need to be coordinated extensively with MMR monitoring and socio-economic efforts on data requirements, model inputs and outputs, and the economic viability of the wide range of management technologies and practices available to agricultural producers and water-resource managers. In addition, coordination will be needed with existing governmental, academic, industry, and other non-governmental organizations. Partnerships and collaborative research efforts may be effective ways to achieve this coordination. An important initial step in this direction will be to establish a comprehensive inventory of existing research and modeling efforts in the Mississippi River Basin and to improve communication within the modeling and research communities related to these on-going projects. Regularly held workshops may represent one way to provide a forum for communication through the sharing and reporting of data, research findings, and modeling information. The proposed meta-analyses of existing data and inter-model comparisons would benefit from access to a comprehensive inventory of existing research as well as workshop interactions. Additional efforts to improve communication should include developing a standardized set of protocols to support model comparisons and linkages over different spatial and temporal scales. Existing modeling projects should be encouraged to participate in these efforts and should seek to refine the models in ways that enable effective model comparisons and support the adaptive management framework in the Mississippi River Basin. These projects include the relatively few large basin-scale models used in the Mississippi River Basin (i.e., Soil Water Assessment Tool/Hydrologic Unit Model for the U.S. (SWAT/HUMUS), and SPARROW, as well as the more numerous small- and intermediate-scale watershed models (e.g., Hydrologic Simulation Program-Fortran (HSPF), Agricultural Non-Point Source (AGNPS), and Generalized Watershed Loading Functions (GWLF)). These modeling projects also should be encouraged to expand their research to quantify nutrient sources in the Red/Ouachita River Basin and their contributions to nutrients delivered to the Gulf of Mexico by the Atchafalaya River.

Refinements in the watershed modeling and related research activities will need to be closely coordinated with the objectives of other Task Force working groups, such as the sub-basin management implementation group, as well as those of local water-resource managers and agricultural producers to create an effective adaptive management framework. This includes establishing effective communications between the research and modeling project personnel and the various management and producer groups as to their information needs. For example, research and modeling projects in the Mississippi River Basin would benefit from having detailed information as to what modeling objectives (e.g., simulation, interpolation, monitoring design evaluation) and model predictions (e.g., types of metrics; time and space scales) are most critical to support management needs. In addition, knowledge of the types of BMPs of greatest interest to producers and managers may assist researchers and modelers in the design of experiments and refinement of simulation models.

Coordination of the watershed research and modeling efforts with the wide range of local and regional water-quality issues of stakeholder groups is a key component of the strategy for supporting the adaptive management framework. These issues include TMDLs, best management practices, nutrient standards setting, and stream, wetland, and Delta restoration efforts. Other than concerns about nitrate concentrations in relation to drinking-water standards, local water-management agencies frequently focus on water-quality issues related to phosphorus, sediment, and pesticide control rather than the management of nitrogen. The MMR strategy needs to be integrated closely with these local water-quality issues in a manner that is mutually beneficial to local concerns and the broader regional concerns focused on nitrogen transport and Gulf hypoxia. This integration is especially critical to support the small-scale research and modeling focused on assessing the effectiveness of management technologies (i.e., BMPs) for controlling nutrients and sediment on farms and in small watersheds. Local managers also should be encouraged to provide data and work products as part of their water-quality activities (e.g., TMDLs) that assist in quantifying the riverine flux of nitrogen and phosphorus from Mississippi River Basin catchments and watersheds. Research on the effectiveness of farm management practices in improving water quality and stream ecological health also will need to carefully account for the social and economic concerns of agricultural producers and their relations to suppliers and dealers. In addition, significant attention is being paid to nutrient water-quality standards development by state and local governments, and this will strongly influence management decisions. Coordination on these issues will be essential. Research also needs to be closely coordinated with ongoing and future investigations on the response of trophic conditions in streams to nutrient enrichment conducted as part of USEPA's nutrient criteria work.

Basin Social and Economic Research

The strategy for reducing hypoxia in the Gulf relies on adopting nutrient management practices, landscape changes, and enhanced pollution controls. If successful, improvements in water quality and landscape changes throughout the Mississippi-Atchafalaya River Basins should result in enhanced recreational opportunities, reduced drinking water costs, increased wildlife habitat, and other associated benefits.

These benefits come at a cost that is borne by landowners, industry, and taxpayers. Control costs include expenditures by individuals for nutrient management practices and by firms and treatment works for pollution control practices and equipment, increased costs of goods for consumer, and government expenditures on program implementation, monitoring, and enforcement of pollution control policies.

Environmental policy impacts are generated through a chain of actions and reactions. Some of these involve interactions within the economy, some involve interactions within the environment, and some involve interactions between the environment and the economy. In standard analysis, the first reaction is that of producers to the implementation of the policy instrument. Typically, it is assumed that producers take actions to maximize their profits or net returns, or alternatively, to minimize the costs of compliance. A fundamental contribution of economics to environmental policy analysis is describing and forecasting behavioral responses to policy initiatives. These forecasts play two crucial roles. One is to provide information for assessing the costs of changes in resource allocations. The second is to forecast changes in production practices that will be made to meet environmental goals. Additional impacts with economic welfare consequences may be generated through economic linkages to input and output markets. If the amount of land or number of producers directly affected is sufficiently large, then the prices of inputs or outputs may change, affecting input suppliers and consumers.

Environmental benefits are initiated by impacts on the volume and timing of pollution flows that result from changes in farm resource allocation, changes in urban/suburban runoff controls, or in the level of pollutant discharge from point sources. These in turn result in changes in chemical and biological attributes of water resources. Forecasting the impacts of changes in land management practices on environmental quality attributes requires the use of physical models (for example watershed or other hydrologic models) linking specific land-based activities to pollution loads, and to chemical and biological indicators of water quality. Improving water quality generates a number of benefits, including recreational, commercial, municipal, agricultural, aesthetic, and ecosystem.

Social and economic research has two broad roles in the Hypoxia Action Plan. One is to assess the factors that motivate landowners to adopt management practices that improve water quality. A better understanding of these factors would aid in developing appropriate economic and educational incentives for the long-term adoption of desirable management practices. A second role is to assess the costs and benefits of implementing alternative strategies. The impact on production costs, prices, government expenditures, and the resulting environmental benefit needs to be known to guide policy makers as they design and implement elements of the action strategy.

Needed Framework for Social and Economic Research

The needed Basin social and economic research framework must address the following three goals:

1. Identify effective incentive strategies for encouraging landowners in the watershed to adopt alternative management practices to improve water quality in the Basin and to reduce nutrient loads to the Gulf of Mexico.
2. Identify and quantify local benefits and costs within the Basin for strategies that improve water quality.
3. Identify and quantify benefits and costs of improving water quality in the Basin and reducing the size of the hypoxic zone.

Achieving these goals will require diverse research that cuts across many disciplines and that links land use to water quality in receiving waters and ultimately, the Gulf.

Existing Social and Economic Research Activities

The existing literature contains much research that provides guidance and information that can be used to assess the implementation plan. Without providing a detailed literature review, we can summarize current knowledge in the following ways.

Adoption of alternative management practices - The key for voluntary programs is that landowners believe it is in their own private interests (which can include environmental concerns) to change practices. Unless an economic or social connection is made with recommended practices, voluntary approaches are unlikely to succeed. In addition, management practices that require a radical departure from current farming practices are less likely to be adopted.

There is an extensive literature and knowledge of alternative management practices for reducing the movement of nitrogen and other pollutants to water bodies. This information has been developed over the years by the Agricultural Research Service (ARS); State Departments of Agriculture, Environment and Natural Resources; land grant universities; and private input suppliers at a host of research sites scattered across the country. The environmental and economic performance characteristics of these practices are known in a general sense, based on field experiments, demonstrations, and experience. ARS and other institutions are currently conducting research on new nutrient management practices and programs, such as the Certified Crop Advisor program, and they are training specialists to provide this information to farmers.

There is an extensive body of literature on alternative mechanisms for inducing individuals to adopt alternative management practices. These include financial incentives (taxes and subsidies), education, and regulations (standards and compliance). Under certain conditions, all three could induce change. The Action Plan stresses the use of voluntary incentive mechanisms rather than regulations. Education-based approaches rely almost solely on alternative practices directly benefiting the landowner over the long term. Market incentives (taxes, subsidies, and risk management) and regulation (standards and compliance) provide more direct economic benefits or costs that policy makers may find easier to control. These approaches, however, are generally more costly to the government or politically unacceptable.

Measuring benefits and costs of reduced nutrient loadings - Benefits to local areas of improving water quality have been estimated for a variety of activities, including recreation, water treatment, irrigation, and wildlife habitat, although such estimates are few. Methods for estimating environmental benefits are well known, and an extensive body of literature has been developed on such methods and their appropriate use. These methods can generally be categorized as stated preference (utilizing valuation surveys) or revealed preference (utilizing data on observed actions).

Costs of adopting alternative land management practices have been estimated in a number of studies, particularly for agriculture. Methods for estimating costs are well known, including representative farm models, programming models, and econometric models. Estimates also have been made of the costs for point sources to adopt alternative pollution control technologies using engineering models and programming models.

Suites of models have been developed for examining the relation between farm practices and pollution loads, and between pollution loads and chemical indicators of water quality. These models exist at various scales, including field, sub-basin, and basin-wide. Economists must rely on hydrologists and other scientists to develop these tools.

Limitations in Existing Activities and Related Science Needs

Although much is known about the aspects of the adoption of alternative management practices, and the benefits and costs from nutrient management and how to estimate them, there are significant gaps in information as it applies directly to the Mississippi River Basin and the Gulf.

Issue - Any program to alter farmer behavior is influenced by the policy environment in which agriculture operates. Recent changes to commodity programs (2002 Farm Bill) have created economic incentives that work against the voluntary adoption of management practices by linking government payments with production. In addition, crop and flood insurance programs reduce the risk of producing on marginal land, making it profitable to produce crops in flood plains and on wet soils that might be more beneficial as wetlands and/or vegetative buffers. These incentives may make it more difficult for conservation programs like the

Conservation Reserve Program (CRP) and the Environmental Quality Incentives Program (EQIP) to succeed.

