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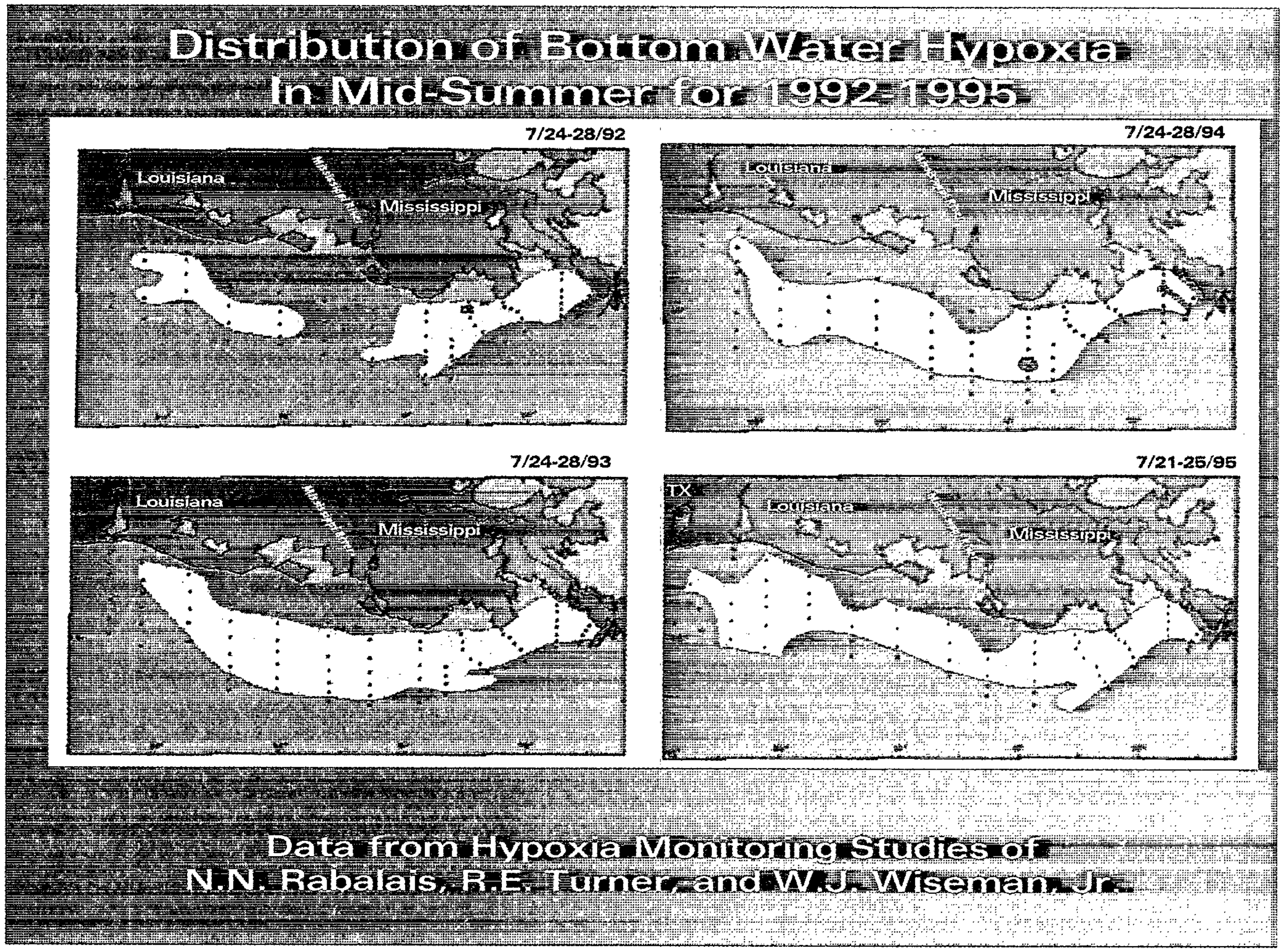

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Science, Policy and Coastal Eutrophication: the Chesapeake Experience

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Abstract

Science and Policy Development Related to Eutrophication of Coastal Ecosystems

In assessing the policy options appropriate to addressing hypoxia in the northwestern Gulf of Mexico, it is helpful to learn from experiences in the use of science elsewhere. The Chesapeake Bay and other U.S. coastal systems, and northwestern Europe provide instructive case studies. Coastal eutrophication commonly results from nutrient inputs from diffuse sources, thus effects are not easily seen as connected to causes. Both science and policy must address the scale mismatches over space (responsible actions far removed from effects) and time (present, pre-existing and future conditions) scales and human activity sectors (e.g., agriculture and fisheries).

At the first level, science must address the question of whether such effects as hypoxia or algal blooms have worsened over time and whether they have harmful or undesirable consequences. Next, ties need to be made between nutrient inputs and responses (e.g., in the Chesapeake major disputes were waged as to whether N or P limited algal production). Models have been very helpful in summarizing complex science in a way that policy makers could pose "what if" questions and have, in some cases, become the central technical tool of management. In the Chesapeake early models were used to justify the goal of 40 percent reduction in controllable nutrients and more sophisticated models are now used to reassess goals and address subsequent policy issues, such as the effect of Clean Water Act ozone reduction on water quality. Finally, policy makers, and society in general, are unlikely to undertake ambitious environmental restoration goals without technological advances that make them feasible (for example, the application of biological nutrient removal for sewage treatment and cost-effective best management practices in agriculture).

Introduction

Eutrophication, the excessive enrichment of aquatic ecosystems which leads to increased primary productivity, noxious algal blooms, food-chain alterations, and depletion of dissolved oxygen, is a widespread phenomenon in coastal waters of developed nations. Furthermore, contrary to many marine pollution problems which have been ameliorated by waste treatment and other controls, coastal eutrophication has been in ascendancy during the latter half of the twentieth century (National Research Council, 1994). This is due in large measure to the important contributions of diffuse sources of nutrient inputs—from agricultural fertilizers, runoff from developed land, atmospheric deposition, and soil erosion—in addition to more controllable point sources, such as sewage or industrial discharges. The multitude of sources and the remote nature of many of the sources make them difficult to identify, much less control.

In a number of places in the United States, Europe and Japan, once the degradation of the environment due to coastal eutrophication was identified, extensive efforts are being undertaken to reduce the point and diffuse sources of nutrient inputs from human activities. Science has played and is playing a major role in identifying the causes and consequences of coastal eutrophication and in finding solutions. Although complete success has been met nowhere, progress is being made in establishing nutrient reduction goals, targeting sources and achieving reductions. Perhaps the most famous, and certainly the most ambitious, of these efforts is in the Chesapeake Bay and its watershed.

To help set the stage for discussion of management of widespread oxygen depletion, or hypoxia, attributed to eutrophication in the northern Gulf of Mexico, I will briefly review the role science has played in the development of policy and management solutions for controlling nutrient over-enrichment in the Chesapeake Bay. My goal is to examine the role of science in addressing critical policy questions so that lessons may be applied to the case of hypoxia in the northern Gulf of Mexico.

The Challenge of Scale Mismatches

At the heart of the problem of understanding and managing coastal eutrophication is the challenge of scale mismatches inherent in the problem. As Lee (1993) puts it: "when human responsibility does not match the spatial, temporal or functional scale of natural phenomena, unsustainable use of resources is likely, and it will persist until the mismatch of scales is cured."

In the case of coastal eutrophication, perhaps the most obvious scale mismatch is on the **spatial scale**. In contrast to most coastal environmental and resource issues, for example waste disposal, coastal development, habitat destruction, and resource exploitation, the sources of eutrophication may not be considered coastal at all. They may originate far up the watershed, hundreds of miles away, or even from outside of the watershed in the case of atmospheric deposition. This poses significant challenges for science in addressing these large scales. Even more importantly, it is hard for people to be aware of or accept that their activities in Pennsylvania or Iowa may be causing a problem so far away at the coast. Furthermore, they may see efforts to reduce nutrient inputs without benefit to them. The beneficiaries are those on the coast in Maryland and Virginia or Louisiana and Texas.

In addition, there are mismatches on a **functional scale**, for example the cause of coastal eutrophication may be related to agriculture, waste disposal, or power generation, but the deleterious consequences may be felt in marine fisheries. Even within the coastal and marine environment it is difficult to connect human responsibility for fisheries with that for water quality or, in the case of the Mississippi delta, wetland restoration with offshore hypoxia.

Finally, there are important **temporal scale** mismatches. In the case of coastal eutrophication these frequently occur because of a lack of understanding of what conditions were like before the increase in anthropogenic inputs of nutrients and to what degree and how rapidly the system will recover.

Key Questions

There are several key questions which must be at least partially addressed before public support and political will can be marshaled sufficiently to undertake and affect the control of nutrient inputs into coastal environments in order to reduce hypoxia. In logical order they are:

1. Is the hypoxia a natural phenomenon? Has it worsened?
2. What are the consequences of hypoxia for resources and environmental quality? Does it matter?
3. Is hypoxia caused by increased nutrient inputs from human activities?
4. What are the sources of these excess nutrients?
5. What will be the effect of reducing these nutrient inputs?
6. How can the sources of nutrients be feasibly reduced?
7. What are the incentives for reducing these sources of nutrients?

All of these pose significant challenges to science and technology. In order to effect solutions, it is not sufficient just to describe hypoxia, put it into historical context, identify causes, pinpoint sources and predict the consequences of nutrient inputs, as difficult as these task are. Science and technology must also help find feasible means for reducing inputs and contribute to the development of incentives to accomplish this goal. I will briefly review how these questions were or are being addressed in the case of the Chesapeake Bay.

Experience of the Chesapeake Bay

The development of scientific understanding of the effects of nutrient loading to the Chesapeake Bay and the impact that science had on policy development has been thoroughly reviewed by Malone et al. (1993). Based on their observations and my own I review how the seven questions have been addressed for the Chesapeake.

Question 1: Is the hypoxia a natural phenomenon?

Although anoxic conditions in the deeper waters of the Chesapeake Bay had been observed since measurements were first made, it was not until 1984 that Officer et al. argued in a paper in *Science* that there was an increase in oxygen depletion between 1950 and 1980. This interpretation engendered controversy and Seliger et al. (1985) countered that when corrected for river inflow, which increases density stratification and nutrient mass loading, there was not a statistically significant trend (Seliger et al., 1985). About the same time, results from studies initiated to investigate the dramatic reduction of submersed aquatic vegetation in the Bay during the 1970's also implicated increased nutrient loading (Kemp et al., 1983). Interestingly, growing public concern about the health of the Bay, coupled with an assessment process begun in the late 1970's, set the stage for policy commitments in 1987 to reduce controllable nutrients by 40 percent by the year 2000 even though Question 1 had not been fully answered.

Subsequently, Cooper and Brush (1991) and Cooper (1995) were able to demonstrate from biological and chemical indicators in cores that: (a) hypoxia was part of the Bay's ecology for a long time; (b) eutrophication due to human activities began with extensive land clearing in the late 18th century; and (c) anoxic conditions have become more frequent and persistent during the mid-20th century in association with both rapid population growth and the advent of widespread use of artificial fertilizers. From their and other work, one can sketch a modern environmental history of the Chesapeake Bay (Table 1) in the context of which can be placed the more recently observed deterioration of the environment and the restoration goals.

Table 1.
The modern environmental history of the Chesapeake Bay

Period	Years	Description
Pre-Colonial and Early Colonial	(<1730)	Watershed is mostly forested, nitrogen flux to the Bay *about 15% of present level*
Agrarian	(1740–1860)	Deforestation for expansion of agriculture leads to increased soil erosion and loss of forest nutrient retention capabilities, which in turn leads to decreased water clarity and increased organic production
Agrarian	(1880–1940)	Urban population growth results in collection and discharge of sewage; industrial development results in increased inputs of trace metals; mechanical harvesting greatly reduces oyster populations resulting in a substantial reduction of benthic filter feeding
Petrochemical	(1950–1980)	Increased use of petroleum and manufacture of synthetic organic compounds results in severe contamination of port areas and widespread, low level contamination elsewhere; use of artificial fertilizers and increased combustion of fossil fuels increases diffuse loading of nutrients, leading to intensified anoxia and loss of submersed aquatic vegetation
Sustainability?	(>1980)	Recognition of problems associated with nutrient over-enrichment leads to ban of phosphates in detergents, nutrient removal in sewage treatment, improved agricultural management practices, population growth management, reduction of emissions from vehicles, and restoration of oyster populations for environmental rather than commercial reasons

Question 2: What are the consequences of hypoxia?

Somewhat surprisingly, very little has been done to quantify the impacts of hypoxia on living resources, either before the 1987 policy commitment to reduce nutrient loading or subsequently. Although the effects of seasonal hypoxia on benthic organisms have been well documented (Holland et al., 1987) and the physiological tolerance of motile fishes and invertebrates indicate that they cannot survive long in near-anoxic waters (Sea Grant Programs, 1992), the effects on fisheries and shellfisheries have not been directly assessed. In fact, landings data do not show an increase or decline in the total fisheries productivity during the latter half of the twentieth century, although there has been a shift in harvested biomass from benthic (e.g., oysters) to pelagic (e.g., menhaden) species. Rather, the reductions in important fishery resources that have occurred are thought to be primarily the result of over fishing, habitat modification and barriers to anadromous fish migration. Hypoxia in the Chesapeake Bay has generally been assumed to be detrimental to living resources, but its role relative to these other pressures is not well understood.

On the other hand, scientific understanding of exchange of nutrients with bottom sediments indicates that anoxia has a positive feedback to eutrophication (Boynton et al., 1995), further reducing water quality. Hypoxia in bottom waters results in episodic fluxing of phosphorous from sediments. Persistent anoxia can also greatly reduce denitrification rates by shutting down nitrification of ammonium. The net effect is rapid recycling of phosphorous and attenuation of the nitrogen sink, resulting in increased phytoplankton production, decreased water clarity, and increased oxygen demand in bottom waters.

More attention has been given to the other effects of eutrophication on living resources, such as the loss of submersed aquatic vegetation, decreases in water clarity, and changes in food chains. Several lines of evidence suggest that nutrient enrichment, at least during this century, has not resulted in increases in harvestable secondary production. The Chesapeake Bay is characterized by high primary productivity relative to nutrient loading and high secondary productivity relative to its primary productivity (Nixon et al., 1986). This suggests that factors other than nutrient availability are controlling secondary production in this system at this point in its eutrophication history.

Question 3: Is hypoxia caused by increased nutrient inputs?

The Chesapeake Bay restoration effort is well known for its commitment to reduce controllable loadings of nutrients by 40 percent, a commitment which is now involving hundreds of waste discharges, thousands of farmers and citizens, and massive investments of public and private funds. It is important to keep in mind that it has been just since the early 1980's that the notion that the Bay was suffering ill effects from excess nutrients began to gain wide acceptance (Malone et al., 1993). During the late 1960's, massive algal blooms, oxygen depletion and fish kills in the upper tidal (freshwater) Potomac River led to large investments in the early 1970's for sewage treatment facilities for the metropolitan Washington area. These treatments included removal of phosphorus, which was known to be the culprit in causing eutrophication in freshwater lakes, as well as BOD. Substantial improvements in water quality in the tidal freshwater Potomac resulted (Jaworski, 1990).

It took about a decade more to conclude that the Bay had undergone widespread eutrophication, to understand that excess nitrogen as well as phosphorus was posing a problem, and to effect policy for broader control of point sources of nitrogen and phosphorous. The scientific community first presented inferential evidence such as data on trends in nutrient loadings and nutrient ratios which suggested that nitrogen may be limiting primary production in more saline parts of the Bay (Boynton et al., 1982). This evidence suggested that nitrogen removal was needed in new sewage treatment facilities then being planned for the upper Patuxent River estuary in order to avoid further declines in water quality, a view that conflicted with the position of federal and state agencies that only phosphorus removal was required. The science and uncertainties were debated in court and in a conflict-resolution conference which concluded with the agreement to remove nitrogen as well as phosphorus in these new facilities. Only later was more direct evidence of nitrogen limitation of phytoplankton growth provided from mesocosm studies (D'Elia et al., 1986). Meanwhile, investigations of the cause of the widespread decline of submersed aquatic vegetation contributed more to the understanding of the consequences of nutrient enrichment than did studies addressing the relationship of nutrients to hypoxia (Malone et al., 1993). These findings also brought attention to the importance of nonpoint sources to the overall eutrophication of the Bay.

Development of policies which culminated in the regional federal-state commitment to reduce controllable inputs of nitrogen and phosphorous by 40 percent were initiated with very modest understanding of the relationship of these inputs to hypoxia. As Malone et al. (1993) observed: "In a qualitative way, these links made sense, but the scientific evidence needed to make the case remained weak." Nonetheless, in 1983 the EPA published a framework for action for the Chesapeake Bay which focused on the control and monitoring of nutrients "to reduce point and nonpoint source nutrient loadings to attain nutrient and dissolved oxygen concentrations necessary to support the living resources of the Bay." This set the stage for the first multi-jurisdictional Bay Agreement, a flurry of legislative actions, the establishment of a monitoring program, and a decade of intense scientific studies of nutrient dynamics. Findings of these studies have greatly enriched our understanding of the sources of nutrients, their effects on plankton production and submersed aquatic vegetation, nutrient cycling and loss (Boynton et al., 1995), and their effects on hypoxia (Sea Grant Programs, 1992). These have confirmed the wisdom of the policies developed earlier based on much more limited scientific evidence.

Question 4: What are the sources of these excess nutrients?

Although it was long understood that nonpoint sources of nutrients must be significant for an estuary with such a large watershed as the Chesapeake Bay, early management efforts focused on controlling point sources, particularly sewage treatment plants. Concerns about the health of the Bay led to a five year study begun in 1977 which yielded the first good estimates of total nutrient load to the Bay. These showed the quantitative importance of nonpoint sources. Current best estimates are that agricultural lands, developed areas, and atmospheric deposition contribute 2.5 and 1.8 times the amount of nitrogen and phosphorus, respectively, that point sources deliver (Table 2). As a consequence, extensive efforts are underway to reduce nutrient losses from agriculture—by applying "best management practices" and nutrient management procedures throughout the watershed—and from developed areas—through sediment erosion controls, storm water management, and limitations to shoreline development.

Table 2.
Estimated portions of total nutrient loads that enter the Chesapeake Bay from land-based sources and activities, i.e., excluding inputs from the ocean (Magnien et al., 1995).

	N	P
Forests	18%	3%
Agriculture	39%	49%
Development	9%	8%
Atmosphere*	11%	6%
Point Sources	23%	34%

* Includes deposition directly on the water; atmospheric N deposition on land accounts for an additional 16% of total N load, but is included as part of forest, agriculture and developed land sources.

The agreement to reduce controllable inputs of nitrogen and phosphorus into the Chesapeake Bay includes only a portion of the total nutrient loadings apportioned in Table 2. Excluded from the total controllable pool are inputs into the small parts of the watershed located in Delaware, New York, and West Virginia, states not signatories to the Chesapeake Bay Agreement. Furthermore, there is assumed to be base inputs from various land uses (i.e. agriculture, developed land, and forests) which are not amenable to reduction. Also, atmospheric inputs were not included at all in the definition of controllable sources, but these too are receiving increased attention for control strategies, particularly for nitrogen. This is a difficult challenge because a significant fraction of the atmospheric deposition of nitrogen in the watershed emanates from sources outside of the watershed, particularly from the Ohio River basin.

Question 5: What will be the effect of reducing these nutrient inputs?

The expectations regarding the degree of improvement of conditions in the Bay which could be achieved by reduction of controllable nutrients by 40 percent were general, hopeful and not very quantitative when the policy was adopted. Since then, as mentioned earlier, much has been learned about the dynamics of nutrients in the Bay and the relationship of nutrient inputs to both hypoxia and conditions for growth of submersed aquatic vegetation. This increased understanding has been rather rapidly incorporated into various models which allow a scientific assessment of the effects of the nutrient reductions targeted and others which may be achievable.

Particularly prominent has been the three-dimensional, time-variable numerical model of the Chesapeake Bay which has evolved over the last decade or more (Figure 1). This model incorporates hydrodynamic, geochemical and biological processes and allows one to predict dissolved oxygen conditions and nutrient concentrations (useful in assessing the effects on submerged vegetation) as a function of point and nonpoint source inputs. The linked watershed model includes inputs from atmospheric deposition and meteorological models and is adjustable for changes in land use. The watershed model determines the effects of nutrient loading changes throughout the watershed on delivery of nutrients by rivers to the Bay but is, in general, not founded on the same level of scientific understanding as is the Bay model.

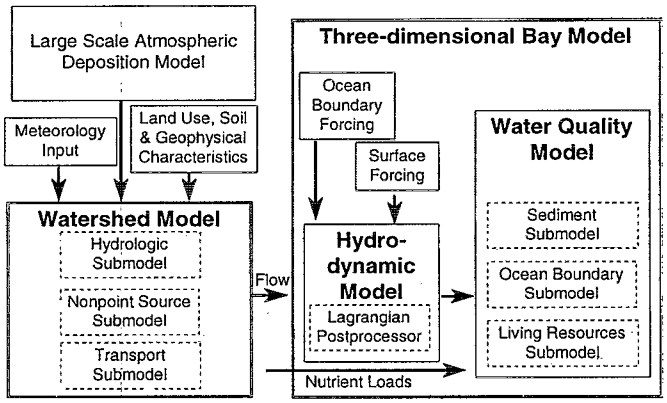

Figure 1.
Schematic depiction of the linked watershed and three dimensional Chesapeake Bay numerical models used to guide assessments of the relationship of nutrient inputs to hypoxia and other ecosystem effects in the Chesapeake Bay Program.

These models have been used to predict changes in the extent of hypoxia in the Bay under future conditions. This has allowed a re-evaluation of the original goal of 40 percent reductions of nitrogen (about 20 percent of total input) and phosphorus (about 30 percent of the total input). The models predict a decrease in anoxic volume-days of just 21 percent with a 40 percent reduction in controllable nutrients and even at the limits of nutrient control technology anoxia (<1 mg/l dissolved oxygen) would only be reduced by 32 percent. Also depicted in Figure 2 are the effects on anoxia of reducing atmospheric nitrogen inputs through implementation of Clean Air Act Amendment's goals for ozone attainment via reductions in NO_x emissions. These model predictions inject some reality for environmental quality objectives: the Chesapeake Bay will exhibit significant summer hypoxia even with more rigorous pollution controls as long as much of the watershed is in agricultural production employing artificial fertilizers, handles the wastes of 15 million people, and receives the residuum from extensive fossil fuel combustion.

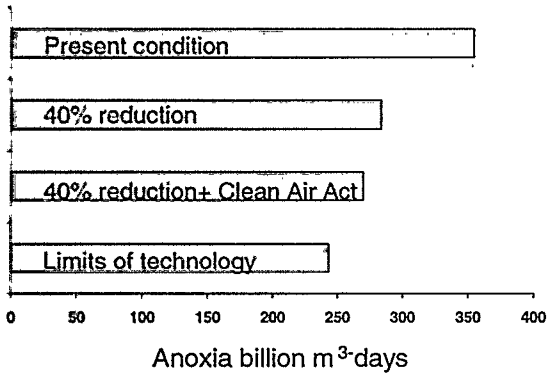

Figure 2.
Predicted effects on the extent of anoxia in the Chesapeake Bay as a result of achieving various management goals (Thomann, et al., 1994).

More optimistically, there may be significant environmental quality improvements beyond the reduction of anoxia in the Bay as a result of meeting the 40 percent reduction. These include significant improvements in dissolved oxygen in waters presently hypoxic, but not anoxic, and reduced ambient concentrations of nutrients to levels which permit growth and survival of submersed aquatic vegetation (Dennison, et al., 1993).

The watershed and Bay models also allow scientists and managers to identify the processes and responses which are poorly known but significantly influence the models' predictions so that research and monitoring may be strategically focused. Among the critical questions now receiving attention are how agricultural practices affect rates of loss of nitrogen into ground water, residence time in ground water for the wide variety of geological conditions which exist in the Bay, nutrient retention as a function of forest age, and denitrification processes in wetlands and Bay sediments. Resolution of such issues is important at this juncture because, although phosphorus concentrations have been significantly reduced in the Bay as a result of point and nonpoint source reductions, riverine fluxes of nitrogen and concentrations of nitrogen in the Bay have not yet decreased (Boynton, et al., 1995).

Question 6: How can the sources of nutrients be feasibly reduced?

Experience indicates that until feasible solutions to problems are identified, the will to correct the problems will not be mobilized no matter how undesirable the consequences. With regard to nutrient reductions in the Chesapeake, the dramatic improvements in water quality which resulted from advanced waste treatment at the top of the Potomac estuary had built some confidence that feasible, albeit expensive, solutions could be found. In addition, following this experience and the experience of the Great Lakes, phosphate detergents were banned in many jurisdictions in the Chesapeake watershed. However, the difficulties and formidable costs associated with reducing sources of nitrogen were, in no small measure, responsible for the denial by both federal and state agencies that the Bay was being over-enriched with nitrogen. The demonstration of the feasibility of biological nutrient removal (BNR) as a cost-effective sewage treatment technology helped overcome this resistance. BNR is now being implemented or planned for most sewage treatment works discharging to the tidal waters of the Bay.

Controlling the agricultural sources of nutrients has also proven challenging. Upton Sinclair once observed: "It is difficult to get a man to understand something when his salary depends upon his not understanding it." Similarly, there was at first strong denial that agricultural uses of fertilizers and animal wastes could be contributing to eutrophication in the Chesapeake Bay, so far away. To a certain degree, such skepticism still exists in the agricultural community as it confronts additional costs in implementing BMPs and the threat of government regulation. Nonetheless, extensive efforts are underway to implement management practices such as minimum-till, buffer strips, and reforestation of riparian areas. However, there is growing evidence that such conventional methods are not as effective as projected in controlling nitrogen losses. Many of these methods were developed to reduce soil losses. Although they are relatively effective in controlling phosphorus losses, they are less effective for the retention of nitrogen, which is more soluble and escapes into ground water. Other approaches, such as winter cover crops, precision agriculture which minimizes the amount of fertilizer applied to just that required by the crop, and new animal food formulations which reduce nutrient losses via manure, are beginning to be applied, but are more costly.

The commitment of the states to reduce nutrient inputs to the Chesapeake Bay has also become a pervasive organizing principle for many other aspects of environmental management. The importance of forests in the watershed in retaining nutrients is being considered in forestry and reforestation. Retention of nutrients is also an important issue in the conservation of nontidal wetlands. Management of human population growth is another issue that is being pursued in part because of the impact of land development and sprawl on nutrient inputs to the Bay. These growth management goals coincide with those related to regional transportation, infrastructure, natural heritage, and community development. And, finally, as mentioned above, reduced NO_x emissions are being sought not only because of concerns about their effects on ground level ozone but also because of their contributions via atmospheric deposition of nutrients. In short, commitments to reduce nutrient inputs are providing impetus to move toward ecosystem management of the Chesapeake Bay and its watershed.

Question 7: What are the incentives for reducing these sources of nutrients?

It is not enough to identify the problem, its causes and feasible solutions. The solutions must be mandated or there need to be incentives to implement the solutions voluntarily. In the Chesapeake, these incentives included state and federal financial assistance in construction and upgrading of sewage treatment plants and implementing stormwater management programs. In addition technical assistance and matching funds have been provided to assist farmers in implementing BMPs. However, these sources of public financing have been greatly reduced in recent years as a result of changes in federal legislation and the competing fiscal pressures at the federal and state level. Realizing that one often cannot simply mandate nutrient reductions from nonpoint sources from Harrisburg, Annapolis or Richmond, the Chesapeake Bay Program is pursuing Tributary Strategies which involve the diverse local interests within each of some 30 sub-watersheds to find effective community-based approaches to meet goals for reducing nutrient inputs. These solutions may include trading off reductions from one source for another, tax incentives, growth management, and local ordinances.

Another motivating factor, particularly for communities located well up in the watershed, far-removed from the Chesapeake Bay, is that there are many local benefits to be had in reducing nutrient inputs. These include improving water quality in lakes, streams and rivers, reducing groundwater contamination, managing population growth, forested and agricultural land preservation, and improving air quality. Also, in the long term there are frequently cost savings in pollution prevention. For example, effective nutrient management in agriculture may actually save costs by reducing the amount of fertilizer which must be purchased.

Driving Forces

There are a number of reasons why the Chesapeake Bay region has led the way in terms of recognition of the effects of large scale eutrophication and making major commitments to reduce nutrient inputs in order to restore this ecosystem. These include at least the following:

- The region has a history of sustained scientific investigation, including strong basic research and monitoring.

- Many people regularly see the Bay and enjoy it. Catastrophic events and decimated resources brought attention to the problem.

- There were very effective political champions who emerged at the right time.

- Even though the region is large, there is a sense of community or a sense of "place" about the Chesapeake. This is evident in polling which shows that the importance which the public assigns to restoring the Chesapeake is as high in headwater regions as it is on the Bay front.

- The public's attitudes about the Bay, coupled with the educational and economic status of the region, creates a condition in which there is strong public support for Bay restoration. For example, the Chesapeake Bay Foundation has over 84,000 dues paying members.

- There is a voluminous flow of information about the Bay, both in the popular media and via other periodicals such as the widely distributed *Bay Journal*.

- The Chesapeake has received national attention, but although there have been some advantages to proximity to the nation's capital in garnering federal support, this has been, in my opinion, less important than those who envy our progress in the Chesapeake think.

- Certainly, these conditions do not always exist in other areas which are experiencing eutrophication, such as the northern Gulf or Mexico. Nonetheless, my observations of how the seven key questions have been addressed in the Chesapeake do, hopefully, suggest some focal points and shortcuts toward resolution of issues and development of effective solutions for the deleterious effects of coastal eutrophication.

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Gulf of Mexico Hypoxia Management Conference Presentation

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Abstract

On January 24, 1995, eighteen environmental, social justice and fishermen's organizations, represented by the Sierra Club Legal Defense Fund, petitioned EPA and the State of Louisiana to convene an interstate management conference of all the states contributing nonpoint source pollution to the Mississippi River. That conference is seen as the best hope to develop and implement enforceable controls to reduce nonpoint pollution in the Mississippi River and clean up the Dead Zone in the Gulf of Mexico. While refusing to convene a formal interstate management conference, EPA has convened this conference to begin a strategic assessment process in response to the petition.

The Gulf's Dead Zone poses an enormous threat to the biological integrity and productivity of the Gulf of Mexico, and exposes the precarious ecological condition of the entire Mississippi River. The Dead Zone is a wake-up call to EPA and the states to take immediate and concerted action to control nonpoint pollution entering the River and the Gulf. EPA and the states must commit to and develop a long-term, written and enforceable strategy to clean up the Dead Zone. A successful strategy also will stem the devastation of the Mississippi River ecosystem and improve each state's water and environmental quality.

Introduction

I thought it would be useful to give you a brief history of the Petition that prompted EPA and the Gulf of Mexico Program to convene this meeting, and to address some of our expectations for the process that this meeting is starting.

The Impetus for This Conference

The Dead Zone is a 7,000 square mile swath of Gulf of Mexico water so devoid of oxygen that marine life cannot survive. The Dead Zone, which appears in the Gulf in the summer months, has grown substantially in size over the past two years. It now stretches from the mouth of the Mississippi River to the Texas border. The existence of the Dead Zone, and its implications for the health of the entire Gulf region and the Mississippi River watershed, prompted concerned groups to ask the U.S. Environmental Protection Agency (EPA) to take action to clean it up.

On January 24, 1995, 18 environmental, social justice and fishermen's organizations, represented by the Sierra Club Legal Defense Fund, petitioned EPA and the State of Louisiana to convene an interstate management conference of all the states contributing nonpoint source pollution to the Mississippi River. The petitioners were not limited to groups from Louisiana and Texas—the states suffering the most direct impacts of the Dead Zone—but included groups representing individuals from Minnesota to Louisiana. That call for action has been joined by the Gulf Restoration Network, a coalition of over 30 local, regional and national groups dedicated to protecting and restoring the health of the Gulf of Mexico.

The petition was prompted by scientific research showing that the Gulf's Dead Zone is caused in large part by the nutrient loads entering the Gulf from the Mississippi River. I am sure that many of you are aware of Dr. Rabalais' research on the Dead Zone. While you will be hearing from Dr. Rabalais directly at this meeting, I would like to highlight one very significant conclusion reached by her. At a Gulf of Mexico Program Symposium held in March 1995, Dr. Rabalais stated that the Dead Zone could not be cleaned up without reducing nonpoint pollution entering the Mississippi River, and ultimately the Gulf, from the up-river states.

The beauty of the requested interstate management conference is that it would bring together those very states identified by Dr. Rabalais—all the states within the Mississippi River watershed—that have the *actual authority* to control the nutrient runoff causing the problem. Moreover, those states would come together for just one purpose: to create real in-the-water reductions of nutrient loading into the Mississippi.

EPA refused to convene the interstate management conference. Instead it elected to attempt to address the Dead Zone through the Gulf of Mexico Program, and other programs already addressing nonpoint source pollution. The State of Louisiana also informed the Petitioners that it would like to use mechanisms already in place to address the Dead Zone problem, despite the fact that in June of this year, the Louisiana Legislature passed a resolution calling for our requested interstate management conference. Louisiana officials have said, however, that the State is prepared to request an interstate management conference if those mechanisms prove insufficient to address the problem.

This meeting *begins* EPA's attempts to respond to our petition without utilizing an interstate management conference.

The Dead Zone Is a Wake up Call for Action

The Dead Zone must be seen as a wake up call for immediate action to begin the clean up process. And that alarm must be heeded.

The magnitude of the Dead Zone problem cannot be overstated. When last measured, the Dead Zone covered more than 7,000 square miles—an area larger than the states of Connecticut and Rhode Island combined. Over the past few years, the Dead Zone has more than doubled in size. Indeed, it is now larger than many bodies of water in EPA's watershed protection program.

The Dead Zone poses a serious threat to the biological integrity and productivity of the Gulf of Mexico. Its impact is akin to taking Saran Wrap and placing it over an area the size of Connecticut and Rhode Island, slowly pulling it down and suffocating everything that cannot escape out the sides. While the area appears to undergo recolonization beginning each fall when the Dead Zone dissipates, the long term implications of a yearly die off remain unclear. By causing such devastation, the Dead Zone also poses a very real threat to the economy of the Gulf region. Already, officials at one seafood processing plant that closed down in

Louisiana, blamed the closure in part on the Dead Zone. As a result of that one plant closure, Louisiana lost 176 jobs. Forty six jobs were lost altogether, and 130 others were relocated to Texas.

Because the Dead Zone is caused by excess nutrients entering the Mississippi River, and ultimately the Gulf, it is a manifestation of land use practices throughout the entire Mississippi River watershed. As such, the Dead Zone exposes the precarious ecological condition of that entire watershed, and should raise alarm bells in each watershed state. We are not alone in this analysis. Many biologists with the Upper Mississippi River Conservation Committee believe that a sudden collapse of the Upper Mississippi River System "is likely to occur." Upper Mississippi River Conservation Committee, *Facing the Threat: An Ecosystem Management Strategy for the Upper Mississippi River* (Dec. 1995) at 8. Indeed, the Committee is meeting this week to develop an ecosystem-wide protection strategy.

Efforts to clean up the Dead Zone will of necessity help stem the devastation of the Mississippi River ecosystem. Those efforts will improve the environmental and water quality in all the states in the Mississippi River watershed.

Decisive Action and StrongLeadership Are Needed to Clean upthe Dead Zone

The Petitioners, the Gulf Restoration Network and the Sierra Club Legal Defense Fund fully recognize that cleaning up the Dead Zone will not be an easy task. We also understand the importance of basing policy decisions to control nutrient enrichment on sound science. As such, we applaud the efforts of the Gulf of Mexico Program in convening this meeting. It is an important first step.

However, we would not have filed the Petition requesting an interstate management conference, if the existing science did not already make clear that actions must be taken to clean up the Gulf, and that those actions must begin *now*. While there may be a need to fill in data gaps, that need cannot be used as an open-ended excuse for not taking action. Additional studies will not make the Dead Zone go away. Only appropriate controls will accomplish that task.

Existing scientific knowledge shows that controls to reduce nonpoint pollution entering the Mississippi River must be implemented quickly. It also shows where at least some of those controls should be. Methods for reducing nitrogen loading (the primary culprit in the Dead Zone) are well recognized and have been implemented successfully in many places. Thus, site specific controls could be implemented immediately in areas of direct nitrogen application and runoff. All that is missing is the appropriate leadership and political will.

Additional innovative control measures also have been suggested. These include reestablishing a natural vegetative corridor along the main stem of the Mississippi River. This would help reduce nitrogen (and other) runoff, and would have the added benefit of returning some of the natural processes of this great floodplain river. This also is an action that could be funded by EPA as a best management practice.

If we are to have any hope of succeeding in cleaning up the Dead Zone, some basic ground rules must be in place:

1. The appropriate parties must be at the table to develop—and then implement—viable controls. It is estimated that 80 percent of nutrients are in the Mississippi by the time it

passes Cairo, Illinois, and the vast majority of nitrogen entering the system is coming from the up-River states. Unfortunately, the Gulf of Mexico Program does not have the authority or the mandate to pull those states into the process being started by this meeting. Thus, it will be up to EPA to show strong leadership and bring into the process all the states in the Mississippi River watershed.

2. An aggressive clean up strategy *cannot* wait until all scientific data gaps are filled. We must begin immediately to develop an aggressive timetable for action. It is essential that we quickly develop a written strategy that prescribes specific solutions to be implemented within a set time frame. The strategy also must set a realistic timetable for this process to show concrete results. One such concrete measurement would be a commitment by the up-River states to reduce their proportionate share of nutrient loading in the River.

3. EPA must show strong leadership, and provide a long term commitment of resources if we are to have any hope of seeing real in-the-water improvements in the Gulf.

The Petitioners, the Gulf Restoration Network, and the Sierra Club Legal Defense Fund have that long term commitment to solving the problem before us, and will do everything necessary to ensure that the process I just outlined is implemented, and continues, until the Dead Zone is cleaned up.

Presentation Discussion

Melissa Samet (Sierra Club Legal Defense Fund—San Francisco, CA)

Eugene Buglewicz *(Corps of Engineers—Vicksburg, MS)* asked Melissa Samet to better define the Coalition's expectation of terms "clean up" and "get results."

Melissa Samet responded by saying she had no scientific definition for the term, but suggested the concepts could be based on reducing the size of the Dead Zone to historical proportions. She added that it was imperative to reduce the area as much as possible.

Clive Walker *(Natural Resources Conservation Service—Texas A&M University, Temple, TX)* commented on Melissa Samet's statement that EPA has money to fund the nonpoint source program for the purposes of placing vegetated buffer strips along the specific rivers. He pointed out that in the wake of EPA budget cuts, these funds would need to be diverted from other programs, and asked her which programs she would suggest cutting.

Melissa Samet responded by saying that she had no specific programs in mind, but she would not recommend cutting programs that are showing on-the-ground and in-the-water improvements. She continued by saying that EPA has money for nonpoint source controls. Many states along the river, as well as the entire country, will benefit from solving the nonpoint problem along the Mississippi River.

Phillip Barbour *(Delta Council, Slidell, LA)* asked Ms. Samet to comment on the land use/ landowner's role in the process.

Melissa Samet suggested that private landowners would have to change their practices in order to achieve consistent nonpoint source pollution reduction, and that it was in their own best interests to do so.

Ron Kucera *(Missouri Department of Natural Resources—Jefferson City, MO)* raised two issues.

- The State of Missouri has implemented a self-imposed sales tax for nonpoint source controls through a Soil and Water Conservation program.

- The Sierra Club often supports positions that are counterproductive to solving water resource issues in the Missouri River Basin. For example, the MNI-SOSE Intertribal Water Coalition, Inc., a tribal corporation interested in water marketing, is claiming 20 percent of the Mississippi River flow above Cairo, Illinois, and 40 percent of the Missouri River flow above St. Louis, Missouri. The MNI-SOSE Coalition asserts that they should be able to market those water rights outside of the Missouri River Basin. Since the Department of the Interior is supporting the initiative to achieve the best use of the resources, and since marketing those rights in the upper river areas would not reflect the interests of the Gulf Coast or the State of Missouri, he asked the Sierra Club to discuss potential reduction in available freshwater quantity with him.

Melissa Samet agreed to discuss the issue with him during the conference, but pointed out that the Sierra Club Legal Defense Fund was a separate entity from the Sierra Club.

EPA Committed to Addressing Gulf Hypoxia

Robert H. Wayland III

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Washington, D.C. 20460

Abstract

This is an important conference and the "Dead Zone" in the Gulf of Mexico is an important issue. We're going to be committed to addressing it from the national level at EPA. There are a number of efforts underway at the national level that can play a role in clarifying the severity of the problem, developing strategies to counter it, and implementing those strategies. Just to cite a couple of examples in areas where I have been directly involved recently: Yesterday I was kicking off a two-day National Nutrient Assessment Workshop that EPA is sponsoring. We have convened 22 experts from EPA, 17 academic experts, 10 state officials with particular expertise in nutrient management, 7 people from the consulting community, and 3 experts from local and interjurisdictional governments to help formulate a better tool box for addressing nutrient problems nationally. Last month I addressed the Inter-governmental Conference to Adopt a Global Program of Action for the Protection of the Marine Environmental from Land-Based Activities. More than a hundred countries participated in this meeting which grew out of the UNEP-Rio Conference in which there was an international commitment to better address marine resources and the impacts to them from land-based sources.

EPA Funding Will Affect Our Ability to Address Hypoxia

At the same time, however, our ability to deal with this and other environmental problems is closely related to the availability of resources with which to work. The President has stated that he will veto the Appropriations bill for EPA because the Senate and House have cut funding below the Administration's request and below the FY 1995 level. This is the first trip I've made by airplane paid for by EPA since the beginning of the fiscal year on October 1. I'm also gratified to say that the Section 319 Program to address run-off has been fully funded by both the House and the Senate at the $100 million level the Administration requested.

The Problem and Its Causes

First let me talk about the problem and its apparent causes: Hypoxia and other effects of nutrient over-enrichment are not just limited to the Gulf of Mexico, or even to our coastal waters. Nutrient over-enrichment is a pervasive problem which reduces the quality and productivity of the Nation's Waters. It has been the primary focus of efforts to restore the productivity of the Chesapeake Bay. There has been a dead zone for many years in Long Island Sound—not caused by toxic chemicals but by lack of oxygen.

My first illustration (Figure 3)shows that indeed nutrients are a problem upstream in the Mississippi-Missouri Watershed as well as downstream in the Gulf of Mexico. The states shown in green are those states that, in their 1994 Water Quality Assessment Reports to EPA, identified nutrient enrichment as the primary cause of water quality impairment in their waters. River and streams have a natural flushing action which often makes the effects of nutrient enrichment less apparent and does, in fact, transport the nitrogen and phosphorus in fertilizers, animal waste, and domestic sewage to downstream areas, either lakes or estuaries, where there is limited or no flushing action for it to sink. Cross-hatched states are states which identify nutrient enrichment as the primary cause of impairments for their lakes and reservoirs.

Thus, control of nutrients in the upper watershed of the Mississippi and Missouri Basins will potentially benefit not only the Gulf of Mexico and downstream states, but also have at-home benefits for many of those states further up in the watershed. Although states shown here in blue did not list nutrient enrichment as a primary cause of impairment, it may be a primary cause in some waters or a secondary cause in many waters. In the aggregate, nutrients are the leading source of water quality impairment in the United States.

Sources and Distribution of Nutrient Discharges

Let me turn to the amounts and distribution of the activities that contribute to nutrient loadings. There are about 11.5 million tons of nitrogen fertilizer currently applied to croplands, 6.5 million tons of manure generated by 11 billion farm animals, 3.2 million tons of nitrogen entering our waterways as a result of atmospheric emissions. About .8 million tons are discharged from public owned wastewater treatment works.

Figure 4 depicts potash fertilizer use in tons per square mile, on a county-wide basis. The heaviest use rates are shown as yellows and reds. (The greatest number of these is in the upper Mississippi basin.) Information on the prevalence of livestock which, of course, correlates with manure, shows a highly similar picture (Figure 5). Figure 6 shows nitrogen fertilizer use in 1991 on a county basis.

Nutrient Reduction Experience

EPA and partner states have substantial experience in developing strategies to address nutrient over enrichment in coastal areas. Of the 28 estuaries enrolled in the National Estuary Program, Galveston Bay, Tampa Bay, Sarasota Bay, Corpus Christi, and Barataria-Terrebonne are all on the Gulf Coast. All of those estuaries, and in fact all of the estuaries in the National Estuary Program, identify nutrient enrichment as a primary environmental problem that they want to deal with.

Of course, the consequences of hypoxia aren't generally public health problem, rallying public concern and public interest, is more of a challenge than if we were confronting a drinking water contaminant or a toxic cloud. Ground water contamination by elevated levels of nitrate is a public health concern in some instances, however.

For the most part, we are talking about both an economic problem—lost economic returns in terms of fisheries productivity and catch, and aesthetic problems in terms of lakes, estuaries, and other water bodies which are unable to fully support recreation due to algae blooms and other problems.

While the relative contribution from point sources and run-off varies from watershed to watershed, nationally, only about 6 percent of the nitrogen loadings come from point-source discharges. It is generally possible to remove a pound of nitrogen from non-point sources in a far more cost effective manner than is true for removing that same pound of nitrogen from a point source.

Cost-Effective and Cost-Saving Run-off Control Measures

I think some of the most encouraging news I can share with you is that there are simple, practical and affordable control measures for reducing nutrient run-off from non-point sources. A number of these take the form of prevention approaches, meaning that the environmental benefit is realized by reducing use of the potential pollutant, in this case fertilizer, without reducing the benefit to food production or the producer. I'm sure John Burt will talk in a few moments and perhaps later in the Conference about some of the progress being made in agronomic practices. Just a few factoids I've collected are:

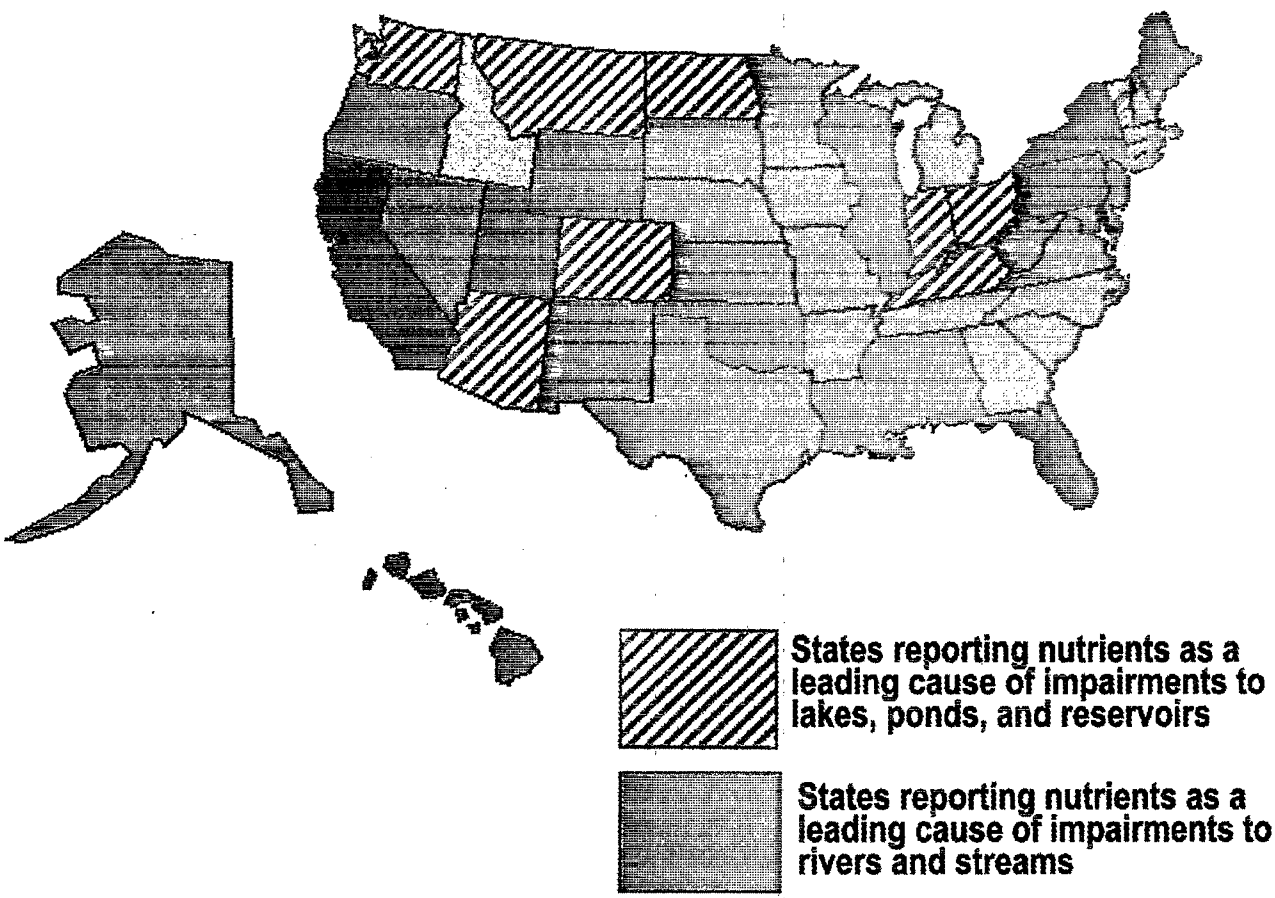

Figure 3.

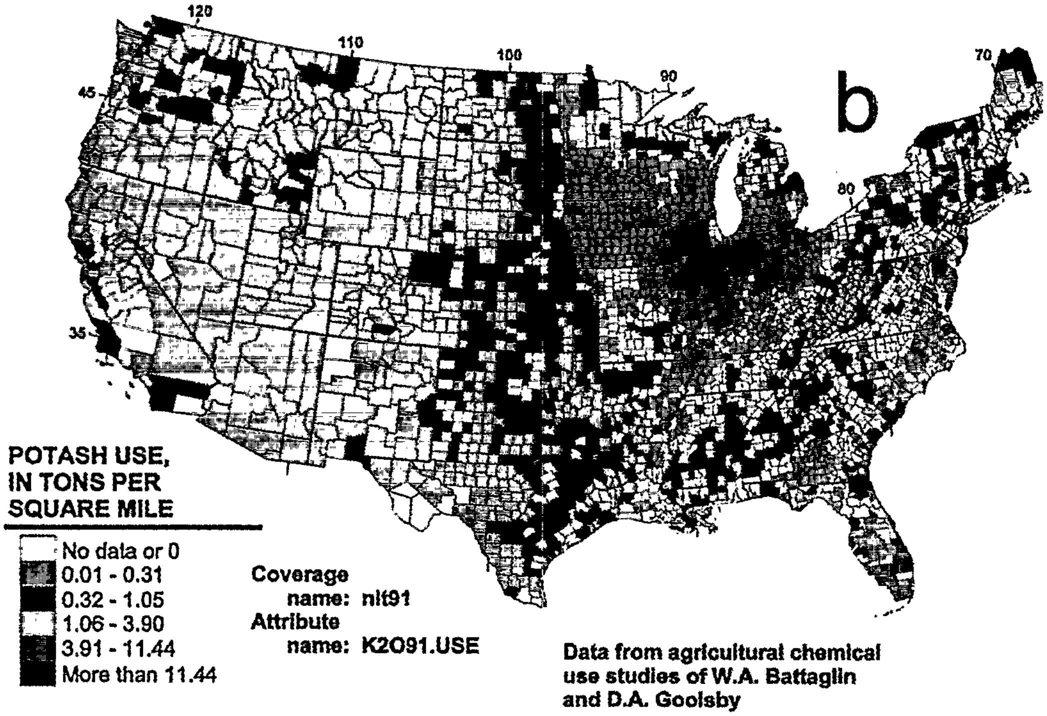

Figure 4.

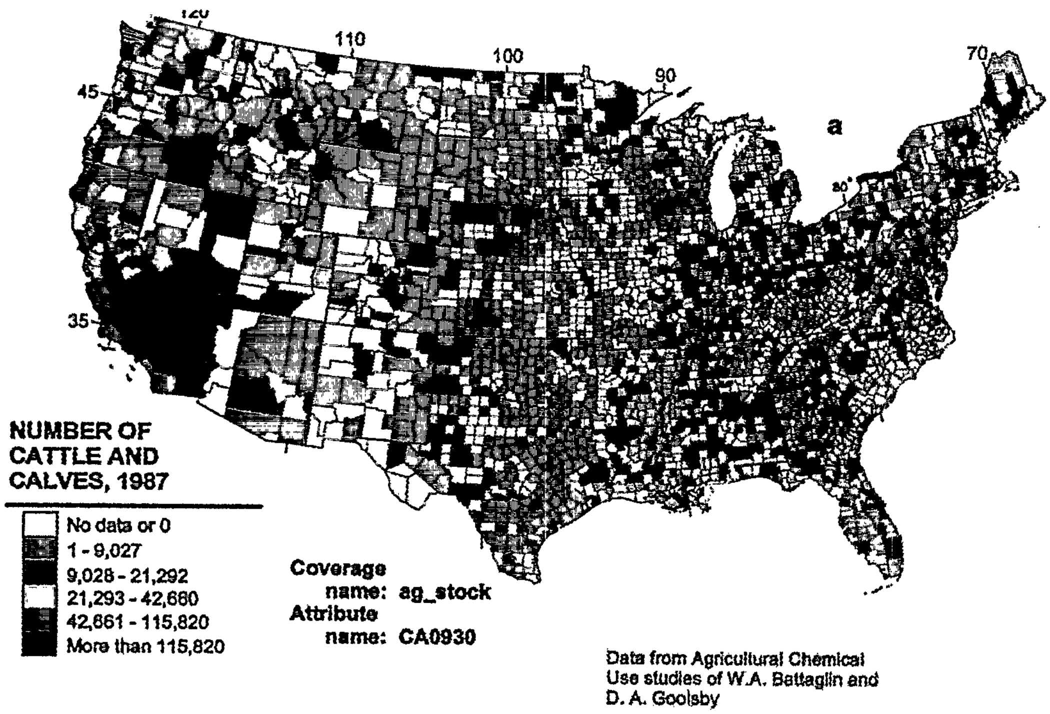

Figure 5.

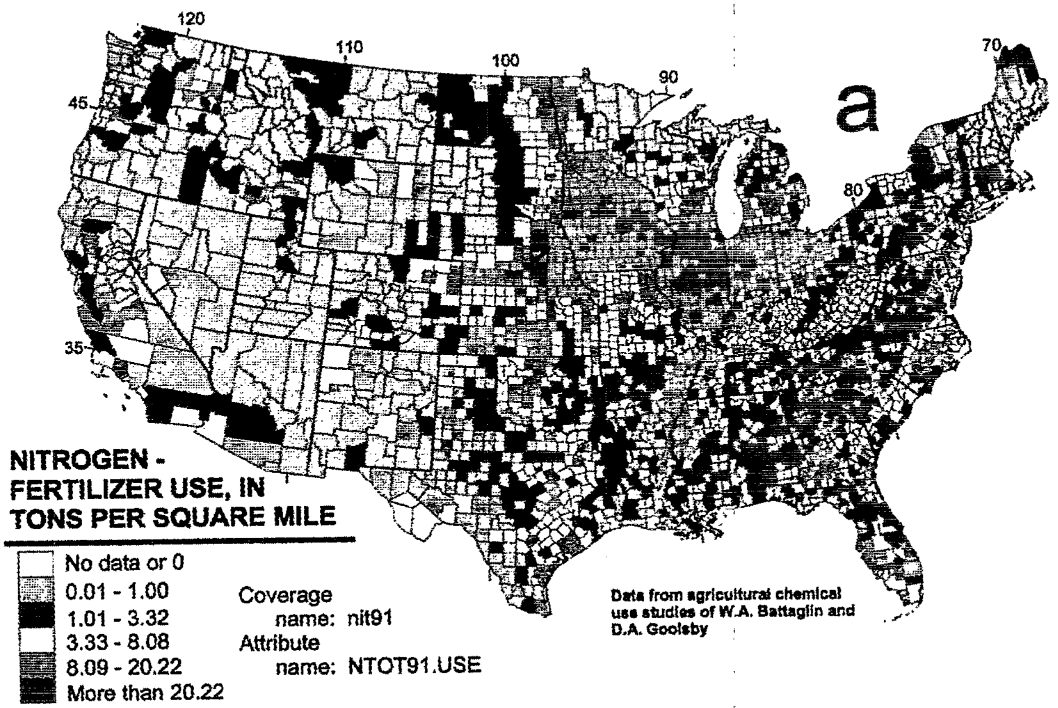

Figure 6.

In the Big Spring Basin Demonstration Project where they've been working with new farming techniques since 1981, farmers have reduced their nitrogen fertilizer use by 34 percent from about 115 lbs/acre in 1993 compared to 174 lbs/acre in 1981, realizing a cost savings of $360,000 or about $1800 per producer with overall improvements in yield.

Participating farmers in Maryland's state-wide nutrient management program have achieved an average reduction of 35 lbs. of nitrogen per acre and 41 lbs of phosphates per acre; in Nebraska, nitrogen applications to corn have been reduced by 30 lbs./acre with no decrease in yield and at a cost savings of about $900,000 annually for participating farmers.

Of course, there are other controls, as opposed to prevention methods, like the use of buffer strips to physically and biologically intercept run-off. There are also *mitigation* strategies, like the restoration of wetlands, which can sequester some of the nutrients, before they reach lakes or estuaries or the Gulf. The work we are doing nationally to demonstrate and evaluate a variety of control methods or prevention methods and their cost-effectiveness will be highly beneficial to the work that's undertaken to address problems in the Gulf. Strategies to reduce nutrient loadings to the Gulf are also likely to return significant water quality improvements and benefits for those who live in upstream states.

A National Context for Addressing Gulf Hypoxia

I want to quickly mention a couple of national trends that I think are going to affect the nutrient management picture and therefore, affect what's taking place with this Conference and its follow-up work. The first is the changing paradigm for addressing water quality problems in the nation. We're increasingly moving, along with states and our federal colleagues, away from a source-by-source or a pollutant-by-pollutant approach to a whole watershed approach Don Boesch illustrated in his discussion of the Chesapeake Bay experience. I think the Bay experience, along with our experience in the Clean Lakes Program and National Estuary Program, demonstrates that watershed management is the approach we need to use to engage the stakeholders who can be a part of the problem and can become a part of the solution. The Clean Water Act re-authorization debate has been underway for some time now. I don't think we're expecting significant changes in federal law in this Congress. Not withstanding that, we've moved forward with the states to realign programs on a watershed basis.

Louisiana has been a participant in a related effort of redesigning and revitalizing the National Non-Point Source Program. I alluded earlier to the fact that EPA's Clean Water Act Section 319 grants program is fully funded at the level requested by the Agency and equal to last year'slevel. We're also very close to articulating a new policy for pollution trading. This market-oriented mechanism will encourage point sources to meet their pollution reduction requirements by financing or undertaking non-point source control practices which may save them significant resources.

All of the Gulf states, along with 20 or so other states, have prepared and submitted to EPA, coastal non-point source control programs developed as a result of legislation enacted in 1990. We're expecting to see some significant water quality improvements as a result of these programs. We are evaluating the State programs now to determine which can be approved, which would be conditionally approved, and which disapproved.

I look forward to the expert presentations which have been arranged for the balance of this Conference and outlining, at the conclusion, some thoughts on how we proceed from here.

Presentation Discussion

Robert Wayland *(U.S. EPA, Washington, D.C.)*

Don Boesch ***(University of Maryland, Cambridge, MD)*** commented that to gain local support, it is imperative to communicate the local water quality benefits as a result of solving the nonpoint problem instead of solely focusing on the benefit to the hypoxia area. For example, Pennsylvania began participating in the Chesapeake Bay Program because it benefitted their local water quality.

Hypoxia in the Gulf—Who's Problem Is It?

William A. Kucharski
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Abstract

The Mississippi River basin drains over 40 percent of the land area of the United States. The Gulf of Mexico, into which the Mississippi flows, also supports approximately 40 percent of the fishery landings for our country. An area of low oxygen concentration, termed a hypoxia region, has been documented in the Gulf. This conference is being held to present and review the technical realities of the problem and to bring together all interested parties for discussions and education.

This presentation will remind the participants that we actually know very little about a potentially big problem. Further, those states that believe that they have no responsibilities toward the Gulf because they are far away, are misinformed. The problems that manifest themselves off the coast of Louisiana are national problems that will require study and change in many upriver states. The forum under which this study and resultant work will be done is equally important to the future of the environmental protection business. The non-enforcement, non-threatening aspects of this study/program are being looked upon as a measure of the environmental maturity in this country. Those that believe the change can occur without threats must be active in this program.

Introduction

The technical issues related to the depleted oxygen area in the Gulf of Mexico have recently been catalogued to present a more detailed explanation of this phenomenon. Recommendations have followed which express the need for more detailed studies about cause and effect and the development of appropriate control measures. Since this seasonal problem, however big and however serious it finally turns out to be, exists off of the coast of Louisiana, people might assume that this is Louisiana's problem alone. Nothing could be further from the truth. I will attempt to outline in general detail, why the problem is of national concern rather than simply a single state issue. I will also provide support of a multi-state, federal and citizen partnership as the tool for solving, or at least mitigating this problem.

The problem of having a very large area of low oxygen in a normally productive area of the Gulf of Mexico has both environmental and economic implications. What we do not know about this situation is greater than what we do know however. Speaking from a policy perspective, it is sometimes very difficult not to do something before all of the facts are known. We, as policy managers, are often subjected to varying amounts of outside pressure to take steps that are designed to solve simple problems. The fact that most of the issues we have to deal with are not simple, but rather, are quite complex does not seem to deter the "you must do something now" voices. That is one of the issues that this conference must address over these next two days. How do we design short term, intermediate and long term remedies of the problem? First we must be able to describe what the problem actually is. We can describe the manifestations of the hypoxia problem. In fact, the name adequately describes the impact. Low oxygenated waters. This does not however, describe the cause or causes of the hypoxic area. We are all certain that nutrient loadings are one of the primary contributors to the hypoxia problem, but we also know that some level of nutrient loading is necessary to sustain the productivity of the Gulf ecosystem. What we do not know is how much nutrient loading is enough or how much is too much. We do not know when we reached the point of over supply of these nutrients nor are we certain of how long the hypoxic region has existed. In short, we know there is a problem, but beyond that we are guessing about the relative contributions of each factor. I make these observations as a political appointee, not as a biologist or a fisheries expert.

What are the implications of this problem? We often speak of sustainable development and using our natural resources wisely. Killing a large area of the Gulf every year can not be considered responsible stewardship by even the most indifferent polluter. The question is not whether we must address this issue, it is how we must address it. As the Secretary of the Louisiana Department of Environmental Quality, I am obligated by state statutes to protect human health and the environment in my state. How do I protect the environment of my state when the problem is not created in or by my state? How do we as states, who by the way are demanding that the federal government get off of our backs and let us regulate our states, handle interstate transport problems? These are the questions that this conference must also address.

From a single state regulator's perspective this problem can be viewed as a measure of our nation's environmental protection system maturity. Our challenge is how to contact, work with, and when necessary, modify existing practices carried out in multiple states. The question is whether we can accomplish such a task in a voluntary or prescriptive manner. I do not know the answer to this question. I do know that if we states continue to demand autonomy, or the U.S. Congress in its wisdom gives us that autonomy and we fail to use this freedom of action wisely, we will have failed in our charge to effect positive change in the current command and control system we say we dislike. The problems we face in the Gulf are real. The solutions that we may have to implement will require a level of communication, study and action that we have heretofor only thought about. Can we cooperate when a state may have to change how its citizens work, farm or handle waste, and not see any appreciable environmental improvement in that state? This is the real question that we all must face. This will be hard, this will create political challenges to all of the regulatory agencies involved. But let us return to the basic issue. Something is wrong. We have to find out just what we have to fix and then we have to fix it. This will take time, lots of money and a positive attitude that the "fixes" we propose will work. This brings to mind the famous quote from the American revolution, "Gentlemen, we will all hang together, or most assuredly we will hang separately." This is what we face. A multi-state cause, a local effect and a national impact. How we as states handle this issue may frame how environmental controls and regulatory compliance are managed into the twenty-first century. We must, I believe, face this reality of our plight with open eyes, with a willingness to change and a clear recognition that some very tough decisions will most likely be part of any control solution we impose.

Presentation Discussion

William Kucharksi—Louisiana Department of Environmental Quality, Baton Rouge, LA

No questions/discussion after Secretary Kucharksi.

Hypoxia in the Northern Gulf of Mexico: Past, Present and Future

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William. J. Wiseman, Jr.
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Abstract

The inner to mid-continental shelf from the Mississippi River westward to the upper Texas coast, is the site of the largest zone of hypoxic bottom water in the western Atlantic Ocean. The areal extent during mid-summer 1993–1995 (16,800 km^2, 16,300 km^2, and 18,200 km^2, respectively, of near bottom waters < 2 mg/l) rivals the largest hypoxic areas elsewhere in the world. Spatial and temporal variability in the distribution of hypoxia is, at least partially, related to the amplitude and phasing of the Mississippi River discharge. Freshwater fluxes dictate, along with climate, a strong seasonal pycnocline. Nutrients delivered by the Mississippi and Atchafalaya support high primary production, of which approximately 50 percent fluxes to the bottom. The high particulate organic carbon flux fuels hypoxia in the bottom waters below the seasonal pycnocline. Significant increases in riverine nutrient concentrations and loadings of nitrate and phosphorus and decreases in silicate have occurred this century, and accelerated since 1950. As a result of the nutrient alterations, the overall productivity of the ecosystem appears to have increased since the 1950's along with an increase in oxygen deficiency stress this century. Variable changes in nutrients and/or changes in freshwater fluxes will result in differing scenarios for distribution of hypoxia in the future.

Hypoxia is operationally defined as dissolved oxygen levels below 2 mg l^{-1}, or ppm, for the northern Gulf of Mexico, because that is the level below which trawlers usually do not capture any shrimp or demersal fish in their nets (Leming and Stuntz, 1984; Renaud, 1986). In this presentation, we outline the distribution and dynamics of hypoxia in the northern Gulf of Mexico, including present and historical conditions. We further detail historical conditions evident in the sedimentary record and use these retrospective analyses to predict future scenarios, including that of climate change. A more complete review of the subject is provided in Rabalais et al. (in press and in review).

Present Distribution

The inner to mid continental shelf of the northern Gulf of Mexico, from the Mississippi River birdfoot delta westward to the upper

Texas coast, is the site of the largest zone of hypoxic bottom water in the western Atlantic Ocean. The areal extent of this zone during mid-summer surveys of 1993–1995 (approx. 16,000 km^2 to 18,000 km^2; Rabalais et al., in review; Figure 7) rivals the largest hypoxic areas elsewhere in the world's coastal waters, namely the Baltic Sea and the northwestern shelf of the Black Sea.

Conditions during the Great Summer Flood of 1993 point to the importance of the river in the formation and persistence of hypoxia (see references in Dowgiallo, 1994). As a result of higher streamflow, especially in mid to late summer, there were:

- Lower than normal surface salinities
- Higher surface temperatures
- Increased stability in the coastal waters
- Increased overall loading of nutrients
- An order-of-magnitude higher than normal total phytoplankton counts
- A predicted greater flux of carbon to the seabed
- A significantly lower oxygen content of the lower water column
- An approximately two-fold increase in the areal extent of hypoxia with respect to the 1985–1992 mid summer averages, over an extensive area (Rabalais et al., 1994a).

Previous Years

Prior to 1993, the average areal extent of bottom water hypoxia in mid-summer was 8,000 to 9,000 km^2 (Rabalais et al., 1991). Distribution maps of mid-summer bottom water hypoxia since 1985 often show disjunct areas of low oxygen downfield of each of the river deltas (see 1992 in Figure 7). Other distributions are continuous from the Mississippi River delta to the upper Texas coast. When the 2 mg l^{-1} isopleths are not continuous along the shelf, however, the areas between are still undersaturated in oxygen with values usually below 4 mg l^{-1} and mostly below 3 mg l^{-1}.

Annual Cycle

Critically depressed dissolved oxygen concentrations occur below the pycnocline (Figure 8) from as early as late February through early October and nearly continuously from mid May through mid September. The importance of stratification and the physical structure of the water column in defining the distribution of hypoxia was discussed by Wiseman et al. (this volume). Hypoxic waters are distributed from shallow depths near shore (4 to 5 m) to as deep as 60-m water depth. The more typical depth distribution of hypoxic bottom waters, however, is between 5 and 30 m.

In March, April and May, hypoxia tends to be patchy and ephemeral; it is most widespread, persistent, and severe in June, July and August (Figure 9). The persistence of extensive and severe hypoxia into September and October depends primarily on the breakdown of the stratification structure by winds from either tropical storm activity or passage of cold fronts. Hypoxia is not just a bottom-hugging lens of water. It occurs well up into the water column; depending on depth of the water column, hypoxia may encompass from 10 percent to over 80 percent of the total water column.

Continuous time series show long periods of hypoxia and anoxia, a draw-down of hypoxia in the spring in response to respiration in the lower water column and at the seabed and sediment oxygen demand, vertical mixing and loss of stratification, response to winds (e.g., upwelling of deeper oxygenated waters), and, in other parts of the shelf, the influence of tidal advection (Rabalais et al., 1992; Rabalais et al., 1994b). While the 1995 areal extent of bottom water hypoxia was the largest ever recorded for the Louisiana shelf, its permanence over such an extent is not known. Based on monthly monitoring transects off Terrebonne Bay from 5-m to 30-m water depth and a continuously recording oxygen meter in 20-m water depth, the following can be said about the 1995 hypoxia season: Extensive low oxygen occurred as early as late May. During June and July oxygen levels were extremely low over large areas. Tropical storm activity re-aerated the water column during August, but low oxygen conditions again developed and low and extremely low values persisted into late September.

Proximal Causes

The relative magnitude in changes of freshwater discharge and nutrient flux from the Mississippi and Atchafalaya Rivers to the coastal ocean affects water column stability, surface water productivity, carbon flux, and oxygen cycling in the northern Gulf of Mexico.

High biological productivity in the immediate (320 gC m^{-2} yr^{-1}) and extended plume (290 gC m^{-2} yr^{-1}) of the Mississippi River is mediated by high nutrient inputs and regeneration, temperature and favorable light conditions (Sklar and Turner, 1981; Lohrenz et al., 1990). Spatial variation in primary production in a given period is related to salinity and the associated environmental and biological gradients (Lohrenz et al., 1990, 1994). There is a worldwide relationship between flux of dissolved inorganic nitrogen and primary production in coastal waters, and a similar relationship has been observed for the plume of the Mississippi River (Lohrenz et al., in review). The availability of dissolved silicate and its ratio to total inorganic nitrogen are also important in controlling the extent of diatom production and the composition of the diatom community with implications to carbon flux and control of oxygen depletion (Dortch and Whitledge, 1992; Nelson and Dortch, in press).

Particulate organic carbon flux to the lower water column is high in the extended plume over the inner shelf (Qureshi, 1995). The fraction of production exported is highly variable but averages about half of the estimated integrated primary productivity with statistically higher fluxes in the spring. A large proportion of the particulate organic carbon flux reaches the bottom incorporated in zooplankton fecal pellets (55 percent), but also as individual cells or in cell aggregates. Although Qureshi's data are limited to a single station in 20-m water depth off Terrebonne Bay for a 2-yr period, it appears that the amount of carbon fluxed is greater when the spring freshet of the river is higher. Also, the carbon fluxed via fecal pellets (during period of high flux) is sufficient to deplete the bottom water oxygen reserve in spring, thus creating hypoxic conditions that then prevail through the stratified summer period. When fluxes are lower (e.g., in lower flow years, or in summer) the oxygen depletion rates for these fluxes are close to the calculated oxygen depletion rate.

On a seasonal time scale, productivity is most influenced by Mississippi River flow and nutrient flux to the system. Long-term mean seasonal variations in net productivity at a station in 20-m water depth off Terrebonne Bay are coherent with the dynamics of freshwater discharge (Justic et al., 1993). The surface layer shows an oxygen surplus during February-July, the maximum occurs in April and May and coincides with the maximum flow of the Mississippi River. The bottom layer exhibits an oxygen deficit through the year, but reaches its highest value in July (coincident with maximum pycnocline strength). The correlation between the Mississippi River flow and surface oxygen surplus peaks at a time-lag of one month, and the strongest correlation for bottom water oxygen deficit is for a time-lag of two months. The oxygen surplus is also a good indicator of excess organic matter derived from primary production which can be redistributed within the system [which follows Qureshi's (1995) results].

A similar 2-month lag of bottom water hypoxia following peak Atchafalaya River flow was observed by Pokryfki and Randall (1987) for the southwestern Louisiana shelf for data from the early 1980's. Low surface salinities lagged one month behind peak river flow. Their model did not incorporate any biological processes, which with additional lags would increase the accuracy of their predicted low oxygen periods. The physics, geological setting and important biological parameters, such as light fields and nutrient flux, differ on the southwestern Louisiana shelf from that of the southeastern shelf. It is also not clear how the effluents of the Mississippi River and the Atchafalaya River merge to produce the physical structure of the area. Wiseman and Kelly (1994) demonstrated that salinity signals from both river discharges were detectable off the Calcasieu estuary. However, similar biological processes occur on the southwestern shelf so that a large area of hypoxic bottom waters to the west of the Atchafalaya River appears to form each season.

Historical Data

Our systematic surveys began in 1985. Extensive shelfwide distributions of hypoxia occurred each summer of those years, with the exception of 1988 (a record low flow year for mid-summer; hypoxia developed as usual in the spring, but not maintained in the summer). Prior to 1985, the data are mostly ancillary to other studies, thus do not form a complete survey, either temporally or spatially. There were some directed studies in the early 1970's (Ragan et al., 1978; Turner and Allen, 1982).

The mention of low oxygen conditions from the mid 1930's in the Conseil Permanent International pour l'Exploration de la Mer Bulletin Hydrographique for 1935 were identified in Hedgpeth's Treatise on Marine Ecology and Paleoecology (Brongersma-Sanders, 1957; Richards, 1957) as records from the oxygen minimum zone of deeper waters (e.g., 400–500 m deep) and several authors have shown that there is no continuation of the oxygen minimum zone with the hypoxia on the inner to mid continental shelf (Pokryfki and Randall, 1987; Rabalais et al., 1991).

Hypoxia was first recorded in the early 1970's off Barataria and Terrebonne/Timbalier Bays as part of environmental assessments of oil production and transportation development studies (the Offshore Ecology Investigation, OEI, and the Louisiana Offshore Oil Port, LOOP). Ragan et al. (1978) and Turner and Allen (1982) followed up with studies in 1975 and 1976 along the Louisiana coast and documented low oxygen conditions over most of the areas they studied in the warmer months. Environmental assessments for brine disposal areas and further studies of oil and gas production areas revealed low oxygen conditions in most inner shelf areas studied in mid-summer.

Hypoxia along the upper Texas coast is usually an extension of the larger hypoxic zone off the Louisiana coast, although isolated areas may be found (e.g., Big Hill area and Bryan Mound areas, but may be an artifact of the sampling). Most instances of hypoxia along the Texas coast are infrequent, short-lived, and limited in extent. There are no records of hypoxia below the Freeport, Texas area (with the exception of one record at SEADOCK off the Brazos River)

(Rabalais, 1992). There are very few systematic surveys for this area.

There are reports of hypoxia off Mississippi Sound during high stages of the Mississippi River; also reports off Mobile Bay in bathymetric low areas. There are usually more reports in flood years (especially 1993, related to the high flow of the river late in summer and movement of the waters to the east of the delta by the persistent southerly and southwesterly winds).

Prior to the 1970's, there is some anecdotal information from shrimp trawlers in the 1950's–1960's of low or no catches, of "dead" or "red" water, but no systematic analysis of these records.

Changes in Nutrient Loadings

These results are outlined in papers by Turner and Rabalais (1991, 1994a,b), Justic´ et al. (1994, 1995a,b) and Turner et al. (this volume):

- Nutrient concentrations and loadings have changed dramatically this century and accelerated since the 1950s.
- Concentrations of dissolved N and P have doubled, and Si have decreased by 50 percent.
- Nutrient composition in river and adjacent Gulf waters has shifted towards ratios closer to the Redfield ratio and more balanced than previously.
- These changes are closely related to N and P fertilizer applications in the watershed.
- Offshore nutrient compositions shifted along with potential and probable nutrient limitations.
- Water quality changes are specific to changes in nutrients. Freshwater inflow has remained fairly stable, although there is a slight increase in total flow in the last two decades due to an increase in Atchafalaya River flow (Bratkovich et al., 1994).

Ecosystem Changes

Long-term changes in the severity and extent of hypoxia cannot be assessed directly, because systematic sampling of bottom water dissolved oxygen concentrations did not begin until 1985. Therefore, biological, mineral or chemical indicators of eutrophication and/or hypoxia preserved in sediments, where accumulation rates record historical changes, provide clues to prior hydrographic and biological conditions. Similar analyses have proven useful in the Great Lakes and Chesapeake Bay and were done for the Mississippi River bight.

An analysis of long-term data sets and diatom, foraminifera, and carbon accumulation in sediments supports the inference of increased eutrophication and hypoxia in the Mississippi River delta bight primarily because of changes in nitrogen loadings. These results are outlined in Rabalais et al. (in press).

The work of Eadie et al. (1994) demonstrated from two cores in the Mississippi River delta bight an increased accumulation of marine-origin carbon in the last 100 years, consistent with changes in productivity beginning in the mid-1950's when benthic foraminiferans rapidly became isotopically lighter. Beginning in the mid-1960's, the accumulation of organic matter, organic $d^{13}C$ and $d^{15}N$ showed large changes in a direction consistent with increased productivity. The latter period coincided with a doubling of the load of nitrates in the Mississippi River outflow which leveled off in the 1980's. Increased carbon accumulation was also calculated from BSi (a surrogate for diatom production) accumulation rates in Turner and Rabalais (1994a).

Diatom-based productivity and BSi accumulation provide other lines of evidence of increased productivity. In spite of a probable decrease in Si availability, the overall productivity of the ecosystem appears to have increased this century. This is evidence by:

- Equal or greater net silicate-based phytoplankton community uptake of silica in the mixing zone, compared to the 1950s (Turner and Rabalais, 1994b)

- Greater accumulation rates of biogenic silica (BSi) in sediments beneath the plume, but not further away, and in agreement with results found in freshwater systems (Turner and Rabalais , 1994a). The increased BSi in Mississippi River bight sediments parallels increased N loading to the system and is direct evidence for the effects of eutrophication on the shelf adjacent to the Mississippi River.

Finally, an analysis of benthic foraminiferans in offshore sediments indicates an increase in oxygen deficiency stress this century, with a dramatic increase since the 1940's–1950's. Several cores from areas of varying levels of frequency of hypoxia (in the Mississippi River delta bight) were examined by Barun Sen Gupta and colleagues (in Rabalais et al. in press, Sen Gupta et al. in press). They documented a progressive overall rise in oxygen stress (in duration or intensity) with these indicators: (1) an increase in the ratio of *Ammonium* to *Elphidium*, (2) a decrease in species not tolerant of oxygen stress, and (3) an increase in species tolerant of low oxygen stress. These changes were coincident with the rise in river-borne nutrients and accumulation of biogenic silica.

Increased bottom-water hypoxia could result from increased organic loading to the seabed and/or shifts in material flux (quantity and quality) to the lower water column. Oxygen-depleted bottom waters in the coastal ocean are found worldwide. The incidence and extent of such areas in coastal waters is apparently increasing and related to anthropogenic nutrient loadings in rivers (Diaz and Rosenberg in press). The patterns of worsening water quality in coastal waters adjacent to the terminus of major rivers undergoing nutrient flux or water quality alterations are consistent with the conditions identified for the Mississippi River.

Future Scenarios

The enormity of effecting environmental change on the continental shelf at the terminus of the Mississippi River might seem insurmountable for a watershed that includes 41 percent of the conterminous U.S., encompasses parts of many states and innumerable other regulatory or legislative boundaries, and integrates centuries of landscape changes within the watershed and alterations of the Mississippi River proper. Still, effective policy for managing and restoring ecosystems can be accomplished, especially if the results of scientific inquiry are integrated into the process.

Rabalais et al. (in press) made several predictions of ecosystem response given certain changes in nutrients (Figure 10):

If Si increases, and N remains the same; overall N limitations would be similar to present, but Si will no longer be limiting. This would result in increased BSi and carbon accumulation in sediments, and an increase in the extent and severity of hypoxia.

If Si increases, N increases, and Si and N remain in balance; no N or Si limitations. The result would be greatly increased BSi and carbon accumulation and substantial increase in severity and extent of hypoxia. This is the result demonstrated in the 1993 flood and in a doubled CO_2 climate scenario.

If Si increases, N decreases to 1950s values; N would return to the limiting nutrient status, and although Si would be in abundant supply, the system would be restricted by N supplies and hypoxia would decrease.

To reach the 1950s levels of dissolved N would require a 40-50 percent reduction in the current loadings that exit the Mississippi River delta. Identification of sources of nutrients within the Mississippi River watershed that eventually reach the Gulf of Mexico should lead to avenues of management. While the results of changes in nutrient delivery to the northern Gulf of Mexico are clear, the delineation of the sources and their fate and transformation as they are delivered to the Gulf is not complete (however see Alexander et al., Antweiler, and Goolsby in this volume). It is important to understand which agricultural practices, water treatment practices, water quality regulations, consumer preferences, and economic incentives and disincentives result in the amount of dissolved N, P and Si in the Mississippi river. Management alternatives directed at water issues within the Mississippi River watershed may have unintended and contrasting impacts on the coastal waters of the northern Gulf of Mexico.

Howarth et al. (in review) modeled N loadings to the North Atlantic Ocean and treated the Mississippi River watershed as a unit. Sewage input of N is 9 percent of the total inputs from the Mississippi River to the North Atlantic Ocean. Of four anthropogenic sources, application of fertilizer contributes the greatest input of N (54 percent), followed by fixation by leguminous crops (31 percent) and atmospheric deposition of NOy (15 percent). The ratio of current river N export to "pristine" river N export for the Mississippi River ranges from a 4.8 to 7.4 fold increase. The Howarth et al. model points to a reduction in nonpoint sources, agricultural, direct or indirect, as the key to nutrient pollution control.

There is a direct connection between river nutrient loading and the hypoxic zones on the Louisiana shelf. River diversions aimed at wetland restoration might be considered a possible management tool to decrease nutrient loading to the offshore waters and thereby raise oxygen concentrations in offshore bottom waters. However, the amounts of river water to be diverted are so small relative to the size of the total discharge that river diversions will have an insignificant effect on the size, frequency and duration of oxygen depletion within bottom waters offshore. For example, river diversions are currently operating, or being planned, to bring large quantities of water from the Mississippi River into adjacent estuaries of Barataria Bay, Breton Sound, and Lake Pontchartrain. U.S. Army Corps of Engineers estimated maximum flow for:

Davis Pond
10,650 cfs (likely to move west from delta)
Caernarvon
8,000 cfs (to east)
Bonnet Carré
30,000 cfs (to east)
Total
48,650 cfs (equal 10 percent of average flow 4.6×10^5 cfs, 1954–1988).

However, these diversions will function perhaps one or two months of the year on variable schedules for either fresh water or sediment delivery, and the flows listed above are maximal. The total diverted discharge will be significantly less than 10 percent of the total discharge volume for the year. Further, diversions of river waters to the east of the Mississippi River delta may aggravate the limited and ephemeral conditions of hypoxia there or further flow through the Atchafalaya delta might increase the duration, severity or extent of hypoxia on the southwestern Louisiana shelf or the upper Texas coast.

Any discussion of nutrient management scenarios must be undertaken within another overall context--that of global climate change. A general circulation model by Miller and Russell (1992) predicted that runoff in freshwater would likely increase for 25 of the world's 33 largest rivers. Precipitation in the Mississippi River watershed is likely to increase 20 percent with a doubled CO_2 climate, and runoff is expected to increase in most months, particularly May through August. This response is likely to affect water column stability, surface water productivity, and oxygen cycling in the northern Gulf of Mexico.

Justic´ et al. (in press) applied a 20 percent increase in freshwater flux, primarily during the May-August period, to calculate an estimated average monthly runoff of the Mississippi River at Tarbert Landing compared to 1985–1992. The integrated doubled CO_2 runoff at Tarbert Landing will be around $0.5 \times 10^{12}\ m^3\ yr^{-1}$. Assuming that the highest increase in runoff will occur during May, the maximum monthly runoff value for a doubled CO_2 climate will be approx. $4 \times 10^4\ m^3\ s^{-1}$. This result is substantially higher than the monthly maximum for the Great Flood of 1993 ($3.2 \times 10^4\ m^3\ s^{-1}$). Surface salinity in the Gulf is likely to decrease substantially, and water column stability will increase. Manipulations of a physical-biological two-box model (Justic´ et al. in press) indicated that there will be a 30-60 percent decrease in summertime subpycnoclinal oxygen content, relative to the 1985–1992 average. Under those conditions, the hypoxic zone in the northern Gulf of Mexico will probably expand and encompass an area greater than that of the summer of 1993.

Effects on Living Resources

Hypoxia may affect fisheries resources by direct mortality, altered migration, reduction in suitable habitat, increased susceptibility to predation (including by humans), changes in food resources and susceptibility of early life stages. Studies of benthic communities and demersal communities show distinct responses of various members of the communities to decreases in dissolved oxygen concentration (Rabalais and Harper in prep.). Oxygen deficiency stressed benthic communities are characterized by limited taxa (none with direct development, e.g., amphipods), characteristic resistant infauna (e.g., a few polychaetes and sipunculans), reduced species richness, severely reduced abundances (but never azoic), low biomass, and limited recovery following abatement of oxygen stress (Rabalais et al, 1993; 1995).

Summary

Hypoxia is a severe and dominant feature of the northern Gulf of Mexico, that is linked to the freshwater fluxes and nutrient loads of the Mississippi and Atchafalaya Rivers. River water quality has changed since the turn of the century and accelerated since the 1950s. The adjacent continental shelf ecosystem has responded by increased productivity, eutrophication, and oxygen stress. Solutions are warranted that are directed at nutrient reductions through management practices in the watershed.

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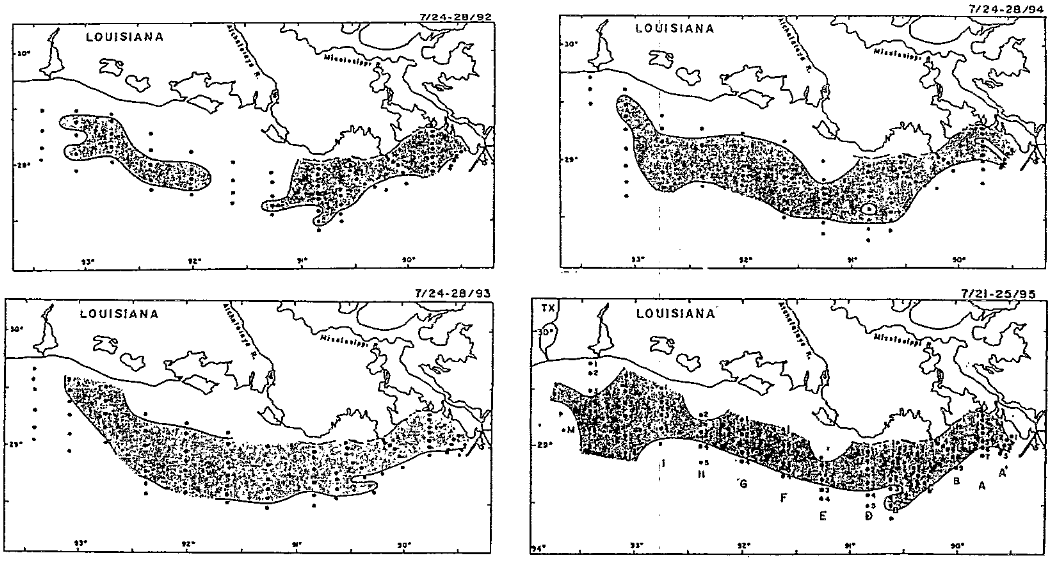

Figure 7.

Distribution of near-bottom water hypoxia (dissolved $O_2 \leq 2$ mg l^{-1}) i mid-summer for the dates indicated in 1992, 1993, 1994 and 1995. Data from hypoxia monitoring studies of N. N. Rabalais, R. E. Turner and W. J. Wiseman, Jr. (From Rabalais et al. in review.)

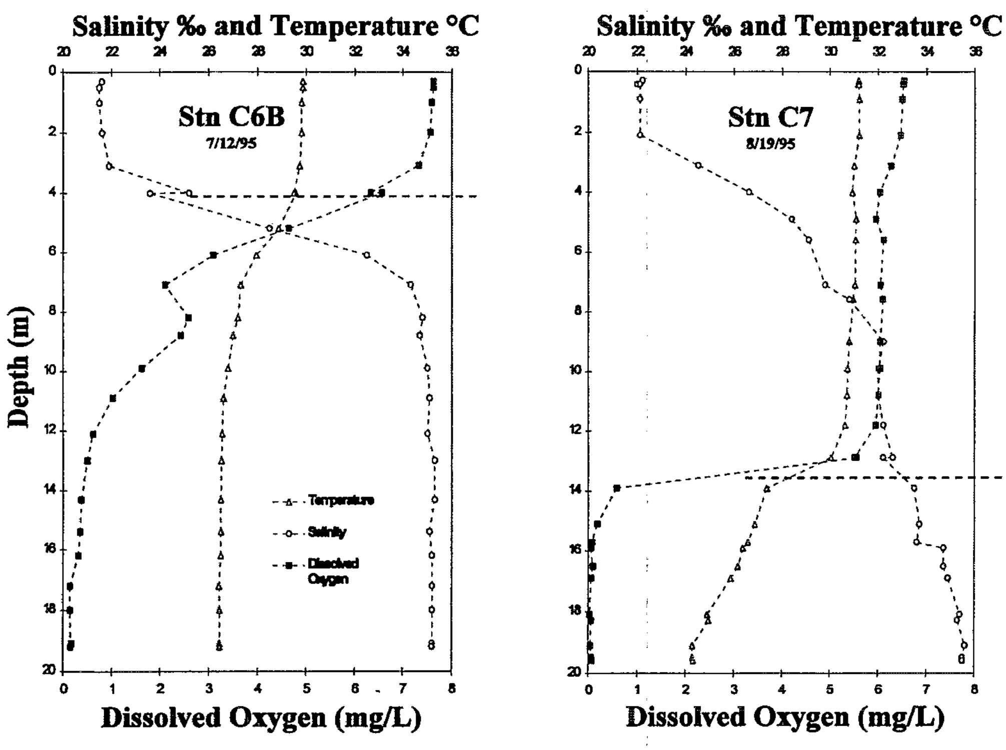

Figure 8.

Structure of water column for a salinity-controlled pycnocline and profile of dissolved oxygen (left panel) and a temperature-controlled pycnocline and profile of dissolved oxygen (right panel). Data from hypoxia monitoring studies of N. N. Rabalais, R. E. Turner and W. J. Wiseman, Jr.

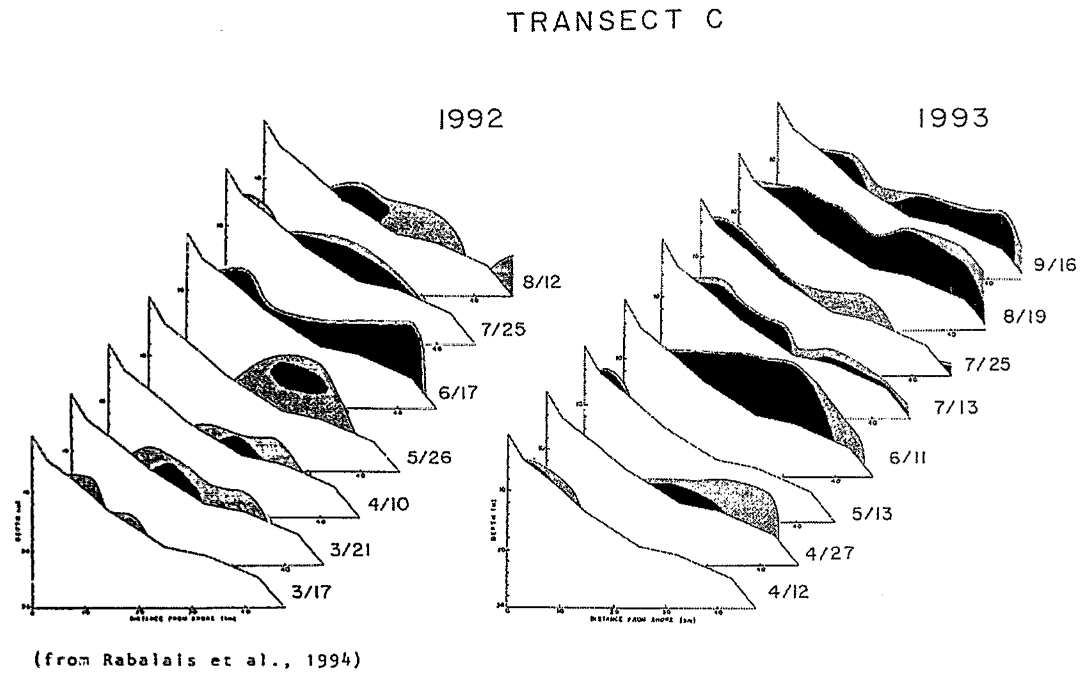

Figure 9.
Cross-section of southeastern Louisiana shelf showing seasonal progression and extent of bottom hypoxic zones during 1992 and 1993. Stippled area indicates < 2 mg l^{-1}; black areas indicate < 1 mg l^{-1}. (From Rabalais et al. 1994a.)

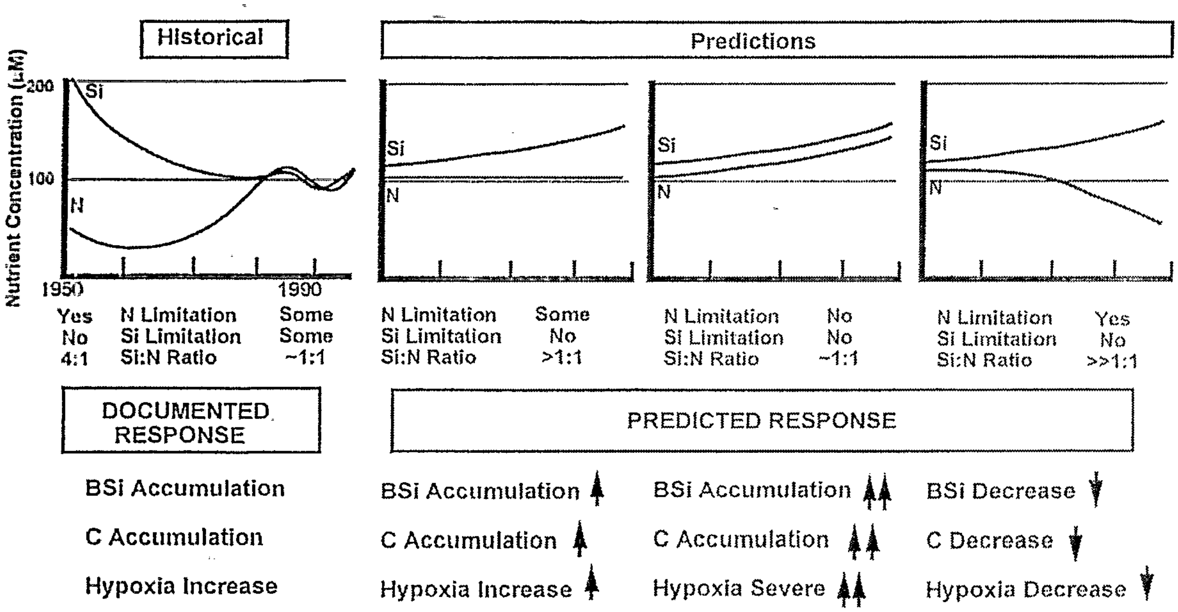

Figure 10.
A schematic of documented historical changes in riverine nutrient concentrations, nutrient ratios, and biological responses, and a series of predicted responses depending on a constant increase of silica and varying changes in nitrogen loadings. A stronger response is indicated by double arrows. (Modified from Rabalais et al. in press.)

Presentation Discussion

Nancy Rabalais *(Louisiana State University—Baton Rouge, LA)*

Alan Ballard *(Gulf of Mexico Program—Stennis Space Center, MS)* asked Nancy Rabalais what percentage of the Mississippi River outflow flows into the hypoxic area.

Nancy Rabalais responded by saying that William Wiseman addressed the amount of freshwater in the shelf and showed the seasonal progression of the freshwater in the area during his presentation. Most of the Atchafalaya River and 50 percent of the Mississippi River discharge water flow west.

Scott Dinnell *(USM Center for Marine Scienc—MS)* added that 10 percent of the total water content of the shelf (although it is seasonal) is freshwater.

Neil Armingeon *(Lake Pontchartrain Basin Foundation—Metairie, LA)* noted that Nancy Rabalais mentioned that one of the proposed river diversions would have little or no impact on the hypoxic zones in the Gulf. He then continued by asking her opinion on the impact that diversion would have on the quality and management of the receiving waters.

Nancy Rabalais responded by saying that she felt river diversions should be done to control freshwater and sediments, not as a panacea for the low oxygen conditions.

Mike Waldon *(USL—Lafayette, LA)* disputed that 48,000 csf is 10 percent of the average flow of the river. He said that the total average is approximately 450,000 cfs. Therefore, 48,000 csf is slightly more than 10 percent. He added that only some of the possible diversions were presented.

Nancy Rabalais agreed that there are other possible diversions. She had presented only those diversions for which she had data, and that most directly affected the southwestern shelf. She continued by saying that she had demonstrated the southwestern shelf down-plume from the Atchafalaya River also experiences extreme bouts of hypoxia and stressed that those areas compared statistically to the two-month time lag of peak river flow in the Atchafalaya River system.

An unidentified gentleman from the audience asked Nancy Rabalais if the growth of soybeans instead of the over application of fertilizer could be the primary contributor to the hypoxia problem since the sources of nutrients in the watershed were 50 percent from fertilizers, 30 percent of that being from leguminous crops.

Nancy Rabalais responded that there are many nutrient sources to the river. Those sources and the fate and transformation of those sources, as they move down the watershed, are not yet well understood.

Lon Strong *(U.S. Department of Agriculture/ Natural Resources Conservation Service—Jackson, MS)* asked if the sewage discharge data presented represented treated or untreated wastewater.

He also asked Nancy Rabalais to comment on her statement that sewage was not a significant source of input. Wastewater treatment discharges are continuous and the total nitrogen content in the effluent ranges between 2–60mg/L, compared to most run-off from cropland which is storm-event driven and lower in nitrogen content.

Nancy Rabalais responded by saying that she did not know all of the details of Bob

Howarth's paper but that Bob Howarth and his colleagues do not consider sewage an anthropogenic input to the system. She concluded by saying the budget presented was for annual inputs for the whole watershed.

Paul LaViolette *(Gulf Weather Corporation—Stennis Space Center, MS)* asked if other effects of modifying the flow of the river through the Atchafalya had been studied.

Nancy Rabalais replied that it was one of the management scenarios for coastal Louisiana.

Responses of Benthonic and Nektonic Organisms, and Communities, to Severe Hypoxia on the Inner Continental Shelf of Louisiana and Texas

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Abstract

We have, over the course of 16 years, accumulated considerable information on the responses of benthonic and demersal organisms to hypoxia (≤ 2 mg/l dissolved oxygen) via direct diver observations, remotely operated vehicle (ROV) video systems, and by sample collection using benthic cores and grabs. As might be expected, the responses of the fauna vary, depending on extent of oxygen depression. In a progressive decrease from 2.0 to about 0.2 mg/l, we have observed progressive disappearance of motile organisms (fish, cephalopods, and crustaceans), to pronounced stress behavior of benthonic organisms incapable of escape, to emergence of deep burrowing benthonic organisms from their burrows, to death of these organisms. At near 0.2 mg/l, the sediment becomes black and sulfur-oxidizing bacteria form "cottony" mats on the sediment surface. At 0.0 mg/l there is no sign of aerobic life, only black sediments.

Episodic hypoxic/anoxic stress may result in temporary destabilization of the benthic assemblage. Evidence suggests that the community recovers to its former diversity and abundance. Repeatedly stressed communities, however, have low diversity, no species with direct development, a few highly tolerant species, low biomass and limited recovery following abatement of hypoxia.

Introduction

Hypoxia (≤ 2.0 mg/l of dissolved oxygen [D.O.]) and anoxia (0.0 mg/l D.O.) occur in many localities (see Tyson and Pearson 1991 and Diaz and Rosenberg 1995, for reviews). In most cases the data generated by studies of hypoxia have reported reduced abundances of benthic fauna and/or the absence of nektonic fauna. There are, however, relatively few studies documenting the effects on these organisms as the oxygen concentration decreases from normoxic to below 2.0 mg/l and continues to decrease toward anoxia. Jorgensen (1980) and Stachowitsch (1991), using scuba, documented behaviors of benthonic organisms during the onset of anoxia, including stress behavior of actiniarians (anemones), ophiuroids (brittlestars), gastropods and bivalves.

In the northwestern Gulf of Mexico (defined here as the Louisiana coast west of the Mississippi Delta and the Texas coast north of Matagorda Bay), prior to 1979, there were a few published reports of dead organisms being collected by trawl or seen by divers (Harper et al. 1981, 1991), and there were anecdotal reports of shrimp fishermen avoiding large areas because nothing was being caught, but no systematic studies had been conducted.

Methods

The behaviors of benthic infauna and epifauna, and demersal nektonic organisms, were observed directly by scuba divers, and by "flying" ROV's. The responses of benthic communities to hypoxia and anoxia were determined by collecting benthic samples using diver-operated, or remotely operated, grab samplers and cores. In addition to direct observation, divers used Nikonos cameras to obtain wide angle photographs and macro-photographs, and the ROV excursions were documented on videotape via electronic signals received from the on-board cameras. These observations and photographic records were made principally during two long-term studies. The first occurred off Freeport, Texas, during a 7-year (1977–1984) study of the macrobenthos, and the second occurred off Cocodrie, Louisiana, during a 5-year (1989–1993) period in which 1-week cruises were made each summer on the Louisiana continental shelf.

Results

In June 1979, during a study of the macrobenthos off Freeport, Texas, divers reported seeing apparently dead infaunal organisms lying on the bottom amidst various sized patches of "cottony" material (probably the sulfur-oxidizing bacterium Beggiatoa); the divers also reported smelling hydrogen sulfide in the bottom water (Harper et al. 1981, 1991). Pavella et al. (1983) simultaneously collected virtually no nekton in the area. Data collected along cross shelf transects indicated the "dead" water extended from about 6-m depth out to about 30-m depth, a cross-shelf distance of 50 km (Harper et al. 1981; Pavella et al. 1983). During, and immediately following, the event, infaunal abundances decreased to the lowest levels reported during the 7-year (1977–1984) study. The deeper study site (21-m depth) recovered quickly to pre-hypoxia conditions (Harper et al. 1991) At the shallower site (15-m depth), however, the benthic community was apparently destabilized, because a succession of dominance occurred in which one species became numerically dominant for 1 to 3 months, then was replaced by another dominant. This process continued for almost 2 years until the spionid polychaete Paraprionospio pinnata regained its pre-hypoxia dominance (Harper et al. 1991).

Detailed studies of hypoxia began off Louisiana in 1985 and continue to the present (Rabalais and Harper, 1991, 1992; Rabalais et al. 1991, 1992, 1994a, b; 1996, in press). These studies have documented that up to 18,000 km2 of the Louisiana continental shelf may be impacted by hypoxic/anoxic bottom water. Week-long late summer cruises off Louisiana from 1989 through 1995 have documented several stages of hypoxia/ anoxia, ranging from hypoxia onset to virtual absence of oxygen and the presence of hydrogen sulfide in the water column. These observations have led to the creation of a step-wise effects diagram (Figure 11). Above 2.0 mg/l (normoxia) divers occasionally observe fish, but fish, squid, and large mobile bottom-dwelling organisms are routinely seen during ROV tows (Figure 12). Another characteristic of normoxic water is that it is generally turbid and visibility is limited. As the oxygen level decreases from 2.0 to around 1.5 mg/l the mobile organisms usually disappear. Very often the turbidity in the water decreases. Further reduction from 1.5 to 1.0 mg/l causes stress behavior in smaller bottom-dwelling organisms; crabs and sea stars climb on top of high points, brittlestars emerge from the sediment and use their arms to raise their disks off the substrate, burrowing shrimp emerge from the bottom, snails move about the bottom with their siphons directed upward, large burrowing worms emerge from the substrate (Figure 13). All these actions are taken to position the organisms' ventilation mechanisms (gills, siphons, etc) above the microenvironment at the sediment-water interface where the hydrogen sulfide concentration may be increasing. At oxygen levels of 1.0 to 0.5 mg/l the sediment surface develops "fairy rings" of thin strands of bacterial filaments that appear to expand outward leaving black sediment in the center of the ring (Figure 14). At this stage, even the most tolerant burrowing organisms, principally various types of worms, emerge partially or completely from their burrows and lie motionless on the bottom (Figure 15). Often these organisms can be revived if placed in oxygenated water; several different motionless, and apparently dead, species have been collected in jars on the bottom, returned to the surface and placed in aerated water, and have revived within a half hour. As the oxygen concentration decreases from 0.5 toward zero, bottom organisms die. They do not, apparently decompose rapidly, because their bodies continue to litter the bottom (Figure 16). The absence of large scavengers is also evidenced by the fact that the corpses remain on the bottom and are not eaten. At 0.0 mg/l the sediment becomes almost uniformly black and there is no sign of life; even the strands of the sulfur-oxidizing bacterium Beggiatoa are absent.

Discussion

One of the principal problems associated with hypoxia and anoxia in the marine environment is that the effects on the benthonic and nektonic communities usually cannot be observed directly; the effects must be inferred via reductions in trawl catches or reductions in collected bottom-dwelling organisms. Without the visual impact of stressed, dying, or dead organisms littering the bottom, the effects of reduced oxygen do not generate the same level of consternation that would occur if the same type of catastrophe occurred on land. We suggest that if, for two to three months each summer, dead animals were strewn over 18,000 km^2 of land in Missouri or Iowa, people would rightly be upset, and that efforts would be immediately undertaken to correct the situation. Those in agricultural states who depend on soils for their livelihood must realize that worms in the marine environment serve the same function that earthworms do on land; they burrow into the soil, cause mixing, and at the same time allow oxygen to penetrate to deeper levels than would be possible without them. The worms, both terrestrial and marine, contribute greatly to increased overall productivity of their respective habitats.

It is generally accepted that the continental shelf of Louisiana is impacted by hypoxia almost annually, but it had been assumed that occurrences off Texas were infrequent to rare. Studies of the benthos off Freeport, Texas, revealed that hypoxia occurs more frequently off the upper Texas coast than had previously been believed. During the 7-year study off Freeport, Texas, there were two confirmed events of D.O. decreasing below 2 ppm, and three other suspected incidents; if these latter occurred, the events were fairly short-lived and were missed due to the schedule of sampling cruises. Because of the limited area being sampled we do not know the area affected during the catastrophic 1979 event. If, however, as we suspect, the hypoxic water mass was imported from the Louisiana shelf, and extended offshore to at least 28 km, an area of at least 5,400 km^2 was affected along the upper Texas coast. The other event(s) was (were) fairly short-lived and probably had minor effects. The shallower site benthic community was apparently destabilized by the hypoxic event and required about two years to return to pre-event conditions.

The Texas experience is in contrast to the conditions that exist on the Louisiana shelf. The benthos off Louisiana are subjected to hypoxia almost annually, and the hypoxia often extends over 3–4 months. Thus the benthos rarely, if ever, attains a climax community. Rather, the community is grossly reduced, or eliminated, annually and must be reestablished following break-up of the conditions producing hypoxia. This prevents establishment of a climax community.

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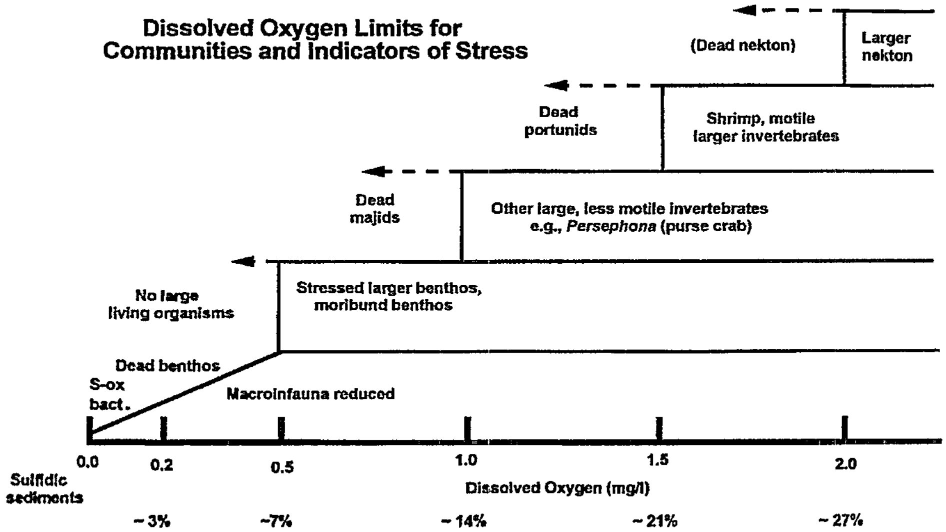

Diagram of components of the demersal and benthic communities and responses to varying levels of dissolved oxygen (mg/l) in the overlying bottom waters. Figure is non-quantitative along the y-axis and represents estimates and ranges along the x-axis. Compiled from benthic studies of N. N. Rabalais and D. E. Harper, Jr.

Figure 11.
Step within decrease in oxygen concentration as observed on the Louisiana continental shelf (from Rabalais and Harper 1992).

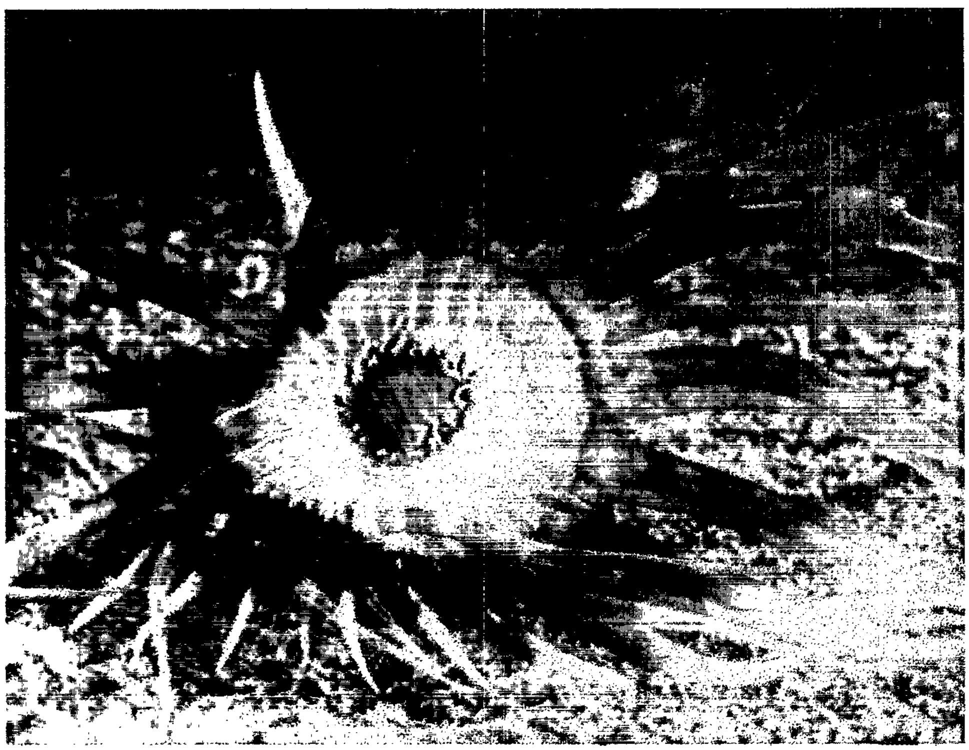

Figure 12. (Photo courtesy of Franklin Viola)
Benthonic organisms photographed in normoxic water.
Cerianthid burrowing anemone

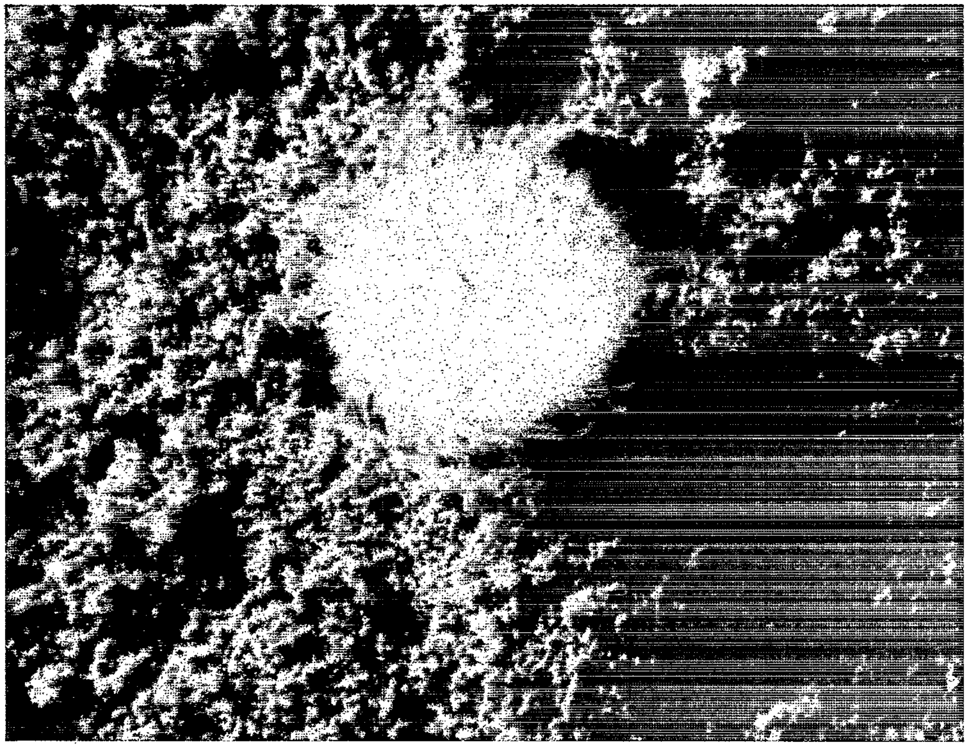

Figure 13.
Small unidentified anemone.

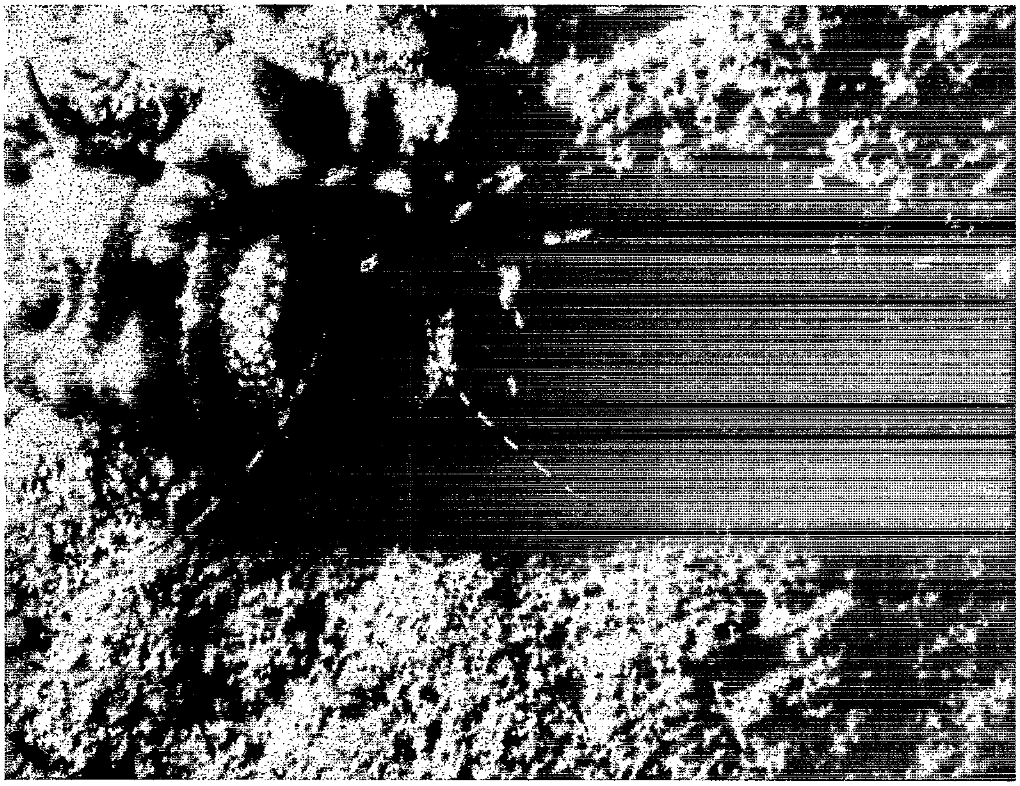

Figure 14.
Hermit crab.

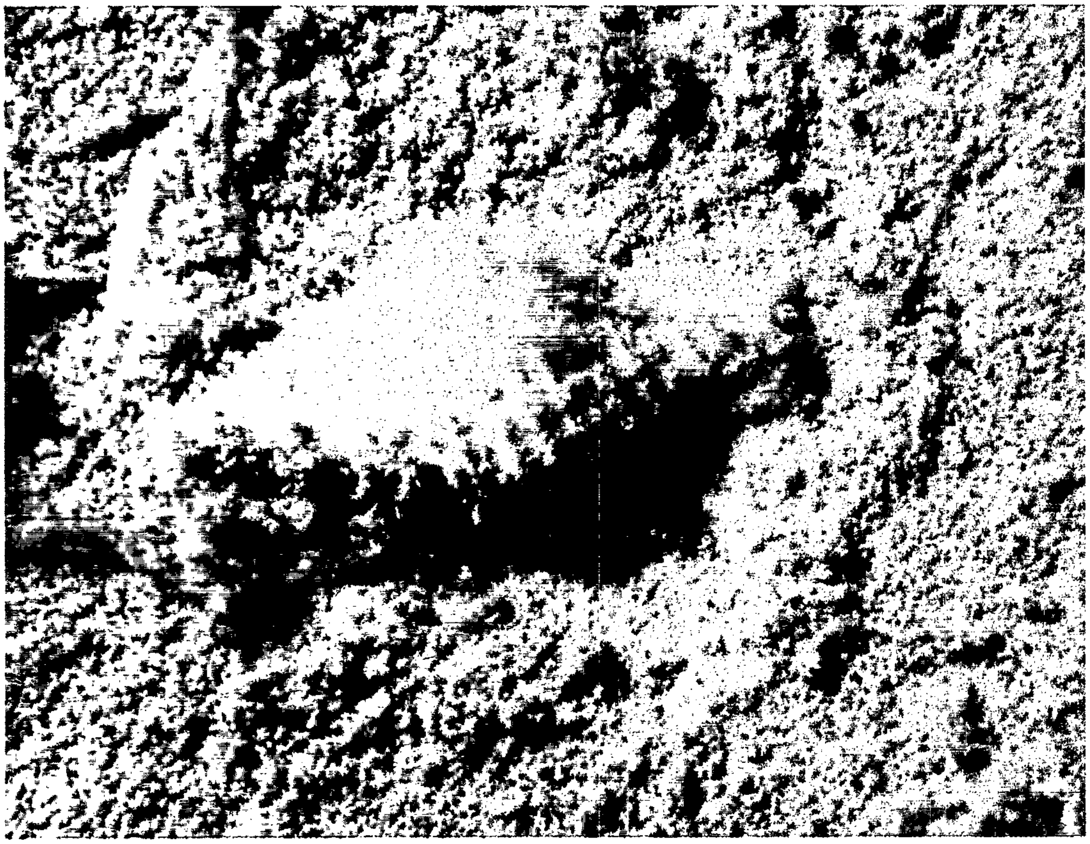

Figure 15.
Cantharus cancellarus snail moving about substrate with siphon directed upward.

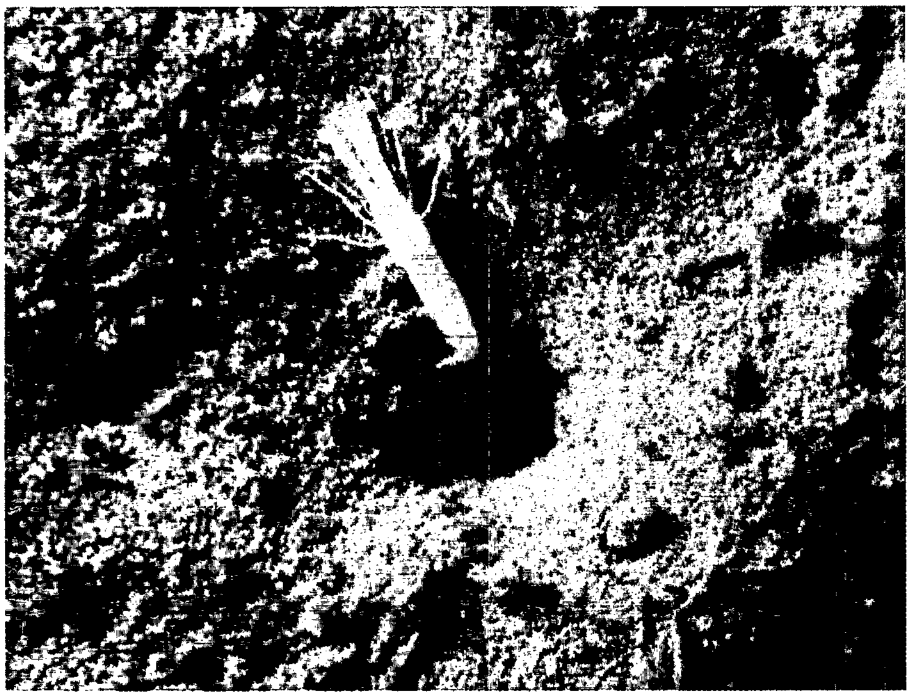

Figure 16.
Unidentified snapping shrimp emerged from burrow.

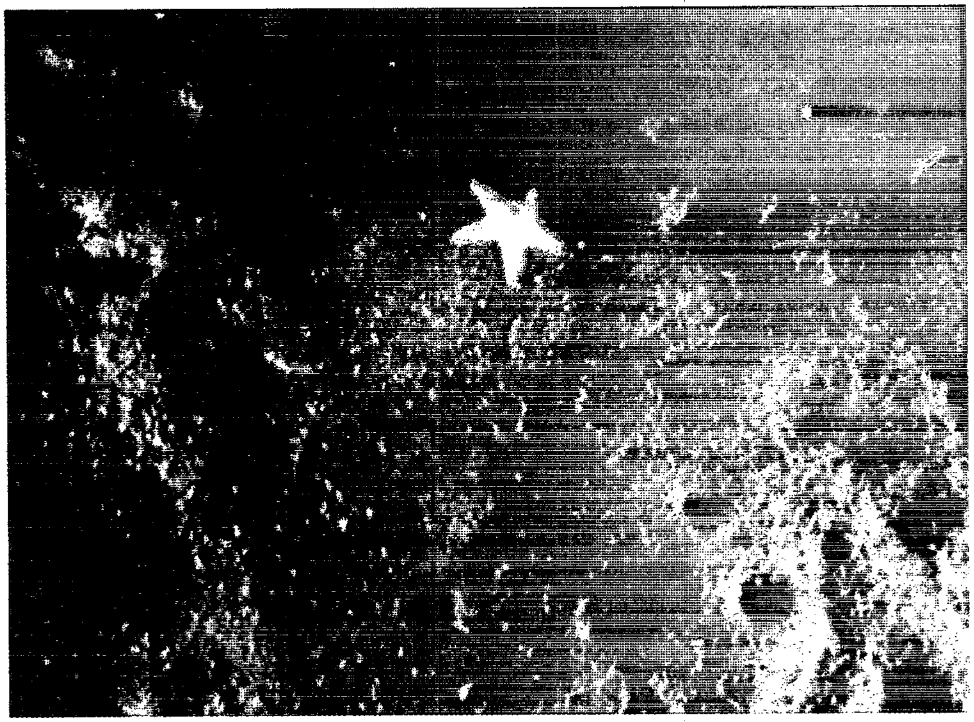

Figure 17.
Astropecten sea star atop a mound.