Action - Conduct monitoring, modeling, and research projects on selected agricultural watersheds that work to enhance nutrient management practices, determine benefits associated with implementation of conservation practices, and identify alternative policy mechanisms that achieve national farm income goals without creating perverse incentives. Such information should be made available in time for the next round of Farm Bill deliberations.

Issue - Voluntary approaches have already been identified as the desired mechanisms for encouraging farmers to adopt management practices that reduce nitrogen loads in the Mississippi River Basin. Although there is ample evidence that farmers will adopt nutrient practices that increase their expected net returns, there is a major gap in information on the extent to which farmers will adopt nutrient management practices that are necessary for achieving the goals of the Action Plan. It is highly unlikely that improving water quality in the Gulf is an incentive that would induce farmers to alter their practices. There is a separation of cause and effect in terms of both time and space; hence, it is hard for the problem to be comprehended by the involved parties. Evidence indicates that many farmers do not see the connection between their own operations and local water quality. Any divergence of goals between the target population and national resource managers would work against a strictly voluntary approach. Additionally, other water-quality concerns such as phosphorus and sediment appear to be of greater concern than nitrogen in many of the watersheds in the Basin. Underlying uncertainty regarding weighting of variables in current models also decreases the perception of a linkage between nutrients applied and water quality.

Action - Conduct an extensive literature review on what motivates farmers in the Basin to alter management practices. Surveys in a sample of watersheds also can be used to assess producer attitudes towards water-quality issues and to compare them to other concerns such as profits. Also, a study on the private economic benefits of nutrient management would have two benefits. First, it would shed light on the extent to which a purely voluntary approach might be effective. Second, it would indicate the extent to which nutrient management practices adopted for their private economic benefits might reduce nutrient loads to the Gulf of Mexico. Some analysts estimate that significant reductions in fertilizer use can be achieved at little cost or effort, due to the pervasive "overuse" of fertilizer. Evaluating the specific gains expected to be achieved from profitable nutrient management would give some further indication of the degree to which more costly efforts are needed to achieve the Basin-wide goals and help determine a role that Farm Bill programs might play through locally led efforts. Also, in relation to the motivation issue, all the environmental outcomes and other benefits of a management practice need to be explicitly quantified. For example, sediment rather than nutrients might be an issue that motivates farm practices in the Basin. Research on the performance of practices across a range of environmental issues should identify a set of practices that effectively addresses environmental concerns and resonates with farmers.

Issue - Alternative practices for reducing nutrient loads are known, but the environmental and economic performance of these practices at the local level (where farmers actually decide to use them) may not be known. Many farmers are skeptical of practices that are not "proven" locally and would be unlikely to adopt them unless provided the opportunity to observe performance in a setting similar to their own. This was clearly demonstrated by the research conducted by USDA during the Water Quality Initiative in the 1990's. In regards to alternative management practices, research is lacking on the benefits and costs of tile-drainage management and water-table management. Some preliminary indications show that BMP-guided tile-drain management practices may result in significant reductions in nitrogen loadings while also being relatively easy to accomplish.

Action - An extensive program of practice demonstrations showing the private benefits of alternative management practices would overcome some of the barriers to adoption. Obtaining farmer input on which practices are most attractive in an area would be beneficial. Research on the effectiveness and economic consequences of practices that focus on drainage tiles and soil water level is needed.

Issue - Few watershed-scale studies have tied together the benefits and costs of adopting alternative management practices. Such studies can be useful in educating stakeholders of the role they can play in improving local water quality (that directly affects them) and educating resource managers on the economic incentives that might be necessary to compensate individuals for lost income.

Action - Set up a number of pilot projects that assess the costs and benefits (in qualitative terms) of reducing pollutant loads within the Mississippi River Basin. These projects should be at a watershed scale and should thoroughly analyze benefits and impacts within states and/or watersheds. Potential social costs, such as dislocation in land use, agribusiness infrastructure, and farm communities, also should be assessed. The analyses should include models for linking fields with water resources. The modeling should focus not only on nutrients, but also keep track of other outcomes (sediment, greenhouse gases) so that unintended consequences can be identified and a complete accounting of benefits can be conducted. Costs to be evaluated include those to the individual producer, those to rural communities, and those to local governments. Cost-effectiveness analysis can be used to examine alternative scenarios for practices (fertilizer reduction versus wetlands) and targeting that can guide the overall Action Plan. Over the long term, these studies could be extended to support the adaptive management process.

Issue - Voluntary incentives have been highlighted as the means for achieving nitrogen goals to the Gulf. As noted above, there are reasons why the effectiveness of such an approach may be limited (contrary incentives, local goals predominate). Alternative incentive mechanisms need to be identified and explored to supplement voluntary programs.

Action - Review the literature on financial, education, and compliance-type mechanisms for supporting the adoption of conservation practices. Compliance mechanisms, tied to financial incentives, have been employed to protect wetlands and highly erodible soils. With the increased levels of government financial incentives and technical assistance to farmers through commodity and conservation programs, current compliance mechanisms might be a particularly effective complement to these programs. Experiments on different sets of policy instruments could be conducted on the watershed scale as pilot projects funded through USDA base programs, Section 319 (Clean Water Act), or other funds and supported by water-quality monitoring. The cost effectiveness of various combinations of policy instruments, such as carbon sequestration markets, nutrient credit trading, hunting lease market development, incentive payments, nutrient compliance, and education, would be assessed and recommendations made on which sets of policy instruments work best in different settings.

Issue - It is important that all constituencies who make efforts to reduce nutrient contamination in our water resources feel that all contributors are doing their "fair share". Although much focus has been placed on reducing nutrient loss from agriculture, there are numerous other sources of nutrients to streams. Another source of nutrients in the Mississippi River Basin is runoff from suburban and urban sources. There is little understanding of the role these sources play in contributing nitrogen to the Gulf, what management measures are appropriate, and the incentives for getting these measures adopted. Point-source discharges from municipal wastewater treatment plants are another source of nutrients to waterways that, although regulated, have been estimated to contribute approximately 11 percent of nitrogen loads reaching the Gulf (CENR, 2000). Potential decreases from this source are limited without water-quality criteria and standards related to effects on downstream waters.

Action - Develop a research program that examines nitrogen losses from landscapes other than agriculture, develop appropriate management measures, and identify incentive mechanisms for getting those measures adopted. Work with USEPA and states to identify municipal treatment plants in need of upgrades. In addition, the contributions that point source measures have already made to improvement in water-quality conditions through the regulatory program and the associated costs should be quantified. Making available information on the wide range of nitrogen sources being considered for improvements and the existing improvements in some areas might also prove educational to many stakeholders in the Basin.

Issue - Some of the strategies proposed for reducing nutrient loads to the Gulf involve flow diversions in the lower Basin. The consequences to agriculture of an extensive program of such changes have not been adequately assessed, nor has the level of nutrient reduction that can be accomplished through these measures.

Action - Conduct a study of how changes in water flow regimes affect agricultural production in the Basin, as well as the potential reductions in nitrogen loads to the Gulf.

Issue - Reducing the size of the hypoxic zone to 5,000 km^2 is expected to generate significant environmental benefits, both in the Gulf and within the Basin itself. Nutrients are an important water contaminant, and a reduction of loadings should be expected to improve water quality in the Basin and generate a variety of economic benefits. Estimating these benefits is a huge challenge. Environmental valuation studies are time consuming and costly, mostly because of the non-market nature of the goods being valued. These include recreation, wildlife, and ecosystem diversity. Surveys and careful econometric methods are required to assemble and evaluate such data. In contrast, some potential benefits such as drinking-water costs are relatively straightforward to estimate, if the data can be acquired. Results from such a study would be used to inform policy makers of the utility of a Gulf policy.

Action - Conduct an extensive literature review on all environmental benefit estimation studies focused within the Mississippi River Basin. Conduct an extensive literature review of all water-quality cost-control studies, focusing on nutrient reduction. The purpose of these exercises is to identify possible data sources and methodologies.

Identify different scenarios of how the goal can be achieved. For example, the goal can be achieved through a combination of wetland use, nutrient management, and reductions in point-source discharges. Effects on such actions on Basin waters need to be estimated using watershed models. These effects will differ by sub-basin.

Identify benefit categories. Environmental benefits that involve the direct use of water or related resources include recreational fishing (Gulf and Basin), commercial fishing (Gulf), duck hunting, wildlife viewing (bird watching), flood control, and drinking-water treatment. Benefits that can be labeled "non-use" and do not involve direct activity include biodiversity (ecosystem health) and carbon sequestration (for global warming). Non-use values are much more difficult to measure than use values.

Design individual valuation studies for each category of use. Changes in costs or benefits must be directly linked to actions taken on the ground through watershed or other models. Changes should be quantified at the sub-basin scale. The types of studies that might be used include stated preference studies (recreation, habitat), revealed preference (recreation), and cost-avoidance and net-return studies (drinking water, commercial fishing). These studies would need to be conducted at the watershed level. A sample of watersheds could be selected for intensive valuation with the results transferred to nearby basins.

Estimate costs that are required to bring about reductions in nutrient loadings. Costs of reducing fertilizer use on the farm can be estimated with a model such as USMP (the U.S. Mathematical Programming modeling framework), as was done in the CENR science assessment (Doering et al., 1999). Costs for nutrient removal from point sources are well known and data are available from the Chesapeake Bay Program, the Long Island Sound Program, and other areas.

Needed Coordination, Information Sharing, Synthesis, and Reporting

The diverse nature of the Basin requires that numerous regional research studies on practices, farmer behavior, and links to water quality be conducted. This requires coordination between research efforts within disciplines, as well as between disciplines. Model builders and economists must cooperate in pilot watershed studies to ensure that the economic and physical models can be linked and that common data sources on land use be used. Credible economic research cannot be conducted without links to water quality. There also must be cooperation between economists working in the watershed and economists working in the Gulf to ensure that all potential benefits and costs are covered and to agree upon methodologies when benefit categories overlap. Current research institutions and organizations should be looked upon to coordinate this research. If necessary, a new research organizational structure should be put in place to accomplish the goals of the Action Plan. Existing efforts and programs that are gathering needed information should be assessed and utilized to eliminate any duplication of effort through creation of new programs.