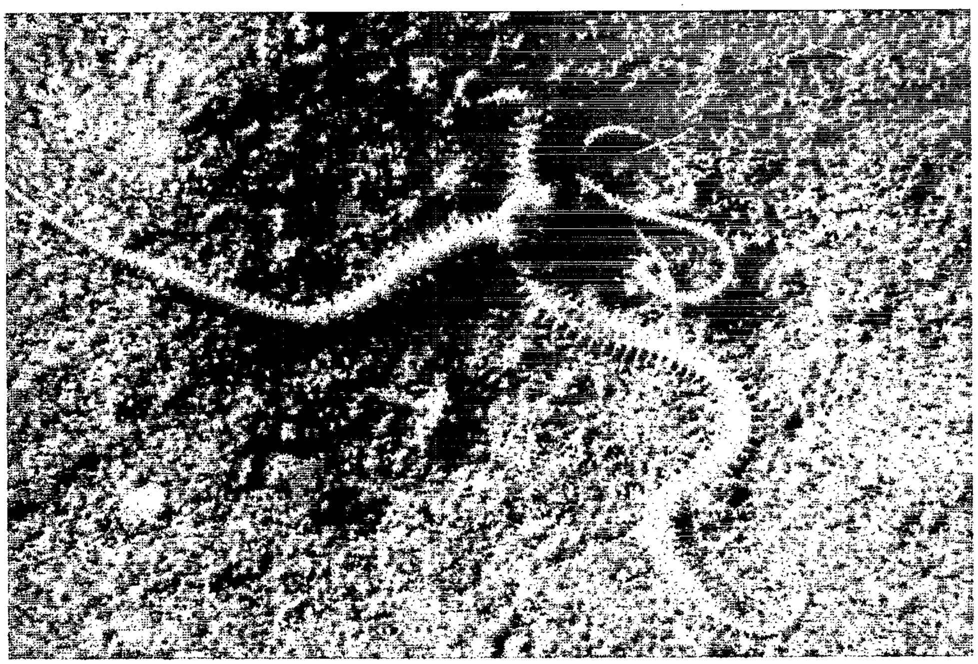

Figure 18.
Unidentified brittlestars on the surface with disks raised above the substrate.

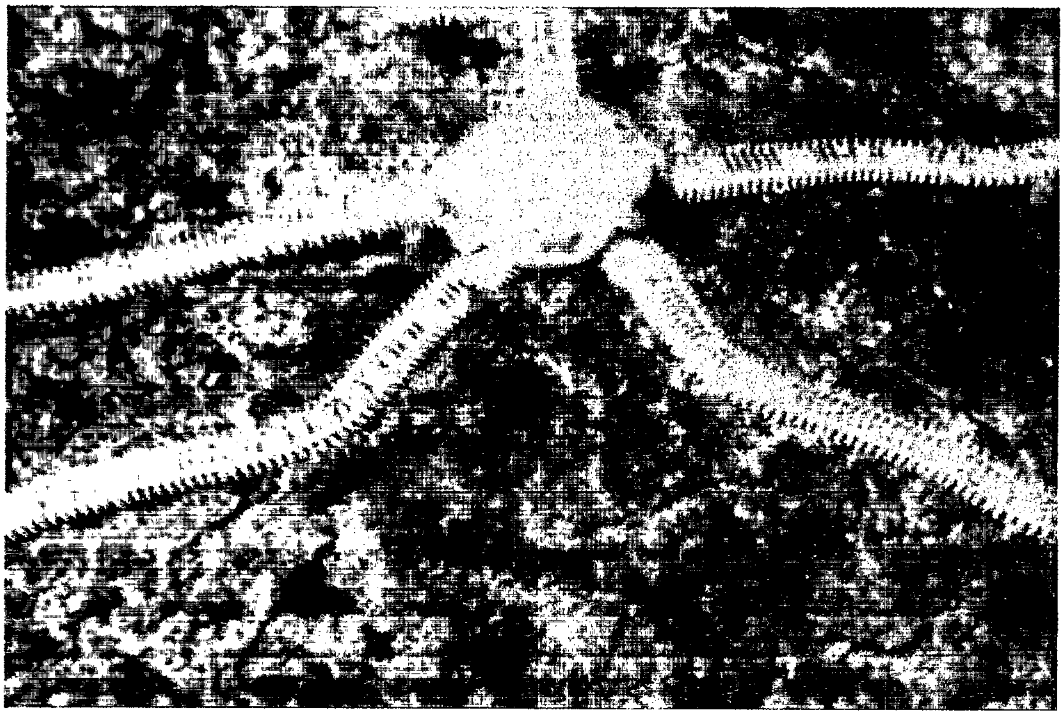

Figure 19.
Unidentified brittlestars on the surface with disks raised above the substrate.

Figure 20.
Choleia viridis polychaete

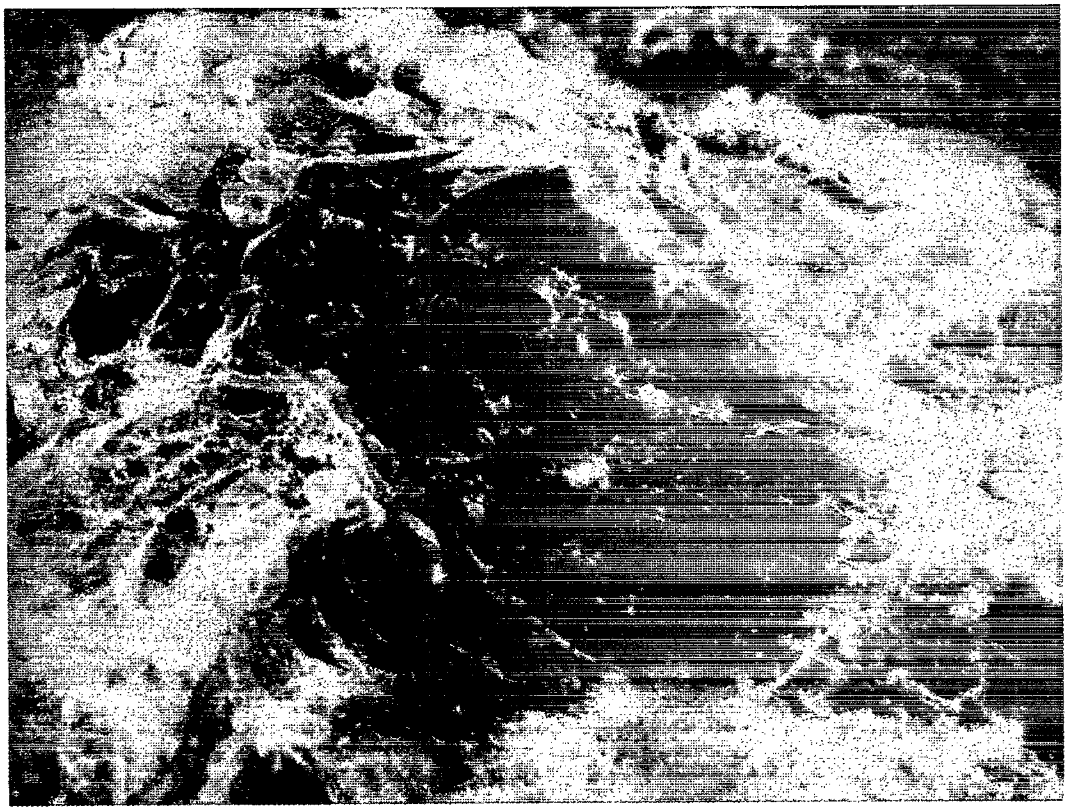

Figure 21. ***(Photo courtesy of Franklin Viola)***
Beggiatoa filaments on the surface of the bottom. Moribund organisms lying motionless on the bottom in oxygen concentrations of 1.0 to 0.5 mg/l.

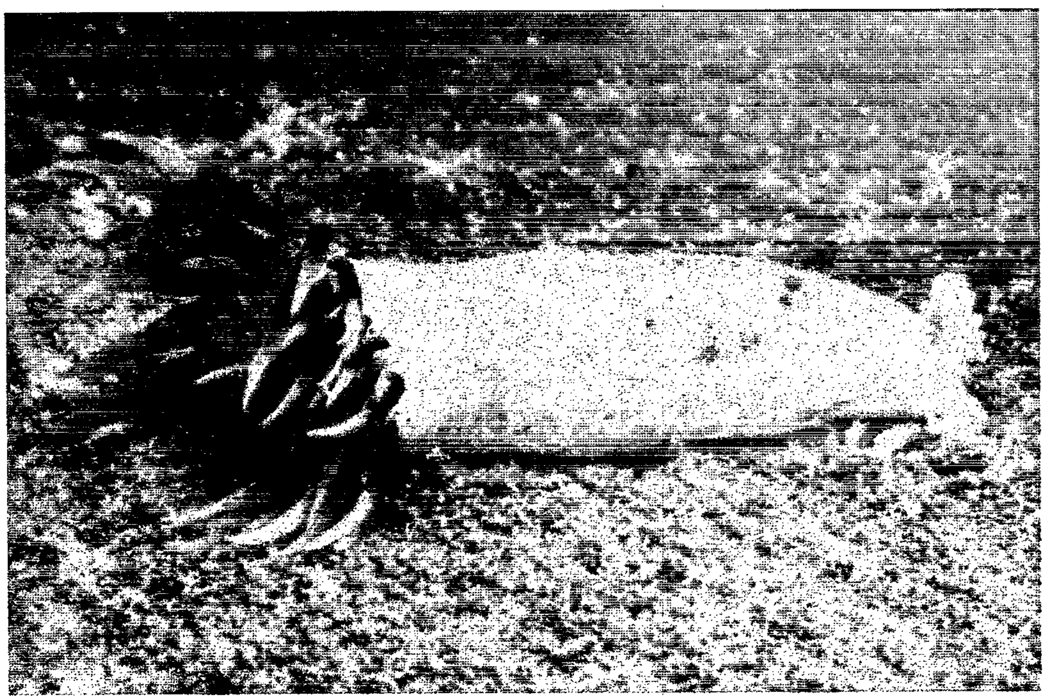

Figure 22. ***(Photo courtesy of Franklin Viola)***
Cerianthid anenome.

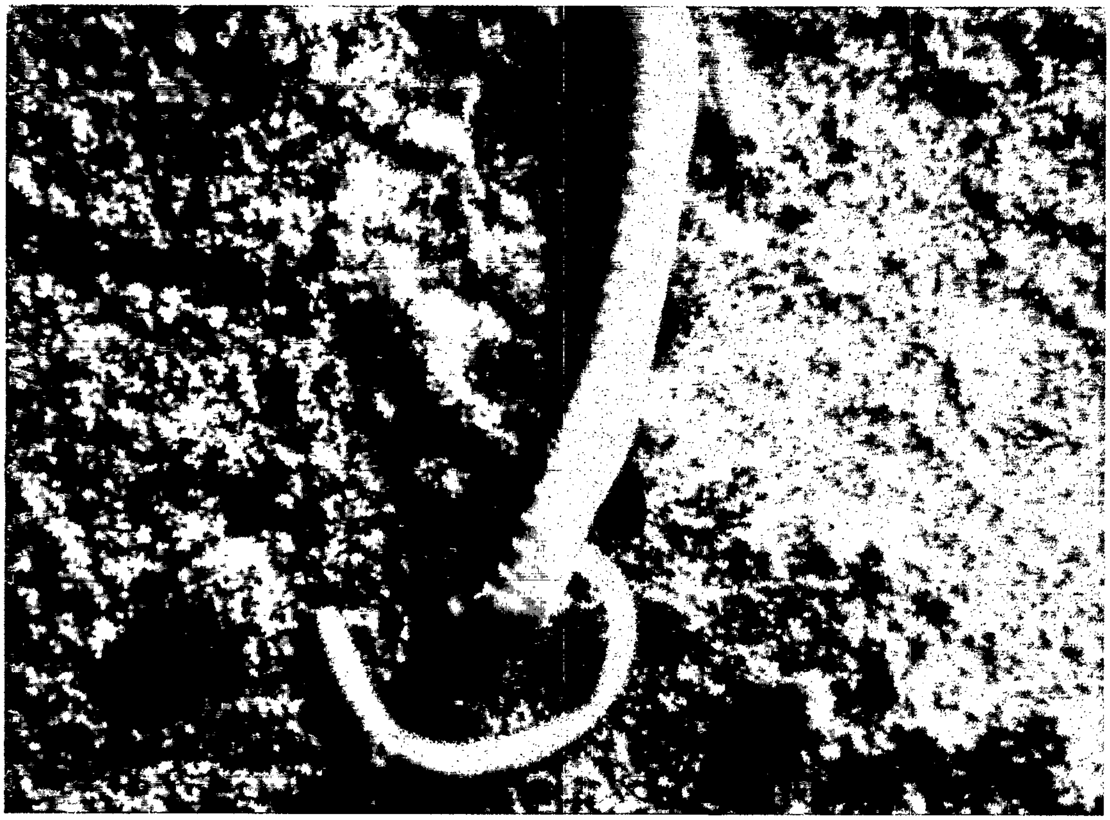

Figure 23.
Unidentified polychaetes.

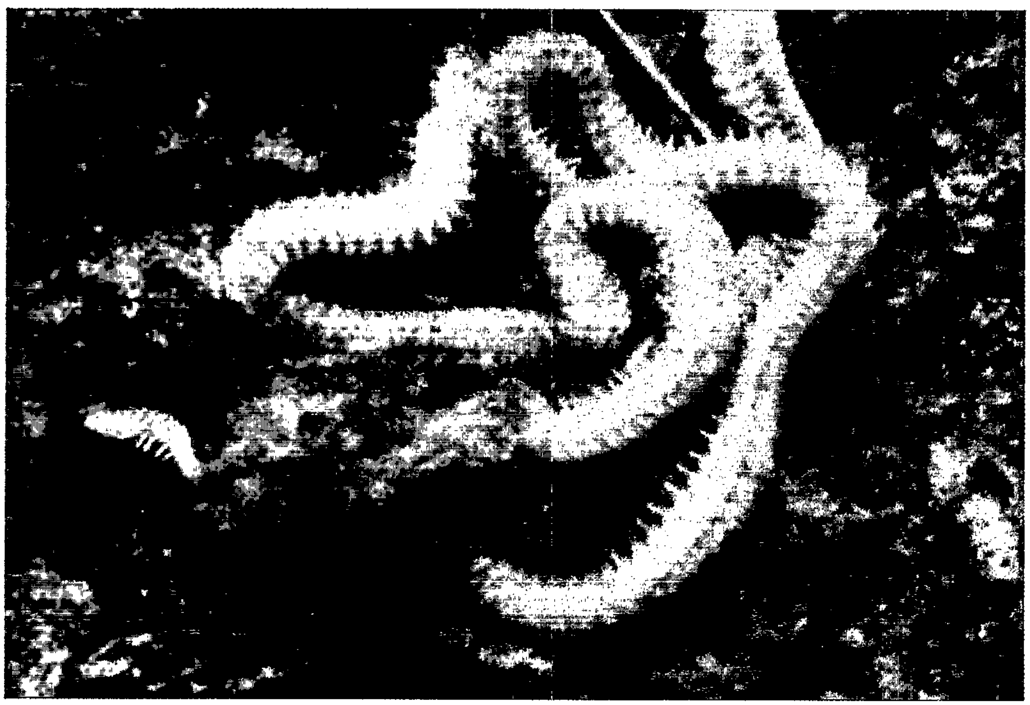

Figure 24.
Unidentified polychaetes.

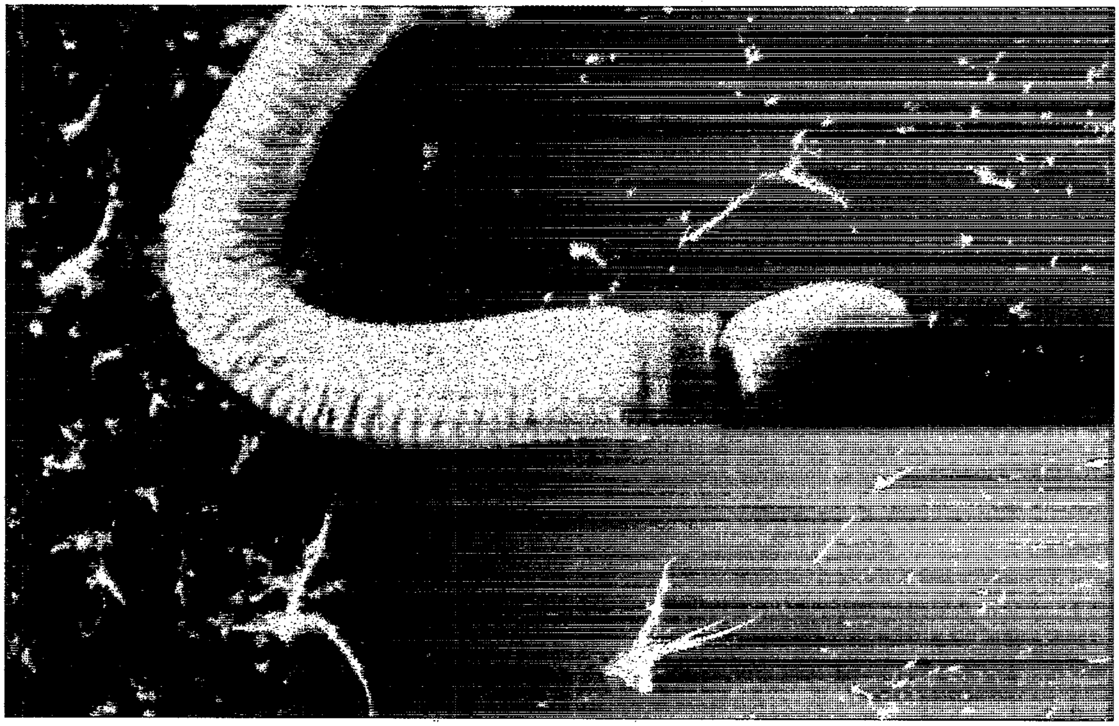

Figure 25.
Hemichordate.

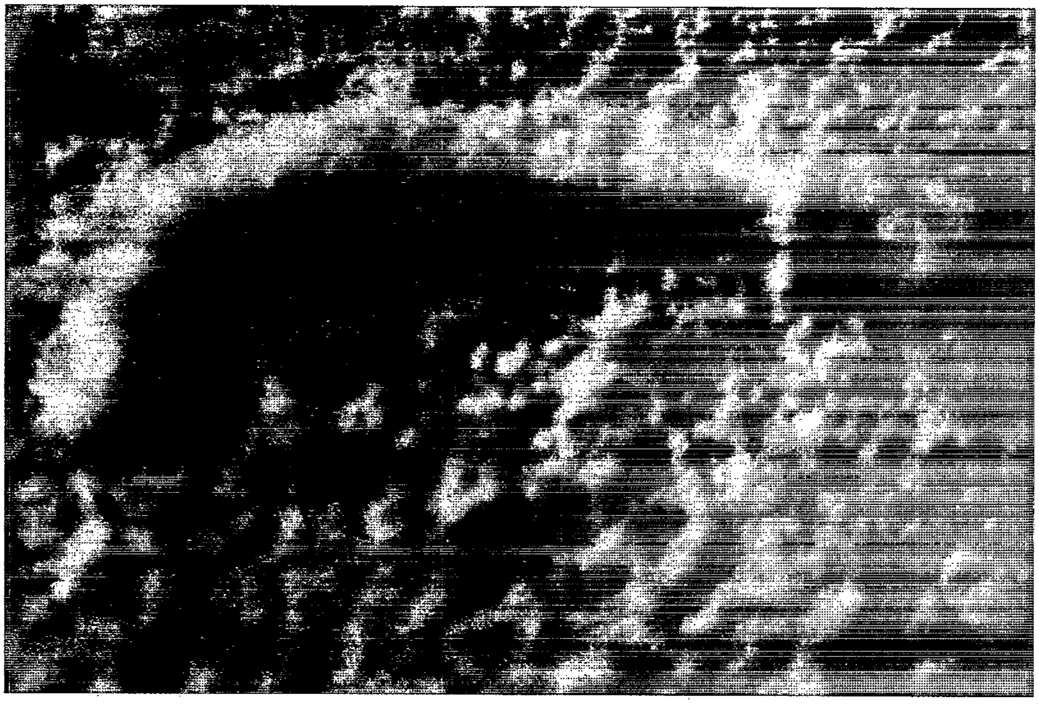

Figure 26.
Dead organisms on the bottom in oxygen concentrations of < 0.5 mg/l.
Unidentified polychaete.

Figure 27.
Unidentified crab.

Figure 28.
Unidentified burrowing shrimp.

Presentation Discussion

Don Harper (Texas A&M University—Galveston, TX)

An unidentified woman from Texas stated that there was some evidence that the episodic quality of hypoxic waters in response to hurricanes passing to the east of the hypoxic area may cause deterioration of benthic organisms on the eastern coast of Texas. She asked Don Harper if he had found any further evidence of this effect, and referred to a quote he made in the *Houston Chronicle* as saying perhaps one of the fish kills in east Texas was associated with the 1983 phenomenon.

Don Harper said he had no evidence which supported that observation and felt that she had misinterpreted his statement. He clarified the *Houston Chronicle* quote by saying he was discussing a fairly localized dinoflagellate bloom and he was not aware of the effects it had on bottom waters.

Don Boesch ***(University of Maryland—Cambridge, MD)*** asked Don Harper if he understood the fate of mobile organisms such as shrimp in areas where the oxygen stress is not severe enough to cause complete mortality of benthic organisms.

Don Harper discussed a series of five summer cruises during which he and Nancy Rabalais used an ROV to generate many videos and slides. Because there was a sharp demarcation between the hypoxic and normoxic waters, they expected an abundance of fish and shrimp along the edge of the zone. Instead, the last segment on the video tape showed a bolus of hypoxic water in the middle of the water mass and a huge concentration of fish above the bolus.

He continued by discussing a cruise that he and Eugene Turner completed during which they crossed a boundary between hypoxic and normoxic waters. The water mass was being moved westward by water which was up welling from the deep-water area off the Mississippi Delta. Heading back toward Louisiana, there was a gradual transition from normoxic to hypoxic waters and no evidence of a strong concentration of fish or shrimp. He believed that this was a result of the shrimp traveling further up the water column, making them ideal prey for sight feeding predators.

He justified this theory by explaining that when bottom water begins to turn hypoxic it becomes very clear because the picnocline (boundary) prevents suspended material from breaking through. The suspended material already in the bottom water settles out, causing the water to become very clear. In these conditions, shrimp are easily seen by sight feeding predators.

Eugene Turner ***(Louisiana State University—Baton Rouge, LA)*** added that he had also witnessed this phenomenon. He has seen squid dive into the hypoxic layer to feed on shrimp.

Don Harper commented that the video tape depicting Nancy Rabalais' "D-transect" showed a concentration of fish in the upper portion and in the lower portion they were absent.

William Herke ***(Citizens for a Clean Environment—Baton Rouge, LA)*** commented that when the water oxygen is normal those types of organisms are found in the bottom of the water column. He asked Don Harper if these organisms were important as a base of the food chain for other commercially important organisms.

Don Harper replied that shrimp spend their time on the bottom when they are feeding and work their appendages into the bottom looking for polychaetes and small crustaceans. Most of the organisms that were viewed in the video were too large to be prey for shrimp. However, benthic communities are extremely important in shrimp production.

Though he has not been able to establish a scientific correlation, the period of time when lowest benthic abundances were found was also the period of greatest shrimp landings in the Galveston region. Therefore, he theorized that the shrimp are feeding on a lot of the benthic organisms during that period. He intends to continue his efforts to demonstrate a correlation between the necessity of the benthic organisms to the overall health of the shrimp community.

Physical Variability in the Louisiana Inner Shelf Hypoxia Region

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Abstract

The inner shelf of the northern Gulf of Mexico from the Mississippi River Delta westward to the Texas-Louisiana border is the site of the highly stratified Louisiana Coastal Current fed by the Mississippi River system. The initial efflux of water from the mouths of the Mississippi River occurs as highly stratified plumes. Lagrangian measurements within the plume of Southwest Pass are consistent with concurrent satellite imagery. Nutrient distribution patterns are similar to those of physical parameters and suggest conservative dilution during the first day following nutrient release from the river mouth. After the waters attach to the coast to form the Louisiana Coastal Current, they tend to flow westward, although they do respond to wind shifts on periods of a few days or longer. The physical structure of this region is dominated by the strength and phasing of river discharge and wind forcing. This structure exerts a strong control on the distribution of hypoxia and the processes responsible for its spatial and temporal variability.

Introduction

The Mississippi-Atchafalaya River system constitutes the dominant control on the oceanographic character of the Louisiana inner shelf. This river system drains 43 percent of the contiguous United States and parts of two Canadian provinces. It delivers, on average, approximately 635 km^3 of fresh water to the shelf each year, as well as massive amounts of suspended sediment and dissolved nutrients. Peak discharge occurs in the spring. Thirty percent of this water enters the Gulf through the Atchafalaya River and the remainder through the Mississippi River delta. Of this latter volume, the amount flowing onto the west Louisiana shelf is uncertain, but often quoted as being approximately 50 percent. Much of this fresh water entering the west Louisiana shelf hugs the coastline and flows westward as a narrow current, the Louisiana Coastal Current. During most of the year, this current flows westward into Texas and even Mexican waters. During the summer months, though, strong southerly winds along the south Texas coast tend to push water back onto the Louisiana shelf and the current may reverse for a month to six weeks, particularly near the Texas-Louisiana border.

It is commonly accepted that the Mississippi River system discharge is intimately related to the development of summer hypoxia on the Louisiana inner shelf (Rabalais et al., in press). In its most simplistic form, the paradigm for the development of summer hypoxia is that the Mississippi and Atchafalaya Rivers load the coastal waters with massive amounts of new nutrients. Rapid phytoplankton growth results. These phytoplankton cells sink to the bottom and utilize oxygen, either through respiration or as they decay. Reoxygenation of the near-bottom waters is prevented by a strong density interface in the water column which results from light, low salinity water from the river system lying over heavy, saltier shelf waters. In order to understand the dynamics of hypoxia on the shelf, it is necessary to understand the physics of the inner shelf.

The Atchafalaya River empties into Atchafalaya Bay, a broad, shallow estuary, and then onto a broad, shallow region of the shelf. It dissipates energy through bottom friction and entrains ambient fluid through lateral mixing (Wang, 1984). In contrast, plumes from the dominant passes of the Mississippi River delta expand buoyantly and entrain water both from the sides and from below (Wright and Coleman, 1971). Studies of the Mississippi River plumes are maturing (e.g. Hitchcock et al., in review), while those of the Atchafalaya input are in their infancy.

The water mass modifications important to hypoxia should be described in a Lagrangian sense, i.e. following a water particle. We have only begun to address this type of description of processes on the inner shelf. Recent plume studies (Hitchcock et al., in review) have tracked water from the mouth of Southwest Pass for time periods of the order of one day, roughly the time necessary for the plume waters to merge into the Louisiana Coastal Current. Near surface current speeds can be as high as 1 m/s. Vertical entrainment rates at the base of the plume are estimated to range between 0.25 and 1 m/hr. Modification of nutrient concentrations (NO_3, SiO_4) during these early periods after water is released from the mouth of the river is not inconsistent with conservative mixing. The subsequent modification of waters entering the Louisiana Coastal Current have not been studied in a Lagrangian sense. Consequently, further downstream changes in water characteristics must be inferred from Eulerian measurements.

The seasonal changes in runoff to the Louisiana Coastal Current alter the stratification of the waters of the current (Wiseman et al., 1986). Fresh water floats atop salty water. Even during winter, when the river and nearshore waters are colder than the deeper and offshore waters, the freshness of the coastal waters maintains their lower density. The timing of floods and stormy weather is usually such that just as spring runoff is peaking, storminess is diminishing (Dinnel and Wiseman, 1986; DiMego et al., 1976). Thus, mechanical stirring and mixing of the water column by the wind is diminishing and maximum stratification establishes itself.

The distribution of stratification is modulated by other processes besides mixing. Winds cause currents which result in waters flowing towards or away from the coast, as well as parallel to the coast (Crout, 1982, Dagg, 1988). During 1986, a transect of stations was occupied 17 times across the inner shelf offshore of Cocodrie (Figure 29). Well mixed conditions were observed during low-runoff and high wind conditions at the beginning of the year. As the discharge increased and wind stirring diminished, stratification developed. Even under low winds, though, the stratification strength varied significantly due to upwelling and downwelling (Wiseman et al., in review).

During the summer, a secondary density interface developed near the bottom. Some years this second density interface is absent from our data. When it is present, it can be either due to salinity, due to temperature, or due to both. It is weaker than the main density interface, but very important to the distribution of hypoxia.

While water column stratification may be moderately constant for extended periods of time, strong currents may still be flowing through the region. These occur on a variety of time scales. Tides in the Gulf of Mexico are weak and so are the tidal currents (Science Applications International Corporation, 1989). Nevertheless, tidal currents stir the waters and interact frictionally with the bottom (Dinnel, 1988). Other currents also occur on similar time scales: inertial oscillations (Daddio et al., 1976) and currents driven by the sea-breeze system. On much longer scales, of the order of many weeks, the density gradients resulting from the spatial distribution of light, fresh water and heavy, salty water are associated with geostrophic currents. The observed shears due to these low frequency currents are very similar to those expected from theoretical considerations (Wiseman et al., in review). The most important current variability occurs on time scales of a few days to a few weeks (Crout et al., 1984; Chuang and Wiseman, 1983; Science Applications International Corporation, 1989; Wiseman and Kelly, 1994). These fluctuations are driven by wind forcing. They are also the strongest currents generally observed over the inner shelf. Flow reversals may occur in less than a few hours. Thus, cruise data that takes a week to collect may be sampling totally different flow conditions at the beginning and the end of the cruise. This makes data interpretation difficult. If one sees spatial variability, it is not clear whether this is the result of local processes or advection.

Strong, persistent seasonal stratification is a necessary condition for the occurrence of hypoxia (Figure 30); it is not clear that this is a sufficient condition. Furthermore, this strong stratification does not necessarily determine the structure of the hypoxic water mass. The oxygen sinks in the system are concentrated in the near-bottom regions of the water column. Weak near-bottom density interfaces confine the low oxygen waters near the bottom (Figure 31).

In summary, the physical processes active over the Louisiana inner shelf are important to the dynamics of hypoxia in the region. Mixing of river effluent with ambient shelf waters occurs rapidly after discharge. These waters then flow, generally, westward along the Louisiana coast carrying with them dissolved and suspended material from the rivers. The density structure of the waters within this flow are intimately tied to the occurrence, persistence, and structure of hypoxia. While the principal determinant of this density structure is the discharge from the Mississippi-Atchafalaya River system, winds and solar heating also modulate the stratification.

There remain numerous open questions:

- How much of the observed variability is the result of local mixing (and biological processes) as opposed to advection?
- What processes are responsible for cross-frontal exchange in the Louisiana Coastal Current?
- How are the processes associated with and influenced by the Atchafalaya River discharge different from those near the Mississippi Delta discharge?
- What processes control the secondary density structures observed in the waters of the Louisiana Coastal Current?

Acknowledgments

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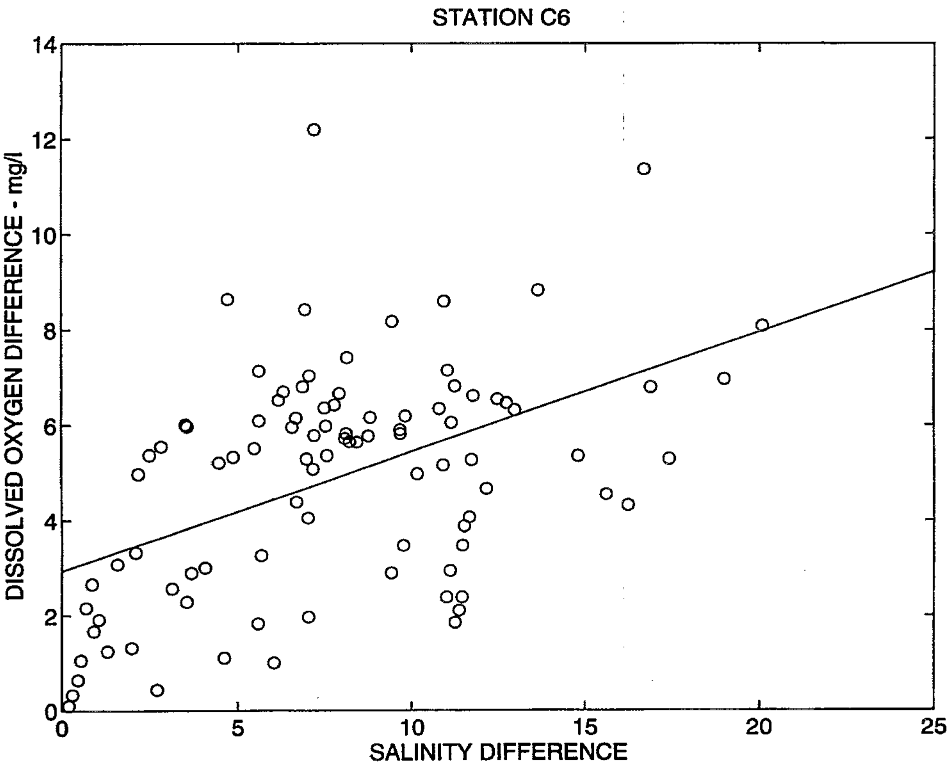

Figure 29.

Time series of salinity along an inner shelf transect offshore of Cocodrie, LA in 1986 (upper), time series of the associated Brunt-Vaisala period (middle), and time series of river discharge for 1986.

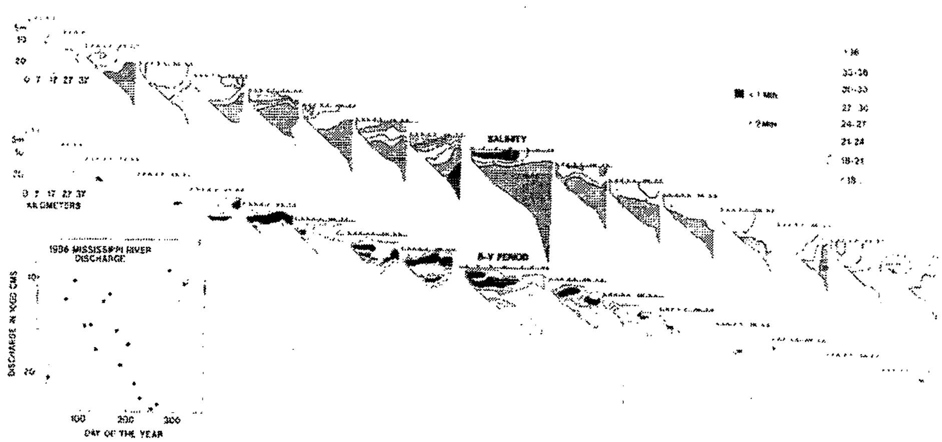

Figure 30.

Scatter plot of surface to bottom oxygen difference versus surface to bottom density difference from multiple occupations of the same station in 20 meters of water offshore of Cocodrie, LA in all seasons of the year. The straight line is a least squares fit to the data.

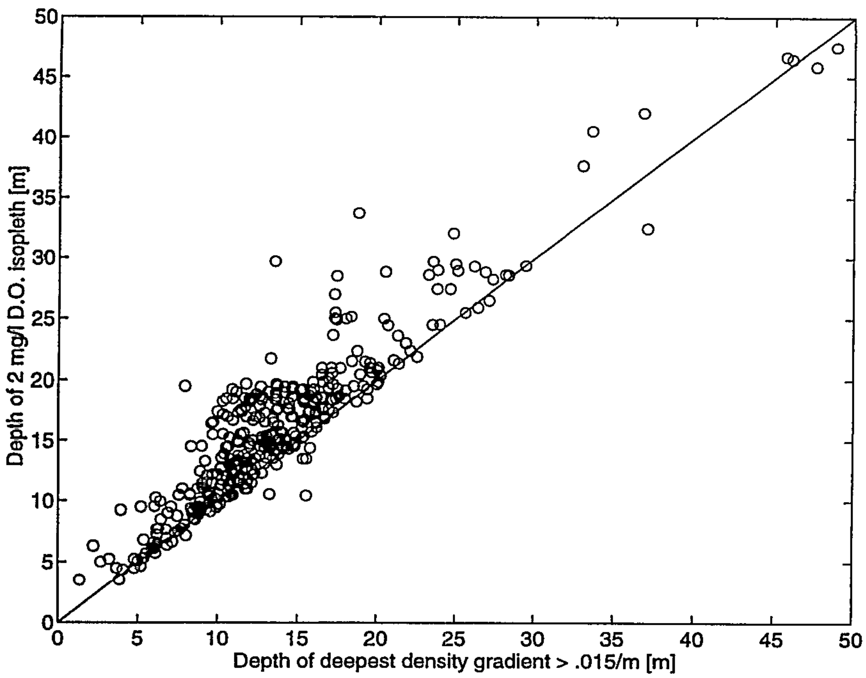

Figure 31.
Scatter plot of the depth of the 2 mg/l dissolved oxygen surface versus the depth of the deepest point where the density gradient exceeds 0.015 /m for 9 years of mid-summer cruise data from the west Louisiana inner shelf. The solid line has a slope of unity.

Presentation Discussion

William J. Wiseman (Louisiana State University—Baton Rouge, LA)

Len Bahr *(Louisiana Governor's Office—Baton Rouge, LA)* asked William Wiseman to discuss the mechanical impacts of significantly shortening the southern-most tributary of the Mississippi river and releasing the nutrient enriched water in an uncontrolled fashion into either the Barataria Basin or the Bertin Sound area, which are much shallower and less susceptible to stratification.

William Wiseman responded by saying that if the resulting stratification were reduced, the flow may short-circuit into deep water fairly quickly; particularly if it flowed through Barataria Bay, where there is a rapid increase in depth close to the shore. If there were a reduction in the salinity deficit of the water flowing onto the shelf, then the stratification of the Louisiana coastal current would be reduced and the bottom waters would be more easily re-oxygenated by weaker winds. If the River were allowed to flow past Morgan City, Louisiana and out through the Atchafalaya, the hypoxia conditions east of the Atchafalaya Delta would certainly be improved, and there would not be a major freshwater cap on top of that water. This process could potentially move the problem downstream into Texas waters.

Paul LaViolette *(Gulf Weather Corporation— Stennis Space Center, MS)* asked how satellite data would be used to help define the area of hypoxia.

William Wiseman did not know how satellite data would be used to define the hypoxia area, though he said it could be used to track plumes, plume dynamics, and occasionally the inner coastal current to analyze dynamics and mixing characteristics. There is a possibility the data could be used to gain an understanding of the distribution of phytoplankton in the surface layers which may indicate where the carbon source will settle.

Trends in Shrimp Catch in the Hypoxic Area of the Northern Gulf of Mexico

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Introduction

An effect of hypoxia on shrimp landings is expected, both through reducing catch in areas of high hypoxia and concentrating catches in adjacent areas. Investigations of seasonal hypoxia in Louisiana offshore reveal that infauna are killed and fish and shrimp are often sparse or absent (Rabalais and Harper, 1991 and 1992; Renaud, 1986). Comparison of hypoxic areas in the New York Bight and the northern Gulf of Mexico indicate similar reductions in abundance of infauna (Boesch and Rabalais, 1991). Although infauna typically recover during months without hypoxia, the community remains in an early successional state because of mortalities during the summer every year (Boesch and Rabalais, 1991). The affected area off of Louisiana is large, covering up to 9500 km^2 (Rabalais et al., 1991), which coincides with historical white shrimp (*Penaeus setiferus*) and brown shrimp (*P. aztecus*) fishing grounds (Lindner and Anderson, 1956; Christmas and Etzold, 1977). These shrimp rely upon benthic infaunal foods as the mainstay of their diets (McTigue and Zimmerman, 1991).

The National Marine Fisheries Service has a database on monthly shrimp landing statistics for the Gulf of Mexico going back to 1960. The database is used to follow shrimp landings trends and estimate shrimp trawling effort for management of penaeid shrimp resources in the federal Exclusive Economic Zone (EEZ). Subareas of reported landings and effort include historical areas of hypoxia and thus may be useful in comparisons of interrelationships. However, it must be recognized that the shrimp statistics database was not designed for detecting effects of hypoxia and reported subareas of landings may be undesirably large for ideal analysis. Notwithstanding this shortcoming, the number of data entries are relatively large and cover many years including the past decade when the area of hypoxia has been measured annually. With retrospective analysis, we may be able to observe trends that suggest relationships between shrimp landings or effort and the annual extent of hypoxia.

Methods

The data on shrimp landings are gathered by 21 port agents in major fishing ports from Key West to Brownsville (Figure 32; Poffenberger, 1991). These port agents canvas 450–500 dealers each month, record landings (a mandatory reporting requirement for the dealers) and assign landings to areas in a statistical grid system designed for the Gulf of Mexico (Figure 33). The statistical subareas are numbered and subdivided into depth zones in 5 fathom increments out to 25 fathoms and landings data is entered for each subarea by depth zone (Figure 34). This census of dealers provides information on the size of catch and the number of trips by area and depth. Some major ports for shrimp landings occur between Freeport, Texas and New Orleans, Louisiana and, not surprisingly, prominent shrimping subareas overlap with areas of seasonal hypoxia in the northwestern Gulf. In particular, statistical sub-areas 13, 14, 15, 16, and 17 incorporate waters offshore of Louisiana and uppermost Texas where hypoxia has been documented.

In order to establish catch-per-unit effort (CPUE), the port agents interview shrimp fishermen, collecting information on trip duration, time fished, and location fished (Figure 35). Since this reporting is not mandatory, the reliability of these data is dependent upon access to cooperative fishermen. A simple equation incorporating interview data and landings data is used to calculate shrimp fishing effort. Landings from the dealers divided by the CPUE from sample interviews is equivalent to effort, which is usually reported in days fished (Figure 36). CPUE is estimated in instances where landings have no associated interviews. At present, about 70% to 80% of the shrimp pounds landed have CPUE interview data and the other 20% to 30% is estimated (Figure 37 and 38).

To evaluate relationships between hypoxia, size-of-catch and CPUE, respective data in each statistical cell off the coast of Louisiana was calculated. A cell corresponds a depth zone with a subarea. For example, the cell closest to shore in subarea 17 is zero to 5 fathoms; the next cell offshore is 5 to 10 fathoms, and so on. Louisiana subareas are demarked longitudinally and depth zones are roughly latitudinal. We entered this information into our geographic information system program (GIS) and color-coded catch to represent average monthly pounds of shrimp landed during July and August each year. The color scale grades from gray, representing very little or no catch, to dark red, representing more than 600,000 pounds of shrimp tails. Intermediate values were represented by shades of orange. The average July and August catch in each statistical cell, months of high hypoxia, was determined for each year between 1985 and 1994 and entered into the GIS. Annual area of hypoxia was plotted from data reported by Rabalais et al. (1991, 1992 and unpublished). The hypoxic area was entered in the GIS, calculated for each statistical cell and superimposed on the image of mean July and August catch for each year. A step-wise regression with catch as the dependent variable and depth, subarea, East/West , years, and percent area of hypoxia in cells as independent variables was performed.

Results and Discussion

Hypoxia and July/August shrimp catch are depicted in Figures 39 through 45, presenting the years 1985, 1986, 1990, 1991, 1992, 1993 and 1994. Offshore hypoxia developed to greater or lesser extent every summer during this ten year period. A number of relationships were evident. Shrimp catch nearshore was always significantly higher than catch offshore regardless of the extent of hypoxia. In addition, a significant relationship in catch between subareas occurred from West to East across years. Catches were significantly higher near the Texas-Louisiana border compared to the Mississippi delta. This corresponds to the generalized distribution of hypoxia which is usually greater in the eastern sector compared to further west. But during years when area of hypoxia was large in the west, shrimp catch was diminished there too. Area and distribution of hypoxia between consecutive years often varied significantly as did overall shrimp catch. The year 1990, with less hypoxia, had higher catch than 1991, with greater hypoxia, including a large hypoxic area which coincided with a reduction in catch in the nearshore 5 fathom zone. During 1993, with hypoxia broadly distributed along the coastline, catch was high nearshore and markedly lower offshore. However, this relationship was not as strong during a similar large hypoxic event during 1994. The magnitude of catch (strength of the year class) was different between 1993 and 1994, but the pattern of catch distribution related to hypoxia remained similar.

Catch plotted against the percent area of hypoxia in each cell reveals a significant negative relationship. Importantly, CPUE plotted against percent area of hypoxia in cells demonstrates that CPUE does not change relative to area of hypoxia (Figure 46). The regression of catch against hypoxia is affected by an interaction of a significant relationship between catch and depth. The highest catches always occur nearshore in cells with a very low percentage of hypoxia area. In cells with a very high percentage of hypoxia, we never observe high catch despite similar CPUEs. This is interpreted as meaning that shrimp fishermen do not trawl in those areas within a cell that have high hypoxia. Converting the data to catch per unit hectare demonstrates the same relationship (Figure 47). However, we also observed low catches in offshore cells with low hypoxia, i.e., the relationship of diminution in catch from nearshore to offshore corresponding to increasing depth.

There was a negative, albeit not always significant, relationship between shrimp catch and area of hypoxia. This may have very important historical implications for the Louisiana shrimp fishery. The traditional inshore and nearshore fishery appears to be promoted and the offshore fishery is discouraged by hypoxia. Catches in offshore waters beyond the hypoxic area are always as low as those in the hypoxic area. High catches nearshore are always in cells with low hypoxia. The interpretation is that the large hypoxic area in intermediate depth zones concentrates shrimp nearshore. This is supported by laboratory evidence that shrimp move away from low oxygen water (Renaud, 1986a) and field evidence of low densities (Renaud, 1986b). Moreover, the phenomena of concentration of nekton avoiding hypoxia in other areas, the so-called jubilees in Mobile Bay, has been known for years (Loesch, 1960). Since shrimp seem to avoid hypoxia, the hypoxic area would effectively block a large part of the population from moving offshore. This blocking phenomena may in part explain persistent low catches in offshore Louisiana beyond the hypoxic zone. Moreover, since CPUE doesn't change relative to percent hypoxia in statistical cells, we take this as evidence that shrimpers do not trawl in unproductive waters, and that waters offshore of the hypoxic zone are indeed unproductive. More simply stated, it is economic reality that as the shrimp move so do the shrimp fishermen and those who do not catch anything in their trawls move on in order to profit. Thus, wherever shrimp fishermen chose to stay and trawl their CPUE is relatively high. The statistical cells with low catch associated with hypoxia and offshore waters beyond mean that shrimpers are actively avoiding these areas. By contrast, higher catches occur in comparable offshore depth contours in Texas where hypoxia does not exist. Indeed, Texas has a very well developed offshore shrimp fishery. An alternative hypothesis is that the shrimp industry in Louisiana developed around white shrimp which is an inshore and nearshore species, and Louisianans did not build vessels big enough to trawl offshore whereas, the Texas shrimp industry developed around brown shrimp which is more an offshore species.

Although the landings data are coarse for the purpose and analyses would benefit from a specifically designed study, evidence of a negative relationship between hypoxia and shrimp catch appears to exist. Overall, offshore areas of extensive hypoxia during the summer months yield lower shrimp catches in July and August than nearshore areas with less hypoxia. Importantly, the shrimp appear to concentrate in shallow waters near shore between the hypoxic zone and the shoreline and the effect of diminished catch extends offshore well beyond the hypoxic zone.

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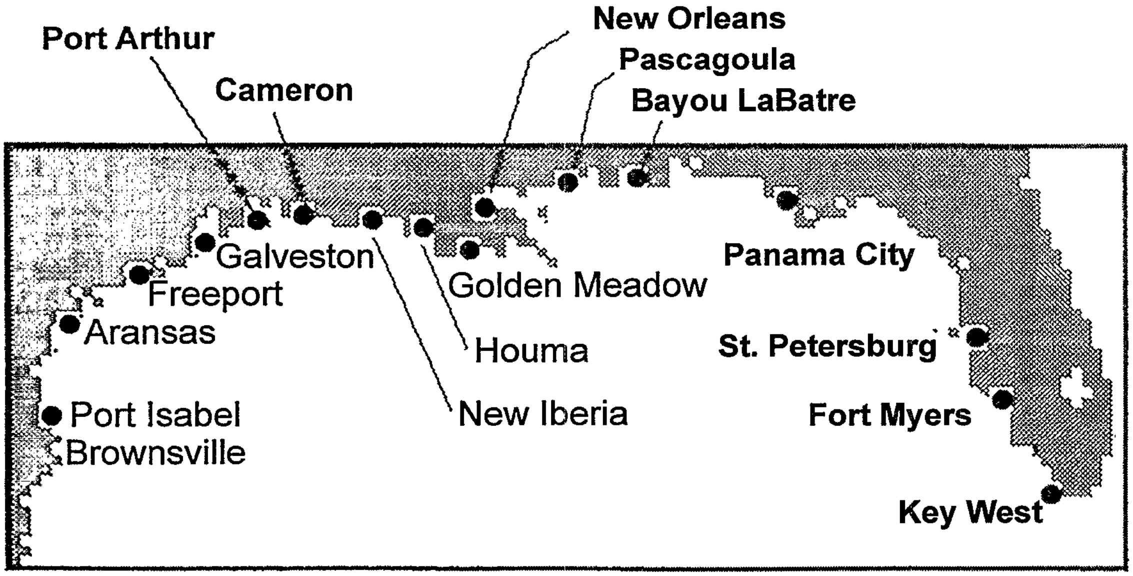

Figure 32.
Port Agents.

Landings Data

- Canvass between 450–500 dealers each month
- Record landings by trip
- Assign grid zones
- A census of catch and trips

Figure 33.

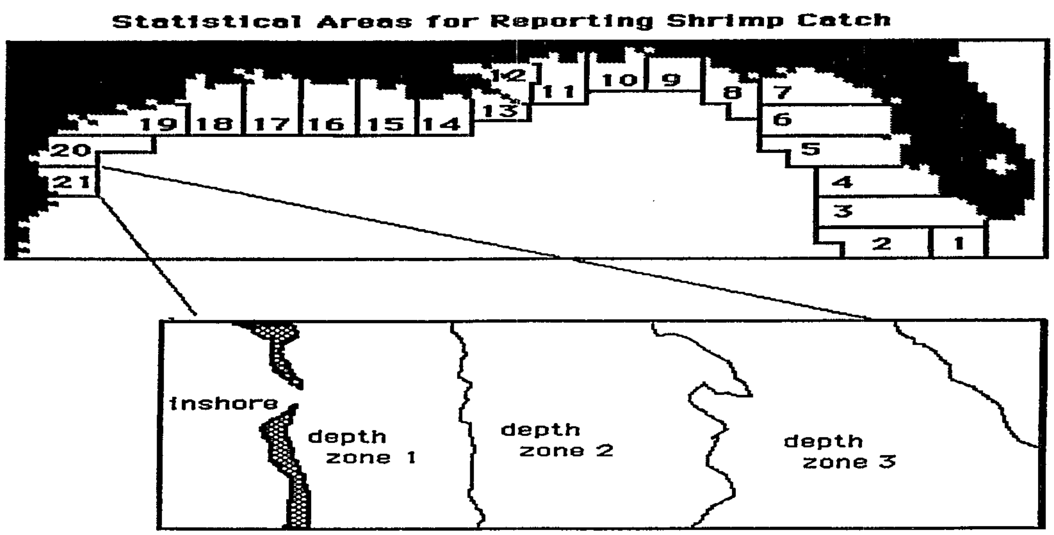

Figure 34.

CPUE Data

- Interview
- Data Items
  - Trip duration
  - Time actually fished
  - Area fished
- A census of catch and trips

Figure 35.

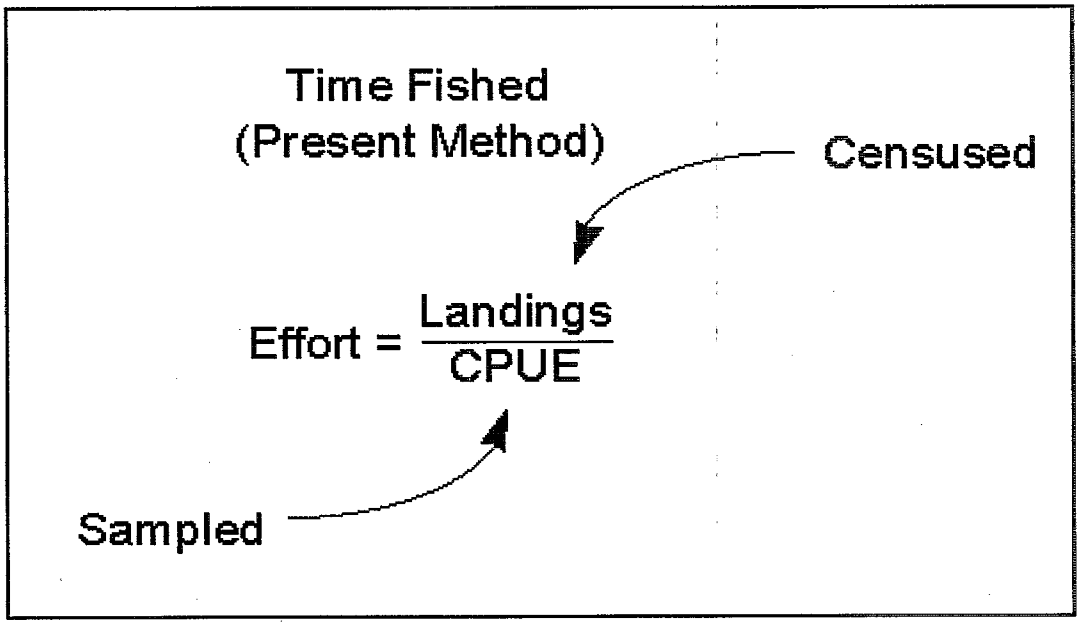

Figure 36.

Cells With Current Interview Data

- 70–80% of the shrimp pounds have an average CPUE associated with them
- What about the other 20–30% of the pounds?

Figure 37.

- Statistical model used to estimate the current CPUE (one model/month)

- $\log CPUE_{(ij)} = \mu_{(ij)} + year_{(i)} + location_{(j)} + \epsilon_{(ij)}$

Figure 38.