MONITORING, MODELING, AND RESEARCH IN THE GULF OF MEXICO

The strategy for science activities in the Gulf of Mexico is described in the following three sections: Gulf Monitoring and Reporting, Gulf Modeling and Research, and Gulf Social and Economic Research. Issues related to coordination among Basin and Gulf activities and resource needs are discussed in the section *Coordination and Information Needs*, near the end of this report.

Gulf Monitoring and Reporting

> "Effective marine environmental monitoring programs must have the following features: clearly defined goals and objectives; a technical design that is based on an understanding of system linkages and processes; testable questions and hypotheses; peer review; methods that employ statistically valid observations and predictive models; and the means to translate data into information products tailored to the needs of their users, including decisionmakers and the public."
>
> *- National Research Council, 2000, p. 202.*

Needed Framework for Monitoring and Reporting

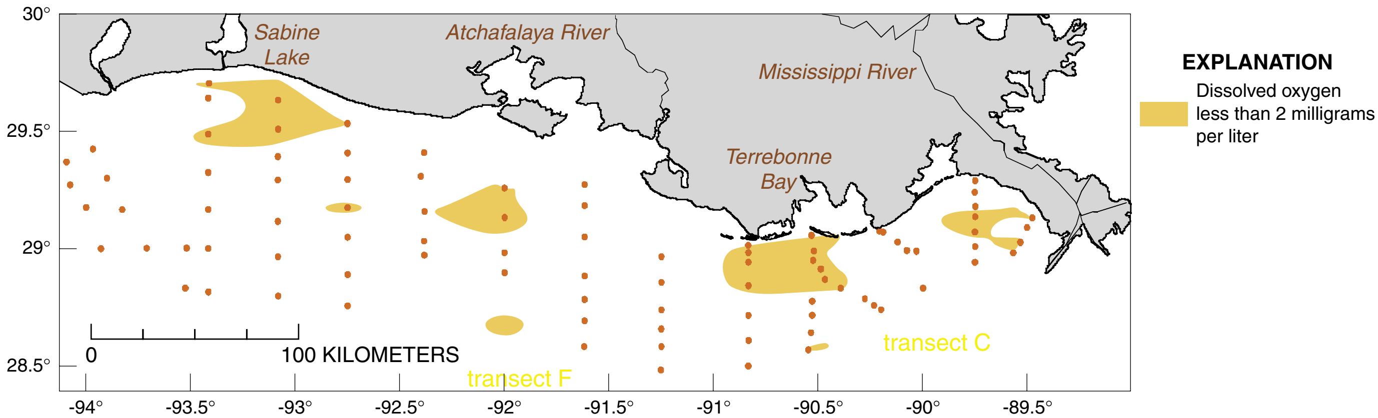
Adequate monitoring of the hypoxic zone that forms every summer in the northern Gulf of Mexico requires measurement in an area that extends from the mouth of the Mississippi River in Louisiana through Galveston Bay off the Texas coast. This enlarged area would not only encompass the hypoxic zone, but also an area far enough beyond the zone to alleviate problems in models resulting from boundary conditions present at the edge of the zone. Data collection should be year-round to document the processes involved in determining the distribution of hypoxia and to provide the data required for suitable temporal models to be generated. Shelf-wide data collections need to be expanded through the period from May to September, not just once each summer. Data that need to be collected include, but are not necessarily limited to, biological parameters (such as benthic, demersal vertebrates, invertebrates, pelagic fauna, and chlorophyll concentrations); ambient environmental parameters (such as dissolved oxygen, water temperature, light attenuation, nutrient concentrations, and physical oceanographic and shelf meteorological observations); and process-rate information (such as rates of primary production, secondary production, and nutrient cycling). The data and information collected from these activities need to be made available on a timely basis through a single clearinghouse or storage and access site.

Existing Monitoring and Reporting Activities

Biological Parameters - The National Marine Fisheries Service (NMFS) has performed two groundfish surveys through the area of interest every year for over 20 years. Known as the Southeast Area Monitoring and Assessment Program (SEAMAP), these surveys are conducted in June/July and again in October/November. The survey objectives are to (1) sample the northern Gulf of Mexico with standard sampling gear to determine the abundance and distribution of demersal and benthic fauna, (2) collect size measurements to determine population size structures, (3) conduct conductivity/temperature/depth casts to collect environmental data, (4) collect ichthyoplankton samples with bongo and neuston samplers so as to map the distribution of fish eggs and larvae, and (5) conduct paired comparison towing with other NMFS vessels. The Louisiana Department of Wildlife and Fisheries (LDWF) conducts the inshore portion of the SEAMAP cruises several times per year, including at least one cruise during the period of summer hypoxia. In addition, fish and invertebrates are sampled shelf-wide, from off the coast of south Texas to south of Mobile Bay, via shrimp trawls. Approximately 250 stations are sampled during each cruise. The LDWF, through a grant from NOAA, also has initiated a project to determine the effects of environmental perturbations including hypoxia on shrimp and commercial shrimping off the Louisiana coast. The project is organized into an Environmental Monitoring Program and a Log Book Program. Ten offshore sampling trips are conducted each year to profile the zone of hypoxia and to find the inshore front of the hypoxic zone during the summer shrimping season. Data collected from the logbooks of shrimpers includes specific trip information, shrimping conditions and locations, landings, and expenses. The purpose of the project is to correlate commercial shrimping sets with formation and location of the hypoxic zone. Texas is implementing a new Sustainable Coastal Margins Program that will add a new array of biological monitoring sensors to buoys that will detect harmful algal blooms.

Ambient Environmental Parameters - Nancy Rabalais, Louisiana Universities Marine Consortium (LUMCON), and her Louisiana State University (LSU) colleagues have been collecting data along transects from the mouth of the Mississippi River to the Texas border since 1985, usually

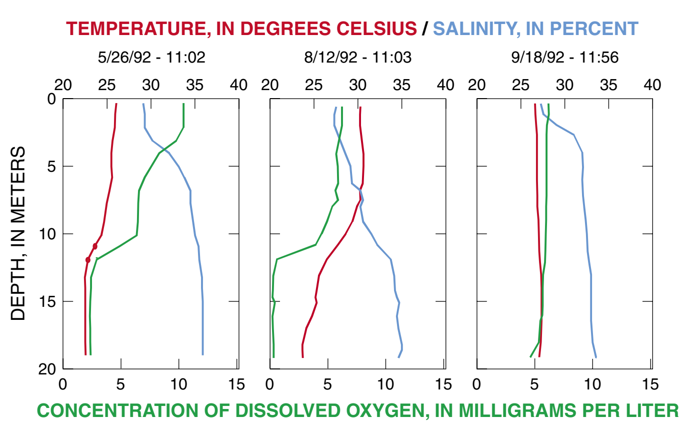
Bottom-Water Hypoxia in the Northern Gulf of Mexico, July 23-28,2003



Source: Rabalais, Turner and Wiseman

during the last half of July. The group collects information on a wide range of parameters, including conductivity/temperature/depth, light penetration, dissolved oxygen, suspended solids, nutrients, phytoplankton, and chlorophyll. The group also collects hydrographic, chemical, and biological data from two transects off Terrebonne Bay (Transect C) on a monthly basis and one transect off Atchafalaya Bay (Transect F) on a bimonthly basis. There is a single moored instrument array in 20-m water depth in the core of the hypoxic zone that collects vertical conductivity/temperature data, as well as near-surface, mid, and near-bottom oxygen data; an upward directed Acoustic Doppler Current Profiler (ADCP) on the seabed measures direction and speed of currents from the seabed to the surface. There also is an assortment of nutrient and light meters. Beginning in 2003, these data will be merged with meteorological and wave data and reported in real time. Two additional moored arrays to measure currents, temperature, salinity, oxygen, nitrate, and vertical particulate fluxes will be placed in the Gulf as part of NOAA's Coastal Ocean Program – Northern Gulf of Mexico Experiment. In 2000, USEPA National Coastal Assessment began collecting

Vertical Profile (C6B) of Salinity, Temperature, and Dissolved Oxygen



Source: Rablais

basic water-quality data and benthic, fish, and sediment samples in the estuarine/tidal waters along Louisiana's coast. Samples are collected once per year in the summer, and collection will continue through the year 2004. Sites were randomly selected and are largely inshore. In addition, as a result of the Hypoxia Action Plan, the USEPA Office of Research and Development initiated a sampling effort off Louisiana in the area where hypoxia develops, beginning in winter 2003, and continuing for several seasons thereafter. NMFS also has teamed with NOAA's National Coastal Data Development Center (NCDDC), the National Aeronautics and Space Administration's Earth Science and Applications Directorate, and LSU's Coastal Ecology Institute in 2001 and 2002 to improve the quality of dissolved oxygen data collected during their groundfish survey cruises to collect supplemental chlorophyll and nutrient data, to provide near real-time maps of the seasonal hypoxic zone, and to make hypoxia-related data accessible to interested parties. The Texas Parks and Wildlife Department - Coastal Fisheries Division's fisheries independent monitoring program has incorporated environmental parameters into their 16 monthly trawl surveys at each of five offshore regions. Parameters measured on these surveys include fish/macroinvertebrate identifications and lengths, dissolved oxygen, water temperature, secchi depth, wind speed and direction, bottom type, and barometric pressure. These surveys are conducted year-round and have been ongoing since 1982.