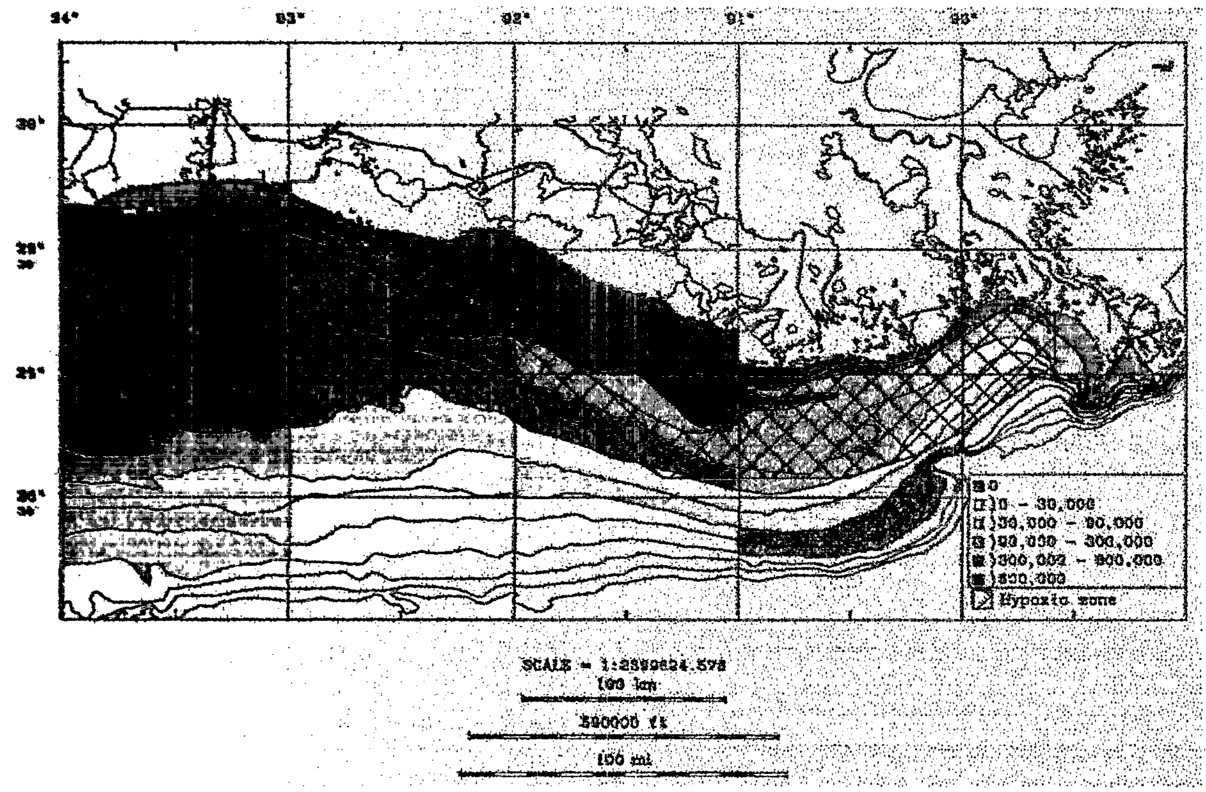

Figure 39.
Total Shrimp Catch (pounds)
July/August 1985

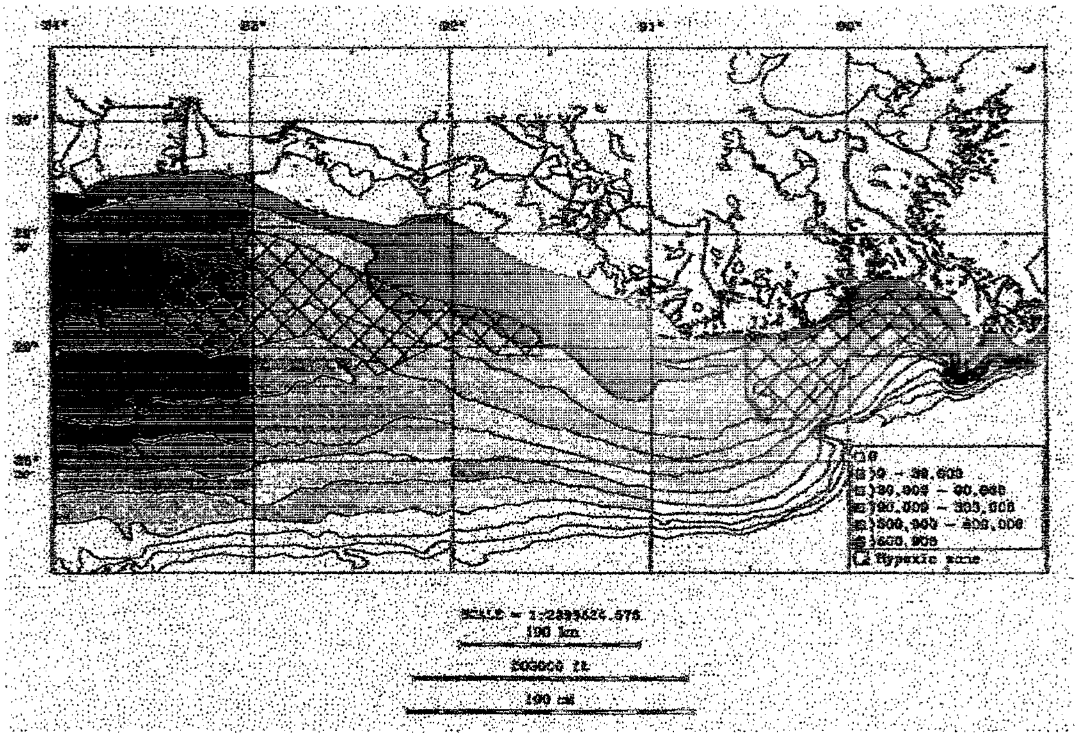

Figure 40.
Total Shrimp Catch (pounds)
July/August 1986

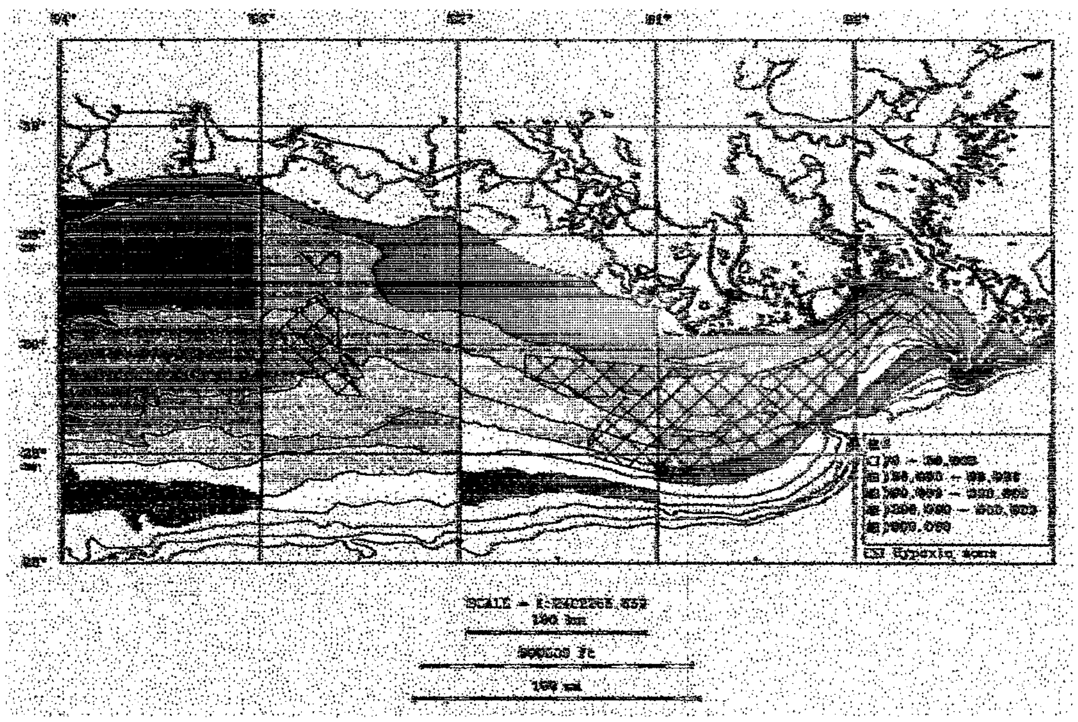

Figure 41.
Total Shrimp Catch (pounds)
July/August 1990

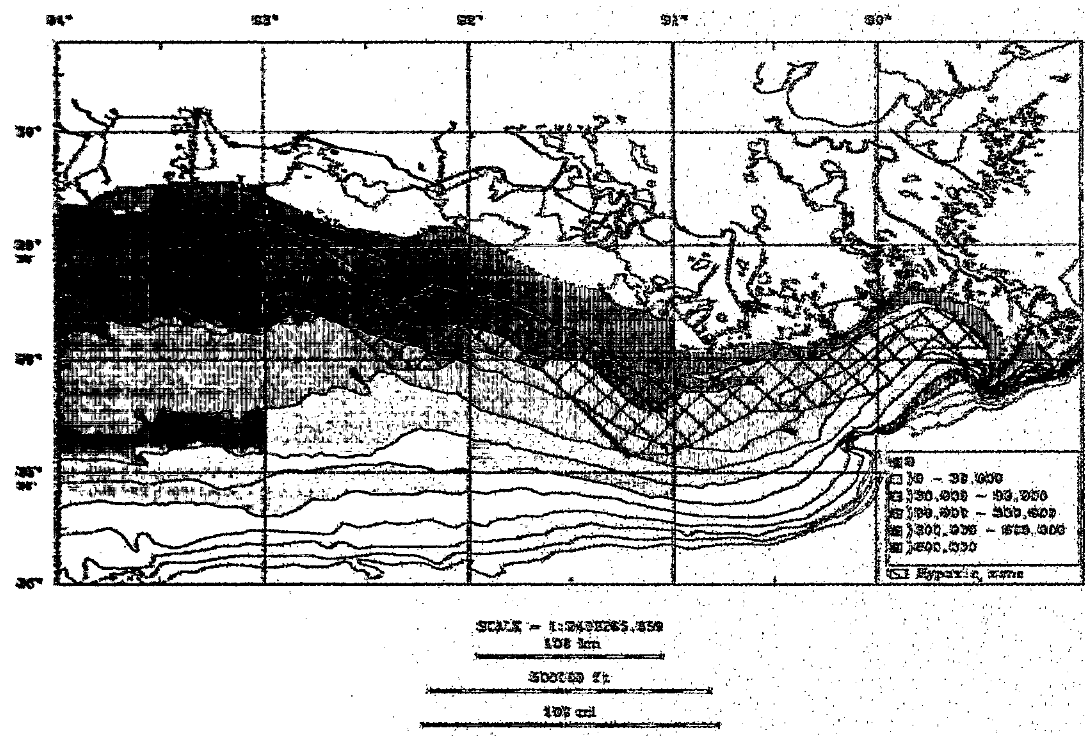

Figure 42.
Total Shrimp Catch (pounds)
July/August 1991

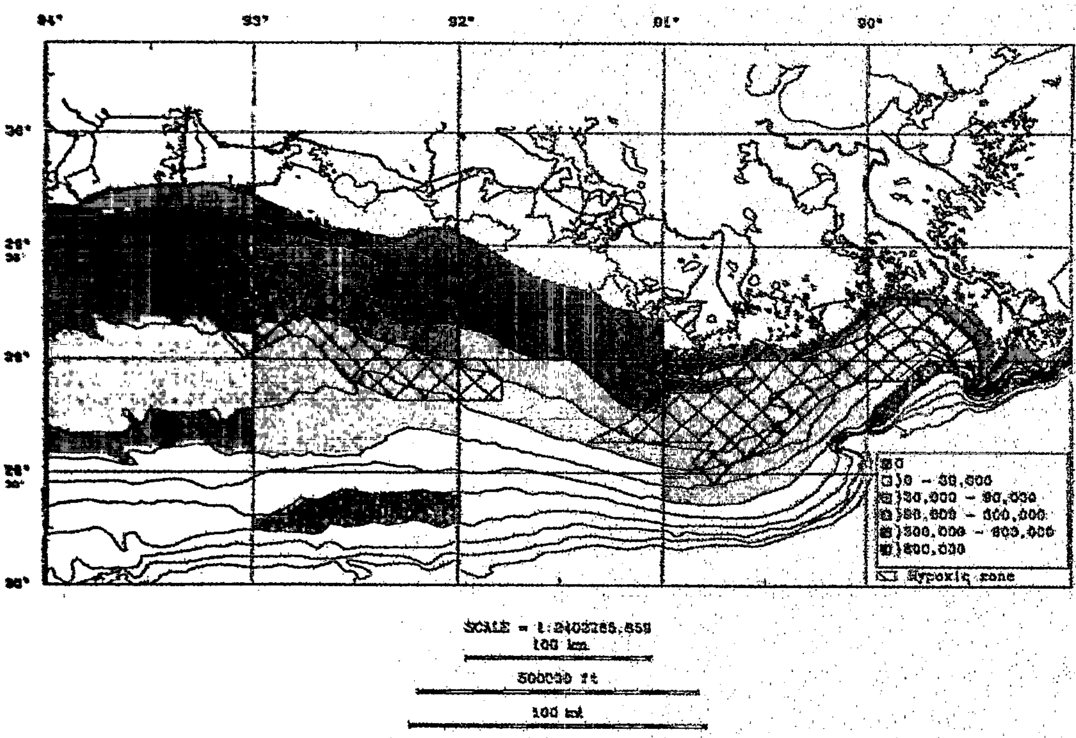

Figure 43.
Total Shrimp Catch (pounds)
July/August 1992

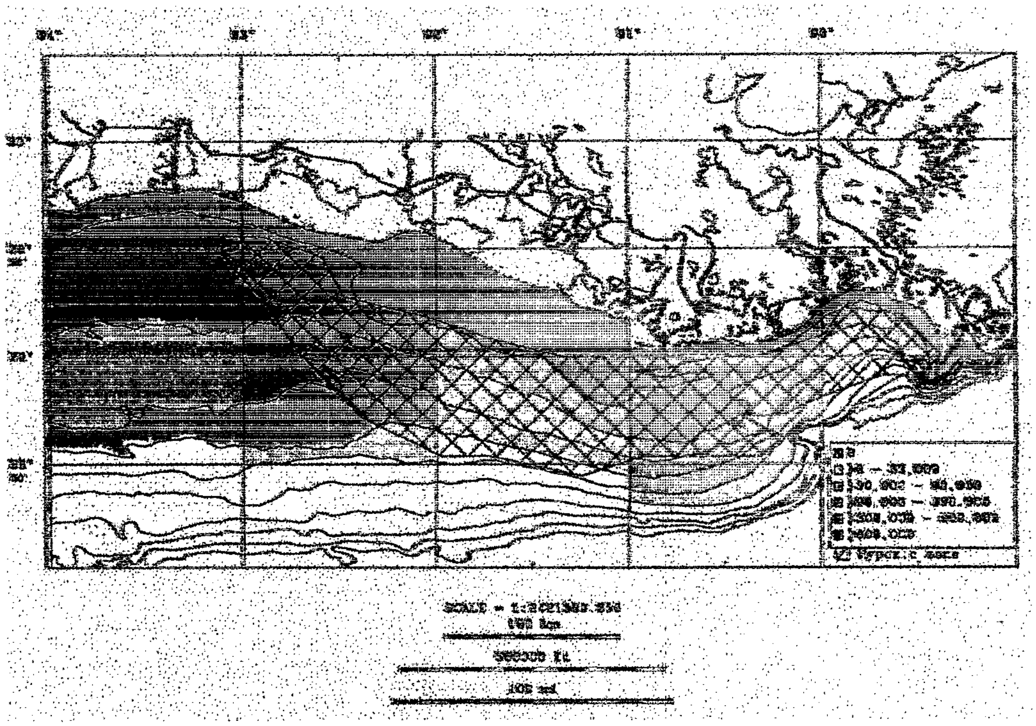

Figure 44.
Total Shrimp Catch (pounds)
July/August 1993

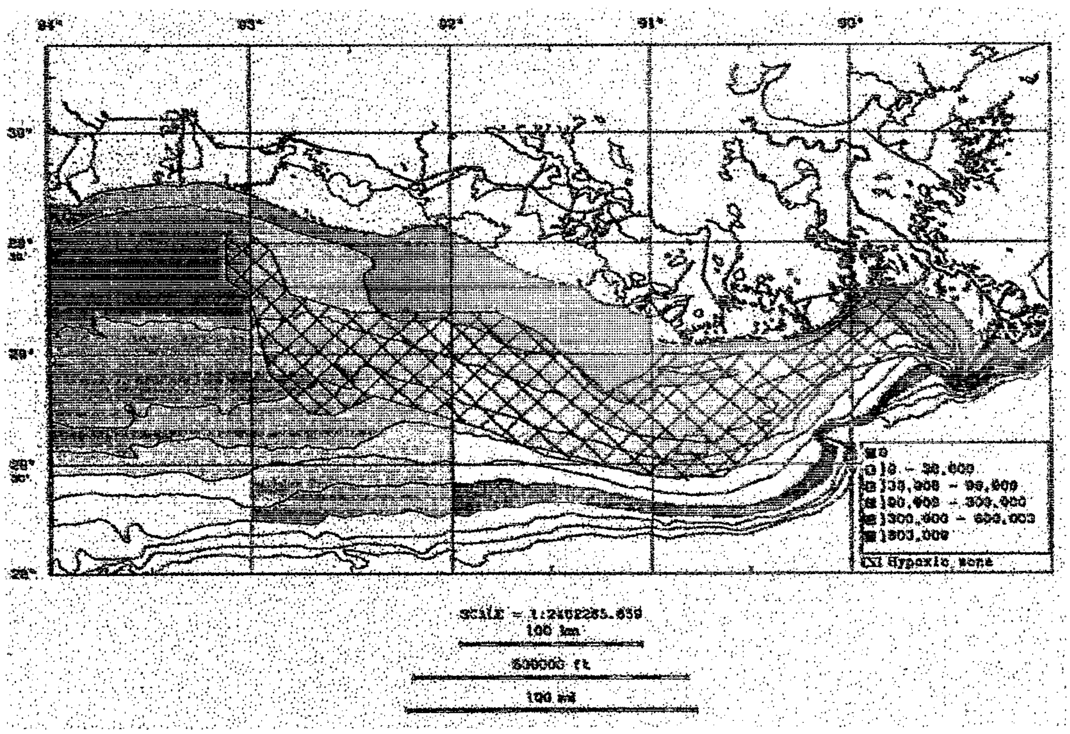

Figure 45.
Total Shrimp Catch (pounds)
July/August 1994

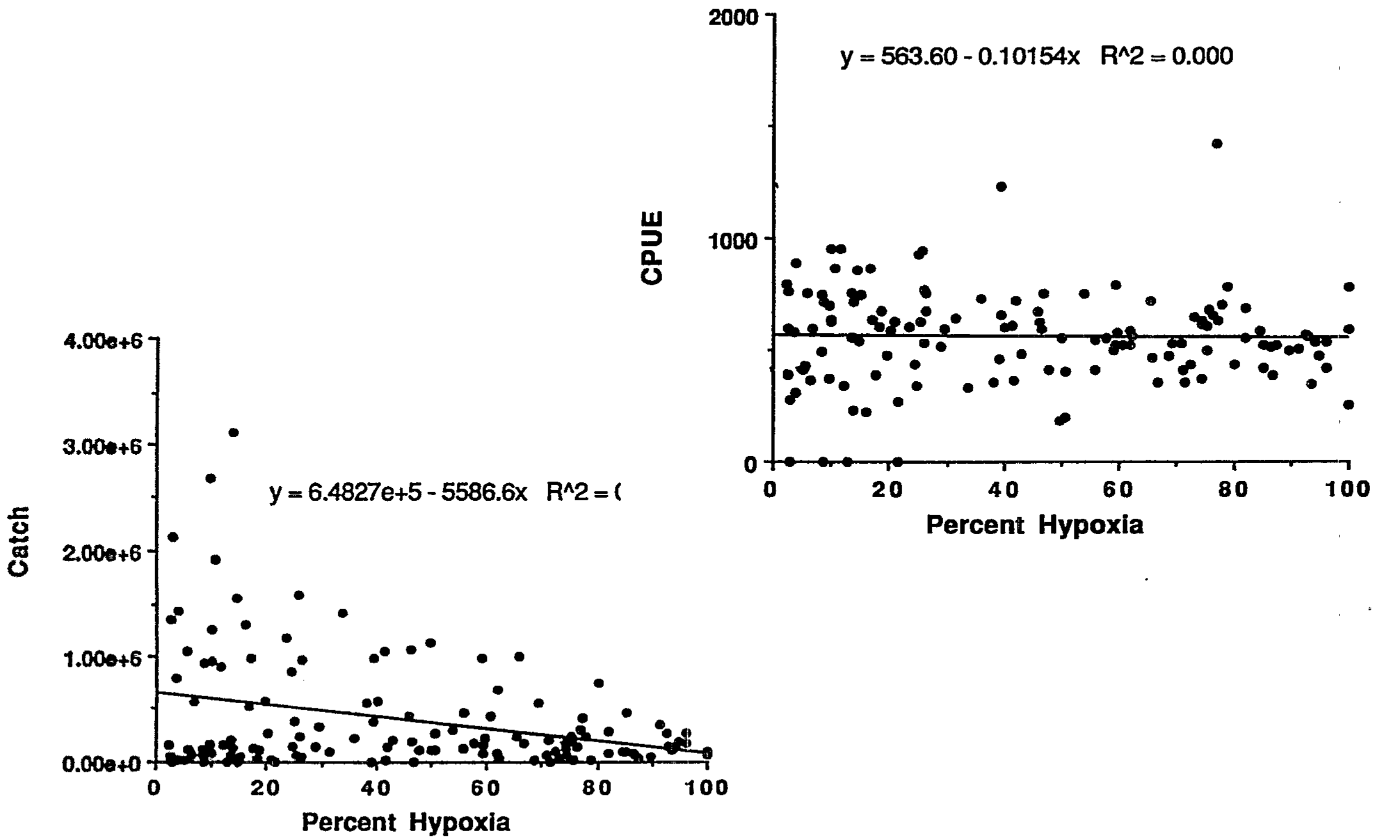

Figure 46.

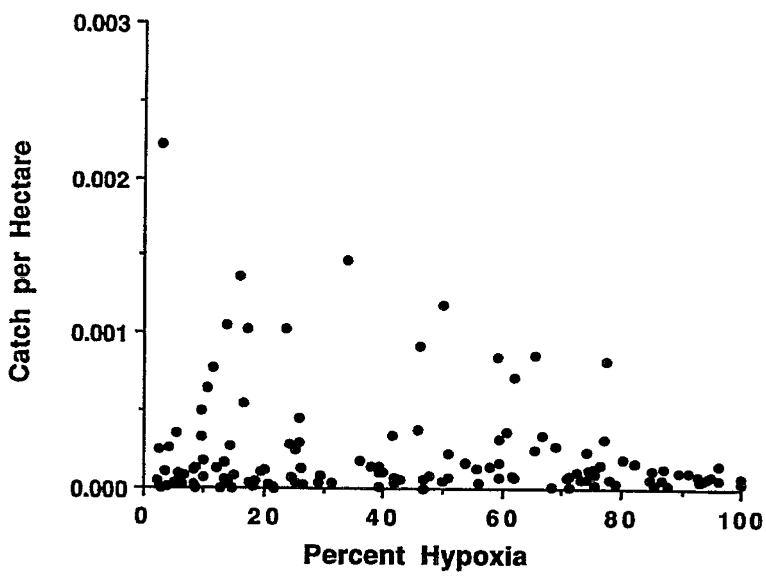

Figure 47.

Pesentation Discussion

Roger Zimmerman (NMFS—Galveston, TX)

Bob Anderson *(The Advocate—Baton Rouge, LA)* asked Roger Zimmerman if anyone had looked at the total shrimp catch per year during the years when there is a large hypoxia zone present.

Roger Zimmerman answered that although there appeared to be a very weak relationship between years, when he performed a step-wise regressional analysis, he could not demonstrate a strong relationship.

Eddie Funderberg *(Louisiana State University Agricultural Center—Baton Rouge, LA)* commented that the shrimp catch in cells of Zimmerman's map with 80 to 100 percent hypoxia appeared to be as good as in cells of zero percent hypoxia. In light of that data, he asked Roger Zimmerman to elaborate on his comment that the catch per unit effort (CPUE) did not vary because fishermen were not fishing in the area of hypoxia.

Roger Zimmerman responded that even in cells of 100 percent hypoxia there may be areas or times that the hypoxia fluctuates. If the hypoxia is absent and shrimp, which are very mobile move in, then it is possible to have a catch in those cells that have been identified as 100 percent hypoxic. Also, some of those cells are only 60 percent hypoxic. The shrimping activity in that cell is averaged over the whole cell. Unfortunately, there is no ability to separate within a cell.

Don Boesch *(University of Maryland— Cambridge, MD)* asked if the inability to catch shrimp in hypoxic waters was a result of a reduction in the shrimp population, or a decreased ability to catch that population. He also asked if Roger Zimmerman had an approach or strategy to study this question with either existing data or new observations.

Roger Zimmerman felt that there were two potential possibilities.

- The first possibility was a correlation between catch data and depth. That relationship could be analyzed by comparing shrimp catches in the 1960's to the nearshore and offshore abundances of shrimp. Hopefully, that would demonstrate that during periods of hypoxia there would be a reduced number of shrimp or a lower percentage of catch relative to near shore.
- The second, and most likely possibility is that the hypoxic zone could be causing the shrimp to migrate up against the shoreline.

William Wiseman *(Louisiana State University—Baton Rouge, LA)* asked if the data presented had been normalized. For example, shrimping activity in Louisiana, is basically localized in the nearshore. It is not considered an offshore fishery. Therefore, comparing the data to shrimping activity in Texas may be inconclusive, because the effort may be distributed differently.

From the research he has conducted on shrimp populations in Louisiana, environmental factors in the spring, (i.e., water temperatures and salinity regimes) have a great deal of influence on what production is going to be and what kind of recruitment we have in late spring and early summer. The fact that hypoxia does not really set up offshore during the spawning and larval migration periods inshore does not seem to be an influence. The ultimate growth and survival of juveniles, which is really dependent upon inshore conditions, does not seem to be affected either.

Roger Zimmerman confirmed that the data have been normalized by effort. He agreed with William Wiseman that the strength of the year class is more dependent upon the conditions in the nursery and inshore than it is in the offshore conditions. He thought they might be just redistributing the year class. It is possible to argue that as the organisms grow and move offshore as sub-adults, and if there is a large hypoxic zone where all the worms are dead, the feeding ground has obviously been impacted. It is similar to lower salinity impacts in the estuaries, which could reduce production in certain parts of the nursery. It is possible that the offshore feeding ground is being eliminated and that could affect growth rates.

Distribution, Abundance, Feeding Growth and Mortality of Fish Larvae Associated with the Mississippi River Discharge Plume, and the Potential Impacts of Hypoxia

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Abstract

From 1986–1992 we made cruises during all seasons to the Mississippi River discharge plume to collect ichthyoplankton using a neuston net (1 x 2 m; .947 mm) and tucker trawl (1 x 1 m; 0.335 mm); CTD casts were made to collect environmental data. Sampling stations were positioned using AVHRR satellite imagery (visible channel) along 15–25 km transects that radiated from the delta outward.

The hydrography in the vicinity of the plume consists of three distinct water masses, a shallow lens of low salinity plume water, high salinity Gulf of Mexico shelf water and the 6–8km wide frontal or mixing zone between plume and shelf waters.

Fish larvae are abundant in the vicinity of the discharge plume in general, but are especially concentrated in the frontal region, e.g., average neuston catches were 6-fold higher than at plume stations and 12-fold higher than at shelf water stations.

The described hydrography promotes strong hydrodynamic convergence within the frontal zone. We used surface drifters to measure apparent surface convergence rates at turbidity fronts of up to 0.8 m/sec. We used an advection diffusion model to simulate larval densities in surface waters at the frontal convergence zone that approximated the mean and median observed densities within the frontal zone.

We deployed radio tracked surface drifters and repeatedly sampled nearby over time to determine if larvae could be retained in the vicinity of the plume, or were advected westward by the average surface flow off the Mississippi Delta. A clockwise circulation with a radius of curvature of about 50km was identified and acted to retain larvae in the vicinity of the plume.

The diet of striped anchovy, *Anchoa hepsetus,* larvae was investigated to determine if fish larvae in the frontal zone were deriving a trophic advantage from the potential food resources concentrated there. The diet consisted of a wide array of prey items including various microcrustaceans (e.g., amphipods, cladocerans, copepods and ostracods) diatoms, larvaceans and polychaete larvae, but according to both frequency of occurrence and number of prey items, copepods and diatoms were the dominant foods consumed. Diatoms occurred more frequently and more numerous at plume and shelf stations (43 percent and 39 percent and 72 percent and 75 percent, respectively), but copepods were the most frequently occurring (49 percent) and most numerous (48 percent) prey items at frontal stations. Because copepods are larger and have a slightly higher C:N ratio striped anchovy larvae in frontal waters may consume a more nutritious diet.

Otolith microstructure techniques were used to determine age and estimate growth rates to determine if larvae in the vicinity of the plume in general, or the frontal waters in particular, grow faster. King mackerel, *Scomberomoras cavalla,* larvae from the Mississippi plume region grew significantly faster than larvae from other areas (0.95 vs. 0.79 mm/d), while Spanish mackerel, S. *maculatus,* and little tunny, *Euthynnus alletteratus,* from the plume did not. Spanish mackerel, yellowfin tuna, *Thunnus ablacares,* and striped anchovy larvae in the vicinity of the discharge plume grew faster at intermediate salinities, i.e., the frontal zone (1.0 vs. 1.3, 0.75 vs. 0.6 and 1.05 vs. 0.85 mm/d, respectively). We regressed $\log_e$ of SL on age for the descending limb of plots for these same species to estimate daily instantaneous mortality rates. Mortality rates were higher in the vicinity of the plume for Spanish mackerel, little tunny, and striped anchovy (0.6 vs. 0.3, 0.9 vs. 0.7 and 0.23 vs. 0.12, respectively).

A relative survival model

$$N_t = N_o e^{-zt}$$

where

z	=	daily instantaneous mortality rate
t	=	L_{max}/growth rate (mm)
L_{max}	=	a 25-mm size refuge

was used to evaluate the advantage of faster growth vs. the disadvantage of increased mortality for Spanish mackerel larvae. Survival was much more sensitive to changes in mortality than growth, suggesting that the specific demographics prevalent in the plume environment may not favor survival and recruitment in the Mississippi River discharge plume.

Introduction

There is considerable circumstantial evidence worldwide that river plumes influence the mechanisms underlying fish production (i.e., growth, mortality and recruitment), recruitment being the most important since it is the largest contributor to variation in fish production. Major fisheries have been eliminated or have declined when river flows were controlled. For example, filling of the Aswan Dam began on the Nile River in 1965 and was completed in 1969, during which time the flow was decreased by 40 km3 yr^{-1}, with a concomitant decline in primary production off the delta. Egyptian fishery catches in the Mediterranean Sea declined from 37,800t in 1962 to 7,142t in 1976, with an attendant decline in community structure (Bebars and Lasserre, 1983). The largest river in North America, the Mississippi, is no exception. A major feature influencing the ocean environment of the Gulf of Mexico—it annually discharges an average $1.83 \times 10^4 \ m^3 \ S^{-1}$ (Gunter, 1979) of freshwater, nutrients, and suspended materials. Fishery landings from the fertile fishery crescent surrounding the Mississippi River delta are extraordinary, accounting for approximately 80 percent of the total commercial landings from the Gulf of Mexico (NMFS, 1994).

There is concern about how the periodic occurrence of a major hypoxia zone off the Mississippi River may influence the valuable fisheries associated with the river. The purpose of this brief report is to summarize the results of research on the recruitment dynamics, i.e., abundance, feeding, growth, and mortality, of fish larvae associated with the Mississippi River discharge plume, and discuss the possible significance of these results to hypoxia and its potential impact on fish production.

Results And Discussion

From 1986–1993 we conducted research cruises during both low (summer-fall) and high (spring) flow regimes to the Mississippi River discharge plume. Plankton samples were collected at stations 4–6 km apart along 15–25 km transects that radiated out from the delta, and were positioned using AVHRR satellite imagery (visible channel) to cross from the plume into Gulf of Mexico shelf waters. Plankton was collected with neuston net (1 x 2 m; 0.947 mm) and Tucker trawl (1 x 1 m; 0.335 mm); CTD casts were made to obtain environmental data at each station.

The water column in the vicinity of the discharge plume has a characteristic hydrographic structure created by the abutment of water masses with distinctly different densities (Grimes and Finucane, 1991; Govoni and Grimes, 1992). Lighter plume waters are represented by a shallow lens of low salinity water overlying heavier high salinity Gulf of Mexico shelf waters; the 6–8km wide frontal, or mixing, zone between these two water masses is where isohalines are closely spaced and approach the surface (Figure 48). Turbidity fronts, represented by sharp color discontinuities, are the seaward projection of concentrated suspended particulate matter, and they are often nested within the frontal zone (Garvine and Monk, 1974).

Phytoplankton, zooplankton and fish larvae are concentrated in the vicinity of the plume in general and the frontal region in particular. For example, average surface phytoplankton biomass, macrozooplankton displacement volume and neustonic ichthyoplankton catch rates were about 4, 2 and 6 fold greater in frontal waters than in adjacent plume and shelf waters (Grimes and Finucane, 1991; see also Govoni *et al.*, 1989 and Govoni and Grimes, 1992).

Surface waters converge at plume fronts, primarily due to strong horizontal density gradients and resulting pressure gradients that are produced within and below the frontal layer. Cross frontal circulation is characterized by vigorous convergence on both sides of the front, typically higher on the high density (seawater) side than on the low density (plume) side, e.g., average 0.2 and 0.1 m sec^{-1} for the Mississippi River plume (Govoni and Grimes, 1992). As surface waters converge, planktonic organisms move passively with the water toward the front where converging water masses move downward with gravity. Surface seeking and buoyant organisms accumulate at the surface as they resist downward movement. This is local, but important, transport mechanism that can concentrate larval fish and zooplankton and account for the high densities of these properties observed at fronts. Govoni and Grimes (1992) measured surface convergence velocity in the Mississippi River up to 0.8 m sec^{-1}. Observed velocity was always greater than the velocity calculated from the density alone (Figure 49) because the observed velocity is the sum of the density driven velocity plus the tidally driven velocity inherent in shelf waters. They used the advection diffusion model of (Olson and Backus (1985) to simulate surface densities of fish larvae at the front that agreed well with observed values (Figure 50).

Having observed the distribution and abundance of these properties, as well as the hydrographic structure and hydrodynamics Grimes and Finucane (1991) developed a modification of the short food chain hypothesis explaining how the Mississippi River might act to enhance recruitment of associated fish larvae. This hypothesis states that fish larvae concentrated in the vicinity of the plume in general, and the frontal region in particular, would take advantage of abundant food resources and consume a superior diet, grow faster and thus experience a shorter larval stage duration and survive better. Implicit in this hypothesis is that fish larvae in the vicinity of the discharge plume are not advected away from the rich plume environment by the low average westward flowing surface currents that prevail off the Mississippi River delta during the period of interest (summer-fall) (Wiseman and Dinnel, 1988).

Radio tracked surface drifters were deployed and repeatedly sampled nearby over time to determine if fish larvae were retained in the vicinity of the plume or were advected away (Grimes and Wiseman unpublished). The surface drifters were entrained in a tongue of Gulf of Mexico shelf water that intruded into the Louisiana Bight and rotated clockwise with a radius of curvature of about 50km (Figure 51). The average variation in abundance of fish larvae in surface collections suggested that the same assemblage of fish larvae was repeatedly sampled nearby the surface drifters because the coefficient of variation in total abundance along drifter tracks was two to four fold less than the variation among samples collected along transects that intentionally crossed plume, front and shelf waters (Table 3). These results suggest that, at least in this instance, a clockwise circulation existed in the vicinity of the plume that acted to retain fish larvae.

Research findings thus far are not totally in accord with the first element of the short food chain hypothesis, i.e., it cannot be stated unequivocally that fish larvae associated with the Mississippi River plume are conferred a trophic advantage. Spot, *Leiostomus xanthurus,* larvae collected off the Mississippi River plume ate twice as many food organisms as did larvae in Gulf of Mexico shelf waters (Govoni and Chester, 1990). However, organisms within the plume were mostly small (tintinnids, copepod nauplii, pelecypod veligers and invertebrate eggs), whereas organisms eaten in shelf waters were larger (copepodites and adult copepods). Because the volume and nutritional quality of gut contents of larvae from the two areas were roughly equivalent, they concluded that larvae in the plume gained no trophic advantage. Similarly, Powell *et al.* (1990) used morphological, gut content and recent growth criteria to evaluate nutritional condition of spot larvae associated with the Mississippi discharge, and could not consistently demonstrate an advantage. A diet study on striped anchovy, *Anchoa hepsetus,* collected along transects crossing plume, front and shelf waters showed that diatoms and copepods were by far the dominant food items, and that the larger more nutritious copepods occurred more frequently and accounted for the highest percentage of food items in guts of larvae collected in frontal waters, followed by plume waters then shelf waters (McNeil and Grimes, 1995). A suite of biochemical indices to nutritional condition (RNA/DNA ratio, percent protein and CS and LDH enzyme systems), were examined on striped anchovy collected along the same transects off the Mississippi plume; larvae collected in frontal waters were in the highest nutritional conditions (Torres *et al.* unpublished). Furthermore, in a recent review of the influence of riverine plumes worldwide on fish larvae Grimes and Kingsford (in press) found that certain taxa, e.g., small opportunistic species, appear to be associated with plumes and may be better adapted than larger more competent larvae of other species to take advantage of abundant food resources around plumes and their fronts.

The second element of the hypothesis states that fish larvae that are conferred a trophic advantage will respond by growing faster, and there is some evidence that growth of some fish larvae, as determined from otolith microstructure, may be enhanced. Growth of king mackerel, *Scomberomorus cavalla, was* higher off the Mississippi River plume (0.95 mm d^{-1}) than at other locations in the Gulf of Mexico (0.79 mm d^{-1}) (DeVries *et al.*, 1990). However, superior growth off the plume was not demonstrated for Spanish mackerel, S. *maculatus,* (DeVries *et al., 1990),* or little tunny, *Euthynnus alleteratus,* (Allman and Grimes unpublished). Other results on Spanish mackerel, (Grimes and De Vries unpublished, Figure 52) as well as those on yellowfin tuna, *Thynnus albacares,* (Lang *et al.*, 1994) and striped anchovy, *Anchoa hepsetus,* (Day, 1993), suggest that larvae associated with the Mississippi plume grow faster at intermediate salinities, i.e., frontal waters (0.6 vs. 0.75 mm d^{-1}, respectively for yellowfin tuna and stripped anchovy).

The final element of the hypothesis states that faster growth leads to shorter duration of the larval stage and better survival, with the caveat that the same dynamics that concentrate prey of fish larvae might also concentrate their predators. There is little evidence to evaluate this element of the hypothesis. Grimes and DeVries (unpublished) estimated instantaneous rates of natural mortality for Spanish mackerel and king mackerel using a catch-curve approach (i.e., regressing the log of frequency on age of the descending limb of age-frequency histograms). Instantaneous natural mortality estimates were approximately 0.3d^{-1} away from the plume and 0.6d-1 or higher in the vicinity of the plume. For little tunny, instantaneous natural mortality was slightly higher in the vicinity of the Mississippi River plume (0.94d^{-1}) than in the Gulf of Mexico off Panama City, Florida (0.85d^{-1}) (Allman and Grimes unpublished). Similar analyses for striped anchovy in water masses off the Mississippi River suggest that natural mortality in the front (0.13d^{-1}) and plume (0.23d^{-1}) may be higher than that experienced in shelf waters (0.09d- (Day, 1993). Conversely, yellowfin tuna (Lang et *al.*, 1994) experience higher natural mortality at fronts (0.41d^{-1}) than in the plume area in general (0.16d^{-1}). These differences in mortality rates should be interpreted with caution. Application of catch curve or survivorship analysis to estimate instantaneous mortality rates assumes equal vulnerability to capture by the sampling gear for all ages used in the analysis. Faster growth rates might lead to biased mortality estimates because fast growing larger larvae become less vulnerable to capture and may be under represented at the older ages used in the analysis. Although these results are tentative they do not support the contention that higher growth rates of larvae associated with river plumes lead to better survival.

To summarize the results of evaluating the elements of the short food chain hypothesis with respect to the Mississippi River, it appears that some species of fish larvae, opportunistic ones, are able to take advantage of abundant prey resources. Also, some species of fish larvae appear to grow faster, but mortality rates may also be higher. So, whether this hypothesis is valid and the population dynamics of fish larvae in the vicinity of river plumes favor recruitment, depends upon the relative magnitude of growth and mortality. A simple and convenient way of evaluating the relative importance of growth and mortality is to use the expression of exponential decay in population size with time

$$N_t = N_o e^{zt}$$

where

N_t = population at time t

N_o = initial population

z = instantaneous mortality.

Z can be directly estimated, while $t = L_c/g$ (where L_c = a critical size refuge where mortality decreases markedly) and g = growth rate that is also directly estimated. The product of zt is an exponent that determines the decrease in N_o. Obviously, the effect of z on N_o (survival to the critical size, L_c) is much greater than g, because z is a direct multiplier and g is a fractional multiplier (the divisor of L_c). Thus, incremental changes in mortality will have a much larger effect on survival and recruitment than incremental changes in growth rate. So, if physical and biological conditions in the vicinity of the Mississippi River plumes aggregate larval fish prey that results in a trophic advantage and faster growth, but also aggregates predators and increases the mortality rate on larvae, the disadvantage of increased mortality may well outweigh the advantage of faster growth, and increased survival and recruitment will not be the result. However, I emphasize that accurate larval mortality rate estimates are difficult to obtain using the time specific approach usually taken, due mainly to sampling bias associated with gear selectivity and the contagious distribution of fish larvae in time and space.

In summarizing their review of the effects of riverine plumes on fish larvae and their recruitment dynamics, Grimes and Kingsford (in press) offer two alternatives to the short food chain hypotheses. One alternative possibly explaining the apparent favorable effect of river plumes on recruitment, the total larval production hypothesis, is that trophic conditions support such high total production of fish larvae that negative effects of unfavorable dynamics are overridden. That is, high primary and secondary production associated with plumes may simply support such high total production of fish larvae that the specific population dynamics at plumes are not often relevant. A second alternative is that plumes and associated circulations facilitate the retention of larvae within an area. The presence of food would of course be important, but variation in physical retention rather than production may explain variation in recruitment; as argued for the member/vagrant hypothesis of Sinclair (1988).

The relationship between hypoxia and the recruitment dynamics of fish larvae in the vicinity of the Mississippi River discharge is in fact unknown, but there are several potentially important possibilities that can be discussed. The present understanding is that the hypoxia is due to both the effects of stratification of fresh and marine waters that restricts vertical reoxygenation of bottom waters, and the oxygen consuming breakdown of organic material mostly derived from high plankton production driven by river borne nutrients. While the hypoxia problem is believed to have been exacerbated by nutrient enrichment of the Mississippi River, the high nutrient load of the river and resulting high productivity associated with the discharge area is also vital to maintaining valuable Gulf of Mexico fisheries (e.g., approximately 80 percent of commercial fishery landings are taken from the region of riverine influence).

Hypoxia and the larvae of valuable fishery species may sometimes co-occur in time and space, almost certainly leading to larval mortality when this occurs. The hypoxic zone is generally located from off the Mississippi River delta westward along the Louisiana coast, and although it can occur in the winter and fall it most consistently occurs from mid-May to mid-September. A number of valuable species spawn at this time in the gulf, and their larvae are abundant off the Mississippi River delta, e.g., both king mackerel (Grimes *et al.*, 1990) and Spanish mackerel (Grimes and DeVries unpublished), cobia (Ditty and Shaw, 1992), dolphin (Ditty *et al.*, 1994) and yellowfin tuna (Lang *et al.*, 1994). Several valuable reef fishes, e.g., gray snapper, vermilion snapper and red snapper also spawn at that time, and while their larvae are collected off the delta (Grimes *et al.* unpublished, Lyczkowski-Shultz unpublished, Comyns unpublished) the adults spawn over hard bottom and thus spawning is probably not associated with the river discharge. Fish larvae are most abundant in near surface waters off the Mississippi plume (Govoni *et al.*, 1989), and the hypoxia is typically associated with bottom waters but it can extend up into the water column. Thus, differing vertical distributions of the hypoxic water and fish larvae may ameliorate potential negative impacts of hypoxia on larvae. However, the concentration of larvae in the frontal region may extend deeper into the water column because the hydrodynamic convergence that acts to concentrate larvae (Govoni and Grimes, 1992) continues unabated to the bottom on the high density (seawater) side of the convergence zone (Govine and Monk, 1974).

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Table 3.

Comparisons of the average variation (Coefficient of variation, CV) in total ichthyoplankton catch at stations along drifter tracks to CV's for catches made at stations along transects that intentionally sampled plume, front and shelf waters.

	CV
Along drifter tracks	
• Gimes and Wiseman (unpublished)	61 (fall)
Among plume, front and shelf waters	
• Grimes and Finucane (1991)	235 (fall)
• Govoni and Grimes (1992)	140 (fall) 129 (spring)

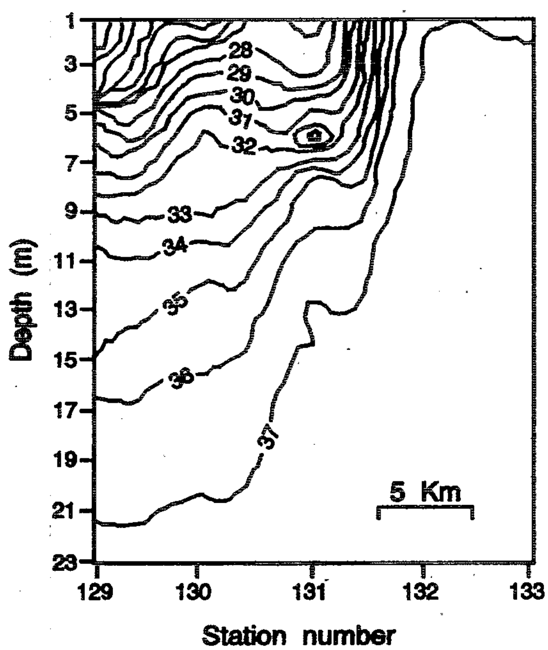

Figure 48.

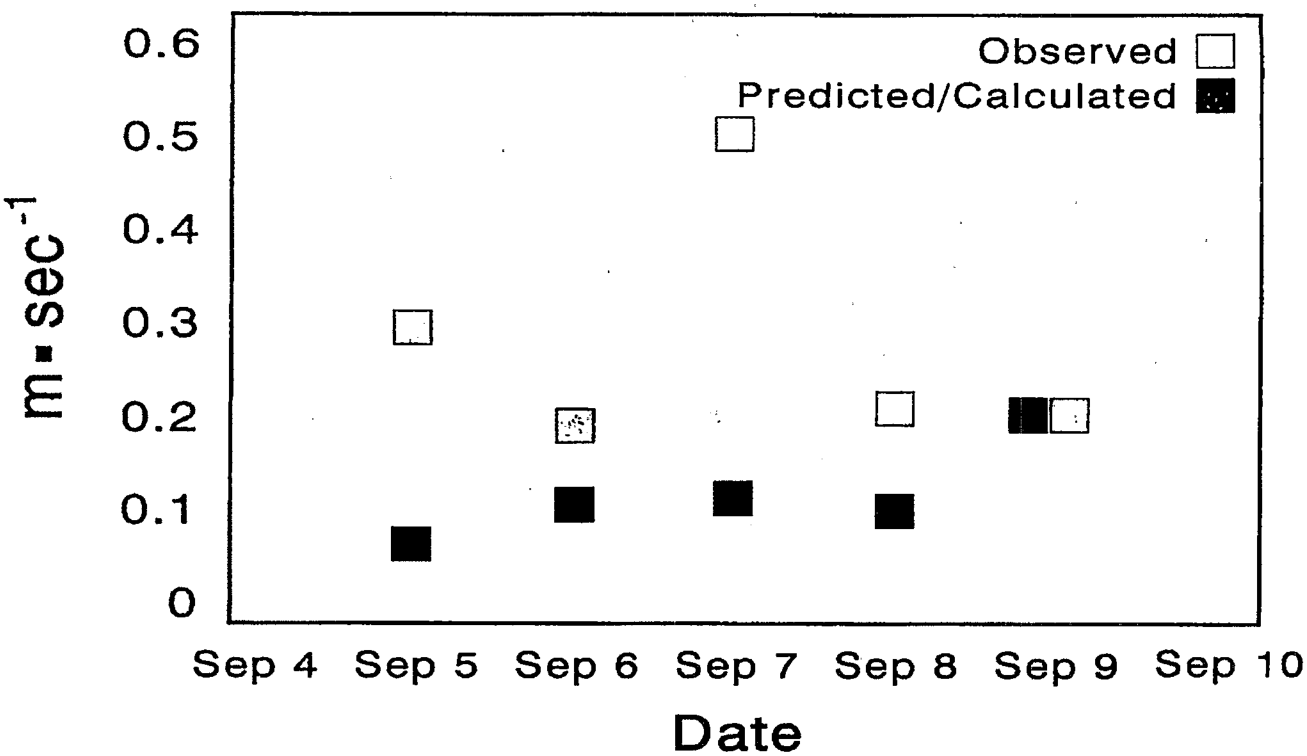

Figure 49.

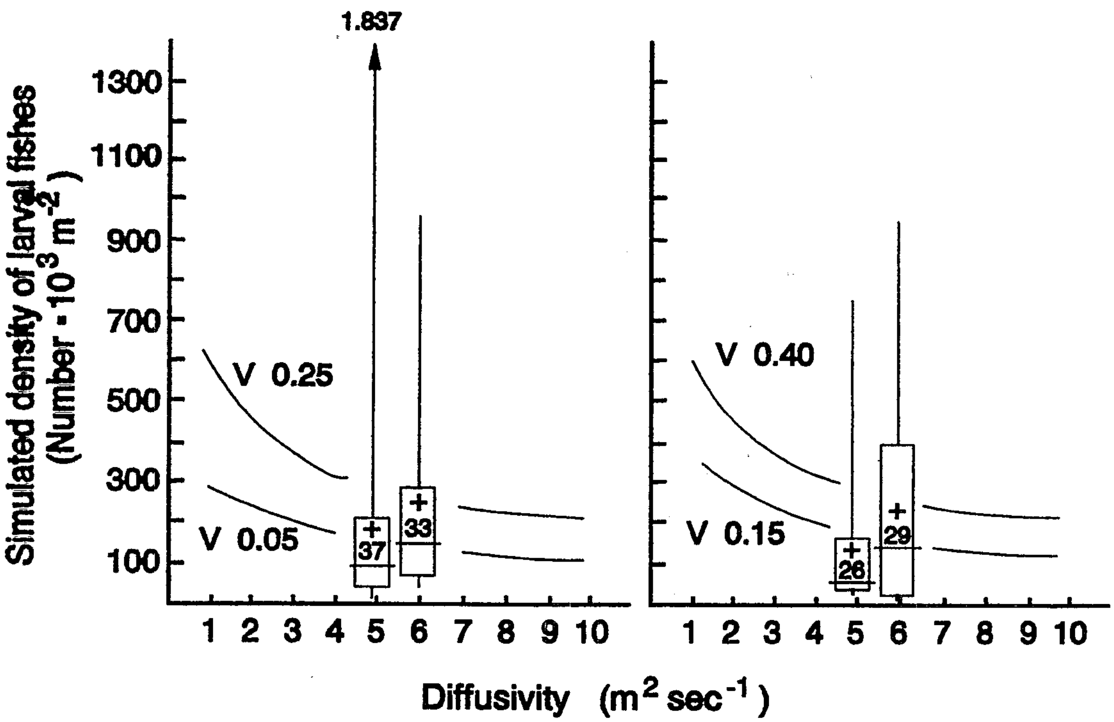

Figure 50.

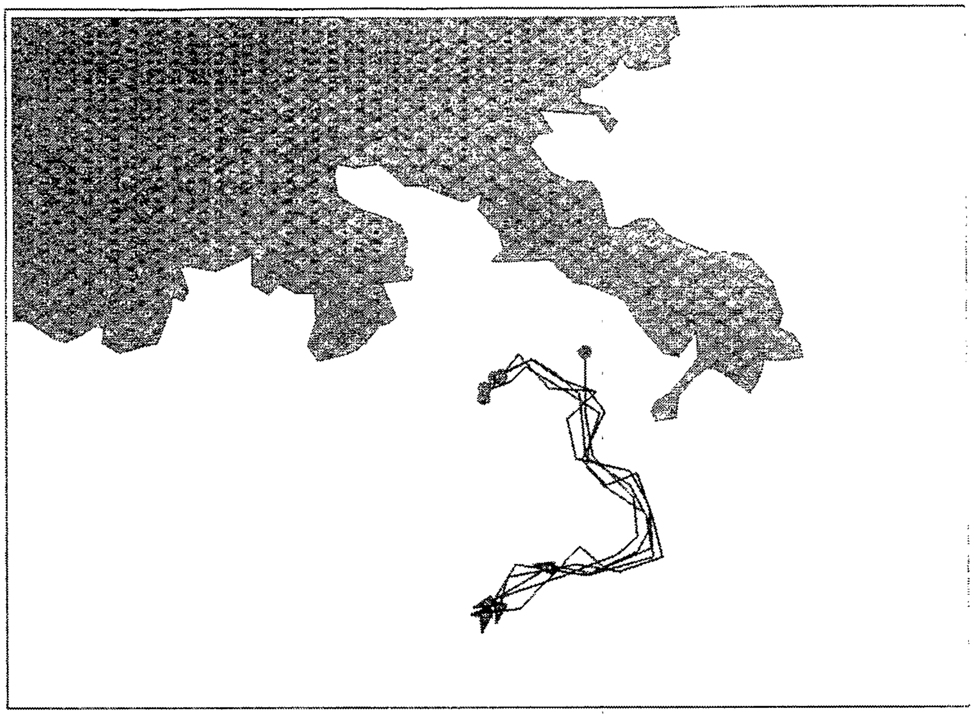

Figure 51.

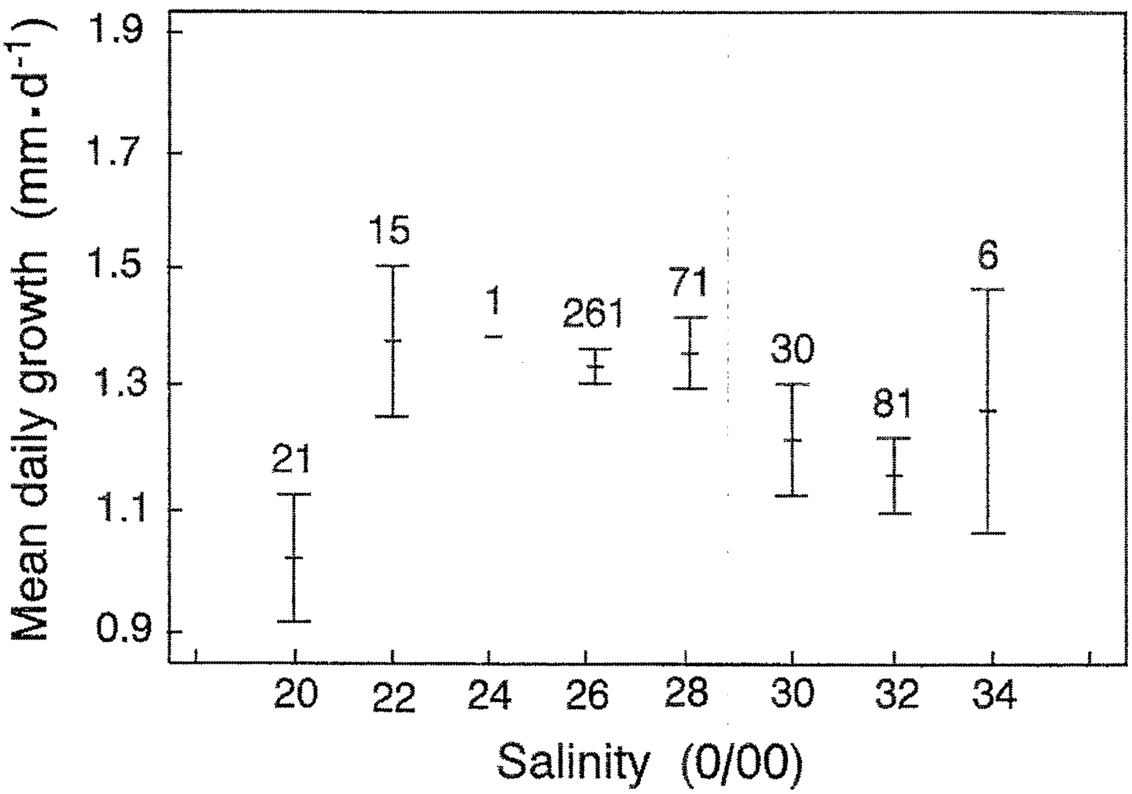

Figure 52.

Presentation Discussion

Churchill Grimes *(NMFS—Panama City, FL)*

Fred Bryan *(National Biological Service—Baton Rouge, LA)* commented that between 11-19 days of age, fish may be approaching the size where they are no longer equally disposed to the gear being used. Therefore, the estimate of mortality could be indicative of the organisms having become more nektonic than planktonic and thus are no longer available to a neuston or Tucker trawl.

Churchill Grimes agreed with Fred Bryan's observation. He said that estimating larval mortality is an extremely difficult task. He attempted to estimate larval mortality by following the same patch of larvae through a specified period of time. However, because the variation in catch was so great, it was impossible to complete the study.

Potential Impacts of Hypoxia on Fisheries: Louisiana's Fishery-Independent Data

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Abstract

The harvest of marine fishery resources of Louisiana, valued at over one-half billion dollars annually and dependent upon the State's nutrient-rich estuaries, potentially are subject to impact from hypoxia. Hypoxic conditions periodically develop in near shore waters in many areas of the world, including the northern Gulf of Mexico. Salinity and temperature stratification in the nearshore Gulf of Mexico results in conditions conducive to the development of hypoxic and anoxic bottom waters west of the Mississippi River delta. Stable summer weather patterns, freshwater inflow from the Mississippi River and local precipitation, and nutrient enrichment from these sources contribute to increased bacterial decomposition and oxygen demand in near-bottom waters. The magnitude of the phenomenon, in terms of depression of dissolved oxygen concentration and areal extent along the coast, varies annually. Likewise, impacts to fisheries vary. The distribution of fishery species is affected by displacement of demersal nekton and mobile epibenthic species assemblages and communities to areas with sufficient dissolved oxygen, and disruption of species movement patterns. Planktonic stages of fishery species are subject to stress and mortality in hypoxic waters. Preliminary indications are that pelagic species have not been impacted, although severe hypoxic conditions extending high into the water column may have affected their distribution and move ment patterns. Other potential impacts to Louisiana's fisheries include: concentration of fishing effort resulting in increased harvest; localized overfishing in some areas; shellfish mortality if hypoxic conditions impinge on coastal bay waters, localized mortality of finfish and shellfish in shoreline areas; and decreased recruitment due to impacts to zooplankton species assemblages. Changes in the relative amounts of nutrients can affect phytoplankton community dynamics, resulting in changes throughout the food web; replacement of diatoms with dinoflagellates may result in development of red and brown tides with resultant adverse impacts to fisheries. Changes in the distribution and abundance of fish species will result in a loss of commercial and recreational harvest opportunities and a net economic loss to the State. Economically marginal commercial participants may leave the fishery, and some recreational participants may elect not to fish. Fishery management decisions that are based on fishery independent data from resource surveys that do not take hypoxia into account may result in a loss of precision in assessment of fishery stocks.

Introduction

The harvest of the commercial and recreational marine fishery resources of Louisiana is valued at over one-half billion dollars annually, and generates over 1.2 billion dollars in economic activity in the state of Louisiana (David LaVergne, Economist, Louisiana Department of Wildlife and Fisheries (LDWF), personal communication). These fisheries, the products of which are used nationally and internationally, are dependent upon the State's nutrient-rich estuaries and nearshore waters of the Gulf of Mexico. They potentially are subject to impacts resulting from the occurrence of hypoxic dissolved oxygen (D.O.) concentrations of less than 2.0 mg/l) conditions in the bottom waters of the nearshore Gulf of Mexico. This phenomenon off Louisiana represents a potential threat to the health and viability of these fisheries.

Hypoxic bottom waters offshore from the Louisiana coast were reported initially from 1935 (Richards, 1957; Conseil Permanent International pour l'Exploration de la Mer, 1936; cited in Bedinger, et al., 1980), and subsequently have been studied and reported by numerous investigators (Ragan, et al., 1978; Harris, et al., 1978; Bedinger, et al. 1980; Harper, et al., 1981; Stuntz, et al., 1982; Turner and Allen, 1982a; 1982b; Rabalais, et al., 1985; Renaud, 1986; Rabalais, et al, 1994; Schurtz and St. Pe', 1984). The Mississippi River flood that ultimately resulted in an unprecedented area of hypoxic water bottoms during the summer of 1993 focused national attention on the Louisiana coast (e.g., Holstrom, 1993).

LDWF has collected hypoxia-related data through its Coastal Study Area fishery management program since its inception in 1966. Other study-specific programs, such as the Cooperative Gulf of Mexico Inventory (Barrett, et al., 1971; Perret, et al., 1971) also have contributed to the Department's understanding of the relationships between environmental factors and coastal fisheries.

LDWF noted the occurrence of hypoxic conditions in 1973 and began regular monitoring of Gulf waters in which hypoxic conditions occur in 1978 (Foote, 1982). In 1982, funding became available from the National Marine Fisheries Service (NMFS) for the Southeast Area Monitoring and Assessment Program (SEAMAP), and limited additional data were collected by LDWF from across the central coast. The expansion of SEAMAP in 1985 provided the opportunity to collect data related to hypoxia and its potential impacts to fisheries from water depths of 5 to 20 fathoms between the Mississippi River and Atchafalaya Bay (Figure 53). The data presented here were collected primarily for other fishery management and environmental monitoring purposes, not specifically for measuring the impacts of hypoxia on fisheries. All fisheries-related data were collected using otter trawls of various sizes and configurations, and the findings are presented as a descriptive summary. Datasets have been combined to illustrate the potential impacts of hypoxia and have not been subjected to rigorous statistical analysis.

Physical and Chemical Data

Hypoxic conditions periodically develop in nearshore waters in many areas of the world, including the northern Gulf of Mexico. (Richards, 1957; Faganeli, et al., 1983). Factors hypothesized to contribute include organic sediment loads (Richards, 1957; Ragan et al., 1978), reduced vertical mixing of the water column due to salinity and temperature stratification coupled with benthic and planktonic respiration (Turner and Allen, 1982a; 1 982b). Stable summer weather patterns, freshwater inflow from the Mississippi River and local precipitation, and nutrient enrichment from these sources contribute to increased bacterial decomposition and oxygen demand in near-bottom waters (Richards, 1957; Turner and Allen, 1982a; 1982b). Salinity and temperature stratification in the nearshore Gulf of Mexico results in conditions conducive to the development of hypoxic and anoxic bottom waters west of the Mississippi River Delta (Figure 54). Typically, only the near-bottom waters become hypoxic/anoxic, principally during the months of May through August (Figure 55). The phenomenon develops because of stable local summer weather patterns that do not provide sufficient energy in terms of wind and wave action to break the density barriers established between the upper and lower water column. The barriers thus established by salinity and temperature isolate the lower reaches of the water column where oxygen demand from respiration and decomposition deplete dissolved oxygen. The resulting hypoxic/anoxic condition persists until the water column again is mixed by a frontal passage, tropical weather system, or other disturbance. Once the disturbance has passed and stable conditions again prevail, hypoxia generally becomes re-established. The regular passage of cold fronts beginning in the fall causes the water column to mix and remain in that state until the next summer.

The magnitude of the event varies annually in terms of the size of the hypoxic area and the depression of D.O. concentrations. This is illustrated by the frequency of encountering a location with hypoxic bottom water. The Midwestern drought in the late 1980's resulted in a relatively small number of nearshore hypoxic observations. Conversely, during the Mississippi River flood of 1993, a record number of hypoxic stations were encountered during routine sampling (Figure 56). The severity of the depression of D.O. levels also indicates the variability of the event. Hypoxic conditions might develop over a large geographical area, but the depression in D.O. levels might be slight as compared to other years. For example, LDWF data indicate that the 1984 event was moderately severe with over 10 percent of samples containing D.O. concentrations of less than 2.0 mg/l, or approximately half the number of stations found in the record event of 1993. However the mean D.O. concentration from samples collected during the summer of 1984 was greater than 3.0 mg/l (Figure 57), indicating that the hypoxic event that year was of shorter duration or covered a smaller area than in other years. During 1993 over 20 percent of stations sampled were found to be hypoxic, and D.O. concentrations were near 0.0 mg/l, indicating a large, severe event.

Concentrations of silicates in surface waters during spring months, although not attributable to hypoxia, show a relationship with its subsequent development. Silicates comprise the skeleton of diatoms, the dominant phytoplankton group in the northern Gulf of Mexico. High concentrations of silicates generally are followed by low measurements of D.O., and vice versa (Figure 58). High levels of silicates in the spring may indicate the potential for a subsequent bloom of diatoms. As these complete their life-cycle and settle into the bottom waters, decomposition consumes the available D.O. and contributes to the hypoxic event. Nutrients remaining in the surface waters are then available to other phytoplankton groups such as cyanobacteria and dinoflagellates. These organisms have been linked to formation of hypoxic bottom waters (Dortch, 1994). Shifts in the species composition of this community may make conditions favorable for blooms of the noxious and toxic phytoplankton that cause red tides.

Impacts to Fisheries

The presence of hypoxic waters in an area can be expected to have a variety of impacts to fisheries. Nekton communities and assemblages, being mobile, will move away from areas with insufficient D.O. and congregate along the borders of the hypoxic area until conditions are conducive to their return. Mobile epibenthic organisms similarly will leave the area if possible. Planktonic communities that are unable to swim away from a hypoxic water mass, or benthic communities associated with specific water bottoms, would be subject to stress and/or mortality depending on the severity of the hypoxic event and their length of exposure to it.

Observed Impacts

The distribution of fishery species is affected by displacement of demersal nekton and mobile epibenthic species assemblages and communities to areas with sufficient dissolved oxygen, and disruption of species movement patterns. Numbers of demersal species, and their abundance, are reduced greatly (Bedinger, et al., 1980; Stuntz, et al., 1983). Pihl, et al. (1991) found that demersal species tended to migrate to shallower water to escape hypoxic bottom conditions.

Preliminary indications are that pelagic species have not been impacted, although severe hypoxic conditions extending high into the water column may affect their distribution and movement patterns. Stuntz, et al. (1983) speculated that pelagic species may congregate around hypoxic water bottoms to take advantage of feeding opportunities on benthic, epibenthic, and demersal organisms that are rendered vulnerable to predation by stress resulting from low oxygen levels. Pihl, et al. (1992) observed a similar phenomenon in demersal species in Chesapeake Bay.

Otter trawls of the type used in the LDWF surveys are designed to collect organisms that reside on or near the bottom. Therefore the catch from this gear generally is comprised of epibenthic and demersal species. Reef-associated species sometimes are caught if the gear passes over an irregularly-contoured area of the bottom that provides reef-like habitat, or if the animals are moving between reef areas. Pelagic species can be caught near the bottom if a school is encountered as the gear is fishing, or off-bottom as the gear is being set or retrieved. The plankton net data reported here were collected in a survey to determine zooplankton species composition and abundance in near-bottom offshore waters subject to hypoxic conditions. Seventy-five species of finfishes, crustaceans, and cephalopods were collected in the Department's fishery-independent trawl surveys in the area where hypoxic conditions occur. The LDWF data indicate that a variety of epibenthic, demersal, pelagic, and reef species were present in both trawl and plankton net catch from the hypoxic zone (Table 4). Target species for directed fisheries, both commercial and recreational, were recorded in the catch regularly.

Composition and abundance of species caught in trawls decreased with D.O. concentration. The LDWF data indicate that 35 percent of nearshore trawl samples collected from hypoxic waters during summer result in no live organisms being caught. Large catches from hypoxic or anoxic waters generally were comprised of pelagic species. Trawl catch in waters with D.O. concentrations between 0.0 and 1.0 mg/l was comprised of 34 species (Figure 59). Although the number of taxa encountered was only slightly less than that found at D.O. concentrations above 3.0 mg/l, the total number of individuals was significantly depressed. Between 1.0 and 2.0 mg/l of D.O., the number of species caught decreased to 24, but the number of individuals in the catch increased by nearly an order of magnitude. Between 2.0 and 3.0 mg/l of D.O. the number of species increased to 46 while the number of individuals decreased slightly. The number of species remained relatively constant as D.O. concentrations rose from 3.0 to 4.0 mg/l, and the number of individuals increased by approximately 33 percent. Weight of the catch exhibited a nearly linear increase as D.O. concentrations rose (Figure 60). Pelagic species exhibited a nearly constant relative abundance in trawl catches, remaining approximately at 20 percent except at D.O. concentrations between 2.0 and 3.0 mg/l (Figure 61). Of the 34 species found between D.O. concentrations of 0.0 and 1.0 mg/l, approximately one-third were epibenthic species that may not have been able to avoid the development of hypoxic conditions. The increase in numbers of individuals between 1.0 and 2.0 mg/l D.O. suggests that animals may be congregating around the margins of the hypoxic area, upon being displaced as the event develops. The relative abundance of pelagic species increased when D.O. concentrations increased between 2.0 and 3.0 mg/l. This increase may be due not only to availability of prey organisms under stress from low D.O. concentrations, but also to increased numbers of prey that have been concentrated by hypoxia.

Potential Impacts

The observed impacts to fisheries vary with the decrease in D.O. concentration, and presumably with the area of the water bottoms that are affected by hypoxic conditions. Mobile organisms move from hypoxic waters to congregate in areas where D.O. concentrations are sufficient to sustain life. Animals unable to move away from developing hypoxic/anoxic waters, either because of life stage or habit, are subject to mortality. The observed redistribution of species, concentration of abundance, and mortality that hypoxic conditions cause may also contribute to other potential impacts to Gulf of Mexico fisheries.

Numbers of pelagic species appear to increase in response to availability of prey organisms concentrated at the edges of the hypoxic area. Numbers of fishermen may increase in these areas for similar reasons. The concentration of fishing effort may result in increased harvest of target and non-target species. If the relative abundance of nontarget species is high in these areas, increased bycatch mortality may result. Similarly, localized overfishing in some areas may be possible if the relative abundance of target species is high. Additionally, if the fishery is prosecuted over a limited area, much of which is affected by hypoxic bottom water, the relatively high proportion of target species can lead to local overharvest.

Particularly severe hypoxic events, or those that impinge closely upon the shoreline, may leave no escape for organisms displaced and crowded by low D.O. concentrations. As a result, localized mortality of finfish and shellfish in shoreline areas may occur. Hypoxia was a factor in a 1973 jubilee and fish kill at Grand Isle (Philip E. Bowman, LDWF, personal communication). Further impingement on the shoreline and encroachment into bay waters may impact the oyster fishery. Adult oysters will shut their valves to withstand hypoxic conditions for short periods of time. If hypoxic conditions persist for days, however, mortality is likely. Furthermore the peaks of oyster spawning are in early and late summer, when hypoxic conditions may exist. Larval oysters, as well as the eggs and larvae of other fishery species, are components of zooplankton assemblages and therefore potentially are subject to stress and/or mortality from exposure to hypoxic conditions (Earl Melancon, Nichols State University, Thibodaux, Louisiana, personal communication). Decreased recruitment to fishery stocks, disease, or slow growth due to exposure to hypoxia are other potential impacts to zooplankton species assemblages. Changes in the relative amounts of nutrients may affect phytoplankton community dynamics, resulting in changes throughout the food web; replacement of diatoms with cyanobacteria or dinoflagellates may result in development of red and brown tides with resultant adverse impacts to fisheries.

Low catch rates have been demonstrated in research and resource surveys (Pavela, et al., 1983; Bedinger, et al., 1980). Similar decreases in directed fisheries have been reported (Krapf, 1994; Barton, 1995). Changes in the distribution and abundance of fishery species may result in a loss of commercial and recreational harvest opportunities and a net economic loss to the State. Fishermen may have to travel farther to productive waters until the point where the economic outlay does not equal the expected return. The recreational fisherman's response may be to reduce fishing effort, and therefore, fishing-related expenditures. Decreased catch in the commercial fishery may affect a suite of related industries, including processors, wholesalers, retailers and restaurants, resulting ultimately in a loss in economic activity. Economically marginal commercial participants may leave the fishery. Hypoxia was cited as one of the factors that led to the closing of the Zapata menhaden processing plant in Dulac, Louisiana in 1995 (Barton,1995).

Fishery-independent data provide indices of population levels to fishery managers. In a highly regulated fishery these data provide the only available measure of changes in population levels. The changes in distribution of species resulting from hypoxia, movement away and concentration, may result in more resource survey samples with high and low abundance. This will result in an increase in the sample variances of resource survey data. Population estimates based on these data will be less precise. Fishery managers then must allow for the larger confidence interval surrounding population estimates in formulating management decisions regarding seasons and quotas.

Summary

Louisiana's fisheries, and to a large extent those of the northern Gulf of Mexico, depend on the Mississippi River for their existence. The sediments and nutrients carried by the river built the Louisiana coastal marshes. Today, as a result of leveeing the river, nutrients and sediments that once built and maintained Louisiana's coastal marshes are being deposited off the Continental Shelf in the abyssal depths of the Gulf of Mexico. Decreasing the nutrient levels in the Mississippi River may serve to lessen the severity of hypoxia in coastal waters, but also may impact the food web of the northern Gulf and decrease fisheries production.

Distributional changes that can be related to hypoxia have been observed in demersal fish and invertebrate communities. Plankton communities are subject to stress and mortality in hypoxic waters since these organisms lack the ability to avoid the area. Preliminary indications are that pelagic species have not yet been affected, other than a possible change in local population density related to feeding behavior. However, an increase in the severity of the phenomenon that leads to hypoxic waters extending high into the water column potentially can also impact the distribution and movement of these highly-mobile species.

Other potential impacts include a concentrating of fishing effort resulting in increased harvest; low catch rates in directed fisheries; localized overfishing; mortality; decreased recruitment due to impacts to zooplankton. Changes in the concentrations of nutrients, such as silicate, can result in a change in phytoplankton community dynamics, and subsequent changes throughout the food web. Diatoms replaced by dinoflagellates may result in development of red and brown tides with resultant adverse impacts to fisheries, such as advisories against catching/keeping certain species, off-flavors, and direct mortality. Changes in the distribution and abundance of fish species could result in a loss of commercial and recreational harvest opportunities and a net economic loss to the State. Economically marginal commercial participants may leave the fishery, and recreational participants may reduce fishing effort.

Fishery management decisions that are based on fishery-independent data from resource surveys that do not take hypoxia into account may result in a loss of precision in assessment of fishery stocks.

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Table 4.
Summary of species caught in LDWF trawl and plankton net samples from nearshore waters, 1978–1995. Bold type indicates a species sought either in the commercial or recreational fishery.

Species Type	Species
Epibenthic	Mud creabs, purse crabs, spider crabs, other crabs, batfish, **southern flounder, ocellated flounder**, other flounders, soles
Demersal	**White shrimp, brown shrimp, blue crab**, mantis shrimp, other swimming crabs, sharpnose shark, anchovies, lizardfishes, catfishes, cusk-eels, **spotted seatrout, sand seatrout, silver seatrout, southern kingfish, croaker**, other drums, sea basses, searobins, puffers
Pelagic	**Squids, Gulf menhaden, other herrings,** spadefish, **Spanish mackerel**, Atlantic bumper, other jacks, bluefish, Gulf butterfish, harvestfish
Other species	Berracudas, pinfish, **red snapper,** mojarras, seahorses, filefish, **triggerfish,** remoras
Plankton	**Brown shrimp, seabob**, other shrimp, **blue crab,** other swimming crabs, anchovies, **herrings,** jacks, **sand seatrout, spotted seatrout, red drum,** other drums, **Spanish mackerel**, other species

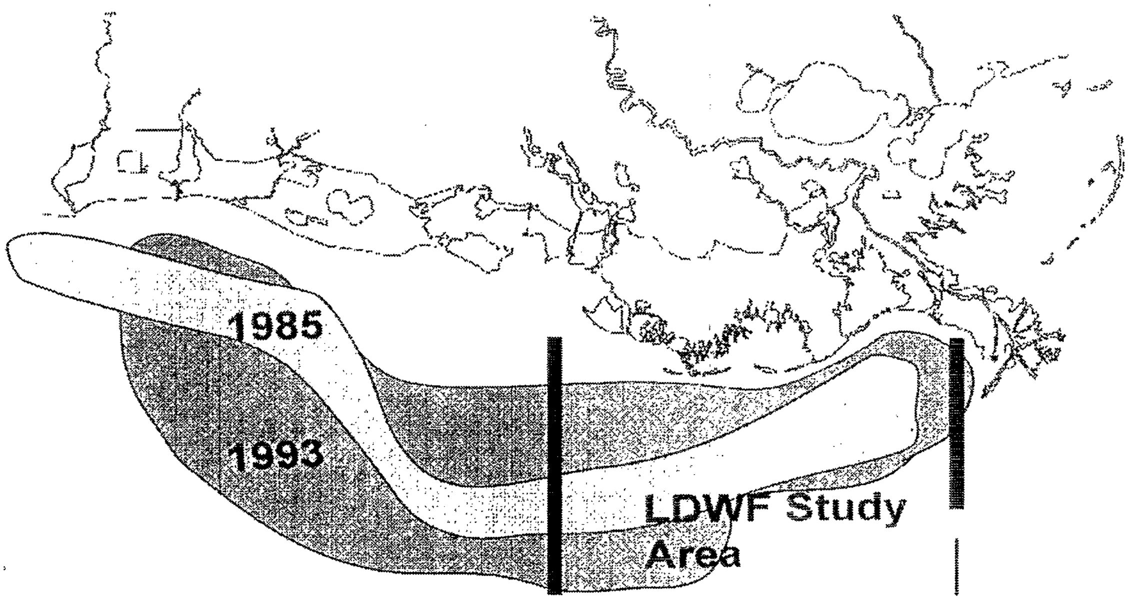

Figure 53.
Map of coastal Louisiana showing approximate side and location of 1985 and 1993 hypocix events, and the location of the LDWF study area.

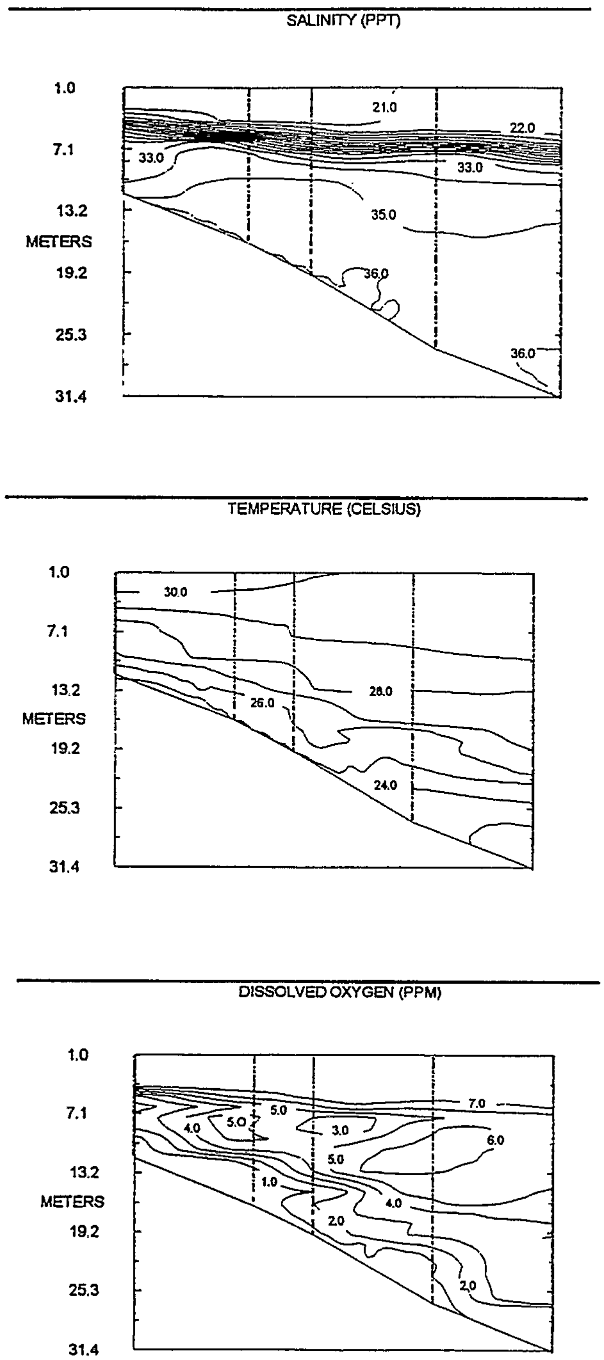

Figure 54.

Nearshore water column profile showing stratification based on salinity (top) and depression of dissolved oxygen concentration in near-bottom waters (bottom). LDWF data, July 1995, sample.

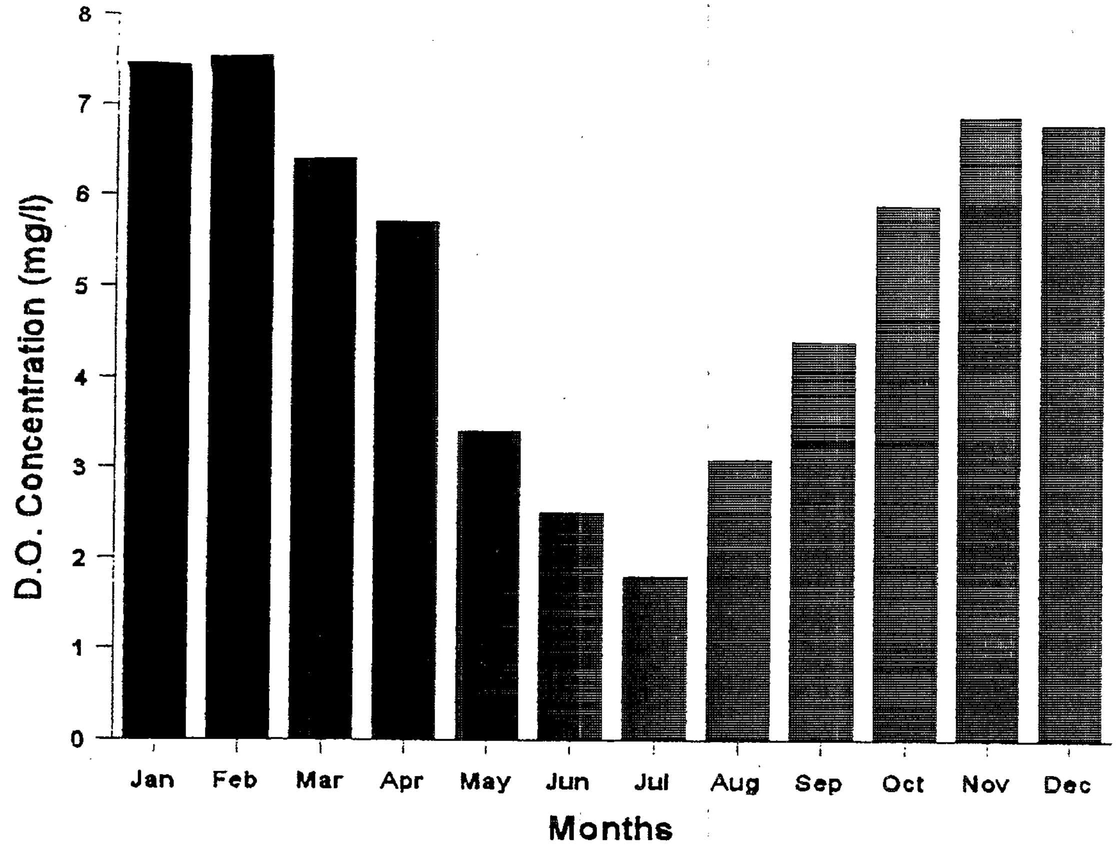

Figure 55.
Monthly mean concentration of dissolved oxygen in bottom waters at nearshore LDWF stations, 1978–1995.

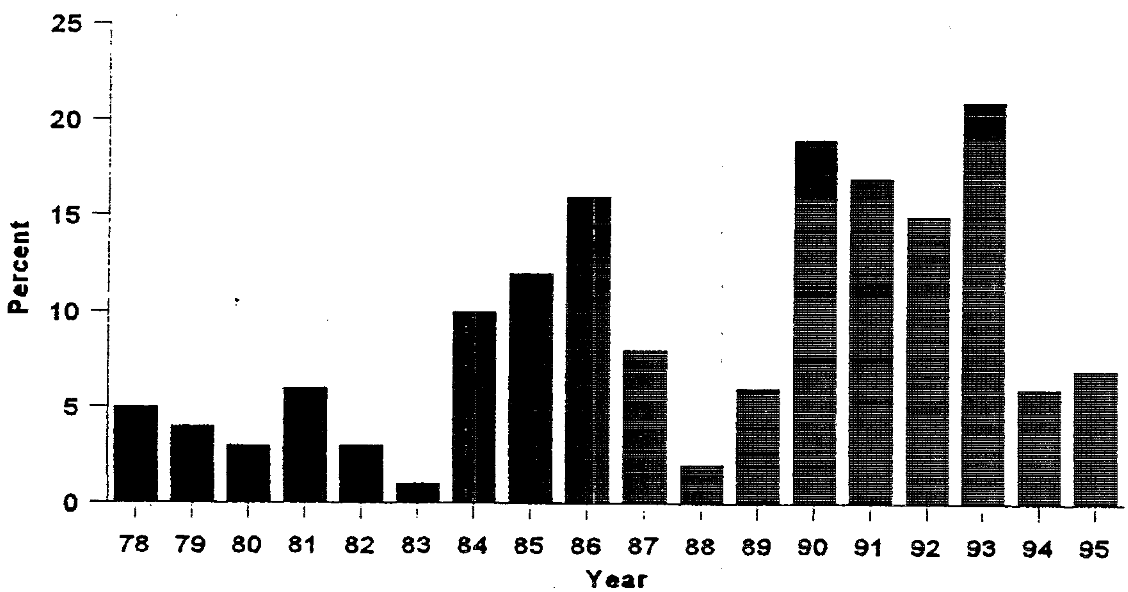

Figure 56.
Percent occurrence of hypoxic conditions in bottom waters at nearshore LDWF stations, 1978–1995.

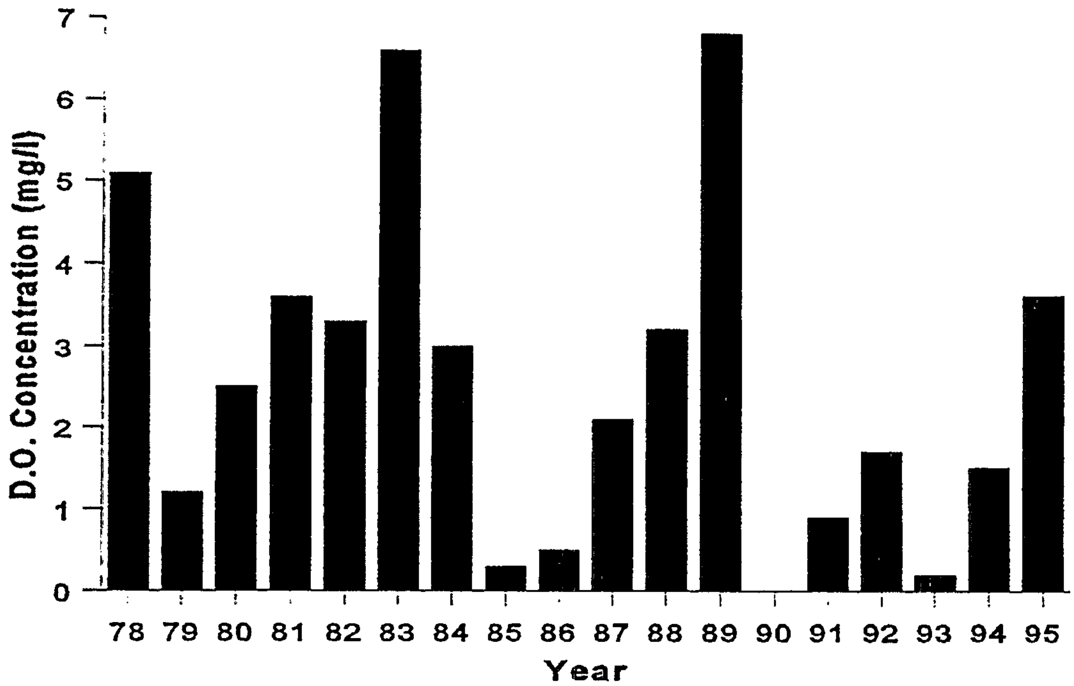

Figure 57.
Mean summer (June, July, and August) dissolved oxygen concentration in bottom waters at nearshore LDWF stations, 1978–1995.

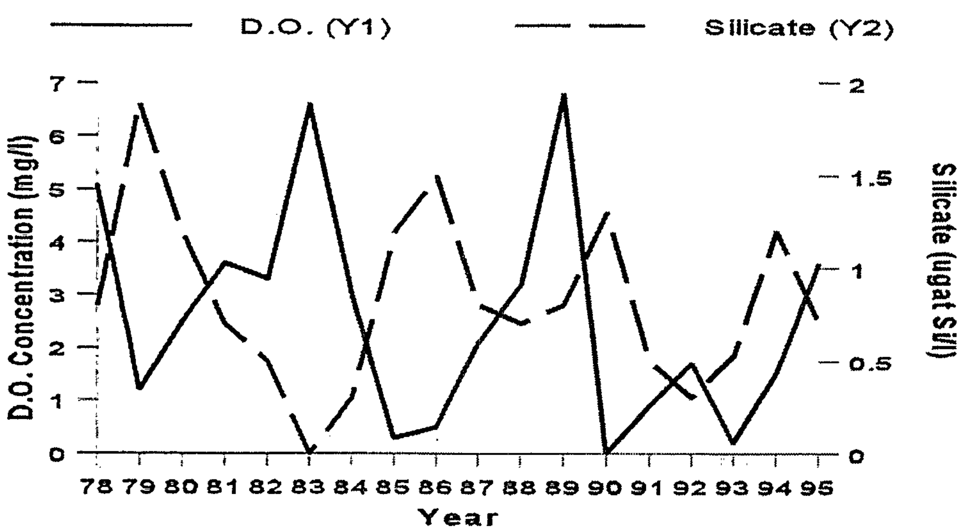

Figure 58.
Concentrations of silicates in surface waters during spring months (April, May, and June) and summer (June, and August) dissolved oxygen concentration in bottom waters from LDWF nearshore stations, 1978–1995.

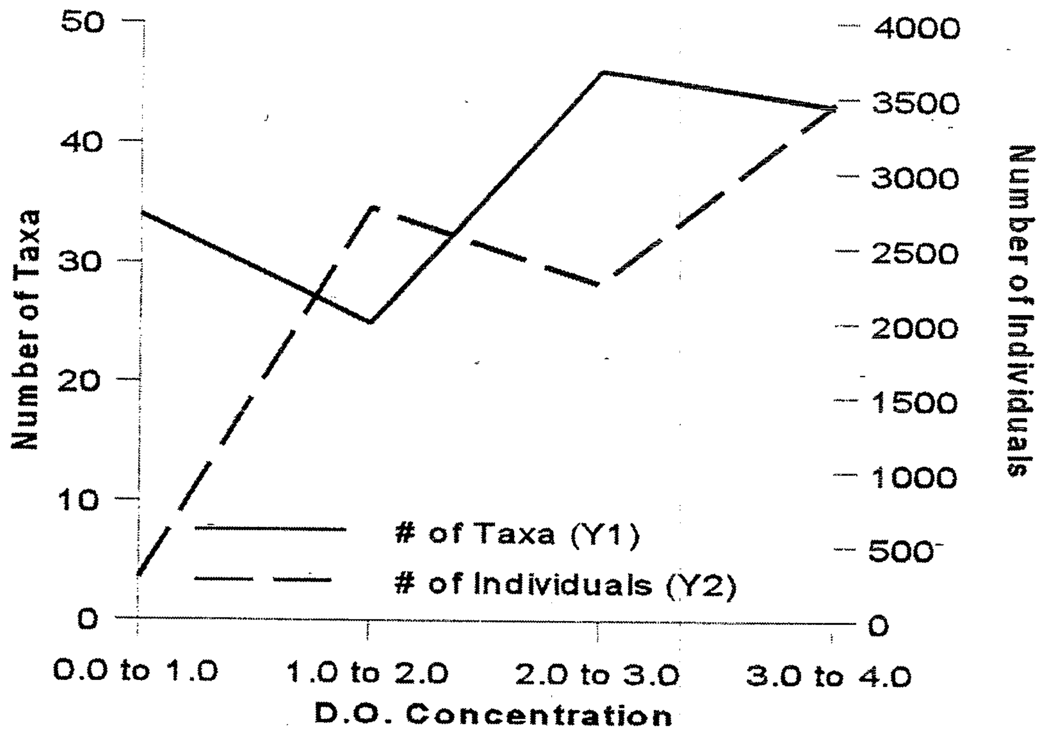

Figure 59.
Numbers of taxa and total numbers of individual organisms caught in LDWF trawl samples from nearshore waters, 1978–1995.

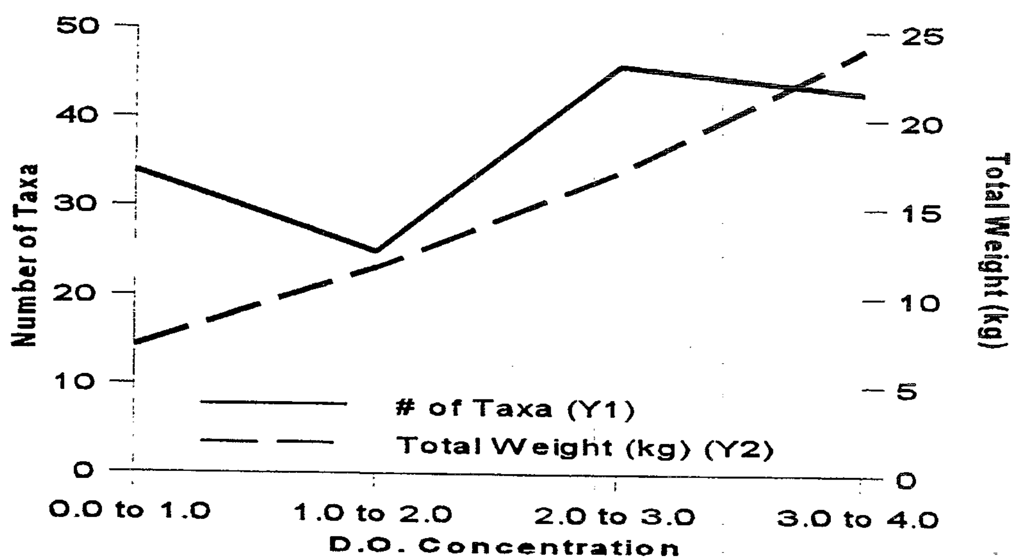

Figure 60.
Numbers of taxa and total weight of catch from LDWF trawl samples a at nearshore stations, 1978–1995.

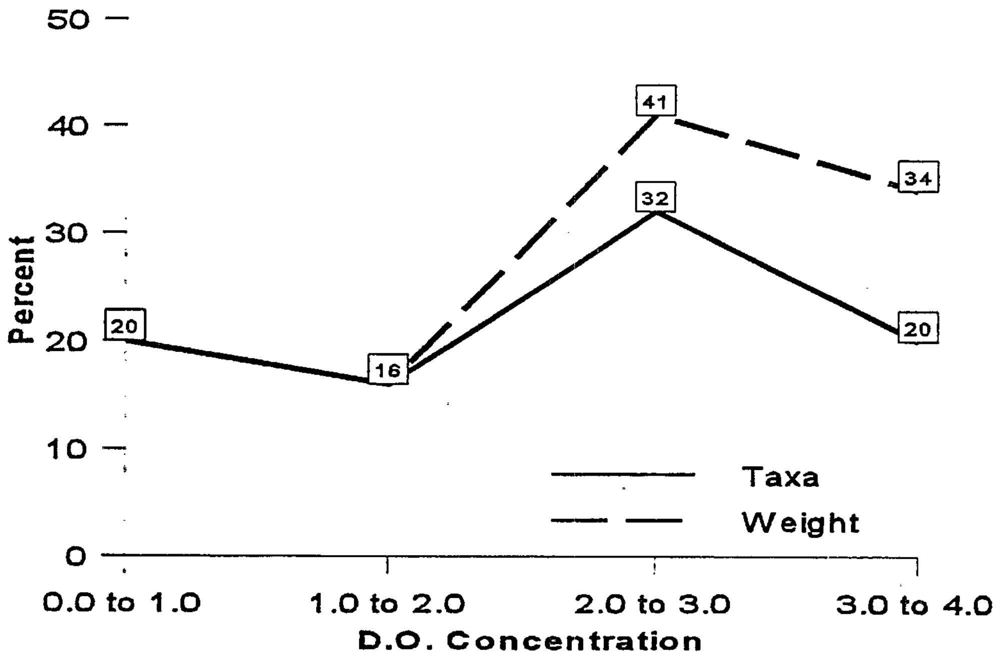

Figure 61.
Numbers of taxa and total weight of catch from LDWF trawl samples at nearshore stations, 1978–1995.

Presentation Discussion

Jim Hanifen (Louisiana Department of Wildlife & Fisheries)

Eugene Turner *(Louisiana State University—Baton Rouge, LA)* commented that the silicate and low dissolved oxygen relationship illustrates many of the problems encountered during large data set investigations. He believed there could be a surrogate which is represented by the silicate relationship demonstrated by a lag between the silicate and dissolved oxygen which have been shown by several models and analyses to be similar with the loadings in the river and hypoxia offshore. The silicate may be a surrogate for salinity or loading because the lower the salinity the higher the silicate. The silicate concentration has been relatively steady through the study year compared with previous years. However, that may be a result of stratification. The same relationship may be demonstrated if salinity were plotted against dissolved oxygen. Therefore, these types of studies should be conducted for more than one year. Unfortunately, funding for ten year studies is rarely available.

Estuarine Hypoxia: The Mobile Bay Perspective

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Abstract

Mass migrations of motile epifauna (e.g., crabs and demersal fish) up onto the shore of Mobile Bay have been documented in the popular literature since the mid-1800s. These events, referred to popularly as "jubilees," are now known to be a result of the movement of parcels of hypoxic and anoxic bottom waters towards shore caused by the winds and tides. Recent research has shown that these hypoxic/ anoxic waters are caused by high rates of oxygen consumption at the sediment surface combined with extremely strong salinity stratification in the water-column that effectively isolates the bottom water from oxygen available in the surface waters. For Mobile Bay, these factors serve to create an environment that is hypoxic approximately 50 percent of the time during the summer period. There does not appear to be a long-term trend (either positive or negative) in the duration of these low-oxygen events. Rather, the frequency and duration of hypoxia/ anoxia is related to short-term variations in the physical structure of the water-column. Despite the frequency of these events, fisheries landings in Mobile Bay remain high and researchers are now addressing the question of whether such events (that may help maintain highly productive "pioneer" communities) may have a beneficial effect on secondary production in the ecosystem.

No Manuscript Submitted.

Presentation Discussion

John Pennock (Dauphin Island Sea Lab—Dauphin Island, AL)

Don Boesch *(University of Maryland—Cambridge, MD)* asked the speaker if he could estimate how many of the Gulf's estuarine systems are at a stage where additional nutrient input would enhance useful production.

John Pennock replied that there are many systems, especially pristine grass bed systems, which presumably could sustain more plankton production. However, theoretically, those nutrient inputs could have a negative, as well as positive, effect on the grass beds. He said that more turbid systems, for example Delaware Bay, can sustain nutrient inputs better than many of the cleaner water systems on the Gulf.

Clive Walker ***(Natural Resources Conservation Service—Texas A&M University)*** stated that they used plots of fertilizer application versus corn production to demonstrate the threshold of benefit from fertilizers. These plots are very similar to the nutrient versus estuarine productivity plots shown in the presentation.

John Pennock said that these two concepts were very similar and it was necessary to link these concepts to resolve both the farmers' and the marine fisheries' issues.

Causes and Effects of Coastal Hypoxia Worldwide: Putting the Louisiana Shelf Events in Perspective

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Abstract

Global Patterns of Benthic Hypoxia and Anoxia: Causes, Responses, and Altered Energy Flows

Synthesis of literature pertaining to benthic hypoxia and anoxia (Diaz and Rosenberg, 1995) revealed that community and population responses to low dissolved oxygen stress were similar across all ecosystems and followed a hierarchical pattern. The occurrence of hypoxia and anoxia is expanding with significant structural and functional changes in affected benthic communities. Benthic-pelagic coupling is also adversely affected. No other environmental variable of such ecological importance to coastal marine ecosystems around the world has changed so drastically in such a short period as dissolved oxygen. While hypoxic and anoxic environments have existed through geological time, their occurrence in shallow coastal and estuarine areas appears to be increasing, most likely accelerated by human activities. The oxygen budgets of most major coastal ecosystems have been adversely affected mainly through the process of eutrophication, which acts as an accelerant or enhancing factor to hypoxia and anoxia. Many ecosystems that are now severely stressed by hypoxia appear to be near or at a threshold of imminent collapse (loss of fisheries, loss of biodiversity, lower system ascendancy).

Introduction

No other environmental variable of such ecological importance to coastal marine ecosystems around the world has changed so drastically in such a short period as dissolved oxygen. While hypoxic and anoxic environments have existed through geological time, their occurrence in shallow coastal and estuarine areas appears to be increasing, most likely accelerated by human activities. Synthesis of literature pertaining to benthic hypoxia and anoxia (Diaz and Rosenberg, 1995) revealed that the oxygen budgets of most major coastal ecosystems have been adversely affected mainly through the process of eutrophication, which acts as an accelerant or enhancing factor to hypoxia and anoxia. Many ecosystems that are now severely stressed by hypoxia appear to be near or at a threshold of imminent collapse (loss of fisheries, loss of biodiversity, lower system ascendancy). Hypoxic events on the Louisiana shelf will be discussed relative to world wide problems with low dissolved oxygen.

System Summaries

Limfjorden, Denmark

- Experiences seasonal summertime hypoxia.
- Oxycline can be sharp with >5.6 ml/l at 0.5 m and 0.4 ml/l at 0.05m above the bottom.

- Annual mass mortality and recolonization occurs.
- Also, Beggiatoa spp. occur in some areas all year.

Gullmarsfjord, Sweden

- Oxygen concentration has declined gradually from the 1950's but remained above 2 ml/l.
  - Fauna appeared stable up to 1979.
- During the winter of 1979 severe Hypoxia occurred, reaching 0.8 ml/l.
  - Fauna remained stable.
- Hypoxia continued and in January 1980 hypoxia reached 0.2 ml/l.
  - Mass mortality of fauna occurred.

Upwelling & Oxygen Minimum Zone

- Stable hypoxia associated with high quality organics.
- Leads to low diversity, but stable high abundance and biomass fauna.

Kiel Bay, Germany

- A declining trend in dissolved oxygen has been observed since 1950's.
- Periodic hypoxia began in the 1960's.
  - Mortality of fauna was observed.
- In 1981 and 1983 severe hypoxia occurred.
  - Mass mortality of fauna.
  - Shift in fauna to opportunistic species.
- The 1981 event was widespread in all parts of Kiel Bay, with H_2S and Anoxia at > 20 m.
  - Event was several weeks long.
- The result was mass mortality of benthos, 99 percent of biomass died.
  - 30,000 mt of macrofauna died, 750 km^2.

Kattegat, Sweden-Denmark

- Classic description of benthic communities from this area. Fisheries well developed.
- By the 1970's there was speculation that the ecosystem was not doing well.
- Annual hypoxia began in 1980.
  - First observations of fish and benthos mortality.
  - 1984 record high catches in trawl fisheries.
- Hypoxia was severe by 1985 and worsening.
  - Mortality of benthos, fisheries reduced to low levels.
- In 1988, 3,000 km^2 affected.
  - Mass mortality of benthos and fisheries, poor recovery.

LA-TX Continental Shelf

- Chronic mild hypoxia may have existed, no long-term data.
- The first measured hypoxic event was in 1973.
  - Reductions in fauna.
  - No mass mortality.
- In 1978 severe hypoxia occurred.
  - Mass mortality of benthos.
  - Shift to opportunistic species.
  - Low fishery catches.

- Currently 8,000–9,500 km^2 are affected annually.
  - Mass mortality of benthos.
  - Low fishery catches.

Black Sea

- Average depth of 1270 m, the largest mass of "naturally occurring" permanently anoxic water on earth.
- About 90 percent of its 5.4 × 105 km^3 volume is anoxic beginning at depths of 150 to 250 m.
- Permanently hypoxic below about 100 m
- Ukrainian northwestern Black Sea shelf is critically eutrophic, periodic hypoxia and anoxia is wide-spread encompassing all of the Sea of Azov and up to 95 percent of the Ukrainian northwestern shelf.
- Periodic events are distinct from the permanent anoxic layer and lead to mass mortalities of benthic populations that colonize the area during normoxic periods.
- In 1991, anoxia along the Romanian coast eliminated an estimated 50 percent of the demersal fish populations.
- Since the 1960's increasing hypoxia and anoxia have been blamed for the replacement of the highly valued demersal fish species with planktic omnivores.
- Of the 26 commercial species fished in the 1960's only 6 still support a fishery.

Baltic Sea

- Trend of declining oxygen concentrations was documented from the 1930's to the late 1960's in the deep basins.
- Beginning in the 1960's and lasting up to the present, large deep bottom areas of the Baltic Sea have been mostly permanently hypoxic or anoxic and devoid of benthic macrofauna.
- Below the halocline, at about 70 m, approximately 100000 km2 of the bottom is more or less permanently hypoxic.
- No significant change in the bottom water oxygen content has occurred up to 1993.
- Biomass "missing" in the anoxic areas estimated to be 1.7 × 106 t wet wt
- Periodic hypoxia in the mesohaline Bornholm Basin in the south Baltic was reported as early as 1948.
- Benthic communities were reduced and even eliminated during periods of hypoxia or anoxia and how bottoms were recolonized following a subsequent return of normoxia.

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Diaz, R.J. and R. Rosenberg. (In Press) Marine benthic hypoxia—review of ecological effects and behavioral responses on macrofauna. Oceanogr. Mar. Biol. Ann. Rev., vol. 33.

Presentation Discussion

Robert Diaz *(Virginia Institute of Marine Science—Gloucester Point, VA*

No questions/discussion following Mr. Diaz presentation

Table 5.

Summary of benthic effects for hypoxic systems around the world. Several of these systems also experience anoxia. In the case of many fjords, and coastal and oceanic oxygen minimum zones (OMZ) there is an anoxic zone within which no macrofauna occur. The absence of fauna from these anoxic zones is not considered a community response but a consequence of stable anoxia. Hypoxia is typed as: Aperiodic—events that are known to occur at irregular intervals greater than a year; Periodic—events occurring at regular intervals shorter than a year, related to tidal stratification/destratification cycles (Haas, 1977); Seasonal—yearly events relate to summer or autumnal stratification; Persistent—year-round hypoxia. Levels of hypoxia are: Moderate— oxygen decline to about 0.5 ml/l; Severe—decline to near anoxic levels, could also become anoxic. Time trends of hypoxia, areal and or intensity, for the systems are: -= Improving conditions; + = Gradually increasing; ++ = rapidly increasing; 0 = stable; . = no temporal data. Benthic community response is categorized as: None—communities appear similar before and after hypoxic event; mortality—moderate reductions of populations, many species survive; Mass Mort.—drastic reduction or elimination of the benthos. Benthic recovery is: No change—dynamics appear unrelated to hypoxia; Some—recolonization occurs but community does not return to prehypoxic structure; Slow—gradual return of community structure taking more than a year; Annual—recolonization and return of community structure within a year.

No.	System	Hypoxia Type	Hypoxia Level	Time Trends	Bent. Com. Response	Benthic Recovery	Fisheries Stocks	Reference
1	Deep Texas Shelf	Aperiodic	Moderate	0?	Mortality	Annual	Stressed	Harper et al. 1981, 1991
2	German Bight, North Sea	Aperiodic	Mod./Severe	+	Mass Mort.	Annual	.	Dethlefsen & Westernhgen 1983
3	New York Bight, New Jersey	Aperiodic	Severe	.	Mass Mort.	Slow	Surf Clam losses	Boesch & Rosenberg 1981, Garlo et al. 1979, Sindermann & Swanson 1980
4	Shallow Texas Shelf	Aperiodic	Severe	+	Mass Mort.	Slow	Stressed	Harper et al. 1981, 1991
5	Sommone Bay, France	Aperiodic	Severe	+?	Mass Mort.	Slow	Collapse of Cockle fishery	Desprez et al. 1992
6	North Sea, W. Denmark	Aperiodic	Severe	+	Mortality	Annual	Stressed	Dyer et al. 1983, Westernhagen & Dethlefson 1983
7	Peru/Chile, El Niño, shallow	Aperiodic	Severe	0?	Mass Mort.	???	Stressed	Rosenberg et al. 1983, Arntz & Fahrbach 1991
8	York River, Virginia	Periodic	Mod./Severe	0	None	No Change	Stressed	Pihl et al. 1991, Diaz et al. 1993
9	Rappahannock River, Virginia	Periodic	Severe	+	Mortality	Annual	Stressed	Llansó 1990
10	Seto Inland Sea, Japan	Seasonal	Moderate	.	Mortality	Annual	.	Imabayashi 1986
11	Louisianna Shelf	Seasonal	Mod./Severe	+	Mortality	Annual	Stressed	Boesch&Rabalais 91, Rabalais et al.1991
12	Saanich Inlet, British Columbia	Seasonal	Mod./Severe	0	Mortality	Annual	.	Tunnicliffe 1981
13	Bornholm Basin, S. Baltic	Seasonal	Mod./Severe	+**	Mass Mort.	Slow	.	Tulkki 1965, Leppäkoski 1969
14	Oslofjord, Norway	Seasonal	Mod./Severe	+	Mortality	Annual	Reduced	Petersen 1915, Mirza & Gray 1981 Rosenberg et al. 1987
15	Kattegat, Sweden-Denmark	Seasonal	Mod./Severe	++	Mass Mort.	Slow	Collapse Norway Lobster	Baden et al. 1990a, Josefson & Jensen 1992, Rosenberg et al. 1992
16	German Bight, North Sea	Seasonal	Severe	+?	Mortality	Annual	Stressed	Niermann et al. 1990
17	Main Chesapeake Bay, MD	Seasonal	Severe	+	Mortality	Annual	Stressed	Holland et al. 1987
18	Port Hacking, Australia	Seasonal	Severe	.	Mortality	Annual	.	Rainer & Fitzhardinge 1981
19	Tolo Harbor, Hong Kong	Seasonal	Severe	.	Mass Mort.	Annual	.	Wu 1982
20	Tome Cove, Japan	Seasonal	Severe	.	Mortality	Annual	.	Tsutsumi 1987
21	Laholm Bay, Sweden	Seasonal	Severe	++	Mortality	Annual	Stressed	Baden et al. 1990b, Rosenberg & Loo 1988
22	Gullmarsfjord, Sweden	Seasonal	Severe	+	Mass Mort.	Annual	Stressed	Josefson & Widbom 1988
23	Swedish West Coast Fjords	Seasonal	Severe	++	Mortality	Some	Stressed	Josefsen & Rosenberg 1988
24	Pamlico River, North Carolina	Seasonal	Severe	.	Mass Mort.	Annual	.	Tenore 1972
25	Limfjord, Denmark	Seasonal	Severe	+	Mass Mort.	Annual	None	Jørgensen 1980
26	Kiel Bay, Germany	Seasonal	Severe	+	Mass Mort.	Annual	Stressed	Arntz 1981, Weigelt 1990
27	Lough Ine, Ireland	Seasonal	Severe	0	Mass Mort.	Annual	.	Kitching et al. 1976
28	Hillsborough Bay, Florida	Seasonal	Severe	.	Mass Mort.	Annual	.	Santos & Simon 1980
29	Gulf of Trieste, Adriatic	Seasonal	Severe	++	Mass Mort.	Slow	Stressed	Stachowitsch 1991
30	Elefsis Bay, Aegean Sea	Seasonal	Severe	.	Mass Mort.	Annual	.	Friligos and Zenetos 1988
31	Black Sea NW Shelf	Seasonal	Severe	++	Mass Mort.	Annual	Reduced	Zaitsev 1993
32	Århus Bay, Denmark	Seasonal	Severe	+	Mass Mort.	Slow	.	Fallesen & Jørgensen 1991
33	Loch Creran, Scotland	Persistent	Severe	0	Mass Mort.	No Change	.	Pearson 1981
34	Byfjord, Sweden	Persistent	Severe	0	Mortality	Some	Pelagic only	Rosenberg 1990
35	Black Sea (except NW shelf)	Persistent	Severe	+	No Benthos	No Change	Pelagic only	Tolmazin 1985, Mee 1992
36	Idefjord, Sweden-Norway	Persistent	Severe	+#	Mortality	Some	.	Rosenberg 1980
37	Baltic Sea, Central	Persistent	Severe	++	Mortality	Some	Stressed	Andersin et al. 1978
38	Fosa de Cariaco, Venezuela	Persistent	Severe	.	Reduced	No Change	.	Nichols 1976
39	Caspian Sea	Persistent	Mod./Severe	0	Mortality	Some?	.	Zenkevitch 1963
40	Peru/Chile Upwelling Deep	Persistent	Mod./Severe	0	Biomass Increase	No Change	Enhanced?	Arntz & Fahrbach 1991 Rosenberg et al. 1983
41	Santa Maria Basin, California	Persistent	Mod./Severe	0	Reduced	No Change	.	Hyland et al. 1991
42	Central California OMZ	Persistent	Mod./Severe	0	Biomass Increase	No Change	.	Mullins et al. 1985
43	Volcano 7, Pacific OMZ	Persistent	Mod./Severe	0	Biomass Increase	No Change	.	Levin et al. 1991
44	Gulf of Finland, Deep	Persistent	Mod./Severe	-	Reduced	Slow	.	Andersin & Sandler 1991

* Stable oxygen gradient associated with organic enrichment.

** These systems are currently in a persistent hypoxic state.

\# Recent imporvements in oxygen concentrations due to pollution abatement.

Evidence for Nutrient Limitation and Sources Causing Hypoxia on the Louisiana Shelf

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Abstract

The conclusion that there has been an increase in the severity or areal coverage of summer oxygen depletion is dependent on knowledge of other coastal systems, nutrient limitations on the modern phytoplankton, and analysis of sedimentary records. Five hypotheses may explain these changes: 1) overland flow through coastal wetlands has been severely restricted this century, 2) Increased nutrient concentration in the Mississippi River since the 1950s, 3) intrusions of offshore waters causing a natural long-term variability that is misinterpreted as a permanent change, 4) Short- or long-term climate changes (riverine fluctuations), and, 5) increased loadings from estuarine sources. Based on the available data, the strong inference is that only Hypothesis No. 2 is sufficient to explain these changes in an efficacious and non-contradictory way.

Introduction

The conclusion that there has been an increase in the severity or areal coverage of summer hypoxia (e.g., Rabalais, et al., this volume) is dependent on knowledge of other coastal systems, nutrient requirements of phytoplankton, and analysis of sedimentary records. Six hypotheses are proposed to explain these changes: 1) overland flow through coastal wetlands has declined severely this century, 2) increased nutrient and organic loadings from estuarine sources, 3) intrusions of offshore waters causing a natural long-term variability that is misinterpreted as a permanent change, 4) short- or long-term climate changes (riverine fluctuations), 5) organic loading from the Mississippi River causes the lack of oxygen, and, 6) the increased nutrient concentration in the Mississippi River since the 1950s. Each of these hypotheses has been tested, and the results outlined in the following discussion.

Six Hypotheses

Hypothesis No. 1

Overland flow through coastal wetlands has been severely restricted this century by navigation and flood control levees on the Mississippi River. The consequence of this disruption in the natural (geologic) hydrology is to reduce the removal of nutrients from water flowing over and through coastal wetlands.

These hypotheses can be tested by examining the amount of flow restricted by these levees, determining the likelihood of nutrient removal in the area available, and comparing nutrient concentrations in the Mississippi River and receiving water bodies.

The amount of flow reduction from human-made levees was determined by Kesel (1988) as part of an effort to measure the effects on suspended sediment transport. He said:

> *"The proportion of water discharge above bankfull was computed from daily records and that proportion used to determine the suspended load carried by above bankfull flows. The amount of sediment during this period that would have been available for overbank flow was estimated to be 163.4 × 10^6 metric tons. This amounted to 14 percent of the suspended sediment carried during flood flows, but only 2.6 percent of the total suspended load carried during the entire 34-yr period."* (Kesel, 1988).

A 2.6 percent reduction in suspended sediment (and therefore nutrient) flow is thus an insignificant proportion of the total flow, which has also tripled in nitrate concentration. Furthermore, there is a mismatch of overland flow potential and river stage. Water levels on the marsh peak in late summer, whereas the peak river stage is in the spring. This mismatch minimizes, rather than maximizes any potential ability of wetlands to remove nutrients limiting phytoplankton growth.

Furthermore, the ability of coastal wetlands to absorb nutrients is not equal among wetland types, and, in fact, most of Louisiana's coastal wetlands appear to export the dissolved nutrient forms that limit phytoplankton growth (Table 6). In addition, the Louisiana experience is that the conditions necessary for optimum nutrient removal are not met (Table 7). There are simply not enough forested freshwater wetlands to remove even 10 percent of the historically low nutrient concentration (prior to 1950) through overland flow.

Table 6.
Import (I) and Export (E) of nitrogen and phosphorus from wetlands through overland flow (g m^{-2} y^{-}).

Location	Wetland	DN	TN	DIP	TP
Fourleague Bay	fresh		E-NO3 E-NH4 E-TKN	E	E
Bayou Chevreuil	swamp	I-NO3 I-NH4 E-DON	I-3.87	E-OP-0.1 E-TP-0.19	I-1.71
Barataria Bay	salt and brackish	E-NO3 E-NH4 E-DON	E-TKN	I	E
Fourleague Bay	salt and brackish	E-NO3 E-NH4 E-DON	E-TKN	E	E
Bonnet Carre'	fresh				

Table 7.
Nutrient removal optimization.

Favored by or indicated by	Louisiana Experience
Long contact time (days/week)	Short (1 day, Bonnet Carre', an engineered crevasse)
Sufficient area	Area restricted/limited by existing upland development and landowner concerns; not extensive relative to loading rates
Higher loading =less retention	Not documented in Louisiana, but is a general experience nationwide
Subsurface flow higher removal than surface flow	Nitrate and phosphate exported from all coastal wetlands *but* swamps

The conclusion is to reject Hypothesis No. 1.

Hypothesis No. 2
Nutrient and organic loadings from estuarine sources has released organic matter offshore in increasing amounts and caused hypoxic water formation offshore.

This hypothesis can be tested by examining the historical progression of estuarine eutrophication, the likelihood of estuarine-offshore exchanges, and the net fluxes.

Estuarine exchanges with offshore waters clearly exist. Evidence for this is the inverse relationship between estuarine salinity and Mississippi River discharge (Wiseman et al. 1990). Eutrophication of the estuaries has also occurred (Rabalais et al. 1995). Therefore, it is possible to exchange nutrients from inshore estuaries to offshore. However, if there were significant dominance of nutrients in either direction (offshore to inshore, or vice-versa), then the sedimentary record of diatom production in nearshore and estuarine sediments would be similar. The deposition/ accumulation of biogenic silica (a surrogate for diatom production) is strikingly different in both end members. The accumulation rate of BSi in estuarine waters reflects the use of fertilizer in the estuarine basin and the accumulation in offshore waters is coincidental with the nutrient loading from the Mississippi River (Turner and Rabalais 1994; Turner et al., unpublished). Thus, there is no coherence between nutrient loadings in the estuarine and offshore waters, and Hypothesis No. 2 is not supported. Further, a crude nutrient and carbon budget for estuarine and offshore waters is dominated by the in situ loadings, not the estuarine sources.

The conclusion is to reject Hypothesis No. 2.

Hypothesis No. 3
Intrusions of offshore waters cause a natural long-term variability that is misinterpreted as a permanent change.

This hypothesis can be examined by documenting physical connections between the oxygen minimum layer (OML; Figure 62) found throughout the open Gulf of Mexico and the continental shelf and determining the respiration rate in the OML.

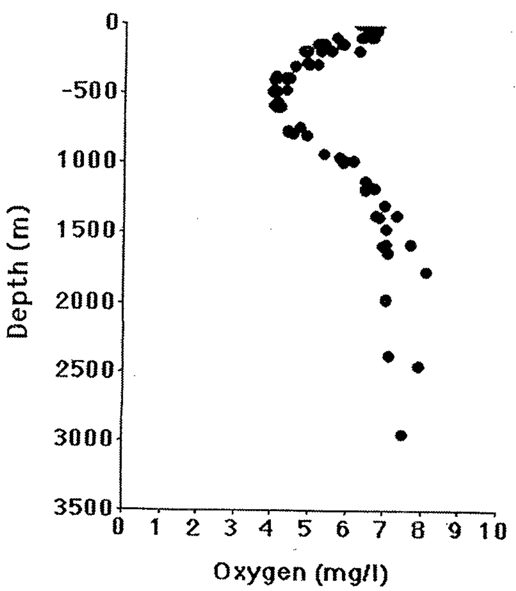

Figure 62.
The oxygen minimum layer in the open Gulf of Mexico.

Throughout years of data collection we cannot find a physical connection between the hypoxic water masses found in the OML within the GOM waters (Figure 62) and in continental shelf waters. Furthermore, the oxygen consumption rates in the OML are insufficient (by several orders of magnitude) to account for the observed seasonal decline in oxygen concentration on the shelf.

The conclusion is to reject Hypothesis No. 3.

> **Hypothesis No. 4**
> Short- or long-term climate changes (riverine fluctuations) occur and are mis-interpreted as an increase in hypoxia.

Hypothesis No. 4 is not supported by examination of the river discharge records (Figure 63) or the sea level rise records, which act as surrogates of major physical forcing functions on the continental shelf.

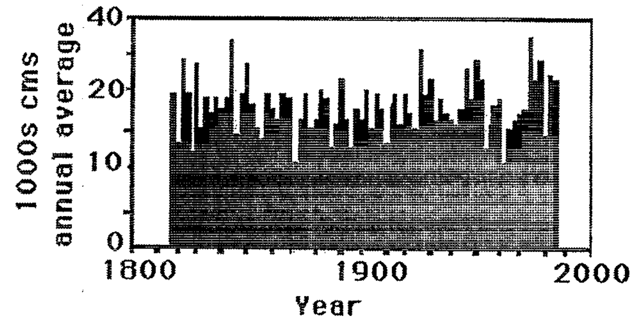

Figure 63.
The discharge of the Mississippi River at Vicksburg, Miss. from the middle of the last century to present.

The conclusion is to reject Hypothesis No. 4.

> **Hypothesis No. 5**
> Organic loading from the Mississippi River causes hypoxic water mass formation.

The amount of organic loading in the Mississippi River is not large enough to account for the observed decline in oxygen over such a large area. There is much more oxygen removed each summer than can be supported by carbon introduced by the river. Also, the chemical signature of the carbon ($^{12/13}C$ isotopic ratio) found in material from the collection devices placed in offshore waters, is different than in the carbon from the river.

The conclusion is to reject Hypothesis No. 5.

> **Hypothesis No. 6**
> Nutrient loading from the Mississippi River causes hypoxic water mass formation.

It appears that the nutrients in the Mississippi River have changed in the same scale and in the amounts necessary to cause the observed hypoxia (Figure 64; Turner and Rabalais 1991; Rabalais et al., 1996, in press). Indicators of oxygen stress are coincidental with the changes in increased organic loading, as well (Sen Gupta et al. 1996; Rabalais et al., 1996).

The conclusion is not to reject Hypothesis No. 6.

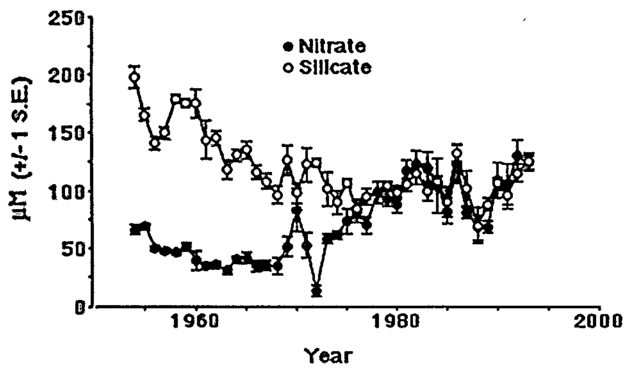

Figure 64.
Nitrate and silicate concentrations in the Mississippi River (from Rabalais et al., in press).

Summary

Based on the available data, there is a strong inference that only Hypothesis No. 6 is sufficient to explain these changes in a efficacious and non-contradictory way. Management measures based on Hypotheses No. 1–5 are likely to be wasted efforts.

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Presentation Discussion

Eugene Turner (Louisiana State University—Baton Rouge, LA)

Bob Wayland *(U.S. Environmental Protection Agency—Washington D.C.)* commented that Eugene Turner seemed to have taken a bottom-of-the-funnel approach to assessing wetland destruction or hydro modification of the river. He asked whether other changes which took place further up the river system might have also contributed to the problem and, therefore, reversal of those upriver problems might also be considered as part of the solution.

Eugene Turner agreed that the nitrate loading is a cause-and-effect relationship upriver as well. However, he pointed out that regardless of the cause (land-use changes are strongly implicated), the major issue is the loading at the river mouth.

Robert Wayland replied that he understood Eugene Turner was discussing overland flow and loss of the attenuation capacity of the wetlands in the lower river, but he was suggesting that the loss of riparian wetlands upstream might have also been a contributing factor.

Eddie Funderburg *(LSU Agricultural Center—Baton Rouge, LA)* opened his comment by saying that there have been multiple sources of nutrients identified as contributors to the river, yet the focus is primarily on fertilizers, particularly nitrogen fertilizers. He asked if there have been correlations developed for other sources, for example, wastewater treatment plants which have been brought on-line since 1950, automobile emissions, or gasoline consumption. It is possible that the graphic relationship would look similar to the relationship shown for nitrogen and phosphorous use.

Eugene Turner replied to his comment by saying that for each of the other sources there is not the same type of relationship or quantity from atmospheric sources as there is from fertilizer use. Atmospheric sources can, in fact, come off the farmland as ammonia and deposit as nitrate. The numbers from sewage plants demonstrate that the contributions are not as significant as the source material in terms of quantity.

Eddie Funderburg then asked Eugene Turner how 20 percent was derived as the amount of nutrient contribution from farmlands to the Mississippi River.

Eugene Turner replied that they assessed the change in nutrient loading and measured how much fertilizer was applied in each of those county/states in the drainage basin. To explain the changes of nitrate in the river, it is necessary to assess if enough fertilizer was applied in the drainage basin to account for the nitrate change in the river.

Finally, he said that there is enough fertilizer applied in the Mississippi River Basin to affect that change and that means that there needs to be only a 20 percent leakage from the system. No system has 100 percent retention efficiency. This is what is typically found in other rivers as well for agriculture systems.

Eddie Funderburg agreed there is some leakage, but questioned that Eugene Turner could demonstrate, using field studies, that 20 percent was moving from land into the Mississippi River.

Eugene Turner countered by saying that people have traced nitrogen isotopes and determined whole nitrogen budgets. In fact, one study was conducted in Iowa in the 1960's.

This conference may or may not decide that to reduce the load it is necessary to more quantitatively determine the exact sources so that risk analyses and cost benefit analyses can be conducted.

Len Bahr made a general comment saying the last two papers presented touched upon an important issue. Unfortunately, the format of the conference was not set up to really discuss the theoretical questions. He said the coastal restoration program is not driven by the hypoxic zone. The need to restore and mitigate wetland losses of 35 square miles per year is reason enough for the program to exist. The theoretical bonus of being able to reduce some of the eutrophication of the nearshore waters is real and should be explored. It should be a major part of the next conference on the hypoxia area.

Lon Strong ***(USDA/NRCS—Jackson, MS)*** reiterated a comment made by Eugene Turner that Mitch and his co-author stated that subsurface flow systems were a lot more efficient than surface flow systems. He asked Eugene Turner if he was referring to man-made or natural systems.

Eugene Turner said that because the contact time is increased, it is a general observation that natural systems, where effluent flows below ground, were more efficient than above ground systems.

Ann Burruss ***(Coalition to Restore Coastal Louisiana—Baton Rouge, LA)*** asked how the nitrogen concentration in the upper part of the Barataria Bay would compare to the concentration in the Mississippi River.

Eugene Turner replied that the nitrogen concentration in the upper part of Barataria Bay is much lower than in the Mississippi River. The concentrations were calculated by doing a transect for the past year and will continue for another year or two. There are 37 stations offshore as far as Bayou Seville.

Estimated Responses of Water Quality on the Louisiana Inner Shelf to Nutrient Load Reduction in the Mississippi and Atchafalaya Rivers

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Abstract

The addition of anthropogenic nutrients from sewage, industrial sources, agriculture and overland runoff has contributed to development of eutrophication in the coastal waters of the northern Gulf of Mexico. The principal source of these nutrients is the Mississippi-Atchafalaya River (MAR) system, the largest single source of freshwater and nutrient inputs to the coastal waters of the United States. An extensive, persistent zone of seasonal hypoxia has been documented in the nearshore bottom waters of the Louisiana-Texas continental shelf.

As part of the NOAA Nutrient Enhanced Coastal Ocean Productivity (NECOP) Program, a mass balance water quality model was applied to the Louisiana Inner Shelf (LIS) portion of the northern Gulf of Mexico. The model was calibrated to field data representing summer average conditions in 1985, 1988 and 1990. As part of the EPA Gulf of Mexico Program, predictive simulations were conducted with the calibrated model to estimate responses of dissolved oxygen and chlorophyll concentrations to potential reductions in nutrient loadings from the MAR system. The objectives of this analysis were to determine whether water quality on the LIS was sensitive to changes in MAR nutrient loadings and to estimate the approximate magnitudes of potential reductions in nutrient loadings that might be necessary to improve present water quality conditions. Results indicated that dissolved oxygen and chlorophyll concentrations on the LIS were responsive to reductions in MAR nitrogen and phosphorus loadings. For a given reduction in MAR nutrient loadings there were large uncertainties in response magnitudes. These uncertainties were due primarily to uncertainties in relationships among MAR nutrient loadings, seaward boundary conditions and sediment oxygen demand, and to inter-annual variability in hydrometeorology.

Background

The addition of anthropogenic nutrients from sewage, industrial sources, agriculture and surface runoff has contributed to development of eutrophication in the coastal waters of the northern Gulf of Mexico. The principal source of these nutrients is the Mississippi–Atchafalaya River (MAR) system, the largest single source of freshwater and nutrient inputs to the coastal waters of the United States. An extensive, persistent zone of seasonal hypoxia has been documented in the nearshore bottom waters of the Louisiana–Texas continental shelf.