Limitations in Existing Activities and Related Science Needs

Currently, monitoring of shelf-wide conditions is conducted only once each year, primarily, but not exclusively, during July. These efforts need to be increased in frequency, at a minimum monthly from May through September. To develop a more complete understanding of ecosystem dynamics, selected sites should be monitored year-round. The spatial boundaries of some of these existing monitoring efforts should be expanded to collect data for defining boundary conditions in modeling efforts. In addition, there is a need to expand existing monitoring, where possible, to include additional parameters (e.g. benthos, other nutrient components, and dissolved materials) as data currently are not collected on all variables of interest. When expansions of existing monitoring efforts are not feasible, new monitoring efforts need to be developed and implemented. For example, some monitoring and data collecting are currently conducted with the use of moored arrays. One way to increase data collection is to increase the volume of instrumentation within the hypoxic zone (i.e., through more moored arrays, fitting additional biological and environmental sensors to existing arrays, and/or taking advantage of additional cruises of opportunity). The Texas General Land Office (TGLO) and Texas A&M University's Geochemical and Environmental Research Group maintain an array of instrumented data buoys, known as the Texas Automated Buoy System, off the Texas coast for assessing ocean physical parameters (e.g., currents, winds, barometric pressure, temperature, etc.) for application in tracking hazardous waste and oil spills in real-time. The Texas buoys could be outfitted with additional instruments to assist in monitoring the occurrence and western extent of hypoxia. A similar system off Louisiana could be used to monitor and track hypoxia. Oversight activities should be implemented to insure commonality of instrument suites. In addition, while several monitoring and study activities are in progress, a comprehensive list of parameters with spatial/temporal resolutions is not available. A matrix of current monitoring and study efforts with parameters that are measured needs to be developed. This matrix then can be used to determine gaps in data collection activities. Finally, a high priority should be given to an intensive effort to process and analyze existing historical data relative to hypoxia.

Needed Coordination, Information Sharing, Synthesis, and Reporting

Data are collected in the Gulf of Mexico on the Louisiana shelf by several agencies, organizations, institutions, and individuals. Much of this data and information are kept by each group or individual and are not centrally archived and maintained, with the exception of those data sets required to be submitted to NOAA's National Oceanographic Data Center (NODC) with the appropriate metadata. For example, results from the studies of Rabalais and others are released through real-time maps, press releases, publications, and data submissions to NODC.

Determining where and how to access these data by those examining the hypoxia issue is often difficult, confusing, and time consuming. Improving access by uniting all data and information collected on the Louisiana shelf into one location, however, may not be a practical solution. Instead, an Internet portal should be developed that would allow data and information to remain where they currently are archived, yet allow researchers, modelers, and managers to access the data through a single site across the Internet. The portal would reside at a single location and be maintained by a single entity. Thus, a lead agency is needed to assume responsibility for data and information accessibility from current and future monitoring and study activities in the area of interest. NCDDC mission goals include single point access for coastal data and geospatial information display/product support and, thus, can play an important role in hypoxia data and information collection and dissemination in future efforts, especially in developing a single-access site for coastal data and information. Lastly, numerous data are collected for purposes other than to study or monitor hypoxia and its effects on the Gulf ecosystem. Because of the many separate monitoring and study efforts in the area where hypoxia develops, it is imperative that efforts be coordinated so that there is no waste of effort or funding. The lead agency responsible for data and information accessibility could coordinate meetings between different monitoring parties to discuss and resolve potential redundancy issues.

Gulf Modeling and Research

The goals for modeling and research in the northern Gulf of Mexico are:

Modeling Goal - To develop a suite of models that explains and predicts the physical setting and the productivity and its fate and the subsequent water quality, hypoxic conditions, and associated effects resulting from human and natural influences, thus allowing for comparative evaluation and design of management actions.

Research Goal - To improve knowledge of the physical, chemical, and biological processes that control hypoxia and its effects and the associated natural and human factors, so as to provide improved methods for monitoring, data interpretation, and modeling.

Needed Framework for Modeling and Research

Specifying the space–time characteristics of hypoxia and the flow field over the shelf are the desired endpoints for water-quality modeling over the northern Gulf of Mexico continental shelf to enable design of alternative management actions and evaluation of their potential impact. In order to arrive at these endpoints, a variety of modeling and research activities are needed. Additional use of box models for process studies is important. State-of-the-science models have not yet been applied to the Gulf for water-quality description or prediction; however, several appropriate modeling frameworks exist. From a purely hydrodynamic standpoint, regional-scale, hydrodynamic models should be developed. Appropriate monitoring along the open boundaries or robust ways to incorporate large-scale model output or satellite products so that large-scale circulation features are correctly represented is needed for these models. Regional models should be designed within a northern Gulf framework for compatibility, linkages, and comparative purposes. Similarly, atmospheric parameters should be monitored or modeled with adequate spatial resolution to achieve sensitivity in these models. Refined models of dispersion, both vertical and horizontal, must be developed for these stratified regions. Process rates are poorly known and need to be better quantified if the eutrophication models are to produce accurate predictions of water quality. Future modeling and research examining causes and consequences of hypoxia must consider the ecology of the entire water column, not just the bottom waters. In addition, the temporal scope of research and modeling efforts must extend beyond the period of hypoxia. Although summer monitoring receives the most emphasis and defines the broadest extent of hypoxia, important processes occur throughout the year. Multi-nutrient models capable of predicting food web changes, such as the heuristic models used in the Great Lakes (used for better understanding, but not for prediction) should be developed. Of utmost importance is that the range of model types, as well as the different regional models, should be developed within an integrated northern Gulf of Mexico framework.

Existing Modeling and Research Activities

Ongoing programs in modeling and research include the continuing support of a variety of projects investigating the causes and ecological effects of the hypoxic zone by NOAA's Coastal Ocean Program. A new initiative by the USEPA Office of Research and Development investigates the hypoxic zone and supports ocean water-quality modeling and atmospheric deposition models. The USEPA Gulf of Mexico Program (GMPO) is helping to coordinate efforts with the USEPA National Exposure Research Laboratory and the National Health and Environmental Effects Laboratory, first to develop a joint research program to focus on the hypoxia issue, and then to create a unified modeling approach for evaluating hypoxia. Several Gulf circulation models have been developed. These include PDOM (Princeton-Dynalysis Ocean Model), CUPOM (Colorado University Princeton Ocean Model), DieCAST (Dietrich Center for Air Sea Technology), MOM (Modular Ocean Model), and MICOM/HYCOM (Miami Isopycnic Coordinate Ocean Model, HYbrid Coordinate Ocean Model; Rosenstiel School of Marine and Atmospheric Science). Texas A&M has developed a vertically integrated model of the northwest Gulf of Mexico shelf. Additionally, numerous estuarine models for the region exist. In conjunction with the Wave-Current Surge Information System (WAVCIS) monitoring program at LSU, wave models for the region are being tested and calibrated. These models may prove useful in predicting sediment redistribution and light fields. For the past 3 years, the GMPO supported the Naval Oceanographic Office in the development of a state-of-the-art, high-resolution hydrodynamic model for the Mississippi Coast as part of a Northern Gulf Littoral Initiative. A partnership among the Navy, GMPO, the Mississippi Department of Marine Resources, the University of Southern Mississippi, and others monitored and modeled the shelf east of the Mississippi Delta. The model is now running on supercomputers at Stennis Space Center, Mississippi, and is being tested for inclusion in the suite of models used to support Naval Operations. Lessons learned during this exercise may prove useful for studies west of the Delta. Important sources of monitoring data needed to support the models include many of the programs mentioned above, as well as satellites that can provide estimates of surface phytoplankton biomass, sea surface temperature, and sea surface height. A new MMS exploratory study of the slope and rise may provide information concerning the variability of offshore boundary conditions. SEAMAP data also are an important potential source of data.

Limitations in Existing Activities and Related Science Needs

Large uncertainties exist at each step of the present paradigm for hypoxia development, and the uncertainties in understanding must be reduced to improve model formulations. For example, more than 50 percent of the carbon delivered to the bottom waters is exported or buried (as opposed to being oxidized), but its final fate is unknown. These uncertainties are further exacerbated by a lack of understanding of the spatial variability of sedimentation rates. Improved knowledge of the fate of the organic matter produced from the river nutrient inputs is needed, including the extent of the effects of nutrient inputs from the Mississippi and Atchafalaya Rivers and how those effects change with changing river flows and nutrient loads. The importance of nitrification as an oxygen sink in the water column and sediments should be defined. Feedbacks throughout the system are important. Lack of knowledge concerning the processes responsible for cross-shelf transport of material is a major existing shortcoming. A better understanding of small-scale river plume physics is needed. The plume regions within a few kilometers of the outflow are regions where physical and biological properties change rapidly. Property modifications in these small regions have a large effect on larger scale plume property characteristics.

Further, models of eutrophication, productivity, and subsequent effects on water quality and living resources in the northern Gulf of Mexico must resolve a variety of important time and space scales. Managers and scientists require a spectrum of models of differing degrees of time and space resolution and complexity to address the many issues associated with hypoxia in the Gulf. These models need to provide greater understanding of ecosystem function and to compare responses of a system to potential management scenarios or other perturbations. A number of empirical and statistical models for determining dose-response relations already exist, but there are benefits to be gleaned from the development of others. Simple box models should be improved and exercised. State-of-the-science, four-dimensional (i.e., including temporal and spatial dimensions), coupled physical-biological-chemical models should be applied to the Gulf of Mexico hypoxic region. These varied models should be used in concert, and relations derived from empirical and statistical models should be applied in the integrated, high-resolution models. In addition, research efforts should explore the development of models with more refined and detailed water-quality components. These models should incorporate, for example, microbial processes, multiple phytoplankton groups, nutrient ratios, and biogeochemical transformations responsible for regenerating nutrients and depleting oxygen. The development and application of such a suite of models would enable the scientific community to provide useful results to policy makers and managers in a timely manner, while simultaneously improving our scientific understanding of critical processes in a continual and adaptive manner.

Other areas where increased research effort would be beneficial include the interaction of benthic production and oxygen dynamics; definition of the significance and consequences of the displacement of mobile species in response to hypoxia development; a detailed assessment of the impacts of hypoxia on species diversity and community structure; an increased understanding of the toxicity of the sediment layer to benthic organisms as a function of the oxygen status of the water column; improved estimation of nitrate delivery to the Gulf; simultaneous in situ measurements of carbon, nitrogen, and oxygen fluxes; in situ benthic uptake data; measures of habitat degradation resulting from hypoxia and the rates of recovery; definition of larval distribution patterns; species-specific inquiries, such as harmful algal bloom studies; long-term monitoring; and hindcasts of hypoxia using proxies.