As part of the NOAA Nutrient Enhanced Coastal Ocean Productivity (NECOP) Program, a mass balance water quality model was developed and applied to the Louisiana Inner Shelf (LIS) portion of the northern Gulf of Mexico (Figure 65) (Bierman et al., 1994). The model was calibrated to field data representing summer average conditions in 1985, 1988 and 1990. As part of the EPA Gulf of Mexico Program, predictive simulations were conducted with the calibrated model to estimate responses of dissolved oxygen and chlorophyll concentrations to potential reductions in nutrient loadings from the MAR system (Limno–Tech, Inc., 1995).

Objectives

The objectives of this analysis were to determine whether water quality on the LIS was sensitive to changes in MAR nutrient loadings and to estimate the approximate magnitudes of potential reductions in nutrient loadings that might be necessary to improve present water quality conditions, especially seasonal hypoxia. The purpose of this analysis was not to establish target nutrient loading objectives, but to determine the potential range of nutrient loading reductions that may need to be evaluated in future studies. An important part of this analysis was investigation of uncertainties due to differences in environmental conditions and external boundary conditions.

Modeling Framework

The conceptual framework for the modeling approach is shown in Figure 66. State variables in the model include salinity, phytoplankton carbon, phosphorus, nitrogen, dissolved oxygen and carbonaceous biochemical oxygen demand. The spatial domain of the model is represented by a 21-segment water column grid extending from the Mississippi River Delta west to the Louisiana Texas border, and from the shoreline seaward to the 30–60 meter bathymetric contours (Figure 67). The spatial segmentation grid includes one vertical layer nearshore and two vertical layers offshore. The temporal domain of this model application represents steady-state, summer-average conditions.

Approach to Predictive Simulations

The calibrated water quality model was run for a series of predictive simulations. These simulations involved a range of reductions from 10 to 70 percent on nitrogen and phosphorus loadings from the MAR system. Emphasis was placed on comparison of results to base calibration conditions, not on absolute predictions.

To address uncertainties due to differences in environmental conditions, separate simulations were conducted for July 1985, August 1988 and July 1990 for each load reduction. The most important differences among these three summer average calibration periods were differences in MAR inflows and freshwater advective flow magnitudes and directions on the LIS. To address uncertainties in specification of external boundary conditions, each load reduction simulation was conducted under two separate sets of assumptions: first, all seaward and sediment boundary conditions held constant at base calibration values; and second, all seaward and sediment boundary conditions reduced by the same percentage as the nutrient loading in each simulation.

The rationale for two different assumptions on boundary conditions was twofold: first, these forcing functions are not computed by the model but must be externally specified using available field data; and second, values for these forcing functions are not independent of MAR nutrient loadings, but can be expected to decrease as MAR nutrient loadings decrease.

This approach was intended to bracket results of the predictive simulations between present conditions and estimates of future conditions for these forcing functions.

Assumptions

Results of the predictive simulations in this summary are premised on the following principal assumptions:

1. The actual environmental system is fully represented by the conceptual framework of the model.

2. Nitrogen and phosphorus are the only nutrients that potentially limit primary productivity.

3. The actual environmental system is represented at the coarse spatial scale of the model segmentation grid. Near-field gradients in the vicinity of the Mississippi and Atchafalaya River plumes, and near-bottom hypoxia, are not explicitly represented.

4. The actual environmental system is represented in terms of a single "snapshot" in time corresponding to an assumed summer average, steady-state period. The potential influences of meteorological events, shelf-edge upwellings and mesoscale shelf circulation are not explicitly represented.

5. All predictive results represent estimates of future states of the system and do not contain any information on the time frame required for the system to fully respond to imposed changes in nutrient loadings.

6. All predictive results for reduced boundary conditions assume that seaward and sediment boundary conditions will eventually hange by the same percentage as the imposed changes in nutrient loadings.

The results presented in this summary are preliminary results from an ongoing research program and should be considered provisional in nature.

Results of Predictive Simulations

The principal water quality response parameters were bottom water dissolved oxygen concentrations and surface water chlorophyll concentrations. Results are presented in terms of comparisons among different years, different response parameters, and loading reductions for different nutrients. All comparisons are made using the average of dissolved oxygen responses for individual bottom offshore segments (Segments 15–21) and the average of chlorophyll responses for individual surface offshore segments (Segments 8–14).

Predicted responses of average dissolved oxygen and chlorophyll concentrations to nitrogen load reductions are strongly dependent on assumptions for boundary conditions. For example, in response to 70 percent nitrogen loading reductions for 1985 conditions, average dissolved oxygen concentrations increase by less than 10 percent for constant boundary conditions and 35 percent for reduced boundary conditions (Figure 68). For the same predictive simulations, average chlorophyll concentrations decrease by less than 10 percent for constant boundary conditions and 60 percent for reduced boundary conditions (Figure 69).

There are substantial differences in responses of average dissolved oxygen concentrations among different years. For example, in response to 70 percent nitrogen loading reductions, average dissolved oxygen concentrations increase by 150 percent for 1990 conditions and 35–40 percent for 1985 and 1988 conditions under reduced boundary conditions (Figure 70). In contrast to dissolved oxygen responses, there are not large differences in average chlorophyll concentration responses among different years. In response to 70 percent nitrogen loading reductions, average chlorophyll concentrations decrease by 60–70 percent under reduced boundary conditions (Figure 71).

In general, there are not large differences in responses of dissolved oxygen or chlorophyll concentrations between nitrogen and phosphorus loading reductions. There was a tendency, however, for responses to be somewhat greater for nitrogen loading reductions than phosphorus loading reductions, especially for dissolved oxygen responses under reduced boundary conditions.

There was no evidence of significant interactions between nitrogen and phosphorus loading reductions in the predictive simulations. Results of simulations in which nitrogen and phosphorus loadings were reduced simultaneously were generally consistent with results of simulations in which the more limiting of the two nutrients was reduced by itself. That is, if nitrogen was more limiting than phosphorus for a particular load reduction and set of boundary conditions, then results for this simulation were not significantly different when nitrogen and phosphorus loadings were reduced simultaneously by the same percentage.

For 1985 hydrometeorological conditions and reduced boundary conditions, average chlorophyll concentrations are less responsive than average dissolved oxygen concentrations at intermediate (10 to 30 percent) nitrogen loading reductions, and more responsive at higher (50 to 70 percent) nitrogen loading reductions (Figure 72). Differences in responses for 1988 conditions follow patterns very similar to those for 1985 conditions. In contrast to results for 1985 and 1988, average dissolved oxygen responses for 1990 are much greater than average chlorophyll responses for a given nitrogen loading reduction under reduced boundary conditions (Figure 73). These differences occur across the entire range of nitrogen loading reductions from 10 to 70 percent. Differences in maximum responses between these two cases are plus 150 percent (dissolved oxygen) and minus 70 percent (chlorophyll).

Discussion

The responses of dissolved oxygen and chlorophyll concentrations to reductions in nutrient loadings from the MAR system are complex functions of internal model processes and external model forcing functions. Part of this complexity is due to the fact that chlorophyll and dissolved oxygen are non-conservative and are each tightly coupled to other state variables in the model. Another aspect of this complexity is that dissolved oxygen concentration is much more strongly influenced by sediment boundary conditions, primarily sediment oxygen demand, than is chlorophyll concentration. Finally, there is considerable uncertainty in seaward and sediment boundary conditions for both the model calibration periods and the prediction simulations.

The reasons for differences in responses between dissolved oxygen and chlorophyll concentrations are very complex. One reason is that the relative influence of MAR nutrient inputs, seaward boundary conditions and bottom boundary conditions differ between the dissolved oxygen and chlorophyll state variables in the model. Another reason is that dissolved oxygen is coupled to more state variables in the model than chlorophyll. Under reduced boundary conditions, for example, dissolved oxygen responses represent the integrated effects of simultaneous changes not only in dissolved oxygen processes per se, but also of changes in carbonaceous biochemical oxygen demand, phytoplankton carbon (through endogenous respiration) and ammonia nitrogen (through nitrification). Still another factor is that surface chlorophyll and bottom dissolved oxygen concentrations are coupled through the dependence of underwater light attenuation on phytoplankton self-shading. That is, reductions in surface water chlorophyll concentrations can stimulate bottom water primary productivity due to increased light penetration, and hence cause increases in bottom water dissolved oxygen concentrations.

Conclusions

The following principal conclusions were drawn from the data synthesis and modeling simulations conducted in this study:

1. Dissolved oxygen and chlorophyll concentrations on the LIS appear responsive to changes in MAR nitrogen and phosphorus loadings.

2. For a given reduction in MAR nutrient loadings, there are large uncertainties in the magnitudes of dissolved oxygen and chlorophyll concentration responses.

3. Uncertainties in the magnitudes of dissolved oxygen and chlorophyll concentration responses are due to three principal factors:

   a. uncertainty in the relationship between MAR nutrient loadings and seaward boundary conditions

   b. uncertainty in the relationship between MAR nutrient loadings and sediment oxygen demand

   c. inter-annual variability in hydrometeorological conditions on the LIS.

4. Responses of average dissolved oxygen concentrations were more sensitive to differences in sediment oxygen demand than to differences in any other boundary conditions.

5. Responses of average chlorophyll concentrations were more sensitive to differences in seaward boundary conditions than to differences in sediment nutrient boundary conditions.

6. Although differences in results between nitrogen and phosphorus loading reductions were generally not large, there was a tendency for responses to be somewhat greater for nitrogen loading reductions than phosphorus loading reductions, especially for dissolved oxygen under reduced boundary conditions.

7. Estimates of water quality responses to changes in MAR nutrient loadings must be premised on specific assumptions for hydrometeorological conditions on the LIS.

Recommendations

On the basis of the data synthesis and modeling simulations conducted in this study, the following principal recommendations are made:

1. The temporal domain of the present water quality model should be extended to include a time-variable representation of water quality conditions on the LIS during the period of vertical stratification.

2. The vertical scale of the present model segmentation grid should be refined to better represent near-bottom hypoxia on the LIS.

3. The spatial domain of the present model segmentation grid should be extended so that its seaward boundaries are beyond the influence of freshwater and nutrient inputs from the Mississippi and Atchafalaya Rivers.

4. Advective flows and dispersive mixing coefficients in the model should be determined using the output of a hydrodynamic model.

5. The conceptual framework of the model should be expanded to include dissolved oxygen processes in the sediment and an explicit dissolved oxygen mass balance between water column and sediment segments.

6. The conceptual framework of the model should be expanded to include diatom and non-diatom phytoplankton functional groups, and silicon as a potential limiting nutrient.

References

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Limno-Tech, Inc. 1995. Estimated Responses of Water Quality on the Louisiana Inner Shelf to Nutrient Load Reductions in the Mississippi and Atchafalaya Rivers. Report prepared for Louisiana State University and A&M College, Baton Rouge, Louisiana, and submitted to U.S. Environmental Protection Agency, Gulf of Mexico Program Office, Stennis Space Center, Mississippi.

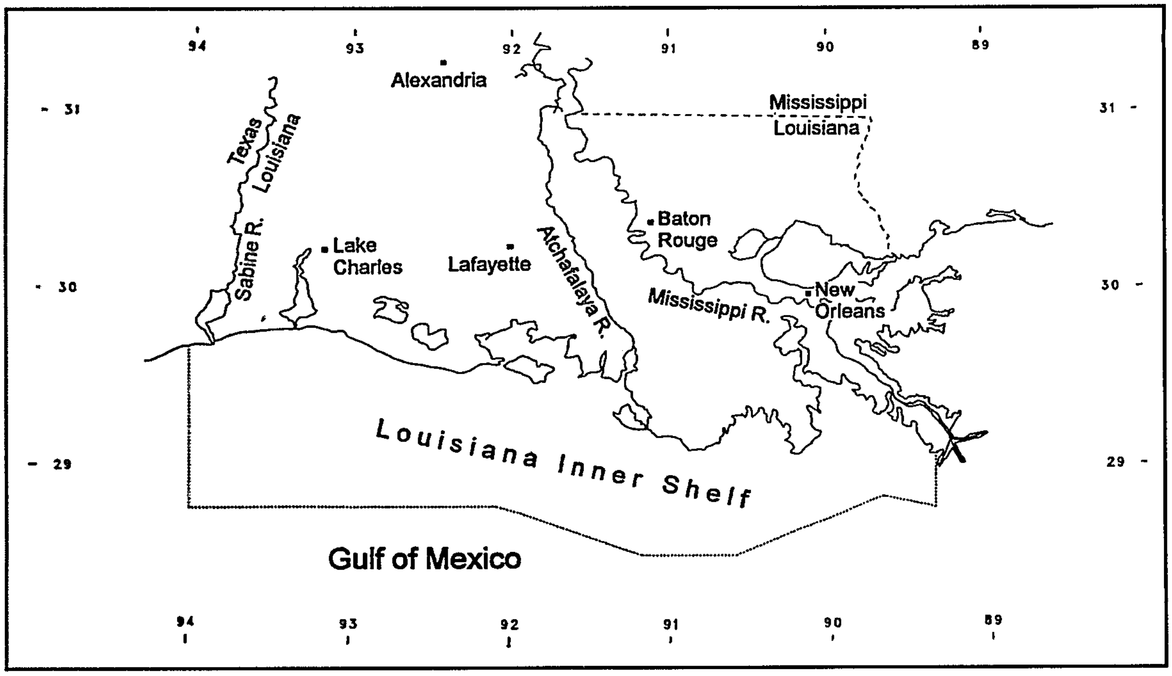

Figure 65.
Location map of study area.

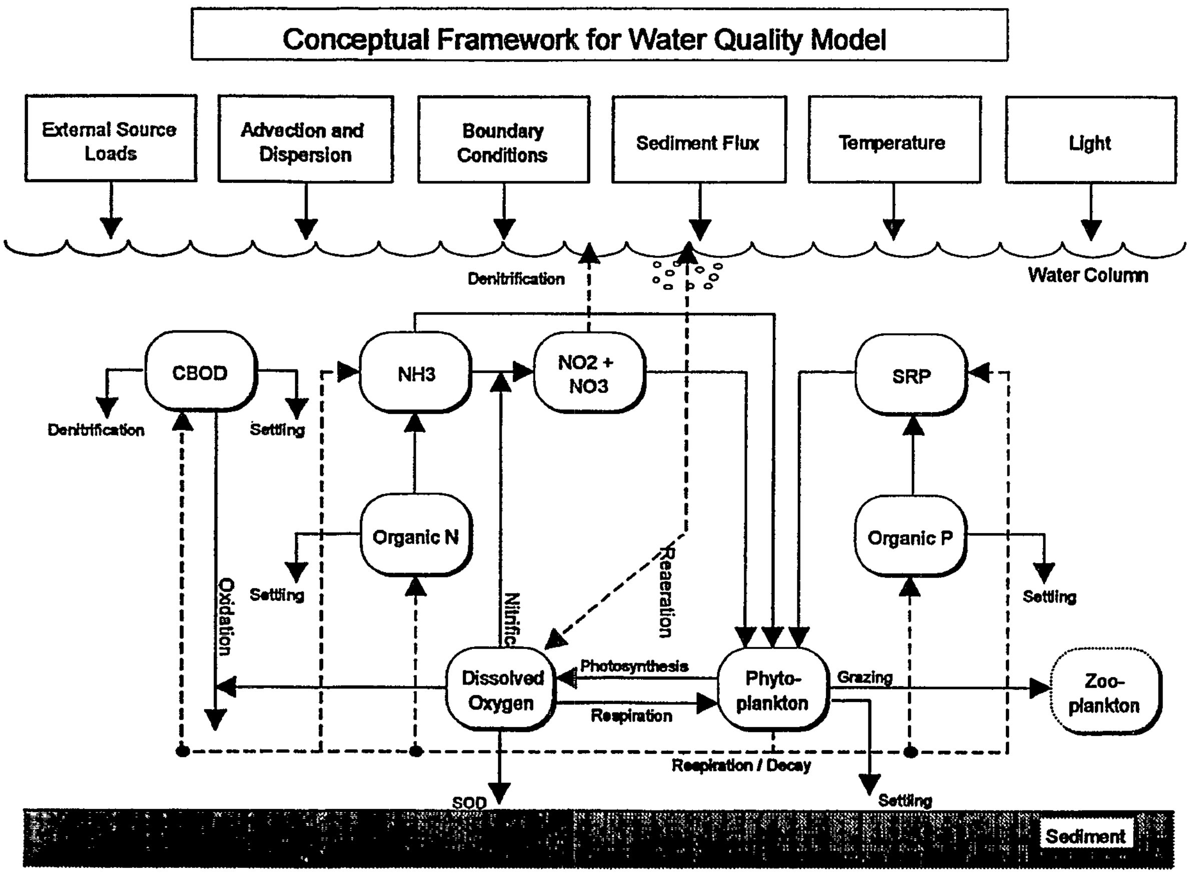

Figure 66.
Schematic diagram of principal model state variables and processes.

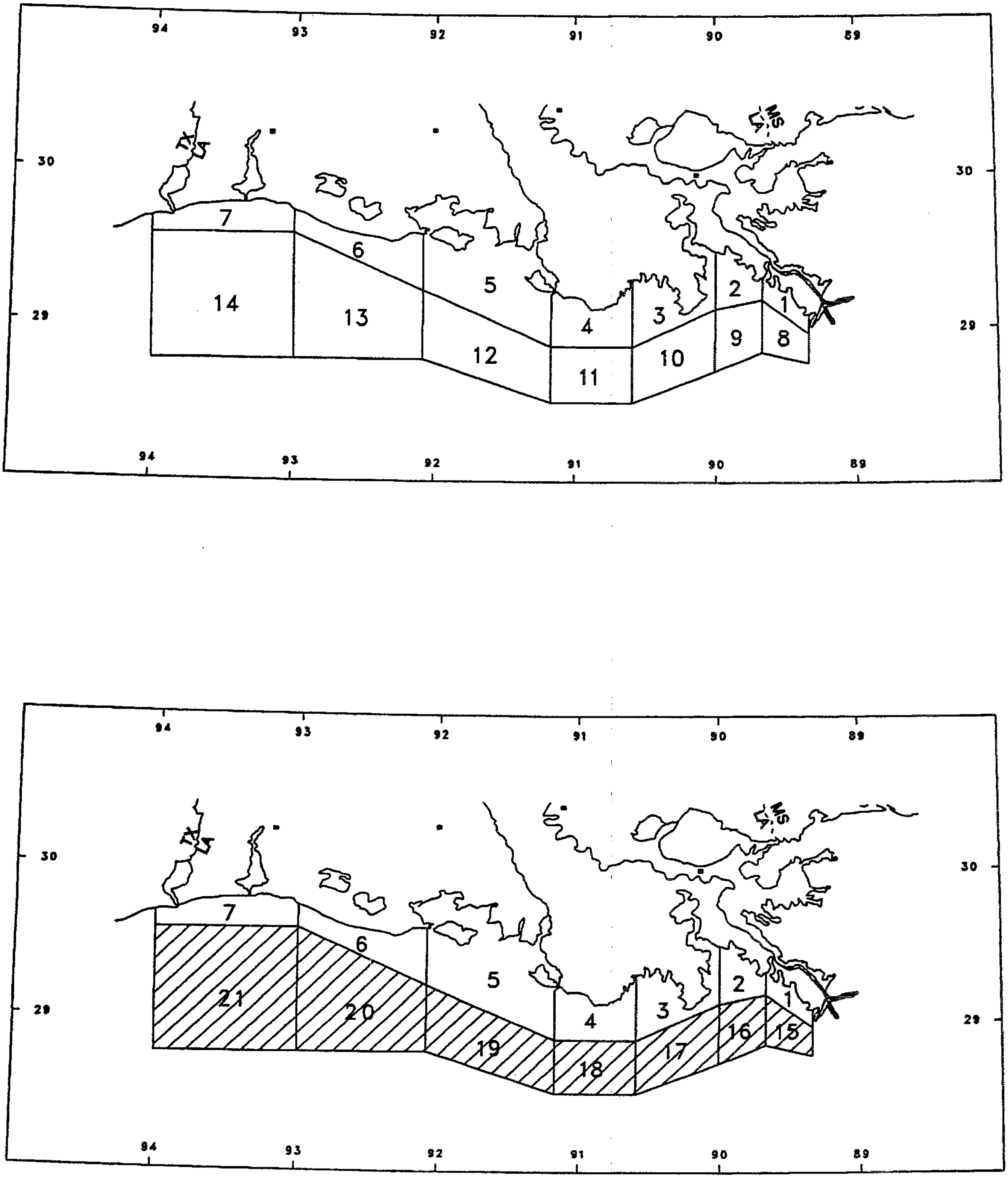

Figure 67.
Model spatial segmentation grid for the Louisiana Inner Shelf.

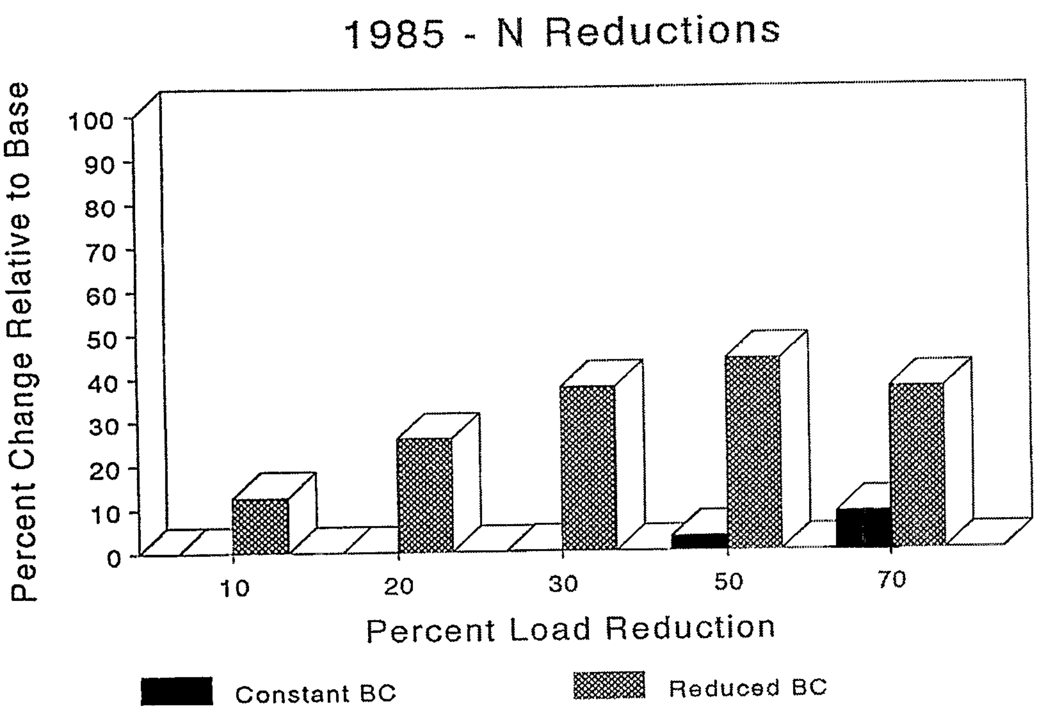

Figure 68.
Predicted responses of average dissolved oxygen concentrations to nitrogen loading reductions for 1985 conditions under constant and reduced boundary conditions.

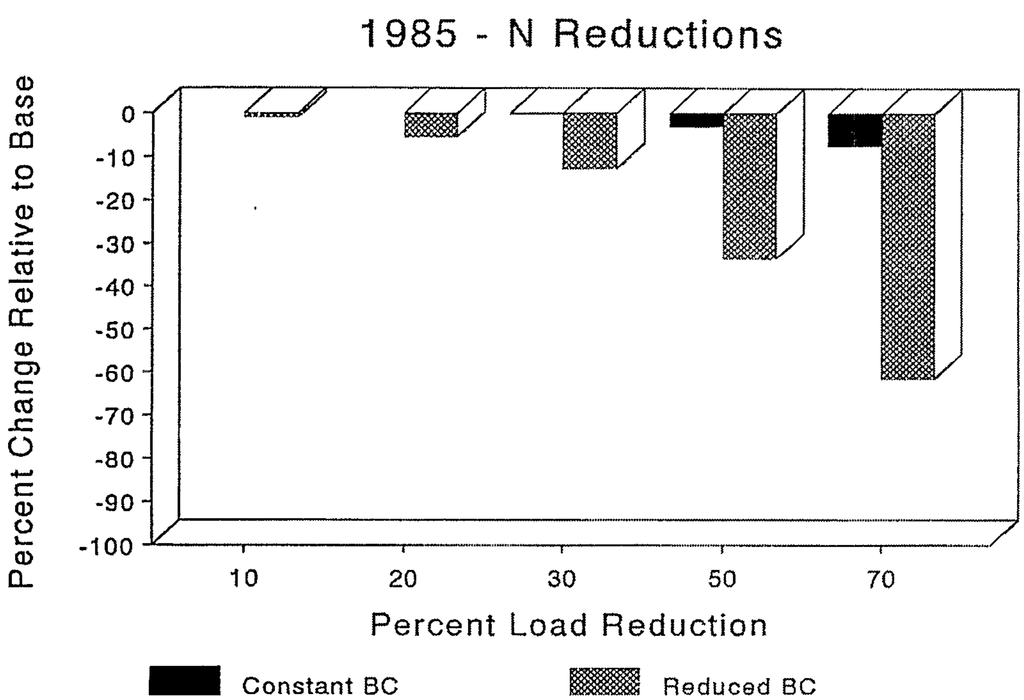

Figure 69.
Predicted responses of average chlorophyll concentrations to nitrogen loading reductions for 1985 conditions under constant and reduced boundary conditions.

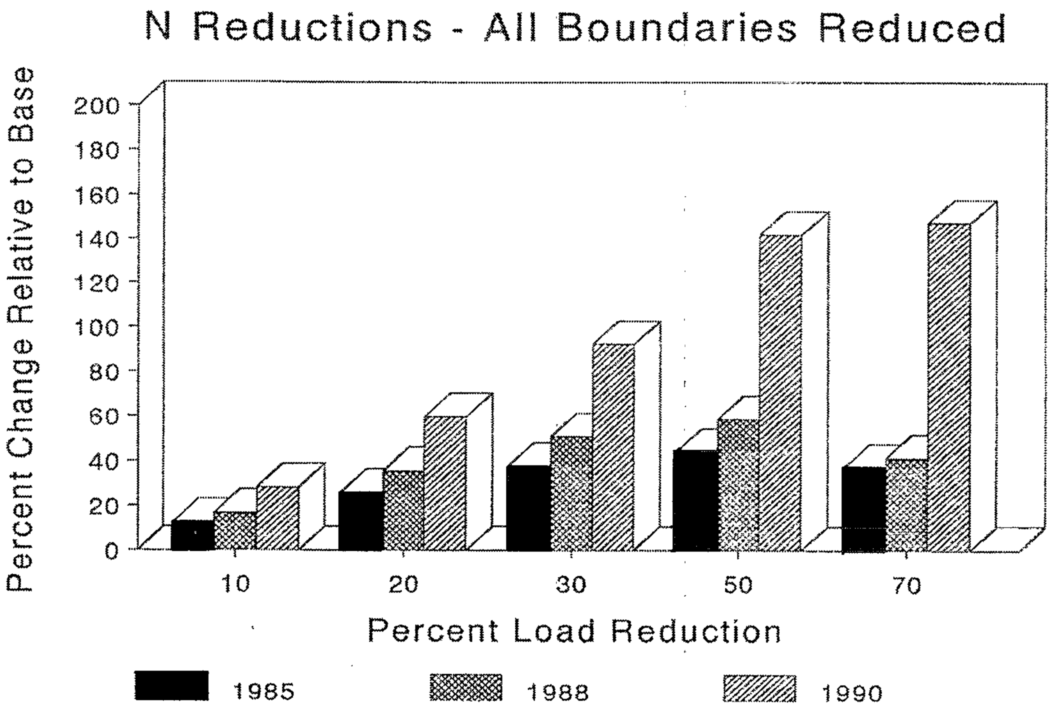

Figure 70.

Predicted responses of average dissolved oxygen concentrations to nitrogen loading reductions for 1985, 1988 and 1990 conditions.

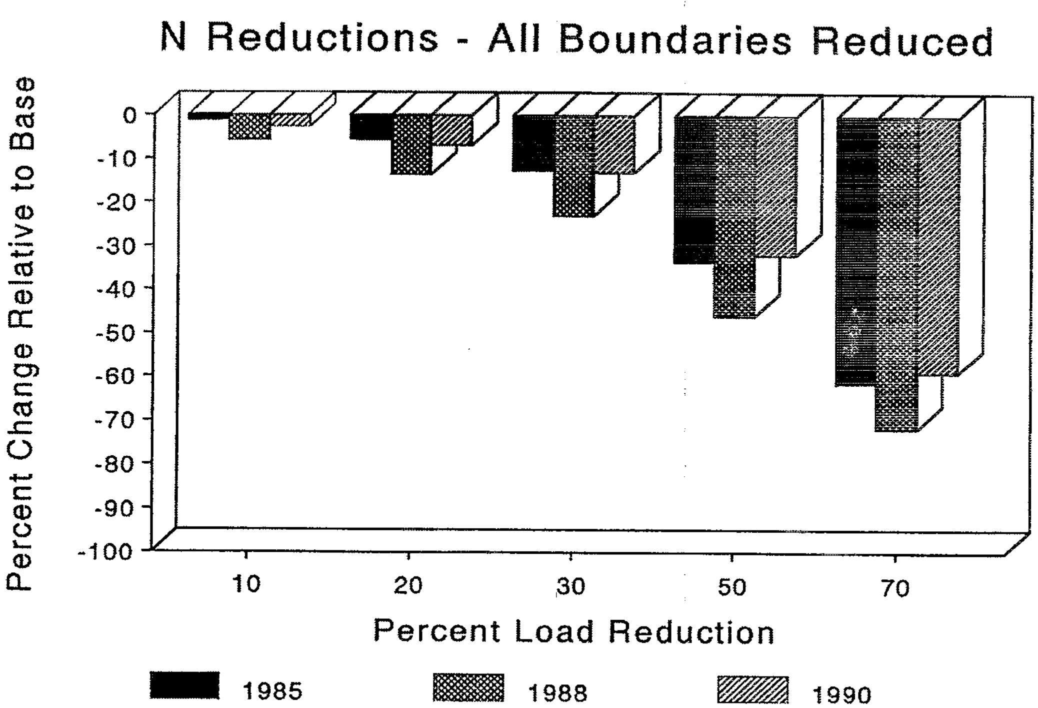

Figure 71.

Predicted responses of average chlorophyll concentrations to nitrogen loading reductions for 1985, 1988 and 1990 conditions.

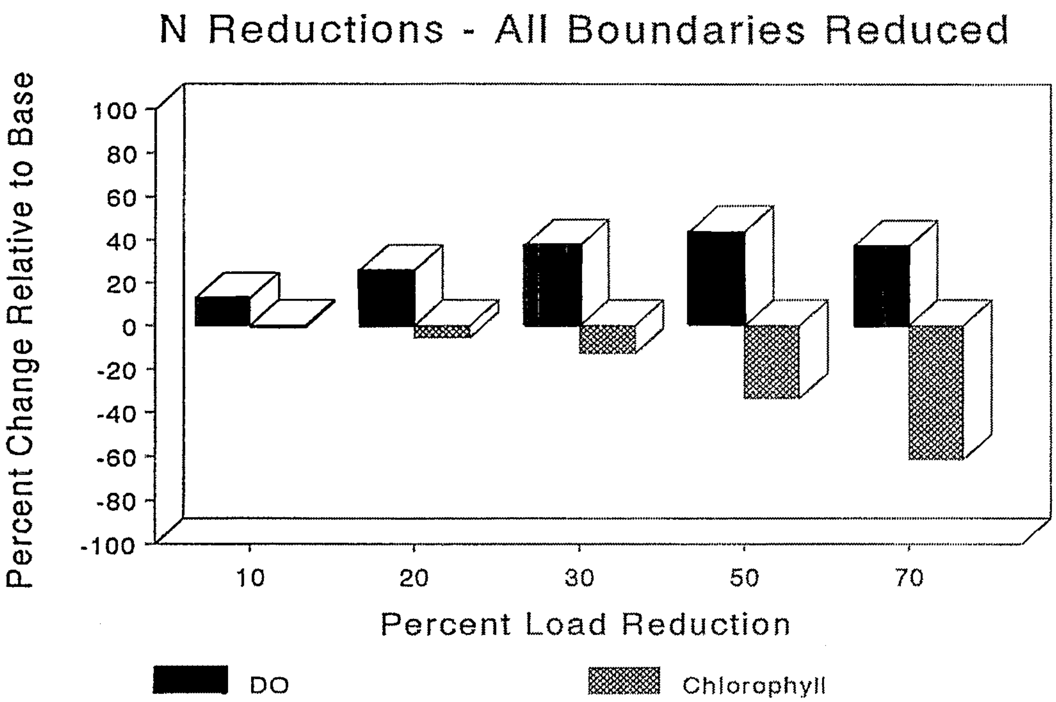

Figure 72.
Predicted responses of average dissolved oxygen and chlorophyll concentrations to nitrogen loading reductions for 1985 conditions.

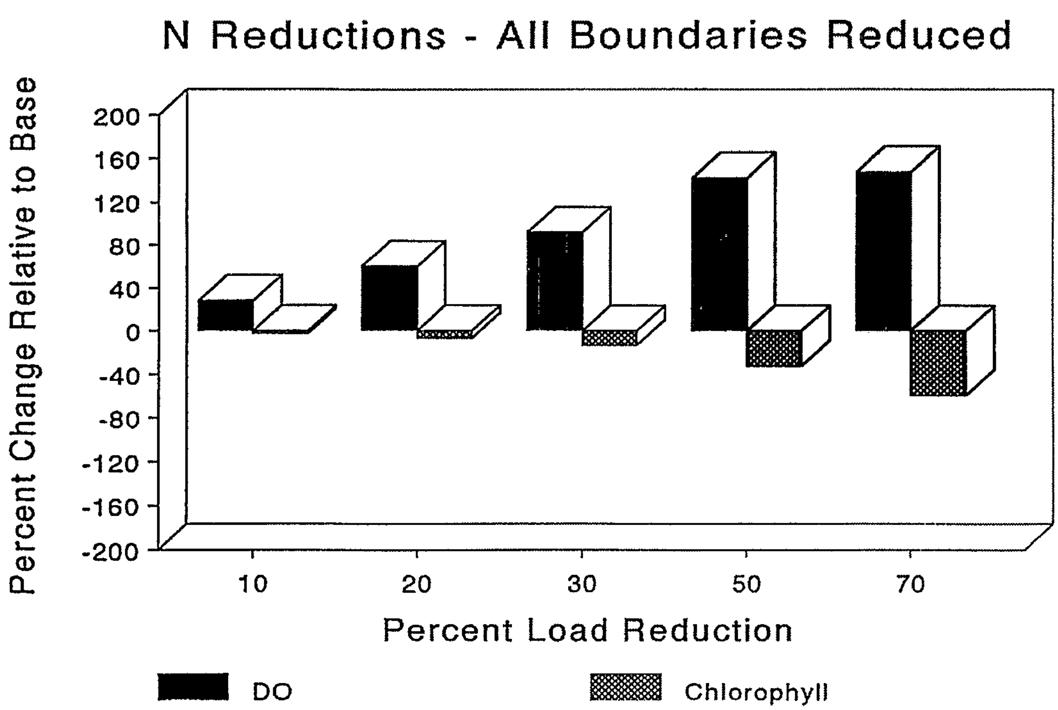

Figure 73.
Predicted responses of average dissolved oxygen and chlorophyll concentrations to nitrogen loading reductions for 1990 conditions.

Presentation Discussion

Vic Bierman (Limno-Tech, Inc.—South Bend, IN)

Mr. Bierman left conference due to an emergency.

John Day
Louisiana State University
Baton Rouge, Louisiana 70803

Abstract

No abstract submitted.

No manuscript submitted.

Presentation Discussion

John Day (Louisiana State University—Baton Rouge, LA)

Nancy Rabalais *(Louisiana State University—Baton Rouge, LA)* asked if John Day knew what the partitioning was of the freshwater outflow through the Atchafalaya Bay because her offshore data (which is limited) indicates that the nutrients (in Fourleague Bay) are central and west of study area due to the long shore current movement and they are entering the Gulf through the Atchafalaya Bay area.

John Day responded that the estimates of partitioning are from five to ten percent flow through the study area, and it is possible that the flow goes in the direction she indicated, but there is a lack of information to determine for certain.

Daniel Ray *(The McKnight Foundation—Minneapolis, MN)* asked if all the wetlands need to be located in the Gulf or if sufficient uptake would occur if the wetlands were located closer to the flood plain.

John Day responded that the solution to the problem is not just in the Delta, bust also for upstream, and that nitrate can be removed very rapidly.

Don Boesch *(University of Maryland—Cambridge, MD)* commented that some of what has been shown is the sink of nitrogen and some of it is conversion of organic nitrogen into ammonium. He then asked what the net permanent loss was through de-nitrification or burial of nitrogen, in Fourleague Bay as opposed to a marsh.

John Day replied that he has talked to some people regarding this topic and has found that usually among concentrations of nitrogen, ammonium, and TKN, nitrate is much higher; in excess of 50 percent. Someone has looked at their wetland systems and almost 90 percent goes to denitrification. It is possible that more than 50 percent is lost through denitrification in Fourleague Bay.

Len Bahr *(Louisiana Governor's Office - Baton Rouge, LA)* commented that if the losses in the Atchafalaya are approximately 30 percent, and the lower Mississippi losses are 70 percent, and one is constrained during the spring, and one has no seasonal constraints, a synoptic study of nutrient dynamics down both branches extending to the nearshore area would be useful. There should be more nutrient uptake calibrated for the different flows of sediment levels in the Atchafalaya.

John Day agreed, saying that the study was absolutely necessary before further work on the project can proceed.

The Regional Transport of Point and Nonpoint-Source Nitrogen to the Gulf of Mexico

Richard B. Alexander, Richard A. Smith, and Gregory E. Schwarz
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Abstract

The quantification of the regional transport of nutrients to the Gulf of Mexico is important to developing management strategies for reducing the hypoxic zone observed in recent summers on the Louisiana coastal shelf. Although existing research clearly identifies the Mississippi and Atchafalaya Rivers as the primary conduits for nutrients, the origin (type and location) of the sources of nutrients in these rivers is less certain. Better estimates of the quantities of point- and nonpoint-source nutrients delivered to the Gulf of Mexico from interior watersheds could improve the efficiency of management strategies.

To assist in identifying the origin of stream nutrients nationally, we developed a water-quality model of nutrient flux in rivers of the United States. This model allows us to estimate the origin of point and nonpoint source nutrient flux at numerous locations on the coastal margin including the outlets of the Mississippi and Atchafalaya Rivers. The regression-based water-quality model relates monitored nutrient flux from 430 watersheds to various measures of upstream pollutant loadings, such as industrial and municipal discharges, fertilizer application, animal manure, and atmospheric deposition. The monitored watersheds range in size from several hundred to several tens of thousands of square miles. Flux estimates are developed from regularly-collected season nutrient measurements and daily estimates of streamflow using log-regression rating curve techniques. The estimated loadings of nonpoint-source nutrients to streams include the effects of watershed physical characteristics including precipitation, soil permeability, and topography. The model also estimates the first-order decay of nutrients during the transport of point and nonpoint sources through a digital stream network of nearly one million kilometers and 60,000 reaches. These decay rates reflect time-of-travel estimates from field studies and the residence time of water in major reservoirs.Through application of the model to unmonitored reaches, we estimate the quantities of point and nonpoint source nutrients delivered to the Gulf from several interior watersheds of the Mississippi and Atchafalaya Basins, including the Missouri, Arkansas, Upper Mississippi, and Ohio River Basins. All model predictions are accompanied by estimates of statistical error.

Introduction

In recent summers, a large area of very low dissolved oxygen concentrations (i.e., the hypoxic or "dead" zone) has appeared on the Louisiana coastal shelf (Rabalais and others, 1994). Although researchers have observed linkages between the nutrient-enriched waters of the Mississippi and Atchafalaya Rivers and spatial and temporal variations in the hypoxic zone (e.g., Rabalais and others, 1994; Justic and others, 1993), the origin of nutrients in these rivers is uncertain. The development of efficient management strategies for reducing the hypoxic zone depends on better estimates of the point and nonpoint-source nutrients delivered to the Gulf from interior watersheds of these rivers.

We developed a water-quality model of nutrient flux in rivers of the United States to assist in quantifying the origin of stream nutrients nationally. This model allows us to estimate the origin of point- and nonpoint-source nutrient flux at numerous locations on the coastal margin including the outlet of the Mississippi River. The regression-based water quality model relates monitored total nitrogen flux from 430 watersheds to various measures of upstream pollutant loadings, including industrial and municipal treatment plant discharges, fertilizer application, animal manure, and atmospheric deposition (R2= 0.83). The monitored watersheds range in size from several hundred to several tens of thousands of square miles. Mean estimates of flux for the period 1985-88 were computed from regularly-collected seasonal nutrient measurements and daily estimates of streamflow using log-regression rating curve techniques. The estimated loadings of nonpoint-source nutrients to streams include the effects of watershed physical characteristics including precipitation, soil permeability, and topography. The model also estimates the first-order decay of nutrients during the transport of point and nonpoint sources through a digital stream network of nearly one million kilometers and 60,000 reaches. These decay rates reflect time-of-travel estimates from field studies and the residence time of water in major reservoirs.

Through application of the model to the Mississippi River and its tributaries, we estimated the quantities of total nitrogen delivered to the Gulf from several interior watersheds including the Missouri, Ohio, White/Red, and the Upper, Central, and Lower Mississippi River Basins (Figure 74). These estimates indicate that more than 70 percent of the total nitrogen delivered to the Gulf by the Mississippi River originates above the confluence of the Ohio and Mississippi Rivers. This nitrogen is transported over distances of more than 1000 miles. The Upper and Central Mississippi Basins, which include portions of the states of Minnesota, Wisconsin, Iowa, Missouri, and Illinois, account for the largest quantity of nitrogen (39 percent) delivered to the Gulf. Smaller fractions originate in the Ohio (22 percent) and the Missouri (11 percent) River Basins. Downstream from the Mississippi/Ohio River confluence, the Lower Mississippi Basin, which drains portions of the states of Tennessee, Arkansas, Missouri, Mississippi, and Louisiana, contributes nearly a quarter of the nitrogen to the Gulf, whereas the White/Arkansas River Basins contribute six percent of the nitrogen.

The development of economically efficient nitrogen removal strategies in the Mississippi River Basin requires consideration of many factors, including the benefits (i.e., nitrogen reductions) expected from the application of controls in different interior watersheds. Estimates of each watershed's contribution of nitrogen to the Gulf per unit of drainage area (i.e., yield; see Figure 75) may be used to approximate the level of benefits to the Gulf expected per unit of drainage area receiving controls. Accordingly, the largest benefits to the Gulf per unit area controlled would be expected from nutrient controls applied in the Lower, Central, and Upper Mississippi River Basins where per unit area nitrogen contributions exceed those in the Ohio, White/Arkansas, and Missouri Basins by more than a factor of two. Although the Lower Mississippi Basin accounts for less than 25 percent of the Mississippi River's nitrogen contribution to the Gulf, the benefits of nutrient controls in this basin would be expected to be more than twice as large as those in other watersheds. The large per unit area nitrogen contribution from the Lower Mississippi Basin (Figure 75) reflects the comparatively small drainage area of the basin and its proximity to the Gulf which lead to fewer losses of nitrogen.

In applying the nutrient model, we separately tracked the contributions of point and nonpoint sources of stream nitrogen to the Gulf. On the basis of these analyses, we estimate that approximately 90 percent of the nitrogen delivered to the Gulf by the Mississippi River originates from nonpoint sources consisting predominantly of nitrogen in agricultural runoff and atmospheric deposition. More detailed applications of the nutrient model will be needed to resolve the relative importance of these two sources. Only about one percent of the nitrogen comes from point sources in the effluent of municipal treatment plants and industries. The remaining nitrogen delivered to the Gulf (9 percent) is from unknown sources as estimated by the intercept of the regression model. These unspecified sources may potentially include inputs of nitrogen from ground water.

References

Justic, D., Rabalais, N.N., Turner, E.R., and Wiseman, W.J., 1993, Seasonal Coupling Between Riverborne Nutrients, Net Productivity and Hypoxia, Marine Pollution Bulletin, v. 26, no. 4, pp. 184-189.

Rabalais, N.N., Turner, R.E., Wiseman, W.J., Justic, D., Dortch, Q., and Gupta, B.S., 1994, Hypoxia on the Louisiana Shelf and System Responses to Nutrient Changes in the Mississippi River: A Brief Synopsis, in National Oceanic and Atmospheric Administration, Nutrient-Enhanced Coastal Ocean Productivity, Proceedings of the 1994 Synthesis Workshop, Baton, Rouge, Louisiana.

Total Nitrogen Flux to the Gulf of Mexico from Interior Watersheds of the Mississippi River Basin Standardized for Drainage Basin Size

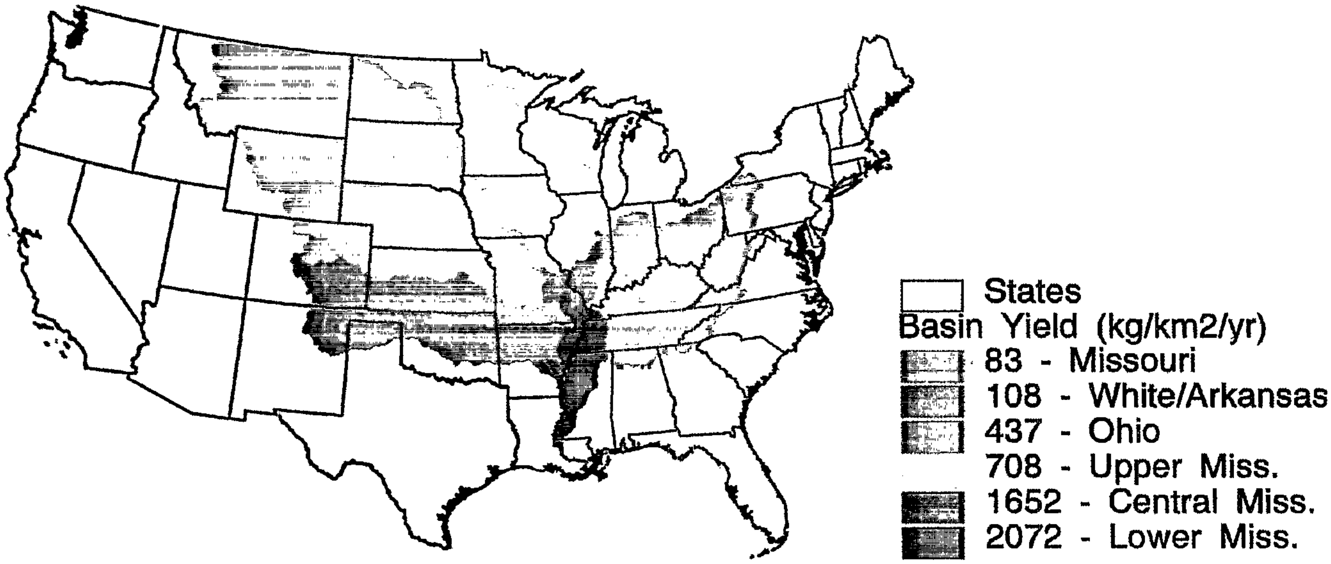

Figure 74.
The U.S. Geological survey recently estimated the quantities of total nitrogen delivered to the Gulf of Mexico from several interior watersheds of the Mississippi River. These estimates, based on river monitoring data and a regression-based water-quality model, indicate that more than 70 percent of the nitrogen originates above the confluence of the Ohio and Mississippi Rivers and is transported over distances of more than 1000 miles. Downstream from the Mississippi/Ohio River confluence, the Lower Mississippi and the White/Arkansas River Basins contribute nearly 30 percent of the nitrogen. Model estimates also indicate that approximately 90 percent of the nitrogen delivered to the Gulf by the Mississippi River originates from nonpoint sources. Of the remaining nitrogen, one percent is from point sources and nine percent is from unknown sources.

Percentage of the Mississippi River Total Nitrogen Flux to the Gulf of Mexico from Interior Basins

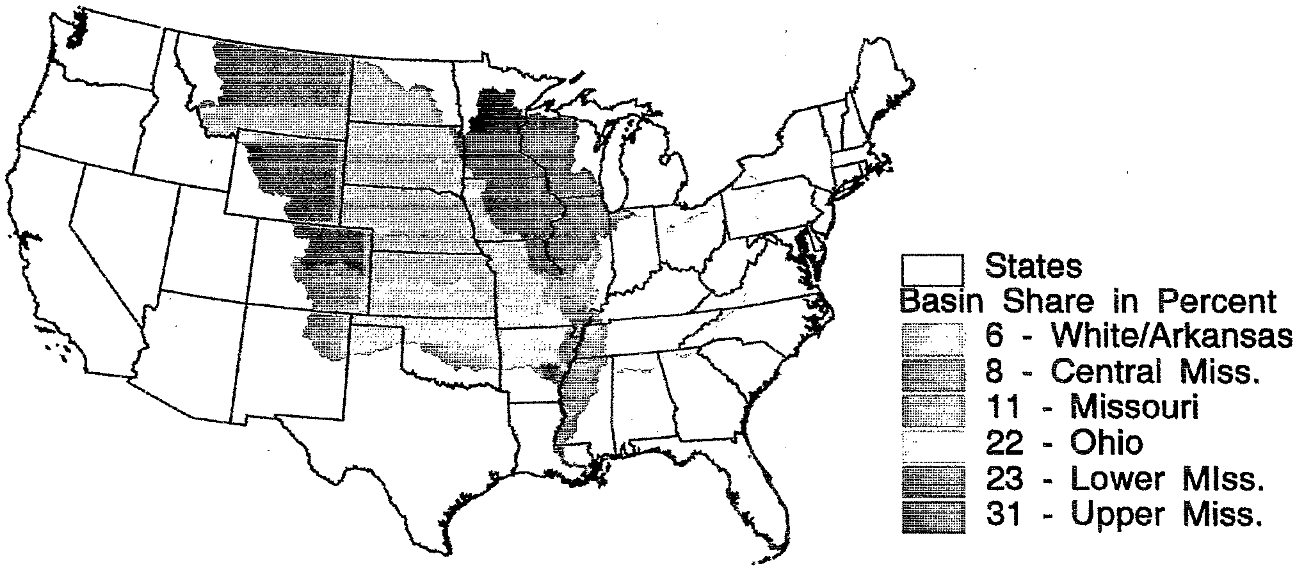

Figure 75.

Estimates of the quantities of total nitrogen delivered to the Gulf of Mexico from several interior watersheds of the Mississippi River per unit of drainage area (kilograms/square kilometer/year) can be used to approximate the level of benefits (i.e., nitrogen reductions) to the Gulf expected per unit of drainage area receiving controls. Developing economically efficient nitrogen removal strategies in the Mississippi Basin requires consideration of many factors, including the benefits expected from the application of controls in different interior watersheds. The largest benefits to the Gulf per unit area controlled would be expected from nutrient controls applied in the Lower, Central, and Upper Mississippi River Basins where per unit area nitrogen contributions exceed those in the Ohio, White/Arkansas, and Missouri Basins by more than a factor of two. Although the Lower Mississippi Basin accounts for less than 25 percent of the Mississippi River's nitrogen contribution to the Gulf (see Figure 74), the benefits of nutrient controls in this basin would be expected to be more than twice as large as those in other watersheds due in part to the Lower Mississippi Basin's proximity to the Gulf.

Presentation Discussion

Richard Alexander (U.S. Geological Survey—Reston, VA)

Fred Bryan *(National Biological Survey/ LSU)* asked if the value Richard Alexander presented for Nitrogen contribution to the river load by the Mississippi River Basin represented a cumulative value or had the contribution of the rest of the watershed been subtracted.

He also speculated that the relative contribution of point and nonpoint source loadings in the lower basin could be estimated by examining the Red-Atchafalaya River System. Most of the point sources in the lower basin are in the industrial corridor between Baton Rouge and New Orleans. Only three or four point sources from Alexandria are in the Red-Atchafalaya system and since the Atchafalaya is 70 percent Mississippi River water by volume, the nonpoint source load could be estimated by comparing the loading in the Red-Atchafalaya system with the loading in the Mississippi River below New Orleans.

Richard Alexander responded to Fred Bryan's question by saying that 23 percent that he cited for total nitrogen is a net contribution. The Arkansas and White Rivers, as well as the upper basin, are subtracted from that value.

In response to Fred Bryan's comment, Richard Alexander replied that they chose not to look at the Atchafalaya, mainly because they do not have a monitoring station at the outlet that meets the criteria for load estimation. He agreed that it is something that needs to be examined and if they did have a monitoring station there it could be included in the budget and the analysis Fred Bryan referred to could be conducted.

Spatial Distribution of Nutrients in the Mississippi River System (1991–1992)

Ronald C. Antweiler and Howard E. Taylor
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Denver Federal Center
Denver, Colorado

Abstract

Concentrations of dissolved nutrients (nitrate, nitrite, ammonium and orthophosphate) were measured on surface-water grab samples collected at ten mile intervals along the entire length of the navigable portion of the Mississippi River during three cruises in June–July 1991, September–October 1991 and March– April 1992. Samples were also collected at the mouths of some of the major tributaries and, at selected points, three-sample cross sections were collected across the river to measure cross-channel variability. Simultaneously with collecting each sample, the discharge of the Mississippi River was estimated, permitting the calculation of the nutrient load in the Mississippi River at each sample point. The large number of samples collected (between 179 and 207 per cruise) give a picture of the instantaneous longitudinal variation of nutrients in the Mississippi River during three different seasons.

Both nitrate and orthophosphate loads appear to increase or remain constant downriver for each cruise, indicating that mechanisms for the removal of these compounds are not as rapid as their introduction into the river. In addition, below the confluence of most of the major tributaries, the loads show a "step" increase caused by the nitrate and orthophosphate contributions from the tributaries. From this data, one can identify the possible sources of nitrate and orthophosphate arriving at the Gulf of Mexico from the Mississippi River. During each of the three cruises (at three different seasons), the majority of the nitrate and orthophosphate appears to have originated from the Upper Mississippi River Basin, above the confluence of the Missouri River.

Ammonium and nitrite loads appear to originate as point-sources, but disappear within approximately one hundred miles of their introduction, probably as a result of conversion to nitrate and/or nitrogen gas. Any nitrite or ammonium from the Mississippi River deposited into the Gulf of Mexico therefore probably originated within one hundred miles of the Gulf.

Introduction and Methodology

Three sampling cruises were taken on the Mississippi River, originating near New Orleans, Louisiana and finishing in Minneapolis, Minnesota during June 23 to July 2, 1991, September 25 to October 4, 1991 and March 25 to April 4, 1992. One purpose of these cruises was to study how concentrations and transport of the dissolved nutrients nitrate, nitrite, ammonium and orthophosphate ions varied longitudinally in the Mississippi River and at the mouths of some of its major tributaries. Concentrations of these dissolved nutrients were measured on surface-water grab samples collected at ten-mile intervals along the entire length of the navigable portion of the Mississippi River. These data can be used to evaluate the potential effects that nutrients have on the Mississippi River system and on the Gulf of Mexico.

Grab samples collected from the upper three meters of the river were taken every ten miles (about once an hour) from the center of the river channel. In addition, samples were collected from the mouth of some of the major tributaries; at selected locations, three samples were collected along cross-sections to measure cross-channel variability. Samples were collected from the river with a clean 2-liter Teflon bottle placed in a weighted aluminum holder and were then transferred into pre-cleaned 250-ml opaque polyethlene bottles. All samples were immediately filtered through nylon or Nuclepore polycarbonate membrane filters with a 0.4-μm nominal pore diameter, and then either chilled (for immediate analysis) or frozen for transport to the laboratory. No chemical preservatives were used.

Analyses were performed on an Alpkem air-segmented continuous-flow colorimetric analysis system, Model RFA-300, as described in greater detail by Antweiler et al. (1994). Determinations were always performed in duplicate; if the two determinations did not agree within the variance of the method, the sample was reanalyzed, again in duplicate. Analyses were supplemented by the determination of standard reference materials and calibration standards to evaluate precision and accuracy. Details of all the above information are given by Antweiler et al. (1995a).

The discharge of the river was estimated at the time of sample collection (Moody, 1995), permitting the calculation of the nutrient load in the Mississippi River at each sample point. The large number of samples collected (about 200 per cruise) in the short time periods (about ten days per cruise) give a picture of the near instantaneous longitudinal variation of nutrients in the Mississippi River during three different seasons.

At three sites on the Mississippi River—Clinton, Iowa, Thebes, Missouri and Baton Rouge, Louisiana—and near the mouths of three tributaries (the Ohio River at Grand Chain, Illinois, the Missouri River at St. Charles, Missouri and the Illinois River at Valley City, Illinois), nutrient samples were collected biweekly from April 1991 to September 1992. These samples were discharge-weighted laterally-composited samples collected in glass or stainless steel containers. They were filtered through a 0.45-μm membrane filter immediately after collection, preserved with mercuric chloride and shipped chilled to the USGS National Water Quality Laboratory, Denver, CO, for analysis. These samples were analyzed using an automated colorimetric procedure (Fishman and Friedman, 1989). Details of both the sampling protocol and analyses can be found in Coupe et al. (1995).

Results

The results of these studies are tabulated by Antweiler et al. (1995a) and Coupe et al. (1995) and described by Antweiler et al. (1995b). The distribution of nitrate and orthophosphate ion concentrations appear to be similar for all three cruises. Concentrations are low above Minneapolis, increase rapidly below the confluence with the Minnesota River (due to its relatively high concentrations compared to the Mississippi River, around mile 1800), generally decrease through southern Minnesota and

Wisconsin (miles 1500–1800), increase through Iowa (miles 1250–1500), remain nearly constant through Missouri (miles 950–1250), decrease at the confluence with the Ohio River (mile 950), and generally remain constant downstream to the Gulf of Mexico (Figure 76). In terms of transport (or loads: they are synonymous terms), these two compounds demonstrate some important features. Both nitrate and orthophosphate loads appear to either increase or remain constant downriver for each cruise, indicating that mechanisms for the removal of these compounds are not as rapid as their introduction into the river. In addition, below the confluence of most of the major tributaries, the loads show a "step" increase caused by contributions from the tributaries (Figure 77).

The data collected biweekly at six sites in the Mississippi River Basin also provide information concerning the transport of nutrients in the Mississippi River. Nitrate transports based on these data are shown in Figures 78 and 79. The pattern of nitrate transport of nitrate at Thebes, Missouri (just above the confluence with the Ohio River) is similar to the pattern at Baton Rouge, Louisiana, during the entire sampling period although the quantity of nitrate at Thebes is less than at Baton Rouge (Figure 78). In contrast, the quantity of nitrate at the mouth of the Ohio River (Figure 79) is considerably less than in the Mississippi River at Thebes, and comparable with that from the Missouri and Illinois Rivers.

From the biweekly and upriver cruise data, one can postulate the possible sources of nitrate and orthophosphate arriving at the Gulf of Mexico from the Mississippi River. By integrating the biweekly data over the course of the year, April 1991 to April 1992, and assuming that 30 percent of the Mississippi River is diverted into the Atchafalaya River above Baton Rouge, Louisiana, it is apparent that the majority of the water originates from the Ohio River (38 percent) and the Lower Mississippi River—the Mississippi River below the confluence with the Ohio River (28 percent) (Figure 80). However, the majority of the nitrate appears to have originated from the Upper Mississippi River Basin, above the confluence with the Ohio River. The Upper Mississippi, the Illinois and the Missouri Rivers account for 68 percent of the nitrate. For orthophosphate, the largest sources again appear to be the Upper Mississippi, Illinois and Missouri Rivers (52 percent), although a large percentage also comes from the Lower Mississippi River below the confluence with the Ohio River (29 percent) (Figure 80).

Ammonium and nitrite ion loads appear to originate as point-sources, but disappear within approximately one hundred miles of their site of introduction (Figure 81 shows typical data for ammonium), probably as a result of either conversion to nitrate ion and/or nitrogen gas or as a result of sorption to suspended sediment. Any nitrite or ammonium ions from the Mississippi River deposited into the Gulf of Mexico, therefore, probably originated within one hundred miles of the Gulf. However, the amount of nitrite and ammonium ions in the Mississippi River are always minor (less than 5 percent) compared with the amount of nitrate ions and therefore contribute little to the overall quantity of nutrients arriving at the Gulf of Mexico from the Mississippi River.

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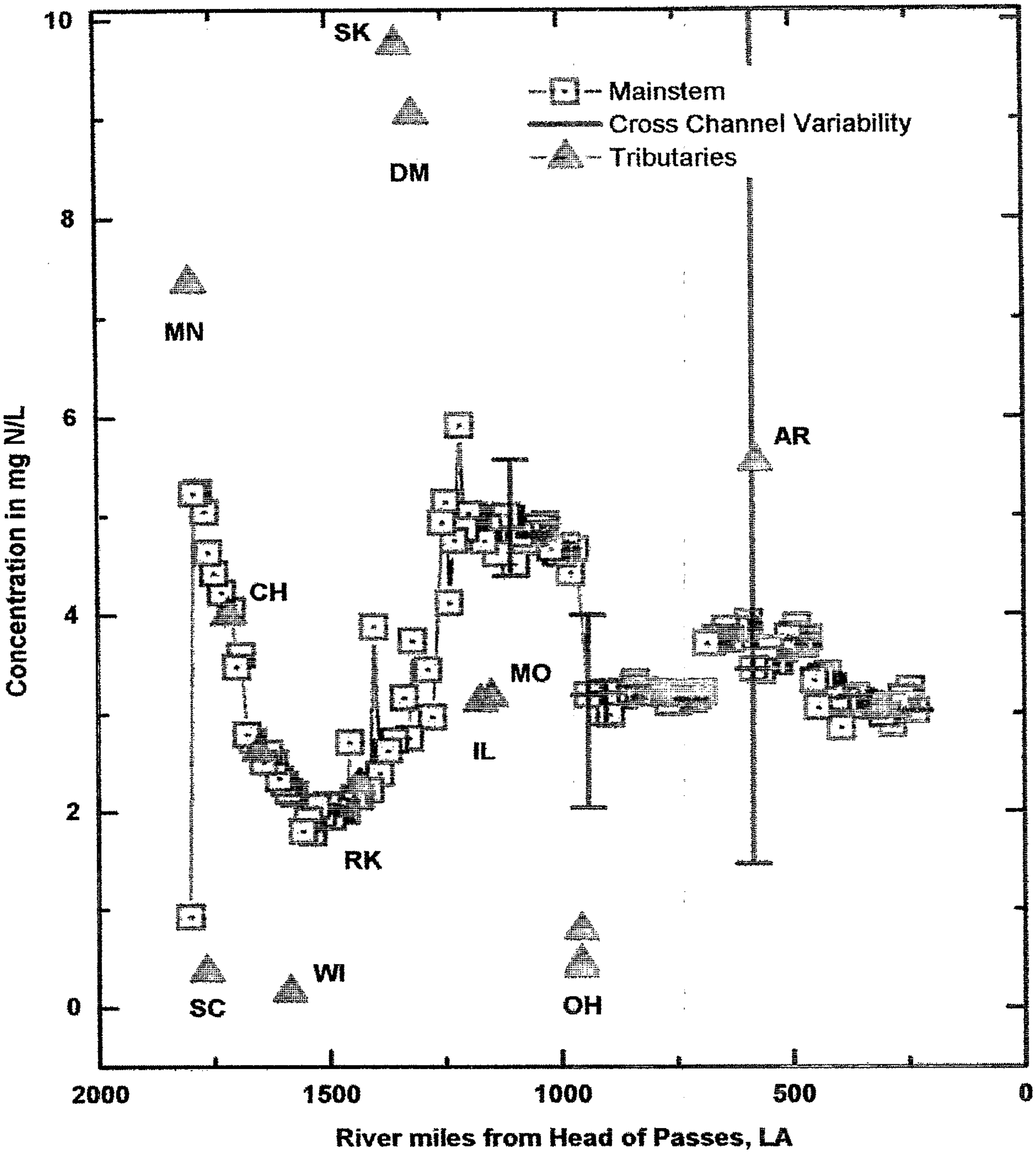

Figure 76.
Concentration of nitrate in milligrams of nitrogen per liter in the Mississippi River during June 23–July 2, 1991.

MN = Minnesota River	*WI = Wisconsin River*	*IL = Illinois River*
SC = St. Croix River	*RK = Rock River*	*MO = Missouri River*
CH = Chippewa River	*SK = Skunk River*	*OH = Ohio River*
BL = Black River	*DM = Des Moines River*	*AR = Arkansas River*

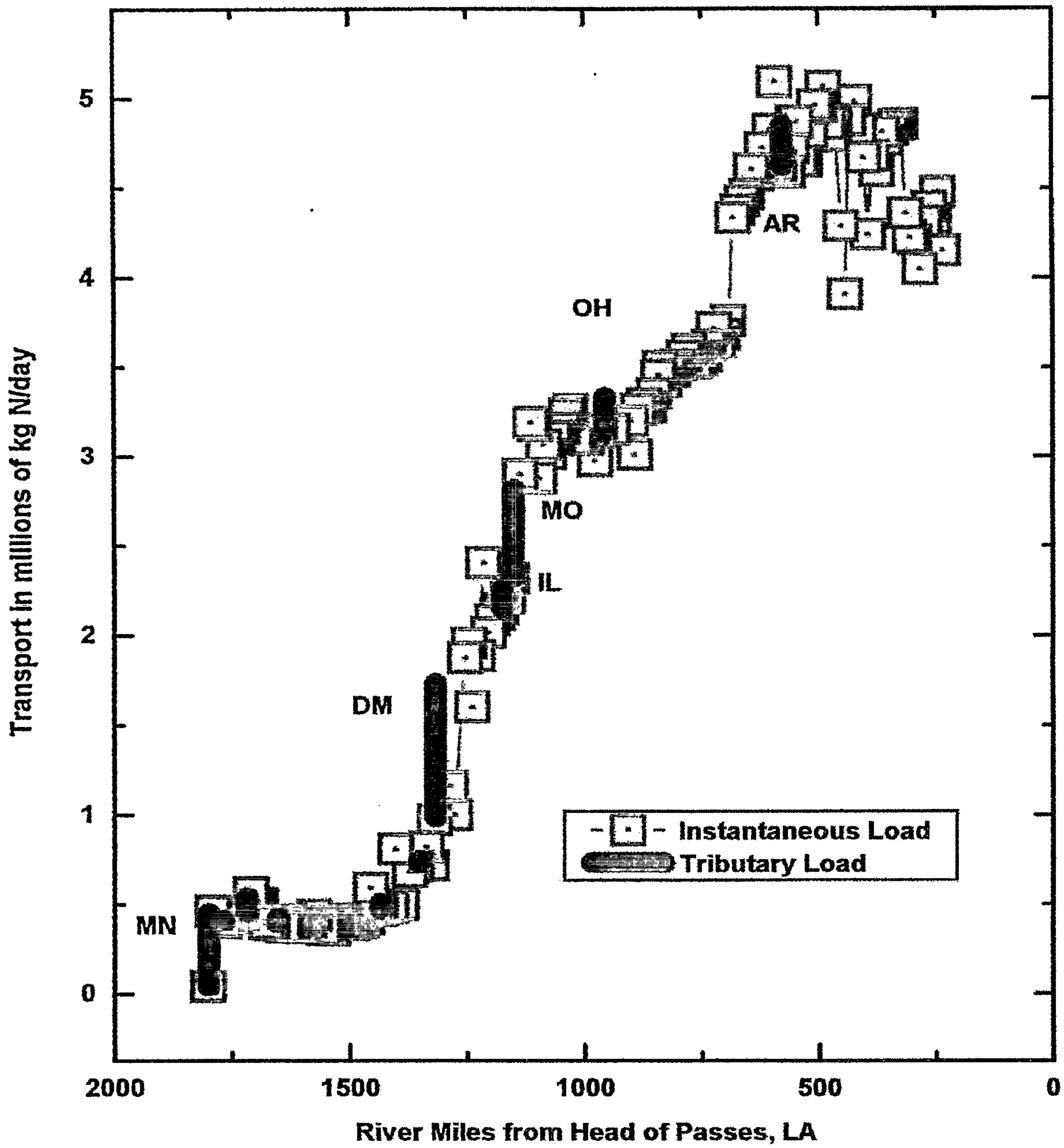

Figure 77.
Transport of nitrate in millions of kilograms of nitrogen per day in the Mississippi River during June 23–July 2, 1991.

MN = Minnesota River
DM = Des Moines River
IL = Illinois River
MO = Missouri River
OH = Ohio River
AR = Arkansas River

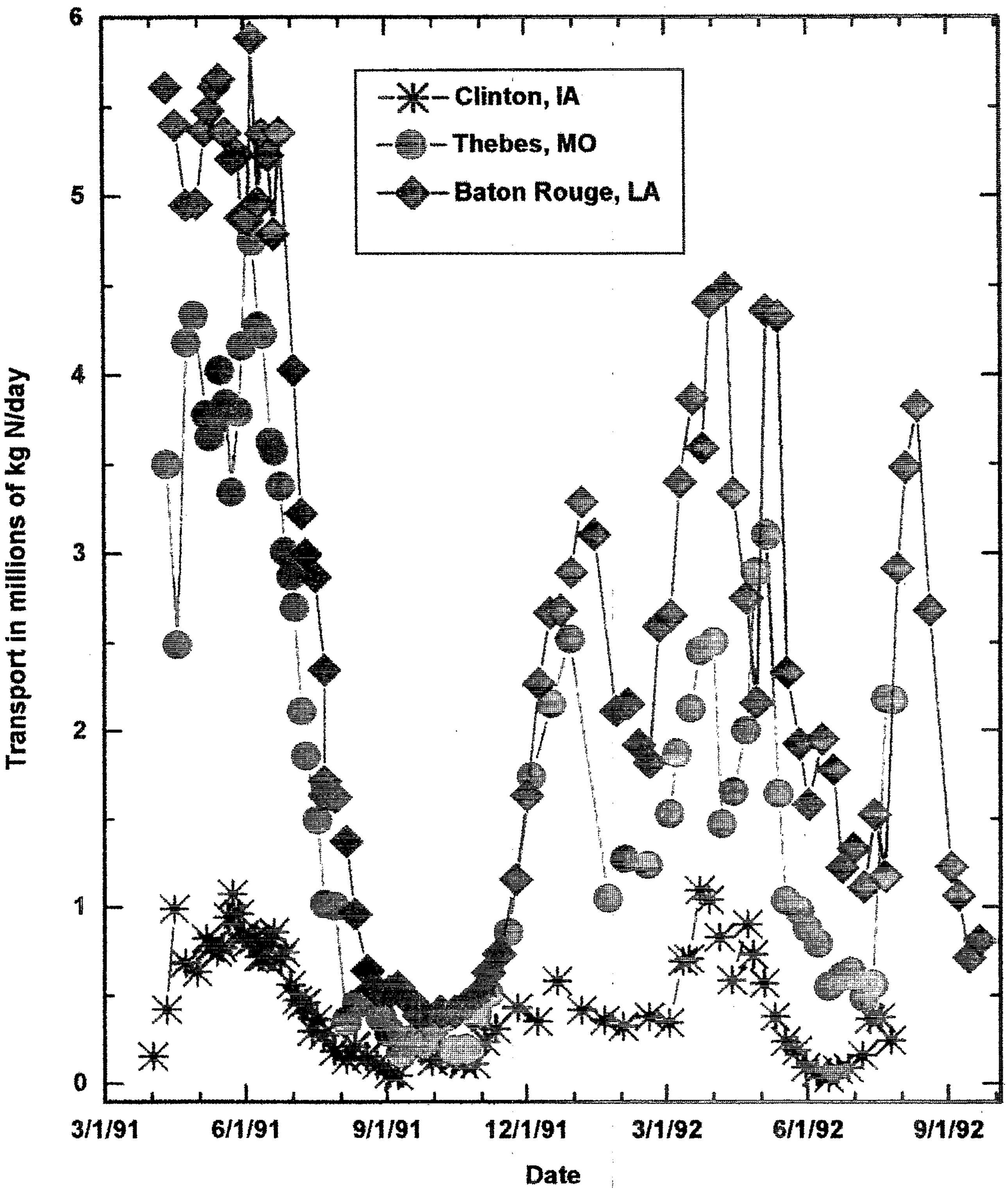

Figure 78.

Transport of nitrate in millions of kilograms of nitrogen per day in the Mississippi River at Clinton, Iowa; Thebes, Missouri; and Baton Rouge, Louisiana during 1991–1992.

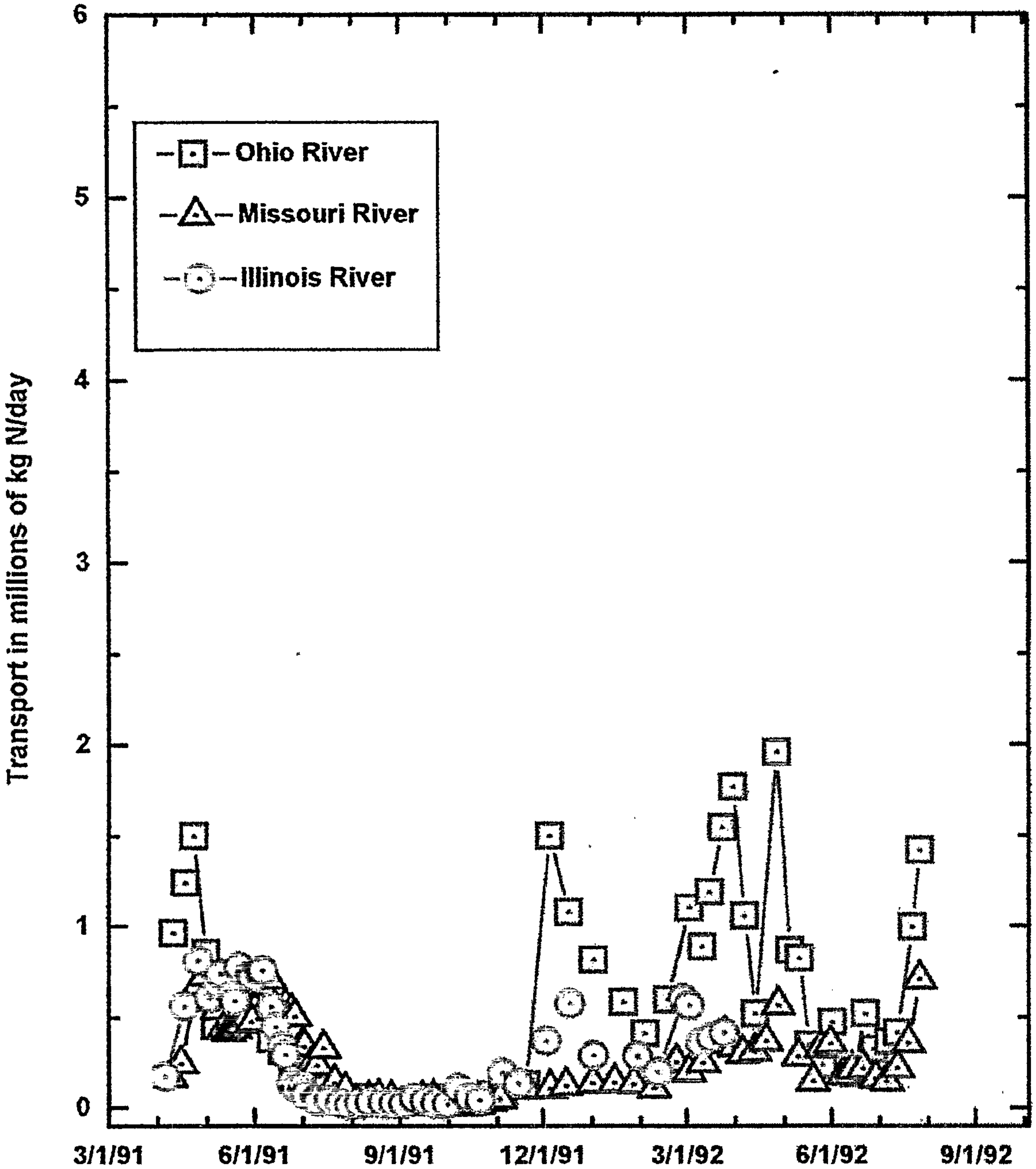

Figure 79.
Transport of nitrate in millions of kilograms of nitrogen per day in three tributaries of the Mississippi River during 1991–1992.

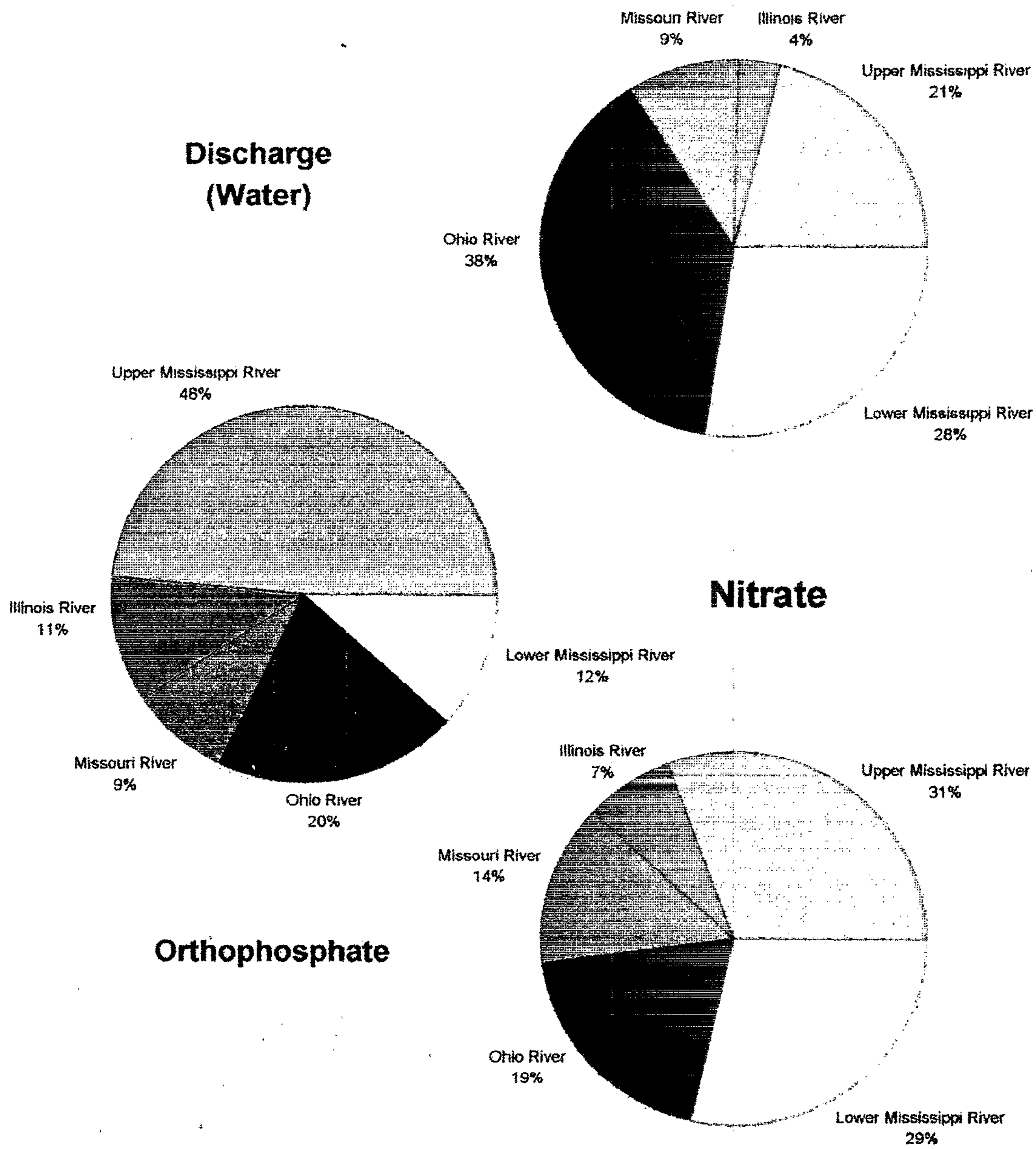

Figure 80.

Sources of water, nitrate and orthophosphate in the Mississippi River during April 1991–April 1992.

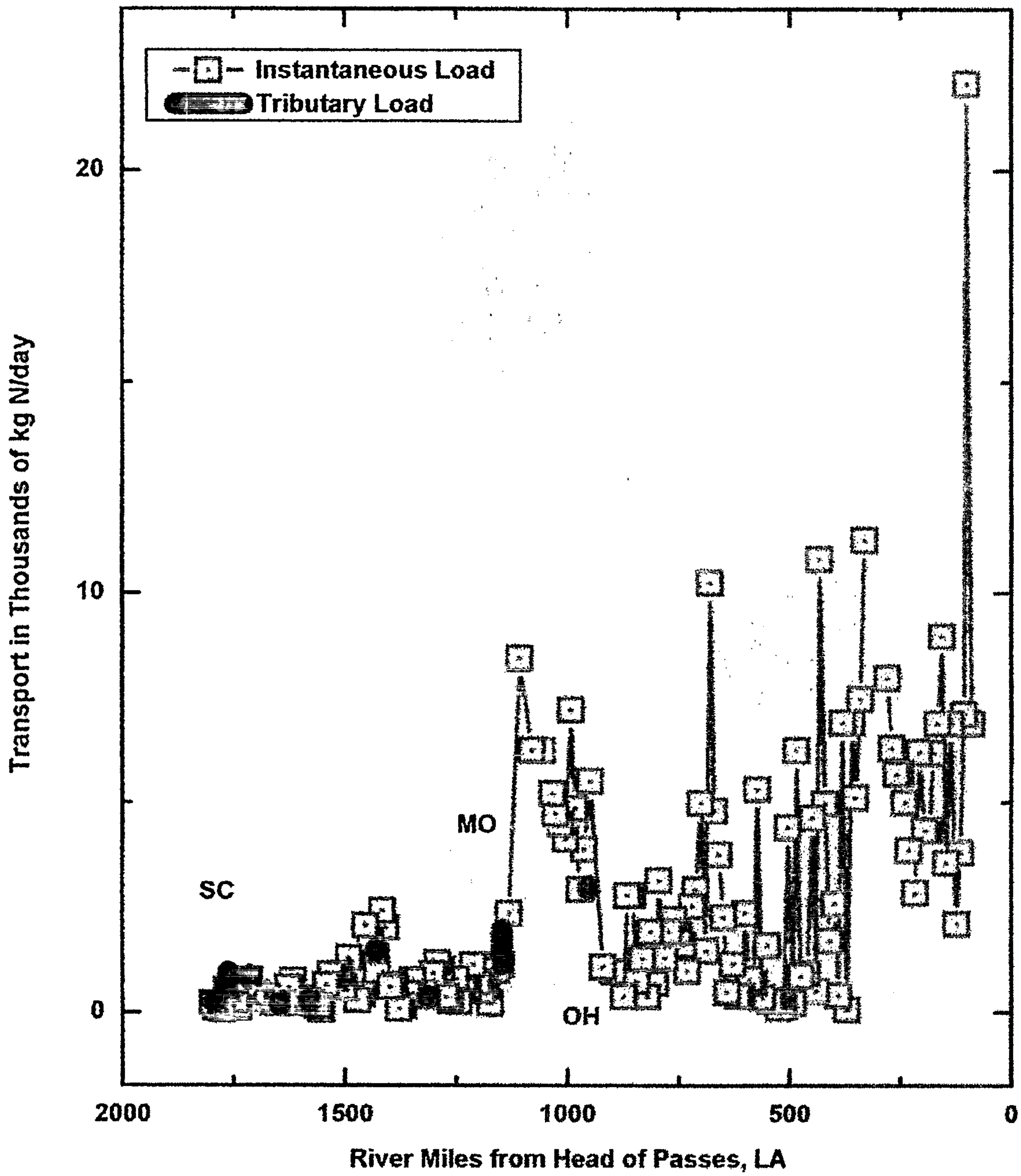

Figure 81.

Transport of ammonium in thousands of kilograms of nitrogen per day in the Mississippi River during September 25–October 4, 1991.

SC = St Croix River *MO = Missouri River* *OH = Ohio River*

Presentation Discussion

Ron Antweiller (U.S. Geological Survey—Boulder, CO)

Fred Kopfler *(Gulf of Mexico Program—Stennis Space Center, MS)* commented that the scale of the loadings presented for ammonium nitrogen was thousands of kilograms per day, while loadings for nitrate were millions of kilograms per day; even if the ammonium was converted to nitrate, it is about three orders of magnitude less. Therefore, it is lost in the background of the nitrate.

Ron Antweiller confirmed that Fred Kopfler's understanding was correct. The highest ammonium loadings in relation to nitrate he has seen was five percent. Even if all the ammonium is converted to nitrate, it still is not significant.

Effects of Episodic Events on the Transport of Nutrients to the Gulf of Mexico

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Abstract

Nutrients (nitrogen and phosphorus) derived from areas of intense agriculture in the upper Mississippi River basin have been implicated as the indirect cause of oxygen depletion (hypoxia) in the Gulf of Mexico along the Louisiana–Texas coast. The largest influx of nutrients to the Gulf typically occurs each year during the spring and early summer when streamflow and concentrations of nutrients, such as nitrate, are highest. During extreme high flow episodes, such as the 1993 flood in the upper Mississippi River, abnormally large amounts of nitrate and other nutrients are transported into the Gulf. During April through September 1993, for example, the nitrate flux to the Gulf was more than 900,000 metric tons (as N). This is 100 percent more nitrate than was discharged to the Gulf during this same period in 1992 and 1994, and 50 percent more than in 1991 and 1995. While these episodic events cause considerable year-to-year variation in flux of nutrients, there is evidence that annual fluxes also have increased. An analysis of historical water chemistry data collected at St. Francisville, Louisiana and Baton Rouge, Louisiana since 1954 shows that the concentration and flux of nitrate in water discharged to the Gulf has increased about threefold, with most of the increase occurring since 1968. Conversely, the concentration and flux of total phosphorus has changed little since 1973 when the first phosphorus records were collected.

The principal areas contributing nutrients to the Mississippi River and ultimately the Gulf of Mexico are streams draining the corn belt states, particularly Iowa, Illinois, Indiana, Ohio, and southern Minnesota. About 60 percent of the nitrate transported by the Mississippi River is derived from less than 20 percent of the basin. Current sources of nitrogen for the Mississippi River basin, in decreasing order of their input include commercial fertilizers, animal manures, legumes, municipal and domestic wastes, and atmospheric deposition. The present use of nitrogen fertilizer in the basin is estimated to be about 6.6 million metric tons per year and accounts for more than one-half the annual nitrogen input.

No Manuscript Submitted.

Presentation Discussion

Don Goolsby (U.S. Geological Survey—Lakewood, CO)

Len Bahr ***(Louisiana Governor's Office-aton Rouge, LA)*** congratulated the U.S. Geological Survey on presenting excellent information and he added that it was the type of information that was needed. He continued by wishing the USGS well on receiving their budget from Congress. He said he was an ecologist, not a soil scientist or an agricultural person, and felt that the information presented was good news. There is an enormous potential for cost savings in nitrate fertilizer application and it certainly appeared that changes in fertilizer use and application could be achieved.

Don Goolsby asked if someone was present from the Department of Agriculture, because he wanted a representative to comment on Len Bahr's statement. He said he knew the Department of Agriculture conducts many programs through which they attempt to account for the nitrogen already in the soil and give credit for that; applying less nitrogen in current years. His understanding was that these programs were working to some degree, and attributed some of the leveling in contributions to those efforts.

Eugene Turner *(Louisiana State University—Baton Rouge, LA)* asked two questions:

- Is some double accounting of manure inputs and fertilizer application.

- Secondly, he questioned if anything can be done to improve sampling at the national water quality stations. He cited that some of those stations are sampled only six or eight times a year.

Don Goolsby responded to the first question by saying that there is some double accounting of manure inputs because the fertilizer produces feed that the animals use.

In response to Eugene Turner's second question, Don Goolsby said that he had mentioned that the NAWQA network was being redesigned. The sampling frequency will be doubled or tripled over the past frequency, but the number of stations will be reduced to 30 or 40 nationwide and will be focused in four large river basins.

Estimating Background Loads of Sediments, Organic Nitrogen, and Organic Phosphorous in the Mississippi River Basin

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Texas A&M University

Abstract

Estimating Background Nutrient Loads in the Mississippi River Basin Using Loading Functions and a GIS

The primary source of measured data available for sediment and nutrient loading on a national scale is found in the stream data published by the USGS (USGS, 1991). However, this data does not provide much information about whether the loadings come from point, nonpoint, or background sources or about where the sources are located. Hydrologic modeling can be used to provide much additional information about probable sources of pollutants and how they are transported through surface water and ground water systems.

USDA/NRCS and TAES have initiated a national scale modeling project to estimate the nonpoint source pollutant loadings (sediment and organic nutrients) from agricultural areas and other land uses in the 48 coterminous United States. We also hope to incorporate existing data on point source loadings in our national modeling effort. Some preliminary results for the Mississippi River Basin from this study will be presented in this paper.

The primary modeling unit areas for this project are the USGS' *Hydrological Cataloging Units (8-digit watersheds*). A GIS (GRASS) is being used with national and regional scale topographic, soils, and land use databases. Interface programs have been developed to link these GIS databases with soil and water assessment models. One model used to estimate sheet and rill erosion rates is the Universal Soil Loss Equation (USLE). In this preliminary, generalized approach, the amount of sediment reaching the water bodies has been estimated by applying a drainage area dependent delivery ratio to the USLE based erosion estimates. Then the amount of organic nutrients was estimated using a sediment enrichment ratio for each nutrient (N and P) based on the organic carbon content of the eroded soils.

This simple generalized procedure provides preliminary estimates of background loadings of sediments, organic nitrogen, and organic phosphorous, not accounting for point source loadings or contributions from the uses of fertilizers in the river basin.

Introduction

The Resources Conservation Act of 1977 (RCA) authorizes the Department of Agriculture (USDA) to appraise the current condition and trends in the uses and conservation of soil, water, and related natural resources on non-federal lands in the nation each decade. The Third RCA Appraisal is due in 1997. The RCA Appraisals are supposed to provide information to be used in developing updates to the USDA National Conservation Program (NCP). The NCP is a public statement of policy of which activities will have the highest priorities for USDA agencies for natural resources conservation activities on non-federal areas.

The Natural Resources Conservation Service (NRCS), the Agricultural Research Service (ARS), the Texas Agricultural Experiment Station (TAES), and other agencies are cooperating on a Project for Hydrologic Unit Modeling of the United States (The HUMUS Project). This Project is designed to develop a weather-driven model of soil-plant-water interactions and to route water flow, erosion, sediment flow, nitrate flow, phosphate flow, and salt transport through the major river basins of the 48 conterminous States for the RCA Appraisal. We started the HUMUS Project in 1992 and will complete it in 1996 or early 1997. We expect, however, that the technology we are using will still be in its infancy. We expect to improve this technology over time and for it to be used by ourselves and others at a wide range of scales from small watersheds to international river basins.

The hydrological model we are using is the Soil and Water Assessment Tool (SWAT) developed by the Grasslands, Soil and Water Research Station of ARS at Temple, Texas. This is a comprehensive but somewhat generalized model of surface water runoff, groundwater return flows, and streamflow dynamics that integrates estimates for small subwatersheds into estimates of flows in major river basins. The SWAT can operate with historical weather data or with a series of synthetically generated weather patterns. The model includes options for simulating ponds, major reservoirs, and wetland areas in the system. The SWAT is scale independent, but the accuracy of the derived flow estimates depends directly on the accuracy of the available data, including data on weather, topography, channel dimensions, reservoir dimensions, reservoir operating rules, soils, land cover, crops, on transpiration rates from crops and natural vegetation through the dormant and growing seasons, etc.

We are using the Geographic Resources Analysis Support System (GRASS) geographic information system (GIS) as our primary tool to manage and manipulate the databases we have assembled from USGS, the Weather Service, NRCS, and other sources, on weather, topography, land cover, soils, crops, stream locations, watershed boundaries, political boundaries, water quality, etc.

Dr. Srinivasan has written an interface program to use GRASS and the databases to develop input data sets for the SWAT model. He is also developing a GRASS-based, report-writing interface program to help analyze and display the results of the modeling in both graphical and tabular formats. We also use the INFORMIX relational data base system for filing and querying some of our databases, especially those having to do with soil properties and with agricultural production and practices. Other GIS from available commercial sources may also be linked to the SWAT.

Early in the development of the HUMUS Project, we experimented with a short-cut approach for estimating background transport of sediments, organic nitrogen, and organic phosphorous. This preliminary work was based on using an earlier version of the SWAT instead of the more comprehensive water and sediment routing subroutines included in the SWAT. This approach uses our basic databases on topography, soils, crops, and land cover, but shortcuts the flow routing algorithms and uses generated, not actual, weather data. Other simplifying assumptions used were that all trees are evergreen trees and all crops were minimum tilled.

Figure 82 shows the resulting estimate of average annual rates of sheet and rill erosion caused by water runoff. The units on this map are metric, but 7.5 to 12 metric tonnes per hectare corresponds roughly to 3 to 5 English tons per acre, the normal range for so-called cropland erosion tolerance or "T" levels established by NRCS. Figure 83 is the same map with only four colors. Green represents areas where sheet and rill erosion is less than 3 tons/acre/ year. Blue represents areas where erosion rates are 3 to 5 tons per acre per year. And red areas show where sheet and rill erosion rates can't be kept to less than 5 tons per year even with minimum tillage on cropland.Table 8 lists the average sheet and rill erosion rates derived with our short-cut method for the 6 major river basins in the Mississippi River Basin. These data suggest that over 1 billion tons of soil are detached from the land surface of the Basin by sheet and rill erosion in an average year. These data also reveal that while the Tennessee River Region, which has only 11 percent of its area in cropland, has the highest rates of sheet and rill erosion. Nevertheless, this relatively small Region has the least total tonnage eroded. Conversely, the Missouri Region, though having the lowest average erosion rate, and about 30 percent of its area in cropland, ranks second in total tonnage eroded. The Upper Mississippi Region ranks third in total area and first in percent of its area in cropland, but fourth in its unit area average rate of erosion.

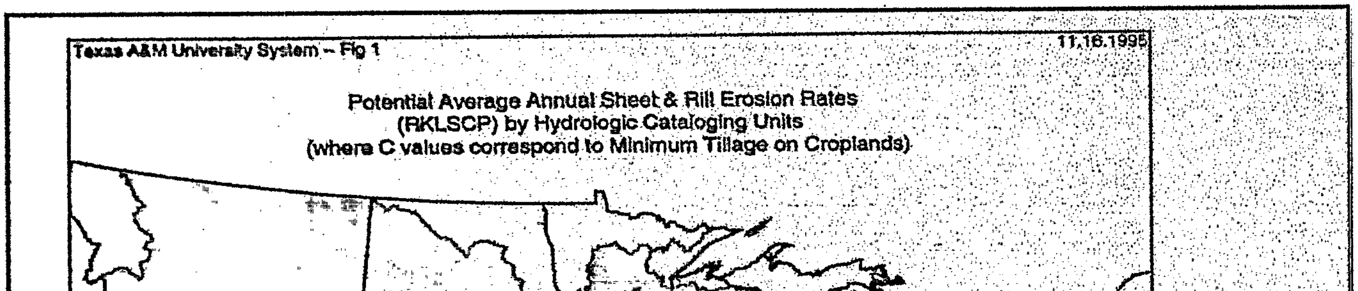

Figure 82.

Resulting estimate of average annual rates of sheet and rill erosion caused by water runoff.

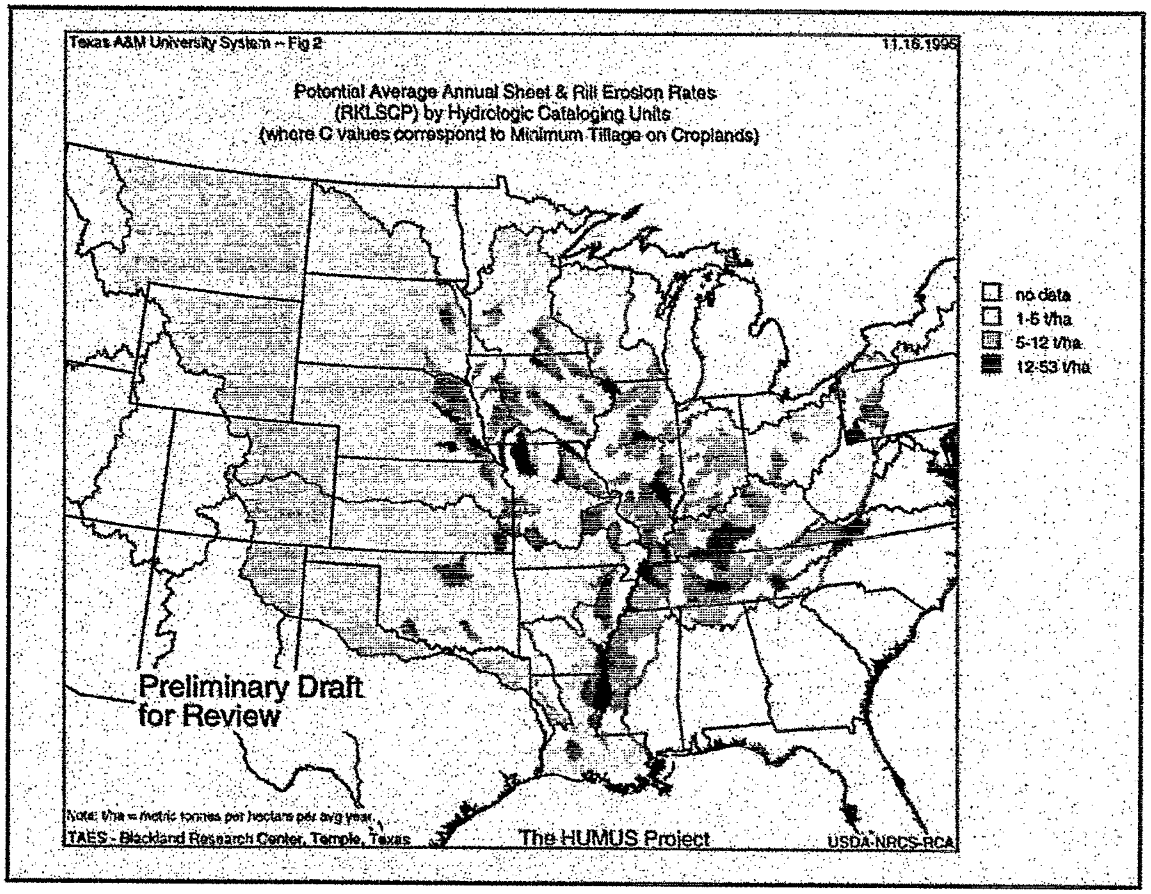

Figure 83.

Resulting estimate of average annual rates of sheet and rill erosion caused by water runoff.

Table 8.

Preliminary estimates of sheet and rill erosion.

Reg.	Hydrologic Regions	Average Annual Erosion Rates		
		Tons/Year	Tons/Acre	Tons/Sq. Mile
5	Ohio River	239,932,000	2.31	1477
6	Tennessee River	63,699,000	2.44	1559
7	Upper Mississippi River	229,509,000	1.9	1213
8	Lower Mississippi River	137,991,000	2.13	1362
10	Missouri River	230,440,000	0.71	453
11	Arkansas–White–Red Rivers	126,719,000	0.8	513
	Totals	1,028,290,000	1.29	823

Table 9 and Figures 84 and 85 present theses data in terms of the relative proportion each of the regions contributes to the total Mississippi River Basin load.

Table 9.
Comparing proportional erosion loads to drainage areas.

Reg.	Hydrologic Regions	Drainage Areas		S&R Eros.
		Square Miles	% of Area	% Erosion
5	Ohio River	162,439	12.99%	23.33%
6	Tennessee River	40,864	3.27%	6.19%
7	Upper Mississippi River	189,189	15.13%	22.32%
8	Lower Mississippi River	101,283	8.10%	13.42%
10	Missouri River	509,172	40.73%	22.41%
11	Arkansas–White–Red Rivers	247,195	19.77%	12.32%
	Mississippi River Basin	1,250,142	100.00%	100.00%

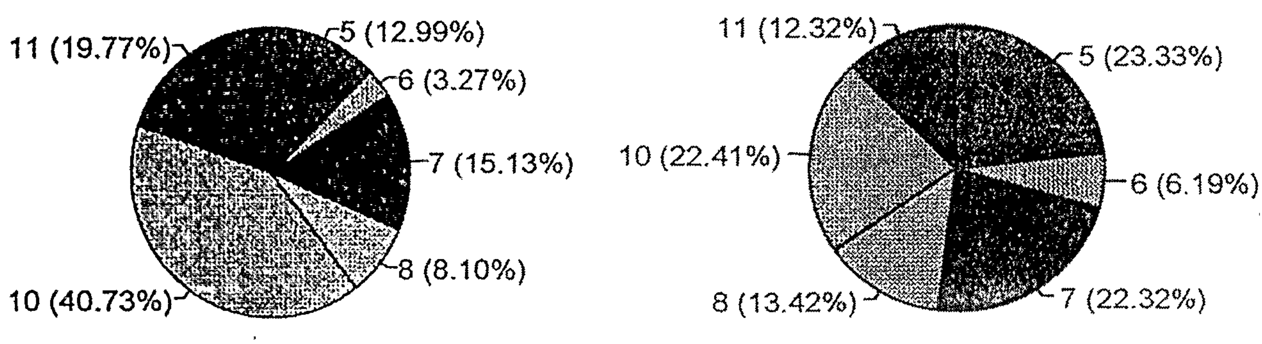

Figure 84.
Charts depicting hydrologic region areas in the Mississippi River Basin (left) and sheet and rill erosion rates by hydrologic regions (right).

Comparing to the NRI

The NRCS has another method for estimating erosion rates, one that has been used since the late 1950's. It is now called the Natural Resources Inventory (NRI). The NRI is a nationwide statistical site sampling procedure designed to make general estimates of erosion rates on non-Federal agricultural lands. The NRI has the advantage of having a detailed set of data on crop and land management practices at a large number of sample sites. Its major disadvantage is that it does not provide complete information about erosion rates on Federal lands or forest lands. This leaves fairly large areas unevaluated, as shown in Table 10a.

Nevertheless, the NRI reports include basin-wide estimates of tons of erosion based on the samples taken in the inventoried areas. Table 10b and Figure 86 show how our preliminary estimates of regional sheet and rill erosion rates compare to the rates reported in the 1992 NRI.

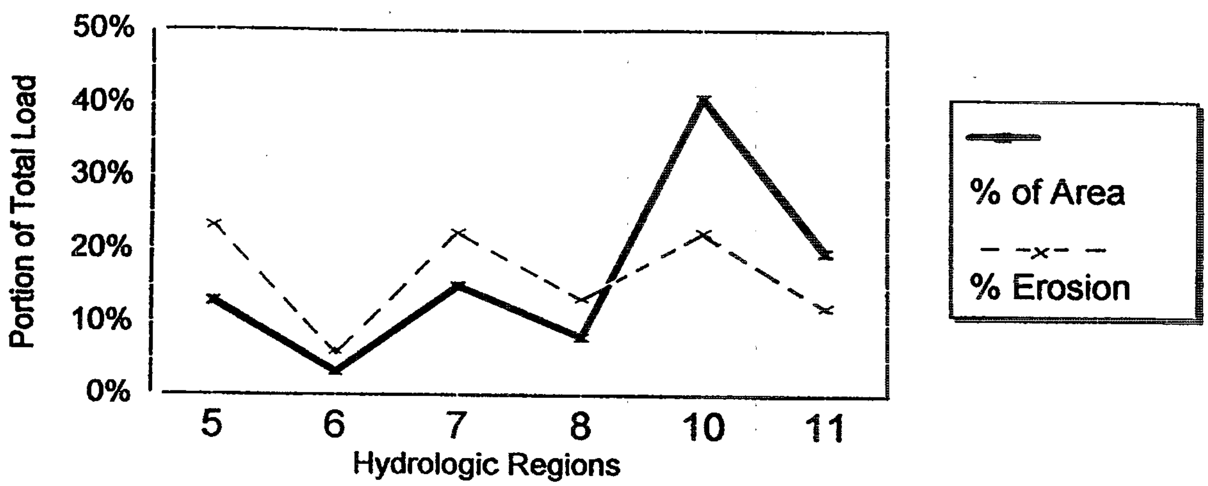

Figure 85.
Relative rates of sheet and rill erosion by hydrologic regions.

Table 10a.
Areas reported for erosion in the NRI.

Reg.	Hydrologic Regions	Total Acres	NRI Report Acres	% Reported
5	Ohio River	103,960,758	49,927,300	48%
6	Tennessee River	26,153,159	8,437,800	32%
7	Upper Mississippi River	121,081,008	84,967,500	70%
8	Lower Mississippi River	64,821,123	31,058,800	48%
10	Missouri River	325,869,927	259,150,700	80%
11	Arkansas–White–Red Rivers	158,204,925	117,138,400	74%
	Totals	800,090,900	550,680,500	69%

Table 10b.
Comparing sheet and rill erosion estimates.

Reg.	Hydrologic Regions	HUMUS Tons/Year	NRI 1992 Tons/Year
5	Ohio River	239,932,000	254,904,360
6	Tennessee River	63,699,000	26,732,160
7	Upper Mississippi River	229,509,000	283,742,740
8	Lower Mississippi River	137,991,000	110,043,360
10	Missouri River	230,440,000	491,417,420
11	Arkansas–White–Red Rivers	126,719,000	176,426,730
	Totals	1,028,290,000	1,343,266,770

The NRI erosion estimates are significantly lower than the HUMUS estimates in the Tennessee and Lower Mississippi Regions. This could be attributed to the large portions of these areas under forest cover and thus unreported by the NRI. In the other three regions, especially in the Missouri Region, the NRI estimates are significantly higher than the preliminary HUMUS estimates. The HUMUS estimates are based on having all croplands in minimum till and the NRI estimates are based on actual tillage conditions in 1992. The differences in the estimates might imply a policy regarding promotion of minimum tillage. If these data are reasonably close to reality, the higher priorities for promoting minimum tillage to reduce erosion might better be focused in the Missouri and Arkansas-White-Regions than in the Corn Belt.

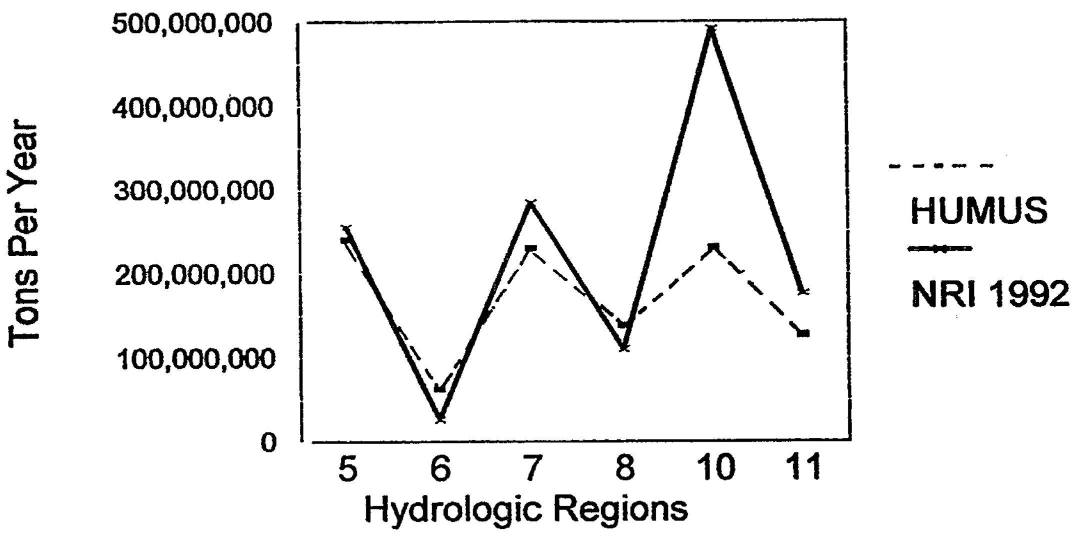

Figure 86.
Comparing S&R erosion rates by hydrologic region.

Sedimentation

In the SWAT, there is an algorithm for estimating edge-of-watershed runoff of sediment. This load of sediment is called "Wash Load" in this paper, though this is a plagiarized term here. The coefficients of sediment delivery are based on the available literature, the gist of which is that the delivery ratio is an inverse function of the logarithm of the drainage areas. The delivery ratios used in this preliminary set of HUMUS Project sedimentation estimates are computed from the drainage areas of each of the contributing hydrologic cataloging unit (8-digit) areas.

When all of the sediment deliveries from these areas are lumped to produce sediment runoff estimates for the Hydrologic Regions, the composite delivery ratio for all of the Regions is about 5 percent.

Table 11a displays the preliminary HUMUS Project estimates of sediment wash loads.

For comparison, the regional composite sediment delivery ratios computed from the HUMUS Project data were applied to the NRI estimates of sheet and rill erosion to derive NRI-based sediment wash load estimates. The resulting hypothetical estimates are presented in Table 11b.

Table 11a.
Estimated average annual sediment "wash" loads.

		HUMAS Preliminary Estimates		
Reg	Hydrologic Region	Tons/Year	Tons/Acres	Tons/Sq. Mile
5	Ohio River	12,185,000	0.117	75
6	Tennessee River	3,362,000	0.129	82
7	Upper Mississippi River	11,760,000	0.097	62
8	Lower Mississippi River	7,220,000	0.111	71
10	Missouri River	11,483,000	0.035	23
11	Arkansas-White-Red Rivers	6,474,000	0.041	26
	Total	52,484,000	0.066	42

Table 11b.
Imputed NRI estimates of average annual sediment "wash" loads

		HUMAS Estimates			NRI		
#	Hydrologic Region	Erosion Tons/Year	Sediment Tons/Year	Eff. Deliv. Ratio	Est. Erosion Tons/Year	Hyp. Sediment tons/Year	Hyp. Sediment t/mi2/year
5	Ohio River	239,932,000	12,185,000	0.051	254,904,360	12,945,375	80
6	Tennessee River	63,699,000	3,362,000	0.053	26,732,160	1,410,909	35
7	Upper Mississippi River	229,509,000	11,760,000	0.051	283,742,740	14,538,927	77
8	Lower Mississippi River	137,991,000	7,220,000	0.052	110,043,360	5,757,717	57
10	Missouri River	230,440,000	11,483,000	0.050	491,417,420	24,487,703	48
11	Arkansas-White-Red Rivers	126,719,000	6,474,000	0.051	176,426,730	9,013,539	36
	Totals	1,028,290,000	52,484,000	0.051	1,343,266,770	68,560,438	55

Table 11c and Figure 87 present a comparison of HUMUS Project and imputed NRI-based sediment wash load estimates with USGS data on suspended sediments as reported for the Hydrologic Regions in the Mississippi River Basin in the National Water Summary of 1990/1991 by Smith, Alexander, and Lanfear.

The USGS suspended sediment data do not include estimates of reservoir sediment entrapment or of bedload sediment transport. That the USGS suspended sediment loads are generally higher than the HUMUS and NRI estimates of sediment wash may be attributed to the fact that a significant part of the suspended sediment load is derived from instream erosion, mass wasting, and deposition of airborne sediments not accounted for by the estimates of sheet and rill erosion.

On the other hand, the available literature on sediment delivery ratios is largely based on historical comparisons of estimates of erosion rates with recorded suspended sediment data from stream gages. A slight change in the selection of sediment delivery ratios could have markedly changed Tables 11a, 11b and 11c and Figure 87.

In the ongoing phase of the HUMUS Project, we intend to use a stream power function to derive new estimates of sediment transport processes. We hope this approach will provide new insights into comparisons between sediment source and delivery estimates.

The reasons for differences between the NRI and HUMUS sediment delivery estimates are probably the same as for the differences in estimated erosion rates. Nevertheless the close correlations between the current condition NRI erosion rates for the Ohio, Missouri, and Arkansas-White-Red Regions are remarkable, given the short-cut method used herein to derive the NRI-based estimates. The low correlations for the Tennessee and Lower Mississippi Regions suggest the need for further research. For example, we need to check with the authors of the referenced USGS report as to whether the USGS estimate of suspended loads in the Lower Mississippi Region include some sediment loading from upstream regions.

Figure 88 is a map showing the preliminary HUMUS Project estimates of sediment wash loads for the 8-digit watersheds in the Mississippi River Basin. Notice that the sediment delivery estimates are particularly high for the Tennessee and Lower Mississippi Regions, areas where the NRI reports erosion for significantly less than half of the contributing drainage areas.

Table 11c.
Estimated average annual sediment "wash" loads

Reg	Hydrologic Region	Humus Preliminary Estimates		
		HUMUS "wash" load t/mi2/year	NRI Imputed "Wash Load t/mi2/year	USGS Suspended t/mi2/year
5	Ohio River	75	80	85
6	Tennessee River	82	35	85
7	Upper Mississippi River	62	77	102
8	Lower Mississippi River	71	57	111
10	Missouri River	23	48	45
11	Arkansas-White-Red Rivers	26	36	31
	Total	26	36	31

Nitrogen and Phosphorous

The preliminary HUMUS Project estimates for movements of nitrogen and phosphorous are based entirely on computations of contributions of organic matter contained in and transported with topsoils detached by erosion. They include no estimates of contributions by fertilizers, animal wastes, urban wastes, industrial discharges, atmospheric exchanges, leaf fall, or any other sources. They are also based on the assumption that all cropsoils are minimum tilled. Thus, they are underestimates of background loads. They represent low levels of nutrient contributions that society probably cannot hope to achieve by any conceivably adoptable set of pollution reduction policies.

Table 12 provides an insight into the implications of our assumptions.

The reason that the percentages for Organic N and Organic P are so similar is that the data are in percentages of total contribution, not actual loads. Though Phosphorous delivery tonnages are much lower than are Nitrogen loads, the percentages of total loads by river basins are so nearly identical that they show as only one line on Figure 89.

Table 12.
Comparing sediment load rates with organic N&P rates.

No.	Hydrologic Region	Percent Total		
		Sed. Wash	Org. N	Org. P
5	Ohio River	23.22	21.14	21.17
6	Tennessee River	6.41	4.64	4.73
7	Upper Mississippi River	22.41	30.69	30.63
8	Lower Mississippi River	13.76	8.11	8.11
10	Missouri River	21.88	26.41	26.35
11	Arkansas-White-Red Rivers	12.34	9.01	9.01
	Mississippi River Basin	100.00	100.00	100.00

These data show that soils in the Upper Mississipppi and Missouri Regions have significantly higher levels of organic content than do the soils in the other regions. The soils in the humid warm Lower Mississippi Region have the lowest levels of organic content. Thus, on a ton per ton basis, they provide the lowest share of associated organic matter contributions to the Gulf of Mexico.

This information is illustrated in the maps in Figure 90 for organic nitrogen and Figure 91 for organic phosphorous.

Although deliveries of organic nitrogen and phosphorous are not directly related to streamflow estimates of nitrates and total phosphorous, some insights can be inferred from correlations between these data.

Table 13 and Figure 92 display comparisons between HUMUS Project estimates of delivery of organic nitrogen under low erosion rate conditions to data on nitrate deliveries as published in the USGS report described above.

Table 14 and Figure 93 show similar comparisons between estimates of organic phosphorous runoff and total phosphorous deliveries reported in the USGS report.

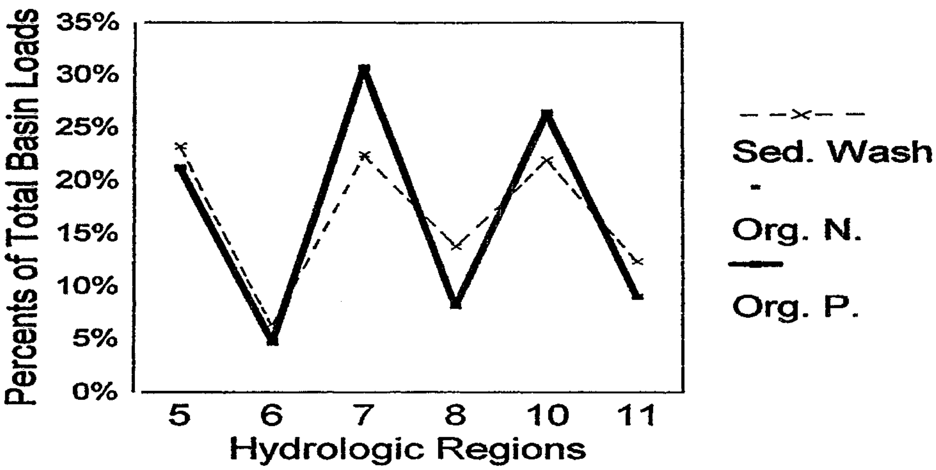

Figure 89.
Comparing sediment, Org. N, & Org. P by hydrologic regions.

Atmospheric wet disposition rate of NADP nitrate (NO3) in 1988 (top) and 1993 (bottom) in mol/m2. NADP sites are located as solid circles; Mississippi River watershed outlined by heavy line.

Atmospheric wet disposition rate of NADP ammonium (NH4) in 1988 (top) and 1993 (bottom) in mol/m2. NADP sites are located as solid circles; Mississippi River watershed outlined by heavy line.

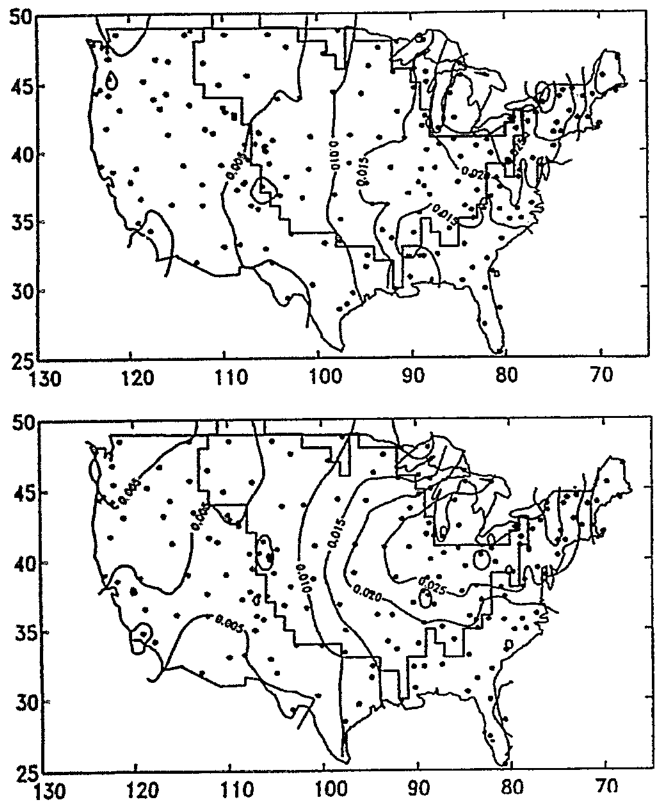

Figure 90.
Organic nitrogen map

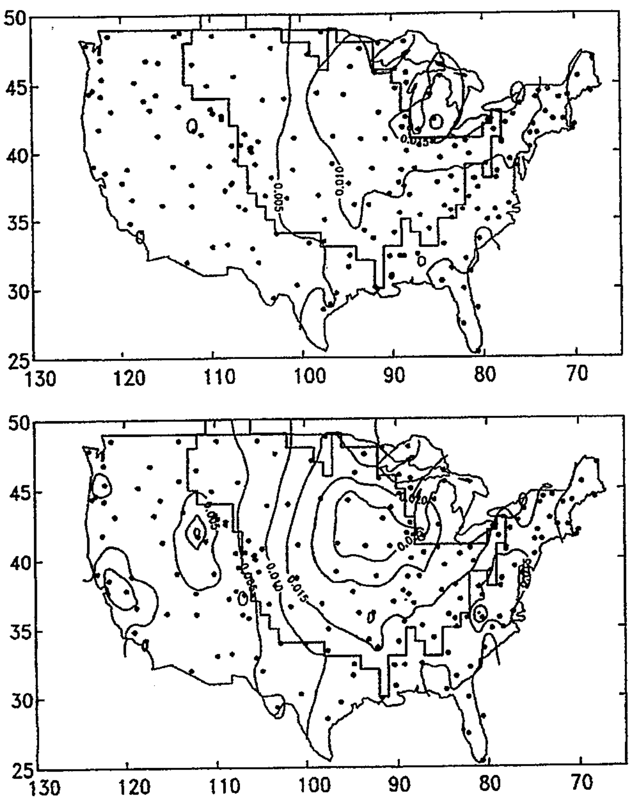

Figure 91.
Organic phosphorous map

Table 13.
Comparing preliminary HUMUS Project estimates with USGS data

No.	Hydrologic Region	Percent Total		USGS Est.
		Avg. Org. N Tons/year	Av. Org. N T/mi2/year	Nitrates t/mi2/year
5	Ohio River	23.22	21.14	21.17
6	Tennessee River	6.41	4.64	4.73
7	Upper Mississippi River	22.41	30.69	30.63
8	Lower Mississippi River	13.76	8.11	8.11
10	Missouri River	21.88	26.41	26.35
11	Arkansas-White-Red Rivers	12.34	9.01	9.01
	Mississippi River Basin	100.00	100.00	100.00

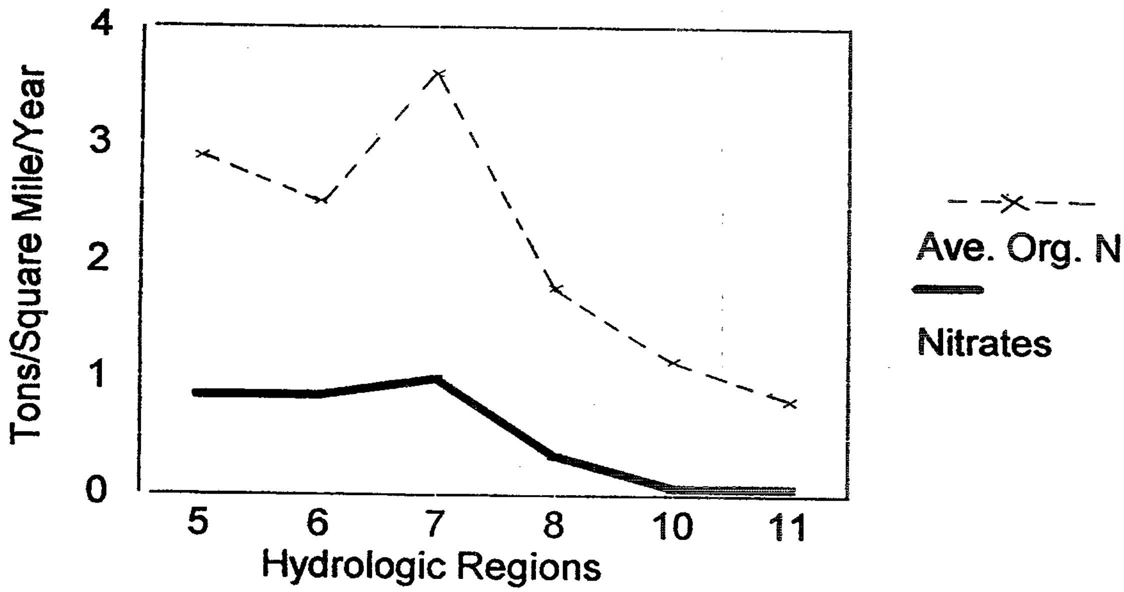

Figure 92.
Comparing organic N with nitrate loads by hydrologic regions.

Table 14.
Comparing preliminary HUMUS Project estimates with USGS data.