As part of this continual improvement of understanding and model development, a number of pieces of information from monitoring and research are imperative. Quantification of process rates is needed to adequately describe the dynamics of carbon, nutrients, and oxygen in the ecosystem. For example, quantitative assessments of carbon fluxes through the food web are necessary to appropriately apportion phytoplankton fate between zooplankton grazing, benthic respiration, microbial transformations, and other loss terms. The potential for a seasonal switch in phytoplankton community dominance among different functional groups (e.g., picoplankton versus nano- and microplanktonic forms, highly silicified versus lightly silicified diatoms) has important consequences for the development, duration, and dissipation of hypoxia. Hypotheses to be tested by models must be explicitly stated. Field data, including state variables and process rate measurements, are needed to parameterize, run, and validate the models. Such validation efforts should include a clear statement of the expected and resultant accuracy of the models when compared to independent data sets. As process studies work to better parameterize the box models and develop more complex model formulations, attention should be directed to meeting the following needs, among others:

- Improved definition of relations between saturation light intensities, underwater light attenuation, and phytoplankton growth rates for key species;
- Improved understanding of factors controlling benthic primary productivity and its contribution to total water column production;
- Improved understanding of factors controlling water column oxygen depletion rates;
- Improved understanding of factors controlling sediment-water nutrient fluxes and sediment oxygen demand; and
- Improved understanding of the structure and function of the microbial food web and its role in regenerating nutrients and depleting oxygen in susceptible regions.
- Better descriptions of the composition, magnitude, and seasonal variability in the vertical flux of particulate organic carbon (POC) and particulate organic nitrogen (PON) also are needed, including an improved understanding of the following phenomena:
- The importance of shifts in phytoplankton and microbial food web community composition in controlling the fates and pathways of organic carbon and nitrogen;
- The importance of silica limitation and its role in influencing phytoplankton species shifts;
- The influence of phytoplankton-zooplankton and microbial food web interactions on fates and pathways of organic carbon, nitrogen, and oxygen;
- The rate and extent of water column nutrient remineralization and nitrification;
- The importance of nitrification, denitrification, and dissimilatory processes in sediments for the total nitrogen and oxygen budgets of the northern Gulf; and
- The relative importance of atmospheric nutrient loadings to the northern Gulf.

Physical oceanographic studies will be necessary to characterize the mixing, dispersion, and air-sea exchange processes in the region of interest. Shelf meteorological data to force the models also are needed, either from improved models with higher resolution over the shelf or from observations. Specific data sets will be required for focused studies with specific models. In particular, open boundary conditions, initial conditions, and forcing function specification would require a significant commitment of monitoring resources. Development of algorithms that correctly estimate light attenuation parameters, suspended sediment concentration, and chlorophyll-a concentrations from satellite data must be developed for the coastal waters of the hypoxic region. Existing historical data should be thoroughly evaluated and combined with further research to identify critical processes not addressed within existing model formulations. Finally, it should be acknowledged from the onset that models should be applied and improved in an iterative manner. Initial applications are unlikely to answer all issues satisfactorily.

In order to determine the consequences of eutrophication and hypoxia over the northern Gulf of Mexico continental shelf, many additional modeling and research efforts are needed to address crucial gaps in our understanding of how hypoxia affects the coastal ecosystem, including ecologically and economically important species. Topics about which additional information is needed and related questions are:

- The consequences of degradation in bottom habitat quality and subsequent use of degraded habitats by highly mobile living resources (both during hypoxic conditions and during recovery). Ecologically and economically important species of nekton are displaced in response to low dissolved oxygen, but the consequences of this displacement for the nekton or their habitat is not understood. What are the consequences of displacement of mobile species from a given habitat? Is growth or survival affected and are the effects realized at the population level? How are food webs and trophic structure affected? Do nekton exploit stressed benthos prior to or during their retreat, and what are the consequences for benthos and nekton? Where are the refuges from hypoxia in the coastal zone that are used by the nekton? Are pelagic juveniles and adults and large demersal nekton displaced and affected in the same ways as small demersal nekton?
- The effect of eutrophication and hypoxia on the trophic structure and energy flow within communities occupying the benthic and water column habitats. How is the structure and function of the microbial food web affected? Is community structure and secondary production of the benthos affected in adverse ways? Do the duration, intensity and frequency of hypoxia affect the recovery of the benthos and benthic habitats? What are the effects of hypoxia on coupling between benthic and water column habitats? Does hypoxia increase risks of predation for early life history stages of fishes in the coastal zone where hypoxia occurs? What is the role of gelatinous zooplankton that occurs in eutrophic systems and their impact on other zooplankton, including the early life history stages of fish and invertebrates? How are these predators distributed (vertically and onshore-offshore) within the coastal zone and how they are affected by hypoxia?
- How hypoxia interacts with other processes to affect recruitment of fish and invertebrates, either through changes in the plankton to support growth and survival, direct mortality of eggs or larvae, or disruption of migrations to required habitats. Do eggs and larvae occur in or near hypoxic bottom waters and are there consequences for their survival? Do their vertical distributions change in relation to the hypoxia? Are their migratory patterns (horizontal and vertical) altered by hypoxia in ways that impact survival or recruitment? What are the interactions of offshore, near-coastal, and adjacent coastal habitats with respect to effects of hypoxia on living marine resources?
- How phytoplankton production, abundance, and species composition affect the bottom waters. How do species composition, production, and abundance affect oxygen concentrations? Are there linkages between nutrient loading and harmful algal blooms that differ from those between nutrient loading and low oxygen?
- A variety of models of economically and ecologically important species and processes controlling their abundance and distributions are needed to address the above questions. The scales to be modeled cannot be defined fully with existing information. In order to understand the impacts of eutrophication and hypoxia on recruitment of some important offshore species, details of their behavior and details of the coastal flow field may need to be more clearly defined.

This section describes many of the uncertainties and science needs for research and modeling to support decisionmaking in the northern Gulf of Mexico. It is difficult at this time to define specific priorities for these activities and is beyond the scope of this report. Priority setting should be an important part of the subsequent planning and implementation activities.

Needed Coordination, Information Sharing, Synthesis, and Reporting

Interaction between the water quality, upper trophic level, and socio-economic modelers is necessary to further clarify desired modeling endpoints and space and time scales involved. Details of the essential, critical linkages with Gulf monitoring programs will require thoughtful development and communication between modelers and monitoring groups. Thorough analysis of existing, unanalyzed historical data should be a first step. Establishment of a data management process will allow for rapid and free dissemination of pertinent new and existing data.

Periodic (annual or biennial) meetings of scientists and managers involved in hypoxia research in the northern Gulf of Mexico are recommended to ensure efficient information transfer. These meetings should include representatives from both the Gulf and Basin interests in an effort to exchange information and ideas on reducing the negative effects of eutrophication in the Gulf. Further, these meetings would be useful to exchange ideas and information on the existing conditions within the watershed and potential future scenarios and to provide a forum where appropriate space and time scales for Basin and Gulf models could be debated and coordinated in order to ensure compatibility of the two sets of activities.

Gulf Social and Economic Research

Needed Framework for Social and Economic Research

A social and economic assessment of the potential consequences of Gulf of Mexico hypoxia first requires identifying the particular sectors of society that may be affected by hypoxia and then developing a monitoring, modeling, and research program tailored for each group. For purposes herein, this research plan considers four types of user groups: commercial and recreational fishermen; fishing-dependent communities; non-harvest users (e.g., boaters, scuba divers, eco-tourists, etc.) and the general public, which may derive existence value from knowing that hypoxia does not threaten the Gulf resource base and, in particular, threatened and endangered species.

Commercial and Recreational Fisheries – A general framework for filling data gaps and building modeling capacity is provided below, subcategorized by information type (economic, environmental, and spatial data, and fisheries models and research).

Economic Data: State and federal agencies need to expand existing commercial and recreational fisheries economic data collections, as well as to implement new surveys entirely, to ensure that adequate economic data are collected and may be used to analyze the potential effects of hypoxia on fisheries. Core data elements in commercial fisheries include: revenue (price and landings), variable costs (input cost and usage), and fixed costs. The survey design should ensure that the data collected would be of sufficient resolution to capture the seasonal and temporal characteristics of hypoxia. In addition, given the annual variation in hypoxia, the economic data collected in both the commercial and recreational fisheries will need to be routinely collected and not implemented on a one-time or cyclical basis.

Environmental Data: Monitoring agencies need to increase data collection of environmental variables by either expanding existing programs (preferred) or creating supplemental programs, so as to ensure that data of sufficient spatial resolution and frequency are available for economists' needs. In the absence of increased water-quality monitoring by existing programs, data could be obtained by provisioning (selected) fishing vessels with water-quality measuring instruments, comparable to the Citizen Monitoring program, thereby allowing for fishery effort data to be linked to hypoxic areas. A potential pilot study of the efficacy of this approach could be conducted in an observed fishery, with the observer making instrument readings. A feasibility study would determine whether the cost of such a program would be prohibitive, and if not, the degree of portability of these instruments. That is, the study should address whether it is feasible for observers to install the instruments prior to debarking on a trip and uninstall the equipment upon return, thus allowing continued equipment use on subsequent observed trips.

Spatial Definition: In the short-term, data collection agencies should work to improve the spatial resolution of existing commercial and recreational fisheries surveys, particularly the state trip ticket report. Upcoming surveys, as well as those still in the planning stages, should be re-visited prior to implementation to confirm that data collected from the survey will allow for analyzing potential consequences of hypoxia. Agencies should identify hurdles to obtaining better spatial data in monitored fisheries and resolve procedures for overcoming this information gap, including government provision or requiring individual purchase and installation of vessel monitoring systems (VMS). Over the long term, the efficacy of current programs should be re-assessed with respect to current and emerging models to identify data gaps.

Fisheries Modeling and Research: One recommendation for filling information gaps associated with assessing the socioeconomic impacts of Gulf hypoxia in the short run is to compute the effect of freshwater flow on recent commercial and recreational fishery harvests and then to compare these results with pre-hypoxia data. Since freshwater flow is highly correlated with the extent of the hypoxic zone, this parameter should have a greater negative impact than that which can be attributed to the effect of hypoxia on harvests in hypoxic years. For example, research has shown that increased freshwater flow negatively impacts shrimp harvest. Such models could be run in virtually all fisheries, with implementation beginning with those fisheries identified as priorities. Model output would provide fishery managers, as well as other decisionmakers, with useful baseline information on whether impacts are occurring. Given the simplicity of the model, however, actual estimates of impacts may be imprecise.

A more long-term approach is to extend existing fisheries models so they can directly assess the impact of hypoxia on Gulf fisheries. Towards this end, a first step is to update the bioeconomic model currently used in the shrimp fishery, incorporate hypoxic effects, and then extend this model to other fisheries. This modeling approach can provide estimates of industry impacts, including impacts on annual catch and revenue. Subsequent simulation models may be developed to determine the impacts of changes in abundance due to hypoxia on fishermen. Under this approach, changes in fleet size, import levels, ex-vessel prices, operating costs, crew size, and net benefits, to name a few, can be determined by changing various model parameters or variable values to reflect the effects of hypoxia on the fishery or regulations to correct it.

In addition to affecting the abundance of a stock, hypoxia also may affect the spatial distribution of a species. Changes in the spatial distribution of a species can affect the travel costs, search time, and productivity of fishermen. To examine these effects, individual fishermen behavioral models (e.g., random utility models of fishing ground choice) that can incorporate the changing distribution of hypoxia to predict the economic gains or losses need to be developed and routinely applied to both commercial and recreational fisheries.

Prioritization of Fisheries-Related Activities: Overall, given that the fisheries data collection activities and, to some extent, modeling and research activities are specific to each user group and/or fishery, tasks must be prioritized. Two key criteria are (a) ranking fisheries (species) by the degree to which they are known/perceived to be directly affected by hypoxia, and (b) the economic and social importance of the commercial or recreational fishery (species). Species that are likely to be directly affected by hypoxia are those found in hypoxic regions, and within these regions, especially those found in bottom waters where eutrophication tends to occur. As more information becomes available and biologists and ecologists establish linkages with respect to the indirect effects of hypoxia on a growing number of species, the prioritization of data collection, modeling, and research activities should be modified to reflect this new information.

A third criterion for prioritizing projects is tractability. In particular, low-cost data collection projects (e.g., economic add-ons to existing surveys) might receive higher priority, particularly if the project has applicability for other fishery management issues. A benefit of this approach is that it establishes a time-series collection that may be useful for revealing more subtle or indirect effects of hypoxia.

Fishing-Dependent Communities – Under National Standard 8 of the Magnuson-Stevens Fishery Conservation and Management Act (Pub. L No. 94-265), NMFS is required to assess the economic impacts of proposed fishery management regulations on fishing-dependent communities. To meet this obligation as well as to assess the impact of hypoxia on fishing-dependent communities, NMFS needs to collect more detailed quantitative economic and demographic information on individuals; qualitative information on social structure and organization; cultural data (e.g., norms and values) related to communities; and fishery participation data. Results will yield a socioeconomic profile for each community, including demographic information, employment information, and descriptions of the fishery-related enterprises, as well as number of households dependent upon fishing as a source of income. Once this stage of the research has been completed, subsequent economic, social, and cultural analyses focusing on fishing-dependent communities can be conducted.

Non-Harvest Users – Determining whether, and if so to what extent, non-harvest users (e.g., boaters, scuba divers, eco-tourists) are affected by hypoxia in the Gulf poses a significant challenge to researchers. A rudimentary first step would be identifying and/or developing databases that set apart the individuals that comprise these user groups. Although developing the “monitoring framework” poses a new challenge, the modeling and research needs do not pose a significant new challenge. That is, existing non-market valuation methodologies are adequate for determining impacts on non-harvest user groups.

The General Public and Existence Value – An assessment of society’s valuation of the Gulf resource or of society’s valuation of the damage imposed by hypoxia to the Gulf resource needs to be conducted. Such studies would provide important baseline information to policy makers for assessing the tradeoffs associated with reducing nitrogen loading in the Mississippi watershed. As with any valuation survey, there would be numerous details to address, ranging from developing a representative sample frame to framing the valuation questions in a non-leading manner. It is clear that the better able the survey is to convey information to respondents on the scope of the effects of hypoxia on the Gulf resource base, the more reliable/defensible will be the willingness to pay estimates. Baseline information is needed simply to determine whether, given the current state of knowledge, society would be better off with reduced eutrophication in the Gulf. Notwithstanding these issues, this would still be a straightforward study to implement in that current methodologies will suffice.

In addition to valuing the marine resource/hypoxic zone, valuation of coastal wetlands also needs to be undertaken. This valuation is distinct from ecosystem services provided by wetlands in that those services could potentially be valued through their contribution to fisheries. There is increasing evidence signifying that society values wetlands simply for their uniqueness and aesthetic value.

Finally, values need to be placed on threatened and endangered species in the Gulf. Although there is currently no evidence suggesting that hypoxia has a direct impact on protected species, these stocks may be indirectly affected via food web effects or by re-distribution of fishing effort that results in increased interactions of protected species with fishing gears. Given the high value society places on preserving threatened and endangered species, this information will provide important baseline information on the potential losses that may be caused by hypoxia should it be linked to impacts on any protected species stock.

Existing Social and Economic Research Activities

Commercial and Recreational Fisheries – Current monitoring programs and available fisheries economic models are described as follows:

Monitoring Programs: Although there are numerous continuous catch and effort data collection programs in the Gulf commercial fisheries (e.g., the shrimp and large pelagic observer programs; Gulf reef fish, menhaden, and longline logbooks), few economic data collection programs exist. Two notable exceptions are the state trip ticket reports and the general canvas monthly landings statistics maintained by the NMFS, both of which systematically and continuously collect landings and revenue data for the majority of Gulf commercial fisheries. In addition, the Gulf shrimp landings files contain shrimp landings and revenue data from dealers. Data on fishing costs have been collected on several fisheries, primarily via specialized cost-earnings surveys and, to a limited degree, logbooks. In particular, Louisiana has conducted two shrimp cost-earnings surveys (1999 and 2001), and from 1999-2001, a limited logbook program (26 vessels), which included an economic component. In its charter boat fishery, Louisiana also has performed a cost-earnings survey (1999) and a logbook program (46 vessels; 1999-2001). NMFS has conducted a cost-earnings survey in the Louisiana mackerel fishery and also has implemented an economic add-on to its charter boat effort survey (2002) conducted by the Marine Recreational Fisheries Statistics Survey (MRFSS). NMFS will initiate a cost-earnings survey of the offshore shrimp fishery in 2003. The MRFSS also periodically appends economic surveys to its catch and effort survey of individual anglers, which covers all Gulf States with the exception of Texas. Although Texas implements a separate recreational survey of individual anglers comparable to the MRFSS, this survey does not collect any economic data from anglers.

Fisheries Economic Models Currently Available: The high-value shrimp fishery has been the most analyzed of the Gulf fisheries, although a number of these studies are now out of date, and current data that would be used to update those studies are not being collected. Gulf shrimp analyses include baseline models of freshwater inflow on harvest, bioeconomic models, bioeconomic simulation models, time-series models of harvest, and entry/exit models of shrimper behavior. Currently, only the freshwater inflow model examines the impact of hypoxia on harvest.

Fishing-Dependent Communities – To meet its obligations under National Standard 8 of the Magnuson-Stevens Fishery Conservation and Management Act, NMFS has initiated the first phase of research, identifying the fishing-dependent communities. This phase of the research is being performed primarily on the basis of secondary data (e.g., census data, federal and state fisheries landings data, and federal and state permit and license data), which is then validated using rapid assessment techniques.

Non-Harvest Users – To date, there have been no studies conducted to determine whether, and to what extent, non-harvest users (e.g., boaters, scuba divers, eco-tourists) are affected by hypoxia in the Gulf.

The General Public and Existence Value – To date, there have been no studies conducted to determine society's valuation of the Gulf resource or of society's valuation of the damage imposed by hypoxia to the Gulf resource. Such studies would provide important baseline information to policy makers for assessing the tradeoffs associated with reducing nitrogen loading in the Mississippi watershed.

Limitations in Existing Activities and Related Science Needs

Commercial and Recreational Fisheries – An assessment of existing fisheries data collections reveals four key findings. First, few commercial fisheries have economic data that are sufficient for adequately assessing changes in the fishery, environmental or otherwise. Second, even fewer fisheries have fishing effort data on a spatial scale adequate for analyzing the effects of hypoxia. Third, environmental indicators are not collected on a spatial or temporal frequency that encompasses the full range of fishing activity in the Gulf. Finally, the impacts of hypoxia on marine species and ecosystems have not been sufficiently defined for incorporation in fisheries economic models. Limitations in existing activities and related science needs are summarized below, again subcategorized by information type (economic, environmental, spatial, modeling, and research) and with primary emphasis given to developing the commercial and recreational fisheries.

Economic Data: Although revenue and price data are systematically, continuously, and comprehensively collected for the majority of commercial fisheries in the Gulf, primarily via state trip ticket reports, comparable data collection vehicles for cost data do not exist in any commercial fishery. Instead, the mélange of economic surveys that have collected fishery cost data tend to be funded and implemented on a one-time only basis, with no recent cost data available in the majority of fisheries. Further, these surveys were not designed to address hypoxia; hence what cost data exist may not be sufficient for analyzing the economic consequences of hypoxia. For example, if hypoxia affects a fisherman's trips only during summer, then collecting data on average trip expenses may not be sufficient for discerning the economic impact of hypoxia on his operations from other causal factors (e.g., changing regulations, changes in stock recruitment, migratory patterns of stocks). On the recreational side, the MRFSS does not routinely append economic questions to its base effort survey each year, resulting in significant data gaps. Given the annual variability of hypoxia, this lack of economic data in the intervening years in which no survey is conducted may be a limiting factor in quantifying any potential economic impact of hypoxia on these fisheries. The lack of any economic data from anglers via the Texas survey poses a more severe constraint on determining economic impacts. Finally, while both Louisiana and the MRFSS have implemented economic surveys in the charter fishing fleet, these were one-time efforts with no plans to implement future surveys, thus resulting in additional data gaps. In sum, the lack of economic data in the majority of commercial and recreational fisheries in combination with the potential inadequacies of existing economic data in surveyed fisheries limits the ability to quantify the economic impacts of hypoxia on these fisheries with any degree of precision.

Environmental Data: Information that would be useful in the short-term includes determination of biological and ecological linkages, especially development of a listing of species according to whether they are (most likely to be) affected directly or indirectly by hypoxia via food web effects. Biologists/ecologists need to propose to hypoxia monitoring agencies additional indicators of the effects of hypoxia on marine life. In the absence of predicted impacts on stocks from hypoxia, output from simulated models, such as Eco-Sim, could be used in fishery economic models. Over the long-term, modeling of ecological and biological systems must quantify impacts on fish stocks, habitat, and protected species. Long-term data need to include information on the impacts of hypoxia on fish stock species at the population level (e.g., relative stock abundance, growth rates) as well as assessing any spatial re-distributions of stocks due to hypoxic events.

Spatial Definition: A significant information gap arises from the inability to link daily catch by latitude and longitude with a measure of water quality within the vicinity and concurrent to the harvesting activity. That is, the current characterization of the hypoxic zone has neither the spatial or temporal resolution sufficient to link with fisheries models. Knowledge of the spatial and temporal variability of hypoxia will guide the level of resolution needed to link with the catch data. Experience in other areas (e.g., Chesapeake Bay) suggests that monthly or bimonthly data may be necessary. Further, routine commercial fisheries data collection in the Gulf is based on statistical reporting areas that are too large to detect the potential impact of hypoxia on fish harvests and net benefits. There are several exceptions, however, including observer programs in the shrimp and longline fisheries, and logbook programs in the longline and menhaden fisheries, where daily harvest records are coupled with precise latitude and longitude coordinates. NMFS collects precise spatial data in their shrimp observer program, but surveys only about 1 percent of shrimping activity. Not only does NMFS specifically need to improve the coverage of the program, it also may want to consider changing this program from voluntary to mandatory to ensure the representativeness of the data collected for the fishery. In the recreational surveys cited, the area fished is not identified with enough precision to determine whether the fishing took place within an hypoxic area. Although some modeling can be done with the existing data, precision of the estimated impacts would be enhanced with improved spatial resolution.

Fisheries Modeling and Research: Economic analysis of hypoxia will require developing quantitative, integrated fisheries assessment models that account for the dynamic processes of, and interactions between, human behavior and the Gulf ecosystem. Fisheries economics is moving in this direction, with emerging theoretical models of fisher behavior that incorporate both stock and ecosystem effects. Assuming that over the long run, economic, spatial, and environmental data deficiencies can be overcome, it appears that the binding constraint on empirical implementation of these models will be the ability of stock assessment and ecosystem modelers to quantify the direct and indirect effects of hypoxia on commercially and recreationally valuable fish stocks. Worthy of pursuit is development of stated preference models that directly ask fishers about their perceptions of the hypoxia problem and to what extent hypoxia has affected their operations. In particular, it would be useful to know whether hypoxia has affected any investment or disinvestment decisions, whether the possibility of a catastrophic hypoxic event has imposed any psychological damages on fishers, and if so, whether that might be alleviated by reducing the probability of such an event.

Needed Coordination, Information Sharing, Synthesis, and Reporting

The Gulf States Marine Fisheries Commission currently plays a central role in coordinating state and federal fisheries data collection. It is recommended that they continue in this capacity. The state and NMFS fisheries economists need to identify an appropriate vehicle for coordinating economic modeling and research on hypoxia in the Gulf. In addition to coordinating social science research, economists need to keep abreast of emerging ecological and stock assessment research, suggesting that multi-disciplinary workshops and meetings need to be established. For example, implementation of the bioeconomic modeling approach will require interaction with the Gulf Modeling and Research activities that will characterize the impacts of hypoxia on factors such as shrimp migration patterns and recruitment. Finally, as part of the Gulf hypoxia socioeconomic research plan, each agency should assess the staff requirements of implementing the data collection programs and conducting routine modeling of the fisheries. The funding needs of relevant socioeconomic research should be determined and appropriate avenues of funding identified and/or developed.

COORDINATION AND INFORMATION NEEDS

Overall Coordination

Goals of the MMR Strategy that relate to overall coordination include:

- Defining information needs and designing a strategy to satisfy those needs in a comprehensive and interdisciplinary manner that brings scientists and resource managers together from a range of disciplines and perspectives, including from Gulf and Basin perspectives;
- Gathering and disseminating needed scientific information in a manner that is cost effective, takes advantage of all existing activities, and explains the practical value of synergies gained from actions taken to address both local water quality and the quality of receiving waters;
- Providing information gathered from monitoring, modeling, and research related to Gulf hypoxia, Basin water quality, and social and economic factors in a form and a timeframe that feed directly into complementary scientific interpretations, management planning, and implementation; and
- Sharing among scientists and managers all information relevant to improving research and management decisionmaking, including those decisions that may be directed primarily at other issues indirectly related to hypoxia, but which will contribute to achieving Action Plan Goals.

The level of coordination addressed herein is that which is needed across all components of Basin and Gulf activities, as well as between science and management activities. Significant coordination related to specific Basin and Gulf activities were described earlier in those respective sections of this report. Achieving the needed coordination will require a high level of organization across all management and scientific entities both directly and indirectly involved in activities that support the Action Plan.

It is the logical role of the Task Force to provide a means of coordination among management and science activities at all levels of government and with appropriate private entities. Such a broad level of coordination will require measures by the Task Force that are formally structured so as to connect activities across geographic regions and scales and to assure that planning and evaluation activities have a consistent timing and schedule. This level of coordination will require maintaining mechanisms of formal communication that include periodic reviews of management and associated science activities and coordination of all Task Force Workgroup activities, thus ensuring that needed information is provided in a useable format and timeframe. Coordination should insure that an appropriate synthesis of all available information on Basin water-quality conditions, Gulf hypoxia, and related social and economic considerations are provided in the context of management decisionmaking and should integrate new information and methods development from ongoing research. Further, sub-basin based science and management activities will need to be coordinated to substantiate the development, implementation, and evaluation of effective sub-basin strategies, as well as to provide for evaluating their integrated effects to achieve Basin-wide and Gulf goals.

Basin – Gulf Coordination

Organization of the collection, interpretation, and dissemination of scientific information addressing the expansive issues associated with excess nutrients in the Mississippi River Basin and hypoxia in the northern Gulf of Mexico is most logically divided spatially according to the Mississippi River Basin and the Gulf of Mexico. As a result, the organization of discussions and activities at the MMR Workshop held in St. Louis on October 16-18, 2002, were organized around Basin and Gulf activities. There is still a fundamental need, however, to coordinate information needs between the Basin and the Gulf, and to assure that there is no gap in collection and exchange of essential information at this interface. The corresponding needs for coordination are described in three areas:

1. **Basin Delivery to the Gulf** – Interpretations of the specific driving factors for Gulf hypoxia, the timing between delivery by the Mississippi River and maximum extent of the hypoxic zone, and the related targets for Basin goals and their linkage to the Gulf goal of reducing the size of the hypoxic zone, all rely on adequate monitoring of temporal and spatial variation of constituent loads from the Mississippi River to the Gulf. This includes measurements of the range of water-quantity and -quality indicators with sufficient temporal and spatial detail to relate to the processes affecting assimilation in the Gulf. Achieving suitable temporal and spatial detail is complicated by the complexities of distributary channels in the Delta and by diversions that alter the manner in which water and associated loads are delivered to the Gulf. Careful consideration of the processes and natural and human factors that affect the delivery of water flow and nutrient loads through the Mississippi River Delta system will be essential for effective characterization of connections between

the Basin and Gulf and the causal and mitigating factors affecting Gulf hypoxia.

2. **Coordination of Modeling Activities** – Models of the Gulf processes that affect development, extent, and duration of the hypoxic zone will rely heavily on accurate information on inputs from the Basin. These inputs will be derived from direct monitoring activities and predictions by Basin models that must be constructed to provide both adequate definitions of Basin processes and conditions and information needed by Gulf models. Development of effective modeling capabilities relies on the factors described under item 1 Basin Delivery to the Gulf and similarly will have related spatial and temporal requirements for explaining the relation between Basin actions and improvements in Gulf conditions.

3. **Coordination of Social and Economic Considerations** – The factors that affect social and economic costs and benefits in the Basin and Gulf are fundamentally different. Comprehensive decisions, however, related to the tradeoffs between the management actions and related social and economic costs and benefits must consider both Basin and Gulf factors. As a result, social and economic information and interpretive tools must be developed to analyze these environments not only individually on the basis of local watersheds or local coastal communities, but also in a consistent and integrated manner at the broadest scale.

Other Information Needs

A substantial amount of information will be needed from other entities and activities not formally included in the MMR Strategy. Mechanisms for the acquisition of some of this information could be addressed most effectively by the other Task Force Workgroups with responsibilities and membership more consistent with the type of information needed. This type of information is acknowledged in general terms in the following discussion with the corresponding Workgroup that would most logically assist in the acquisition of that information.

Inventories of Management Actions – Comprehensive information is needed on implemented management actions, including actions that reduce nitrogen inputs to streams, such as runoff and loss from agricultural fields, reduction in discharges to streams from point sources, and actions that increase denitrification or other means of consumption, such as creating new wetlands, creating new riparian buffers, and diverting river waters for land restoration in coastal Louisiana. This information should include quantification of the amount or extent of activities implemented and their geographic distribution throughout the Basin. The geographic breakdown should be consistent with the scale of performance monitoring that is implemented so that constructive, comparative evaluations of the effectiveness of various management alternatives can be made. The assistance of each of the Task Force's Management Response Workgroups for point sources, nonpoint sources, and restoration is needed to assure that this information is collected and made available publicly.

Management Implementation Strategy – Information on the specific approach and timing of management actions is needed to assure that the collection, interpretation, and reporting of the scientific information needed for adaptive management is provided in a useful and timely manner that can most effectively be used to support management decisionmaking. The assistance of the Task Force's Management Implementation Workgroup is needed to guarantee that information on the details of basin-wide and sub-basin strategies are communicated to agencies implementing the MMR Strategy.

Information on Resource Needs – Inherent resource needs are associated with management implementation, supporting science, communication, and other activities undertaken to achieve Action Plan goals. It is essential that information on existing resource investments and shortfalls is collected and used in a manner that enables appropriate proportionalities between investments in these categories of activities to be considered and utilized in a forum that encourages cost efficiency and maximum use of available information. The assistance of the Task Force's Finance/Budget Workgroup will help in coordinating, gathering, and disseminating this type of comprehensive budget information.

Information on New and Effective Management Actions – Although the analyses described in this MMR Strategy will provide information on the relative performance of the range of management actions implemented, the Strategy does not provide for information on research into new management practices or other specific management actions, as well as focused research on action performance. The assistance of each of the Task Force's Management Response Workgroups for point sources, nonpoint sources, and restoration is needed to ensure that this information is collected and made available to those developing the management implementation strategy.

RESOURCE NEEDS

This document describes a significant scope of activities that are needed to supplement and coordinate existing monitoring, modeling, and research activities in order to acquire scientific information necessary for sound management decisionmaking and to realize the goals identified in the Action Plan. Considerable resources are needed to conduct these essential activities. Management actions taken to improve water-quality conditions in the Mississippi River Basin and northern Gulf of Mexico will include investment of significant resources in incentive, restoration, and other management activities. The adaptive management approach endorsed by the Action Plan and advanced herein is based on providing scientific information on the relative effectiveness of management actions and other natural and anthropogenic factors to enable subsequent improvements in management action. As such, while it is important that the majority of new resources be dedicated to actions directed to improving environmental conditions, it is essential that a proportionate fraction of resources be invested in monitoring, modeling, and research to assure that management resources are invested in a cost-effective manner. It is beyond the ability of the MMR Workgroup within the timeframe of the writing of this document to quantify such specific resource needs.

One of the short-term actions defined in the Action Plan was for the Task Force to develop an integrated budget proposal by December 2000. This budget overview, titled *Funding the National Effort: Clean Rivers/Clean Gulf Budget Initiative*, was prepared by the Task Force and submitted in early 2001 to the federal agencies represented on the Task Force. This budget overview specifically acknowledged the importance of investment of new resources in monitoring, modeling, and research, as well as management actions to improve our understanding of the scientific issues and to provide a management process based on sound science. This document also underscores the importance of initiating funding for monitoring, modeling, and research during the first few years of implementation of a management strategy. The estimated costs for monitoring, modeling, and research activities needed to support management implementation, based on inputs from federal agency members, was estimated to be $50 million per year. This estimate was based on a total resource need of approximately $1 billion annually for voluntary technical and financial assistance, education, environmental enhancement, research, and monitoring programs to support the actions outlined in the Action Plan. The budget overview indicated that after 5 years, funding should be reassessed.

Since early 2001, planning activities conducted by the agencies represented on the Task Force, as well as those of the Task Force's MMR Workgroup, as described in this report, have resulted in significant progress towards understanding the needed supplements to existing monitoring, modeling, research, and coordination activities. Basic observations related to the needs and priority uses of supplemental funding for monitoring, modeling, and research related to excess nutrients in the Mississippi River Basin and hypoxia in the northern Gulf of Mexico include the following.

> "Short-Term Action #1: By December 2000, the Task Force with input from the states and tribes within the Mississippi/Atchafalaya River Basin, will develop and submit to the appropriate federal agencies an integrated budget proposal for additional funds for voluntary technical and financial assistance, education, environmental enhancement, research, and monitoring programs to support the actions outlined in the Action Plan."
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> *- The Action Plan, p. 13.*

- Additional monitoring, modeling, and research activities are required beyond existing activities, necessitating supplemental resources to implement those activities while achieving maximum synergies among ongoing activities.
- Although the majority of new resources made available to address these issues should be dedicated to incentive, restoration, and other management actions directed at improving environmental conditions, it is essential that a proportionate fraction of resources is invested in monitoring, modeling, and research to enable continual improvement in management strategies and to assure that specific resource investments are cost effective.
- Increased communication among ongoing activities will avoid duplication of effort and achieve maximum synergies that will reduce costs. At the same time, however, the need to evaluate the range of modifications and enhancements required for specific programs makes it difficult to predefine total supplemental funding needs.
- It is essential to supplement selected monitoring, modeling, and research activities at the beginning of the management implementation process so that a sufficient characterization of baseline (pre-management) conditions is defined and the best in current modeling and related technology can be directed to the design of the specific management strategy as well as the monitoring and interpretation that will be used to measure the performance of that strategy.

- Activities to increase coordination of existing programs should not be undertaken within existing resources when they will reduce or threaten the integrity of existing monitoring, modeling, and research.
- Initial supplemental funding should be used to refine the long-term requirements for monitoring, modeling, and research that are required for implementation of an adaptive management strategy. Activities related to coordination and enhancement of existing activities should be an important part of the use of that funding.
- Initial supplemental funding should also be used to develop a detailed funding plan that defines specific steps for implementing the MMR Strategy and associated funding needs. The funding plan should include all entities involved, their roles and resource needs, and consider realistic synergies from ongoing activities.

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APPENDIX I: MANAGEMENT QUESTIONS

Development of this Monitoring, Modeling, and Research Strategy focused on providing the ability to answer fundamental management questions related to water-quality conditions in the Mississippi River Basin, hypoxia in the northern Gulf of Mexico, and the attendant social and economic considerations. Global and specific management questions for each of these three areas of consideration were reviewed by the Task Force's Management Implementation and Coordination Workgroup and are provided as follows.

Considerations for the Basin - What are the major sources of excess nutrients; the major causal factors for excess nutrients; and the attendant adverse effects of excess nutrients in watersheds within the Mississippi River Basin and their receiving waters?

1. What is the spatial distribution of nutrient yields in the Mississippi River Basin, and particularly, what are the areas of highest nutrient yields?
2. How does the magnitude and spatial distribution of nutrient yields change with time?
3. What natural and anthropogenic factors affect spatial and temporal changes in nutrient yields?
4. Can we distinguish between changes affected by natural and anthropogenic factors?
5. What is the spatial and temporal distribution of nutrient concentrations in sensitive ecosystems in the Mississippi River Basin?
6. What are the adverse effects of excessive and (or) increasing nutrient concentrations in the Mississippi River Basin?
7. What is the relative effectiveness of management actions in reducing nutrient yields (that is, reducing nutrient loss or increasing nutrient reduction), and what are the determining factors?
8. What are optimal wetlands restoration strategies, either locally or regionally, that would provide the best overall reduction in nutrients within the river and entering the river from nonpoint sources?
9. What are the location and design criteria for Mississippi River diversions that will optimize nutrient removal and Louisiana coastal marsh restoration?
10. What are the predicted future nutrient yields in local-scale (small) watersheds based on the natural and human causal factors, and what are the optimal designs of management strategies for local-scale watersheds?
11. What time lags are associated with changes in nutrient yields in response to both natural and human factors, and how long will it take to see the effects of various management actions?

Considerations for the Gulf - How are the adverse effects of Gulf hypoxia exacerbated by various causal factors, and what are the determining mechanisms?

1. What is the annual and seasonal extent of the hypoxic zone in the northern Gulf of Mexico?
2. What is the relation between the magnitude and characteristics of Mississippi River nutrient loads and streamflow to the Gulf of Mexico and the size of the hypoxic zone?
3. What are the pertinent temporal (annual and seasonal) characteristics of Mississippi River nutrient loads and streamflow to the Gulf of Mexico?
4. What factors related to Gulf ecosystem operation affect the dispersal of nutrient loads and streamflow in the Gulf of Mexico and contribute to hypoxia in the northern Gulf of Mexico, and to what degree do these factors contribute to hypoxia?
5. Can we predict the size of the hypoxic zone on the basis of natural and anthropogenic factors, and can we use such models to design management strategies to achieve reduction goals?
6. What are the effects of the increasing size of the hypoxic zone on the northern Gulf of Mexico ecosystem and fisheries?
7. What are the predicted future effects of the changing size of the hypoxic zone on ecological conditions in and near the northern Gulf of Mexico hypoxic zone, and what are the predicted effects of management strategies?
8. What time lags are associated with the factors that affect the annual size and duration of the hypoxic zone, and how long will it take to see the effects of various management actions on the size of the hypoxic zone?
9. What time lags are associated with the factors that affect the Gulf of Mexico ecosystem and fisheries, and how long will it take to see the effects of various management actions on ecosystem and fisheries recovery?

Social and Economic Considerations - What are the social and economic costs of increased nutrient flows and the attendant deterioration in water quality in the Mississippi River Basin and increased hypoxia in the northern Gulf of Mexico?

1. What are the primary driving factors that act to motivate the behavior and influence the investment changes that are needed to implement effective management actions?
2. What are the social and economic impacts of increased nutrient loss in the Mississippi River Basin?
3. What are the social and economic impacts of deterioration in water-quality conditions in the Mississippi River Basin?
4. What are the social and economic impacts of increased size and duration of the hypoxic zone in the northern Gulf of Mexico?
5. What are the social and economic impacts of management actions to achieve Basin and Gulf goals?
6. What are the actual benefits of alternative management actions and their full consequences, including who bears the direct and indirect costs and who shares in the benefits?
7. What are the real motivations, both inherent and incentive based, for voluntary implementation of management actions?
8. What is the complete assessment of all social and economic impacts (including fisheries, recreation, wildlife habitat, soil nitrogen loss, drinking water quality) and how can we evaluate or integrate the social and economic effects of these specific impacts on the Nation?

APPENDIX II: PARTICIPANTS IN THE MISSISSIPPI RIVER/GULF OF MEXICO WATERSHED NUTRIENT TASK FORCE, MONITORING, MODELING, AND RESEARCH WORKSHOP

Held in St. Louis Missouri,
October 16-18, 2002

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+ - Workshop Steering Committee
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