No.	Hydrologic Region	HUMAS Preliminary		USGS Est.
		Avg. Org. N Tons/year	Av. Org. N T/mi2/year	Total P t/mi2/year
5	Ohio River	94,000	0.58	0.125
6	Tennessee River	21,000	0.51	0.125
7	Upper Mississippi River	136,000	0.72	0.157
8	Lower Mississippi River	36,000	0.36	0.103
10	Missouri River	117,000	0.23	0.028
11	Arkansas-White-Red Rivers	40,000	0.16	0.039
	Totals	444,000	0.36	0.072

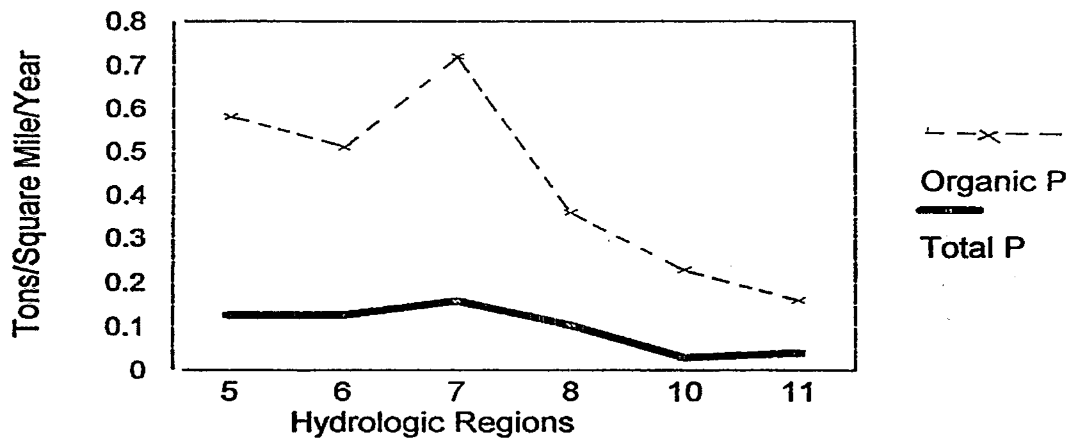

Figure 93.
Organic P runoff vs. Total phosphorous by hydrologic region.

Even though the erosion-related sources of nutrients are only a part of the total load of nutrients to the streams in the Mississippi River Basin, the preliminary estimates of runoff loads of organic N and P are significantly higher than are the USGS streamflow-based records of nitrates and total phosphorous.

This is not at all surprising. This is an indication of the vital importance of instream deposition, reduction, and volatilization of nutrients and of the effects of living organisms in aquatic ecosystems.

Presentation Discussion

Clive Walker (NRCS—Texas A&M University)

No questions after Clive Walker's presentation.

Nitrogen Loading in the Upper Mississippi River

Terry E. Whitledge

Abstract

Daily water samples have been collected since February 1992 immediately below the pool 19 dam at Hamilton, Illinois. The frozen samples were analyzed for orthophosphate, dissolved silicon, nitrate plus nitrite, nitrite and ammonium using standard methods (Whitledge et al, 1986) on a Technicon AutoAnalyzer II segmented flow analyzer. Water samples were filtered for *chlorophyll a* determinations starting in February 1993 to provide estimates of phytoplankton biomass and "potential phytoplankton production."

A strong annual cycle of dissolved nitrogen was observed over the three year period ranging from near depletion in the summer to greater than 370 umole/liter during the winter. The rapid changes in ambient concentrations of dissolved inorganic nitrogen over short time periods implies that local events can induce relatively large changes.

No Manuscript Submitted.

Presentation Discussion

Mr. Whitledge's presentation was canceled.

Estimates of Atmospheric Deposition to the Mississippi River Watershed

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Abstract

Annual values of atmospheric deposition of nitrogen to the Mississippi River System drainage basin were computed for 15 years (1979– 1993) using National Atmospheric Deposition Program wet deposition data and 3 years (1990– 1992) of National Dry Deposition Network dry deposition data. Wet deposition of nitrogen was measured as nitrate (NO_3) and ammonium (NH_4), dry deposition was determined as nitrate, the sum of gaseous nitric acid (HNO_3) and particulate nitrate. Fifteen year average wet deposition of nitrate and ammonium were 44 and 42 × 109 mol/yr, respectively. Three year average dry deposition of nitrate was 33 × 09 mol/yr, approximately 75 percent the like year wet deposition of nitrate. Total annual nitrogen deposition was estimated using NADP data and literature factors for nitrite and organic nitrogen. Average atmospheric deposition of total nitrogen was estimated as 200 × 109 mol/yr. Annual atmospheric deposition of total nitrogen was compared to total Mississippi River nitrogen for the same time period. U.S. Geological Survey water quality data and U.S. Corps of Engineer water discharge data from the Mississippi and Atchafalaya Rivers were used to estimate the annual riverine flux of nitrogen. Average annual riverine nitrogen flux was determined to be 115 × 109 mol/yr. Average atmospheric deposition of total nitrogen accounts for approximately 174 percent the average total riverine nitrogen flux.

Introduction

The Mississippi River has a vast watershed; including the upper Mississippi, the Missouri and the Ohio Rivers, it drains 41 percent of the continental U.S. (Figure 94). The Mississippi River also transports high nutrient loadings from the watershed to the northern Gulf of Mexico. These nutrient loads from the Mississippi River have changed over the last four decades. There has been a doubling in nitrate, from a low in the mid-1960's to a high in the mid-1980's (Dinnel and Bratkovich, 1993), creating an enrichment of the coastal waters of the Gulf of Mexico, and contributing to the summer depletion of dissolved oxygen in the bottom waters (Turner et al., 1987). In order to manage the riverine nitrogen, an understanding of the nitrogen types and sources must be made. One useful method would be to account for all the nitrogen in the Mississippi River watershed. By quantifying the various inputs and outputs of nitrogen, a budget or mass balance, and the relative importance of each nitrogen source can be made. The input and output sources of nitrogen, especially in the vast and diverse watershed, is complex. Using the budget terms following Jaworski et al. (1992), one can appreciate the task. Input terms for a watershed nitrogen budget would be, but not limited to, waste water effluent, animal waste, soil fertilizers, atmospheric deposition, biological fixation and adsorption, importation as commodities and also in ground water. These inputs would have to balance the outputs and whatever storage that would take place. These outputs would be crop harvest, river discharge, volatilization, export as commodities and into the ground water, and denitrification. Storage of nitrogen would take place in the soil, ground water and in the biomass.

A budget such as this has been accomplished for numerous smaller watersheds, but not for one of the scope of the Mississippi River watershed. Some of these nitrogen budget terms are readably quantifiable. One is the nitrogen contained in the river discharge, an assumed major output term, it is of primary importance to the problem of the nitrogen enrichment of the northern Gulf of Mexico coastal waters. Using sampled riverine nitrogen concentrations and water discharge, one can estimate the annual flux from the watershed.

Of the suggested inputs, soil fertilizer has been cited as the leading source of nitrogen in the river discharge (Turner and Rabalais, 1991). It is conceivable that other input terms are quantifiable, and could also contribute to the nitrogen river discharge. Specifically the waste water effluent, the animal waste and the atmospheric deposition terms. It is important to determine if these terms, if any, are of sufficient magnitude as to contribute to the budget. The remaining terms are arguably more difficult to estimate. A direct comparison of any input term to a major output term would be one technique, albeit simple, in determining the relative importance of that input.

The atmospheric deposition term is one that is quantifiable, but for which no quantity has been made. Using sampled precipitation volumes and nitrogen concentrations of the precipitation, combined with estimates of non-precipitation atmospheric deposition, the annual atmospheric deposition term can be determined and compared to the magnitude of the river discharge term.

Methods

Annual Mississippi River nitrogen flux was determined as a combination of the flux down the Atchafalaya River, the major distributary of the Mississippi River, and the Mississippi River proper. Riverine nitrogen flux included total nitrate, nitrite, ammonium and organic fluxes. Riverine nitrogen flux was determined from U.S. Department of Interior (1978–1993) National Stream Quality Accounting Network (NASQAN) concentrations at St. Francisville, Louisiana and Melville, Louisiana and U.S. Army (1978– 1993) Corps of Engineers (USACOE) water discharge from Tarbert Landing, Mississippi and Simmesport, Louisiana, for the Mississippi and Atchafalaya Rivers, respectively (Figure 94). The lower Mississippi River distributes a portion of the water discharge down the Atchafalaya River. Since 1978 this annual portion has been controlled by the USACOE at 30 percent of the total discharge.

The total atmospheric deposition of nitrogen to the Mississippi River watershed was determined as the sum of wet and dry deposition of the various forms of nitrogen. These were inorganic forms such as nitrate, nitrite, and ammonium, and organic nitrogen. Wet deposition was by way of any form of precipitation, and dry deposition was by way of gaseous and particle deposition. In order to estimate annual total deposition of nitrogen various data and relationships were used.

Wet deposition of nitrate and ammonium have been sampled since 1979 by the National Atmospheric Deposition Program (NADP, 1995), sponsored by the U.S. Department of Agriculture and the U.S. Geological Survey. These are weekly concentrations and precipitation volumes for over 200 sites currently in the network. Annual mass of wet deposition of nitrogen as nitrate and ammonium were determined by summing weekly products of precipitation volume and concentrations over each year from 1979 through 1993, for each NADP site. These annual values were contoured using PLOT88, a software library of PLOTWORKS, Inc., on a 10 × 10 grid. The gridded data was then summed over the Mississippi River watershed to get the annual mass deposited by each nitrogen form. Annual wet deposition of nitrite was not measured and so was estimated as 3 percent the nitrate deposition using conservative literature relationships (Meybeck, 1982).

Information on the dry deposition of nitrogen was limited. Although the National Dry Deposition Network (NDDN) sponsored by the Environmental Protection Agency (EPA) was begun in 1986, and combined into the Clean Air Status and Trends Network (CASTNet) in 1990, the data coverage was sparse compared to the NADP data. These sites did not represent the Mississippi River watershed adequately, being predominantly located in the eastern U.S. Three years, 1990–1992, of annual NDDN dry nitrate deposition (ESE, 1995), was determined using a similar procedure as in the determination of the annual wet nitrate deposition. These watershed annual dry nitrate deposition estimates were compared to the same three years of wet nitrate deposition values. The NDDN determined dry nitrate and ammonium deposition by particulate counts of nitrate and ammonium and by sampled nitric acid gaseous concentrations combined with modeled deposition velocities. Mississippi River watershed dry nitrate deposition was estimated as 0.75 the wet nitrate deposition, an average of 1990–1992 comparisons. This was somewhat near the middle of the various dry to wet nitrate relationships reported in the literature (Table 15). Dry to wet ammonium relationships also were quite varied and poorly represent the Mississippi River watershed (Table 15). Dry ammonium was estimated as 0.25 that of wet ammonium using the average of the literature values in Table 15. Dry nitrite deposition was estimated as equal to the wet nitrite deposition. This assumption was likely to underestimate dry nitrite deposition when compared to data from the northeast U.S. where dry nitrite deposition was high (Barrie and Sirois, 1986). The total inorganic atmospheric deposition of nitrogen was estimated as the sum of measured wet nitrate and ammonium values that were increased to include estimates of wet and dry nitrite, and dry nitrate and ammonium. Wet and dry organic deposition was combined and estimated as a 1:2 organic to inorganic ratio (Hendry et al., 1981; Correll and Ford, 1982, Meybeck, 1983; Jaworski et al., 1992).

Using the stated relationships between wet and dry nitrogen forms and among different forms one could compute a total atmospheric deposition on nitrogen for the Mississippi River watershed. The relationships were all based upon the measured wet nitrate and ammonium depositions. Given the annual NADP wet depositions of nitrate and ammonium, the total wet deposition of inorganic nitrogen was the moles of ammonium plus 1.03 nitrate (0.03 as wet nitrite). Dry deposition of inorganic nitrogen was determined as 0.78 the wet nitrate (0.75 as dry nitrate, 0.03 as dry nitrite) plus 0.25 the wet ammonium. The total inorganic nitrogen was then 1.81 the wet nitrate plus 1.25 the wet ammonium. To include in an estimate of organic deposition a factor of 1.5 the inorganic nitrogen was used.

Results

The average annual total riverine nitrogen flux was 115 × 109 mol (Table 16). Total annual riverine nitrogen flux varied from <70 × 109 mol to >150 × 109 mol during the study period (Figure 95). The average major components to riverine nitrogen flux were nitrate (59 percent) and organic nitrogen (37 percent); ammonium (3 percent) and nitrite (1 percent) were minor components. Annual nitrate and organic nitrogen fluxes were fairly well correlated, with higher nitrate to organic nitrogen ratios in low discharge years.

Using a 29.3 percent average runoff or precipitation retention factor for the continental U.S. (U.S. Department of the Interior, 1984), the gauged annual Mississippi River discharge was of the same magnitude and varied in a reasonable fashion as the total annual runoff from the watershed precipitation. This supported the computational technique used here to sum parameters over the watershed, and thus in determining the total annual nitrogen deposition to the watershed as wet deposition. Spatial distribution of annual precipitation varied from a southeastern U.S. high to a Rocky Mountain low, which is in good agreement with 30 year means of the National Weather Service.

Average annual NADP atmospheric wet depositions of nitrate and ammonium were almost equal, with 44 and 42 × 109 mol, respectively (Table 16). Interannual variation was small, values were within ±10 × 109 mol of the means (Figure 96).

The annual distribution of NADP atmospheric deposition rates of nitrate (Figure 97) and ammonium (Figure 98) for 1988, a low precipitation year and 1993, a high precipitation year show a similar pattern. Highest wet deposition rates of nitrate were centered around the southern Great Lakes and extended into New England; deposition rates were lower towards the western portion of the watershed. Although nitrate wet deposition magnitude was consistent, during years of higher precipitation, the total deposition was greater and the region of highest deposition extended farther into the Midwest. Highest wet deposition rates of ammonium were also centered near the southern Great Lakes and decreased towards both coasts. During years of high precipitation ammonium magnitudes substantially increased and high deposition regions were centered in the middle of the watershed.

The NDDN dry nitrate deposition had lower annual values, but with a similar spatial distribution as the NADP wet deposition (Figure 99). The NDDN dry deposition was determined from fewer station locations and for only three years of data. The sparse spatial coverage, relative to the NADP coverage, was likely to contribute to some uncertainty in annual NDDN deposition distribution, but the magnitudes of the three years of NDDN dry nitrate deposition were considered reasonable. The three computed annual values of NDDN dry nitrate deposition were approximately 75 percent the corresponding annual values of NADP wet nitrate deposition. The limited number of years of NDDN coverage forced the use of this factor to relate annual dry nitrate deposition to the longer series of annual NADP wet nitrate deposition.

The average annual total atmospheric deposition, the sum of all measured and estimated components, was 200 × 109 mol (Table 16). This was 174 percent the average annual total riverine nitrogen flux.

Total atmospheric deposition does not exhibit the same interannual variation as the total riverine flux (Figure 100). Although both values did decrease during years of low precipitation, the magnitude of the atmospheric deposition of nitrogen was less variable.

Conclusions

It is clear that the annual total atmospheric deposition of nitrogen to the Mississippi River watershed is of the same order of magnitude, if not larger, as the annual total riverine flux of nitrogen. In a watershed nitrogen budget, one of the previously unquantified input terms, the atmospheric deposition, is found to be of comparable magnitude to one of the presumed major output terms, the riverine nutrient flux. It is therefore essential that the atmospheric deposition of nitrogen be included into any nitrogen budget of the Mississippi River watershed.

Although purposely simple, this analysis does have uncertainties in the annual nitrogen deposition quantities. The vast spatial scale of the watershed creates a number of accuracy problems. The Mississippi River watershed is composed of a number of smaller watersheds, each having different precipitation, different spatial deposition of nitrogen forms, and different depositional relationships between nitrogen forms. Wet and dry temporal variations, as well as spatial deposition variations, were optimistically accounted for with the use of annual quantities in this study.

There are still many points to clarify. First is the question of quantifying the deposition quantities of the various nitrogen forms and the modes of deposition. In this study nitrite and organic nitrogen, as well as dry nitrate and ammonium, were related to the wet deposition of two nitrogen forms, nitrate and ammonium. A number of assumed relationships were used in this study for lack of direct measurements. Additional analysis of existing dry nitrate and ammonium measurements are in order to more accurately determine the dry to wet nitrate relationship or to replace them altogether with information derived from dry deposition measurements. More information is necessary for accurate determination of both wet and dry organic nitrogen deposition. This includes both spatial watershed and multi-year temporal differences. Where decade length measurements are not available, clarification of relationships between wet to dry and between nitrogen forms are necessary.

A major component in determining the role of atmospherically deposited nitrogen is a retention factor. Even a spatial averaged retention factor, such as the continental U.S. value used in the comparison of annual precipitation volumes to river discharge, would enhance our understanding of the relative importance of the atmospheric input of nitrogen.

Certainly a more in-depth accounting is necessary in both time and space. A temporal analysis of the sub-basin watersheds using atmospheric deposition information would improve our understanding of the relationships between the atmospherically derived nitrogen and the transport by the rivers.

Remembering that the ultimate goal is the comprehensive nitrogen budget of the Mississippi River watershed, only with this level of understanding can reasonable management plans be created to address the problem of the excess riverine flux of nutrients to the northern Gulf of Mexico.

Acknowledgments

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Table 15.
Dry to wet deposition relationships for nitrate (NO_3) and ammonium (NH_4).

DRY:WET	LOCATION	REFERENCE
NO_3		
0.25	eastern Canada	Barrie and Sirois (1986)
0.3	midwest U.S.	Baker (1991)
0.4	northeast U.S.	Baker (1991)
0.96	Florida	Baker (1991)
1	no. New York	Shepard et al. (1989)
1	western U.S.	Young et al. (1988)
1.5	so. Blue Ridge	Baker (1991)
1.6	Tennessee	Shepard et al. (1989)
4	Florida	Hendry et al. (1981)
NH_4		
0.14	no. New York	Shepard et al. (1989)
0.19	midwest U.S.	Baker (1991)
0.25	Tennessee	Shepard et al. (1989)
0.34	northeast U.S.	Baker (1991)
0.39	Florida	Baker (1991)
0.38	so. Blue Ridge	Baker (1991)
0.5	Florida	Hendry et al. (1981)

Table 16.

Average annual Mississippi River nitrogen flux, as riverine total, nitrate (NO_3), organic nitrogen (N_{OR}), ammonium (NH_4), and nitrite (NO_2); total average atmospheric deposition of nitrogen to the Mississippi River watershed, and as nitrate (NO_3) and ammonium (NH_4); and the equivalent deposition rates for the Mississippi River watershed, 1979–1993.

NITROGEN FLUX	MEAN ($x10^9$ mol)	DEPOSITION RATE (mol/m^2)
TOTAL RIVER	115	0.036
NO_3	68	0.021
N_{OR}	42	0.013
NH_4	3.2	0.001
NO_2	1.6	0.0005
TOTAL ATMOSPHERIC	200	0.062
NO_3	44	0.014
NH_4	42	0.013

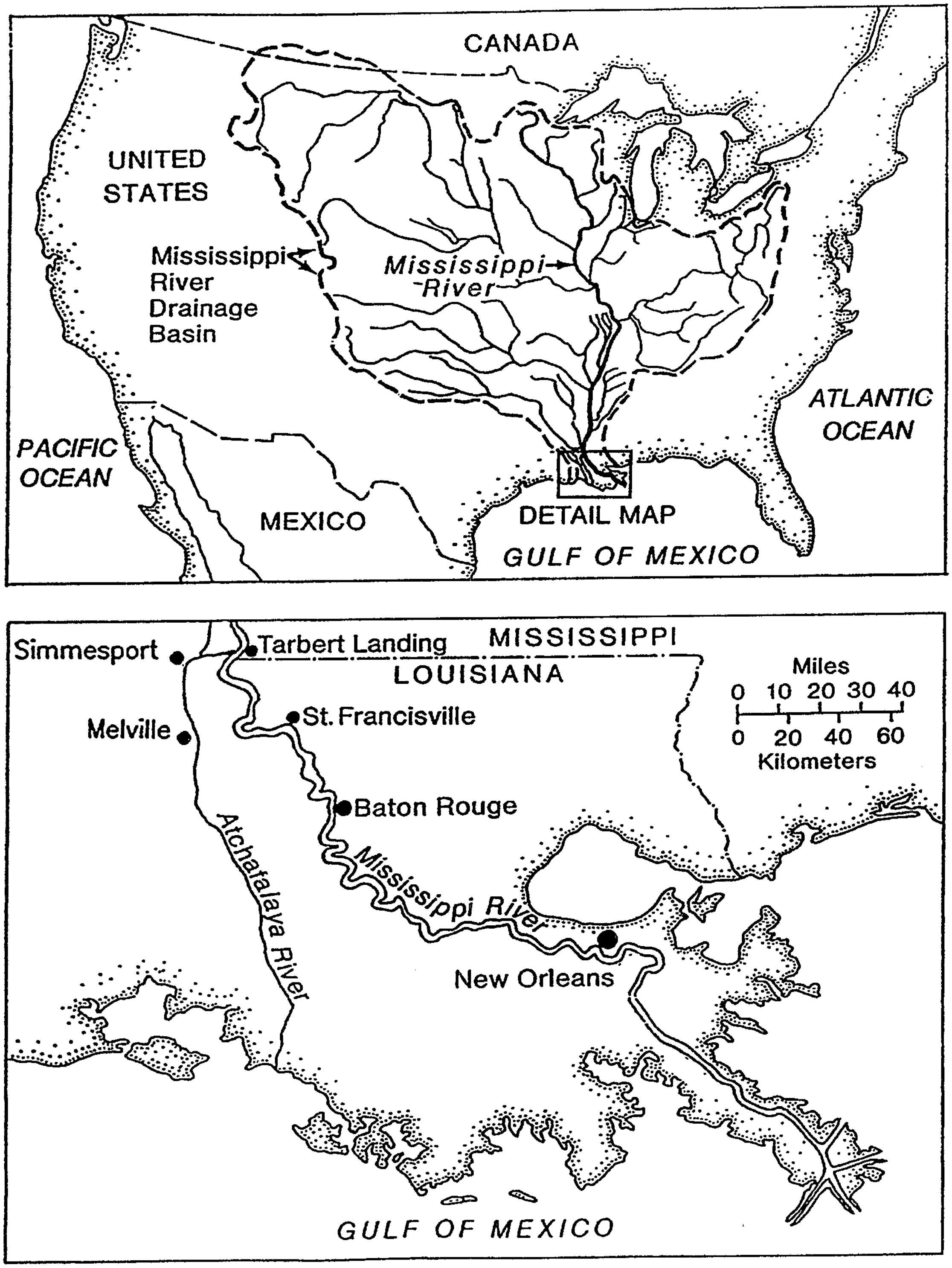

Figure 94.

General limit of the Mississippi River watershed (top). Lower Mississippi River with Atchafalaya River, USACOE discharge gauging sites at Tarbert Landing, MS and Simmesport LA, and USGS NASQAN sampling sites at St. Francisville, LA and Melville, LA (bottom). Redrawn from Dinnel and Bratkovich (1993).

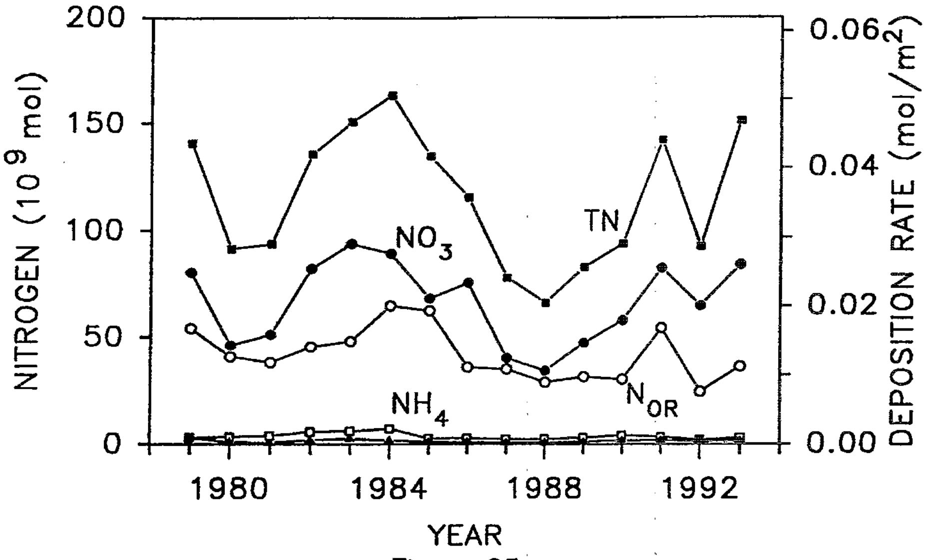

Figure 95.

Annual total Mississippi River nitrogen flux, with equivalent average deposition rate to Mississippi River watershed, 1979–1993. Total nitrogen (TN solid square), nitrate (NO_3 solid circle), organic nitrogen (Nor open circle), ammonium (NH_4 open square), and nitrite (solid triangle).

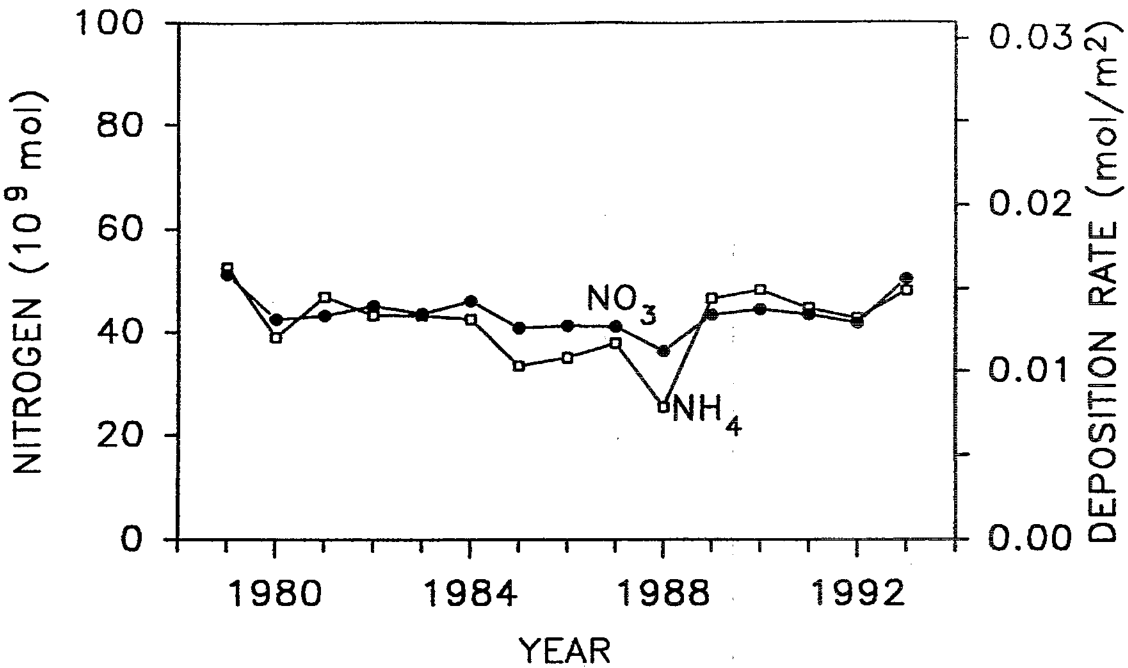

Figure 96.

Annual atmospheric wet deposition of NADP nitrate (NO_3 solid circle) and ammonium (NH_4 open square), with equivalent average deposition rate to Mississippi River watershed, 1979–1993.

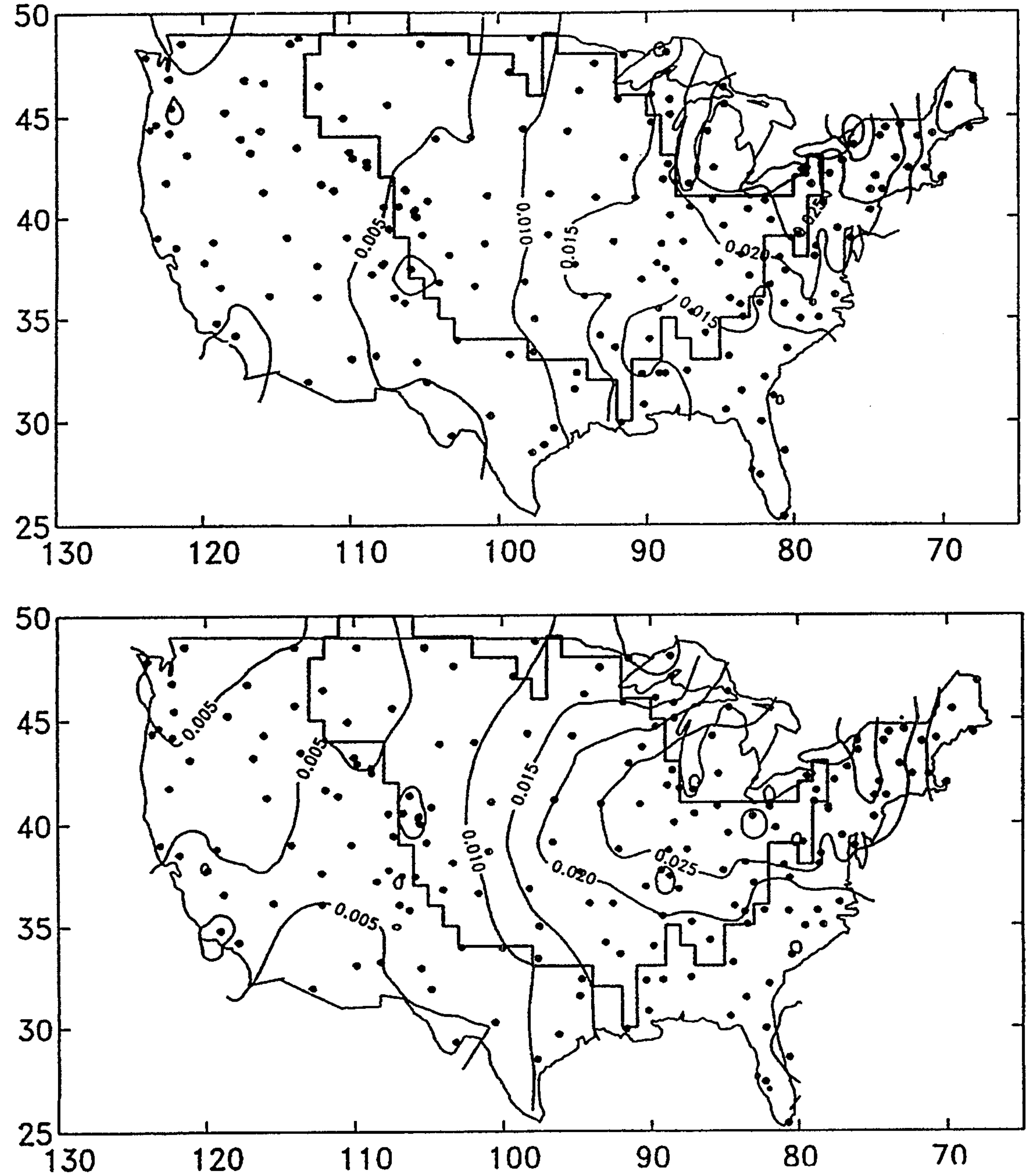

Figure 97.
Atmospheric wet deposition rate of NADP nitrate (NO_3) in 1988 (top) and 1993 (bottom) in mol/m2. NADP sites are located as solid circles; Mississippi River watershed outlined by heavy line.

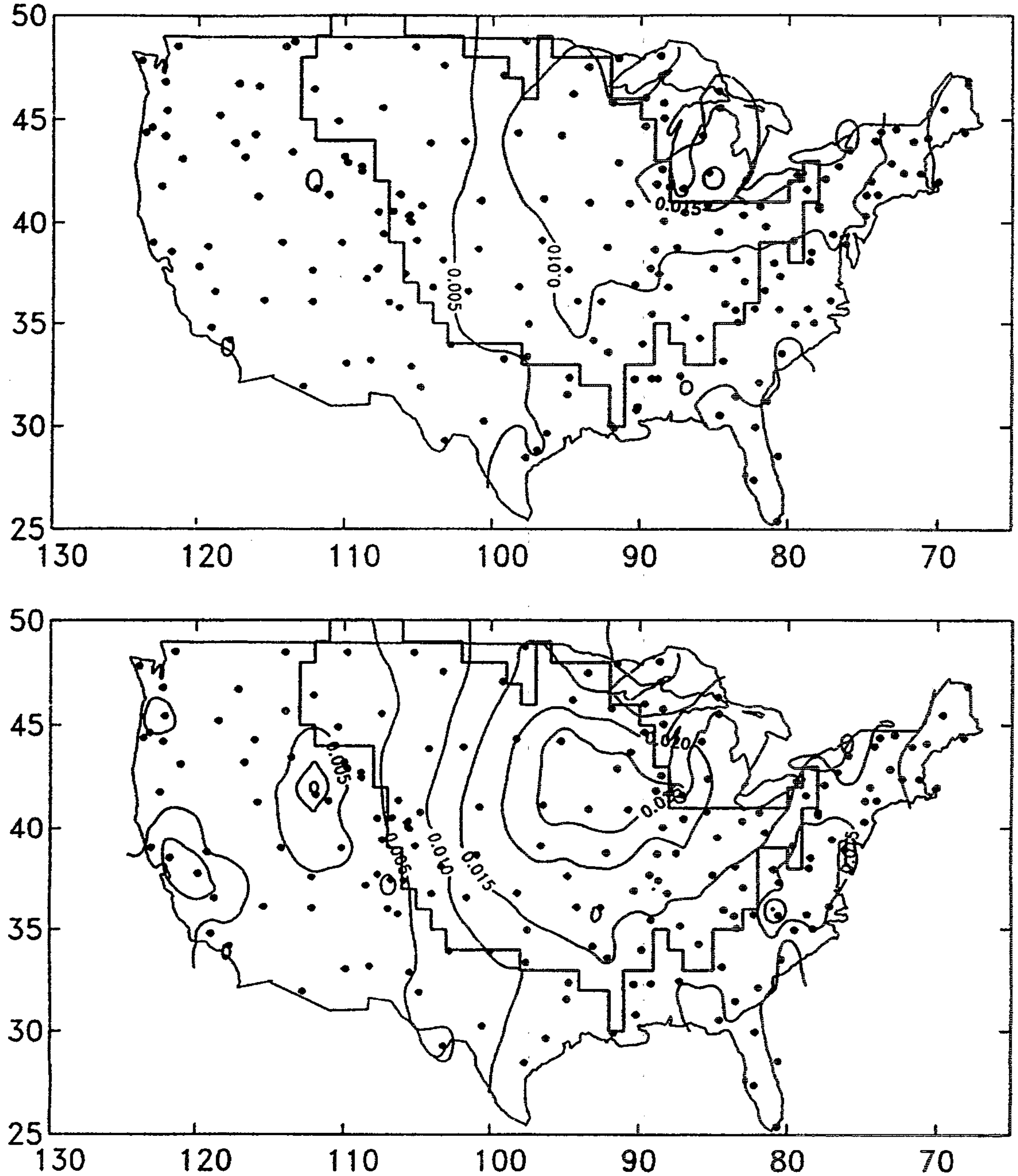

Figure 98.

Atmospheric wet deposition rate of NADP ammonium (NH_4) in 1988 (top) and 1993 (bottom) in mol/m^2. NADP sites are located as solid circles; Mississippi River watershed outlined by heavy line.

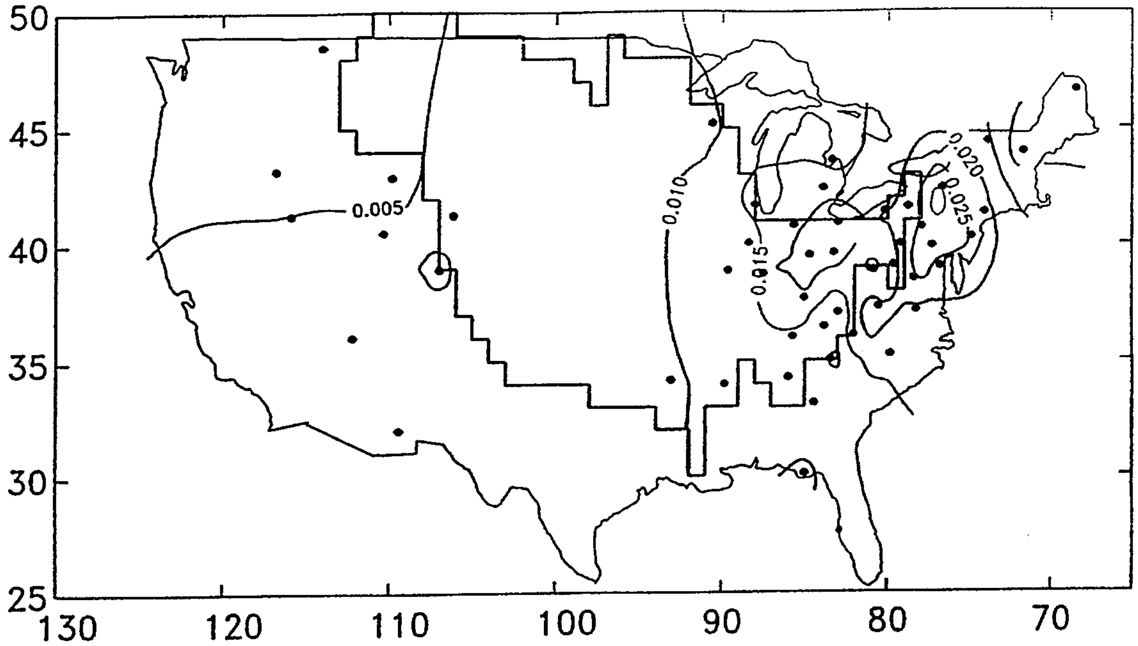

Figure 99.
Atmospheric dry deposition rate of NDDN nitrate (NO_3) in 1991 in mol/m^2. NDDN sites are located as solid circles; Mississippi River watershed outlined by heavy line.

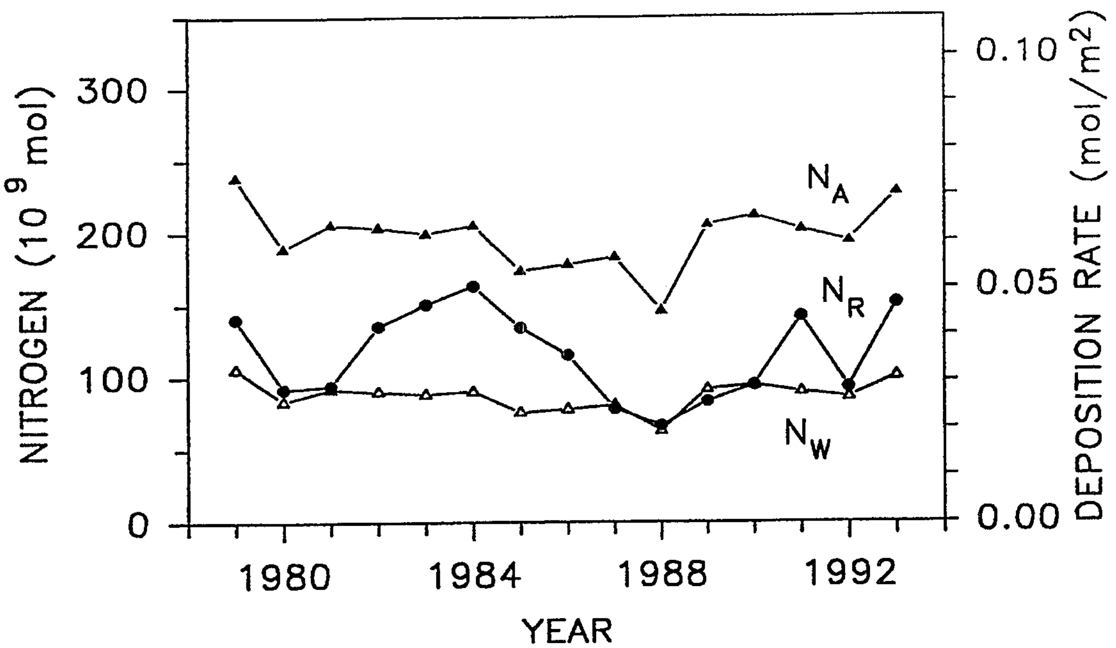

Figure 100.
Annual atmospheric deposition of total nitrogen (NA solid triangle), annual atmospheric wet deposition of nitrogen as nitrate plus ammonium (NW open triangle) and annual total Mississippi River nitrogen flux (NR solid circle), with equivalent average deposition rates to Mississippi River watershed, 1979–1993.

Presentation Discussion

Scott Dinnell (*University of Southern Mississippi—Center for Marine Sciences*)

Don Boesch *(University of Maryland—Cambridge, MD):* asked Scott Dinnell if he could quantify the export of atmospheric deposition from the landscape (groundwater) because a lot of the deposition is taking place in the northeastern part of the Basin, which tends to have higher forest cover than the rest of the Basin. This would presume to be more retentive of that source. He asked him if he has calculated some hypothetical estimates of exports.

Scott Dinnell responded that he has not quantified retention based on different landscapes in sub-basins, even between the Ohio River to the upper Missouri River, or in the plain states where land cover and soil types would cause some kind of variation of the quantities atmospherically deposited versus the amounts found in the river. He said that this type of study was another step that could be conducted. He would like to look at the spatial and temporal differences, for at least the wet deposition information.This weekly data collected over 15 years could be used to look at phasing between the deposition, the heavy deposition times, and the local river signals in the drainage basins. He felt it was important to at least look at the major drainage basins from that point of view. There is a relationship among spatial and temporal distribution and the amounts and locations of atmospheric deposition and different retention factors.

Nutrients in Streamflow of the Mississippi River Basin—Annual Mean Concentrations, Annual Loads, and Temporal Trends in Concentrations and Loads

Dee L. Lurry
U.S. Geological Survey
Austin, Texas 78754-3896

Abstract

The U.S. Geological Survey (USGS) is beginning a study to compute annual mean concentrations and annual loads of total nitrogen and total phosphorus, and temporal trends in annual mean concentrations and annual loads of total nitrogen and total phosphorous, at 41 USGS National Stream Quality Accounting Network (NASQAN) gaging stations on the Mississippi River and its major tributaries (Figure 101). The study is in cooperation with the Nutrient Enrichment Committee of the Gulf of Mexico Program. Of the 41 stations, 9 are on the main stem of the Mississippi River and 32 are on 25 major tributaries of the river. Only data collected during the period October 1967–September 1994 will be used because, before October 1967, methods for nitrogen analysis were different from current (1995) methods. Annual constituent loads will be computed by summing daily loads obtained from equations developed by regressing log-transformed daily loads computed from constituent concentrations on log-transformed daily streamflow. Temporal trends in constituent concentrations and loads will be computed using Kendall's Tau test or shown graphically using the smoothing technique LOWESS (LOcally WEighted Scatterplot Smoothing).

No Manuscript Submitted.

Presentation Discussion

Dee Lurry *(U.S. Geological Survey—Austin, TX)*

An unidentified audience member commented that Dee Lurry said she intended to correct the concentrations for flow and asked if, both the flow and concentration are seasonal and correlated, but are independent in some aspect, what changes in data could occur by doing a flow adjustment.

Dee Lurry responded that she expects to have flow adjusted residuals. She told the audience member that she had just begun the study, but would like to discuss the results when she obtains the adjusted residuals. She asked the audience member to provide his name and telephone number so that she could contact him when the results are concluded.

She said that her approach was very similar to the approach used in a comparable study on trends along the Gulf Coast. One of her colleagues, David Dunn from Austin, Texas, actually conducted that work, which is currently being reviewed by the committee. She suggested that the audience member, David Dunn, and she, could discuss the topic further.

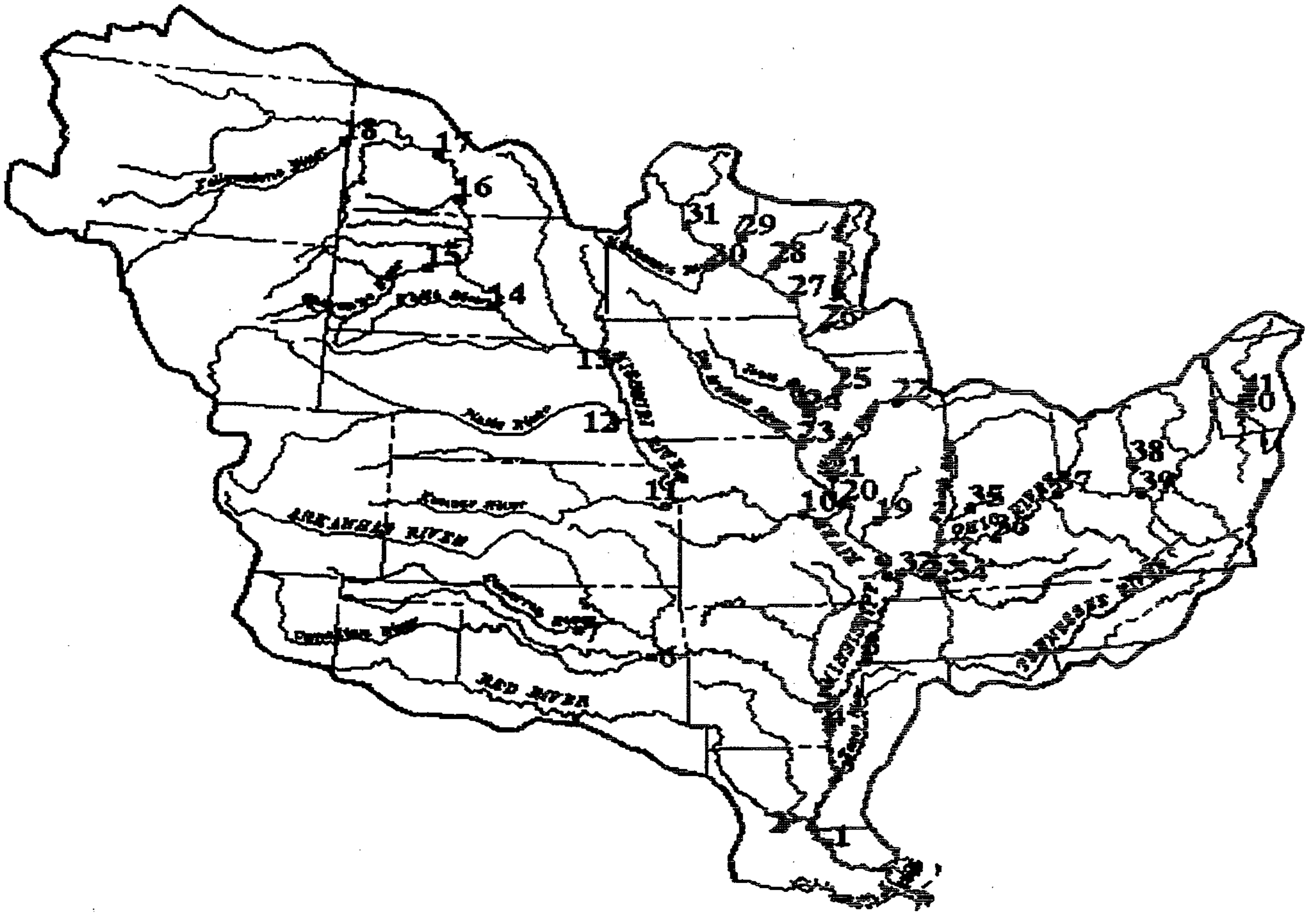

Figure 101.
The Mississippi River and its major tributaries.

An Assessment of Watershed Based Projects in the Mississippi River Drainage Basin

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Gulf of Mexico Program Office
Stennis Space Center, Mississippi 39529

Abstract

Some inventories of ongoing watershed based projects in the United States contain as many as 700 entries. It is estimated that 200–250 of these projects are within the Mississippi River Drainage Basin. The goals of the projects are varied: control of nonpoint sources of nutrients or pesticides or both; control of suspended solids from soil erosion; education of the public about the value of the watershed; monitoring of various pollutants; protection of various fisheries; etc. On a national level the projects range in size from 5 acres to over 150 million acres in size. Funds have been obtained from federal, state, and private sectors on many of the projects.

In a recently released report, the General Accounting Office concluded that two factors are necessary for success in watershed management projects:

1. Flexibility in the kinds of financial and technical assistance provided by the federal agencies

2. Local tailoring of approaches to watershed management that allows for differences in the type and source of pollutants, local agricultural practices and the community's attitudes.

Overview of Existing Watershed Management Programs

Introduction

From the beginning of the modern age people have recognized that natural systems of varying scale are related. For example, Jonathan Swift's familiar little poem:

> *So naturalists observe a flea*
> *Hath smaller fleas that on him prey;*
> *And these have smaller still to bite 'em*
> *And so proceed ad infinitum.* (Swift, 1733)

It is not surprising then that participants in the Gulf of Mexico Program understood from its beginning that the Gulf of Mexico ecosystem is connected to that of its watershed. At the first meeting of the Public Health Committee in March, 1989 members of the Public Health Committee were overwhelmed by the enormous size of the area from which pollutants that could potentially affect the Gulf could arise. Dr. Merrill McPhearson of the Food and Drug Administration acknowledged that the Gulf is influenced by its entire watershed, but by using a deliberate, systematic approach the issues could be dealt with. He suggested that we begin at the bottom of the watershed, identify and rank the public health problems, determine the causes wherever they were located in the watershed and finally develop solutions. This is the path of action that all of the issue committees have been following in developing characterization reports and action agendas.

The members of the Gulf of Mexico Program's Nutrient Enrichment Committee members also recognized the potential impact of nutrients getting into the Rivers far upstream on the Gulf. Based on this understanding of the problem the committee recommended that the Program undertake several activities. One of the first efforts was an attempt to develop a compendium of sources and quantities of nutrients in the rivers of the entire Gulf of Mexico watershed. This report was produced by staff at Purdue University from USGS data taken from the EPA STORET database (USEPA, 1992a). While the report was not sufficiently detailed to determine the sources of nitrogen to the Mississippi River, it was clear that most of the nitrogen in the River at St. Francisville, Louisiana was already in the River at Cairo, Illinois. A companion report described the information available on the effects of nutrient overenrichment in Gulf waters; the hypoxic zone on the Louisiana-Texas shelf was described as an area where there was evidence for excess nutrient input (U.S. EPA, 1992b).

In the spring of 1993 the Gulf of Mexico Program partners organized and conducted a Mississippi River Project to educate students about the issue of nonpoint source pollution, sources of nutrients, effects of nutrient overenrichment, and to make them aware of the fact that their actions far up the Mississippi River could affect the Gulf of Mexico. Vice President Al Gore participated in the project. The Project was successful in reaching students and the public at large through the media coverage that resulted. The project report states that, "Beyond any doubt, students enthusiastically and overwhelmingly responded to the project, its activities and issues. Their letters, comments to Vice-President Gore, and to reporters underscore their desire to actively make a difference in the quality of the environment." (Mote, 1993) The effort to raise public awareness upstream was continued this year when the Program awarded a project (GMPO, 1995a) to develop educational information and displays that will illustrate the effects that excess nutrients in the River can have on the Gulf and the importance of controlling nonpoint sources of nutrients to the River in the upper reaches of the watershed.

The Gulf Program participants have also recognized that one of the most effective ways to reduce nutrient input into the river upstream will be to forge partnerships with similar groups in the Gulf of Mexico watershed to control impacts on the Gulf ecosystem. To this end we have begun to identify these groups and have now a preliminary inventory of 48 activities and projects. (GMPO, 1995b) We intend to complete and maintain this inventory of watershed projects and to build a network for action and education with these groups. This paper describes what we have learned so far about them.

We know from an inventory completed in June of this year by the General Accounting Office (GAO, 1995) that there are considerably more projects than 48 in the Mississippi River Basin. The national GAO inventory reported the identification of 618 watershed based projects aimed at agricultural sources of pollution that have received federal funding. I have estimated that between 200 and 250 of these projects are within the Mississippi River watershed. The GAO reviewed nine of these projects in detail; four of these projects were in the Mississippi River watershed. The conclusions of the GAO report will be summarized later in this paper.

Funding and initiative for many of the projects in the Gulf Program's preliminary inventory are provided by the federal government thru EPA, NRCS, USGS, etc. The funding is provided either solely by the government or there is a cost sharing between federal and state government. Funding does not always refer to direct monetary contribution; "in-kind" funding such as technical expertise and cooperation were provided for many projects by the "funding" agency. At least five of the projects are being conducted using no federal funds; they are funded by private landowners and local property taxes. The projects represent a wide spectrum of management activities at a variety of technical and nontechnical levels. All of the projects are relatively new; the oldest project began in 1986.

Of the 48 projects identified, 12 were basin specific projects of the USGS National Water-Quality Assessment Program. The purpose of this Program is to identify factors that affect water quality and monitoring to determine levels of pollutants. At this conference USGS personnel have presented information based on these projects. This information will be necessary to determine changes in nutrient loading in the rivers and consequently will allow for a measure of the effectiveness of remedial actions taken in the watershed. The remainder of the projects focus on activities to manage and control pollution problems.

The objectives of the management projects ranged from increasing public awareness to multiple objectives such as improving water quality, developing public outreach documents, and implementing best management practices. Most projects have the general objective to improve water quality.

The objective of the four projects occurring in Pennsylvania is the control of drainage from abandoned mines. However, one of the treatment options being considered or actually implemented in each of these projects is the use of a passive wetland treatment system which will be effective for control of nutrients and sediments as well as acid mine drainage and heavy metals which are the primary focus of the projects. About 20 projects focus on three specific objectives:

1. farm animal waste management
2. fertilizer use reduction
3. erosion control;

all of which will help reduce nutrient flux to the rivers.

Three sets of the projects in the preliminary inventory will be reviewed in some detail as examples of the types of activities: Table 17 describes those projects in Arkansas that received funding and support from NRCS, Consolidated Farm Service Agency and the Extension Service; Table 18 provides information on the TVA River Action Team Projects and Table 19 summarizes those projects from the GAO report that received no federal funding. Many of these projects have as one of the goals the reduction of nonpoint source pollution of the river by nutrients. The NRCS and the TVA are active partners in the Gulf of Mexico Program, so working with these upstream projects will be easily accomplished.

Although many projects have resulted in successes such as decreases in erosion or reduction in fertilizer application, few of the projects have been able to quantify their successes (such as: reduction of soil erosion by 7 ton/acre or nitrogen application reduced by 70 pounds/acre). Participants in almost all of the projects reported "unquantifiable" successes, including reports from farmers that they were satisfied with best management practices and new technologies introduced by the program and they would continue to use them; establishment of citizen action and interstate cooperative groups; distribution of public outreach material. These "unquantifiable" successes are the first step to implementing actions that will lead to quantifiable results. Because environmental problems cannot be corrected instantly, a series of indicators of progress toward the ultimate environmental goal is needed. The Gulf of Mexico has adopted a hierarchy of indicators to measure success in achieving the many steps toward our goals. This hierarchy is shown in Figure 102. A suite of indicators to indicate progress toward reducing extent, severity and duration of the hypoxic zone in the Gulf will be developed as part of the strategic assessment and planning process.

The General Accounting Office inventory of watershed based projects was limited to those that have received federal funding and are aimed at agricultural sources of pollution. If it is assumed that the projects in states that are only partly in the Mississippi River watershed are distributed uniformly across each state, it can be estimated that between 200 and 250 of these projects are within the Mississippi River watershed. Nationally the projects ranged from as small as five acres to over 150 million acres in size; they involved both surface and ground water resources; and they addressed such agricultural pollutants as animal waste, fertilizer runoff, pesticides and soil sediment. Through early 1995 these projects had received an estimated $514 million in federal funds.

They reviewed nine of these projects in detail; four of these were in the Mississippi River watershed. Table 20 presents a few facts about these projects.

The Project participants pointed out that even given rigorous monitoring, demonstrating a link between changes in land use and diminished chemical pollution is difficult, if not impossible, especially within a short time frame. Participants in several projects noted that current science can demonstrate only a tenuous link between land use practices and water quality, and it may take years for their projects to produce chemical improvements in water quality. Participants in the Big Spring Basin project said that climatic variations, such as droughts followed by years of heavy rainfall, and other factors have made it difficult to establish a link between changes in farming practices and groundwater quality, despite more than 10 years of monitoring and analysis.

The GAO reported that while their conclusions from a thorough study of 9 watershed projects cannot be projected to the entire inventory of 618 projects, participants in all nine agreed on two key factors for success that have been learned during the course of the projects:

1. Flexibility in the kinds of financial and technical assistance provided by federal agencies

2. Local tailoring of approaches to watershed management.

Because watershed projects differ in characteristics such as the type and source of pollutants, local agricultural practices, and the community's attitudes, participants believed that a prescriptive, one-size-fits-all approach would be inappropriate. At the local level, the projects' participants emphasized to the GAO that the keys to reducing agricultural pollution include

1. Building citizens' cooperation through education

2. Getting stakeholders to participate in developing the project's goals

3. Tailoring the project's strategies, water quality monitoring, and regulatory enforcement efforts to local conditions.

Conclusion

All of the watershed protection activities were begun to protect the water quality of a particular section of a creek or river in this great watershed; none were undertaken specifically to reduce the severity or extent of the hypoxic area in the Gulf. However, the combined effort of all of these management projects and the support of citizens living in the Mississippi River Basin should result in measurable improvements in the Mississippi River water quality that will be detected by monitoring projects such as the USGS National Water-Quality Assessment Program and ultimately reduce the nutrients reaching the Gulf via the River. In fact, while it is too early to say with certainty, the summary of existing data as presented by Turner and Rabalais (1991) indicates that nitrate-nitrogen concentrations in the Mississippi River at St. Francisville and New Orleans, Louisiana may have begun decreasing in the late 1980's which would be commensurate with the formation of these pollution management projects within the basin.

As the Gulf Program works to develop viable solutions through a strategic assessment process, we will rely to a great extent on these existing programs to provide existing data, to participate in the assessment process, to identify and prioritize the areas of greatest need and to undertake demonstration projects to initiate implementation of the strategic plan.

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Table 17.
Watershed projects identified in Arkansas.

Title	Began	Acres	Budget/Year	Purpose/Goal
Long Creek Ag. NPS HUA[1]	1991	96,574	~$1.6 million (proposed 5-yr budget)	Reduction of nutrients and pathogens from animal waste
Millwood Lake Watershed Demo. Project	1991	1,325,000	~$1.5 million (proposed 5-yr budget)	Provide for disposal of manure from poultry and swine operations using BMPs[2]
Muddy Fork of the Illinois R. Ag. NPS HUA	1990	47,122	~$2.5 million (proposed 6-yr budget)	BMPs include waste management for confined animal operations and nutrient management for pasture lands

[1]Agricultural Nonpoint Source Hydrologic Unit Area
[2]Best Management Practices

Table 18.
TVA Sponsored River Action Teams (RAT).

Rat Title	Began	Area	Funds/Yr	Goals/Actions
Flint Creek	1992	290,000 acres	$2.15 million FY92–FY94	Animal waste lagoons; Wastewater irrigation systems; composters for poultry operations; no-till agriculture
Wheeler Elk	1993	5,180 sq. miles	Not available	Install oil/water separator on parking lot; encourage agricultural BMPs
Chickamauga	1995	1,865 sq. miles	Not available	Acid mine drainage remediation
Hiwassee	1992	2,700 sq miles	~$1 million	Stream bank stabilization; animal waste management; erosion control; public education; 20–30 projects/ year.
Holston	1993	3,776 sq miles	Not available	Identification of NPS sources; Installation of 6 Agricultural BMPs; Elimination of unpermitted discharges; Monitoring
Watts Bar...	1994	1,370 sq miles	Not available	Goal is to solve pollution problems in the watershed. Public education and outreach.
Clinch-Powell	1993	2,954 sq miles	Not available	Constructed animal waste treatment system and live stock exclusion fences, revegetated riparian zones

Table 19.
Projects receiving no federal funding.

Title	State	Project Sponsors	Goals/Activities
Piasa Creek Watershed Partnership	Illinois	Am. Farmland Trust Piasa Creek Conservancy Great Rivers Land Trust	Establish water retention basins. Create field buffers and filter strips. Develop whole farm nutrient plans.
Pontiac/Skeator Watershed Area	Illinois	Northern Illinois Water Company	Reduce fertilizer use. Involve and educate citizens. Comply with nitrate/nitrite DW Limits.
Chippewa River Stewardship Partnership	Minnesota	Am. Farmland Trust Chippewa R. Stewardship Partnership	Improve Water Quality. Restore wetlands and riparian areas. Reduce Flood Damages.
S. Washington Watershed District	Minnesota	City of Woodbury MN Board of Water and Soil Resources	Management of urban runoff to control nutrients, sediment, salinity. Control of flooding.
Tributaries of Stillwater, Rock Creek	Montana	Land and Water Services and private landowners	Reduce soil erosion and nitrogen by moving corrals and stockyards away from the river and revegetating banks.

Table 20.
Selected watershed projects in the Mississippi River drainage basin from GAO report.

Watershed	Area (Acres)	Total Funds	Duration
Otter Lake, IL	12,255	$292K	1992–1995
Big Darby Creek, OH	371,000	$5,145K	1990–1995
Black Earth Creek, WI	64,000	$3,245K	1986–1994
Big Spring Basin, IA	66,000	$7,119K	1982–1993

Presentation Discussion

Fred Kopfler (Gulf of Mexico Program—Stennis Space Center, MS)

Daniel Ray ***(The McKnight Foundation—Minneapolis, MN)*** gave an example of the scale of the community-based watershed management infrastructure in place in the upper Midwest, saying that the McKnight Foundation is involved with supporting a network of community-based activities that span throughout the Mississippi watershed and above the quad-cities. He believed this area was approximately 12 percent of the overall Mississippi River Watershed. He said they have identified about 110 community-based, initiatives that cover about one third of the watershed, not including the involvement of federal land. He finalized his comments saying that there is a huge infrastructure available and ready for some direction to pursue a strategy. This infrastructure should be effectively linked into the Gulf Coast comprehensive program.

Fred Kopfler told the audience that Daniel Ray was one of the individuals contacted by Battelle who provided a lot of information. Much of the material was received by Battelle too late in the government fiscal year to be incorporated into the report. The Gulf of Mexico Program has some revisions and changes in format that they will give to Battelle for incorporation into the final report and these changes will include all of the updated information. He agreed to follow up with Daniel Ray to make sure all those organizations are included.

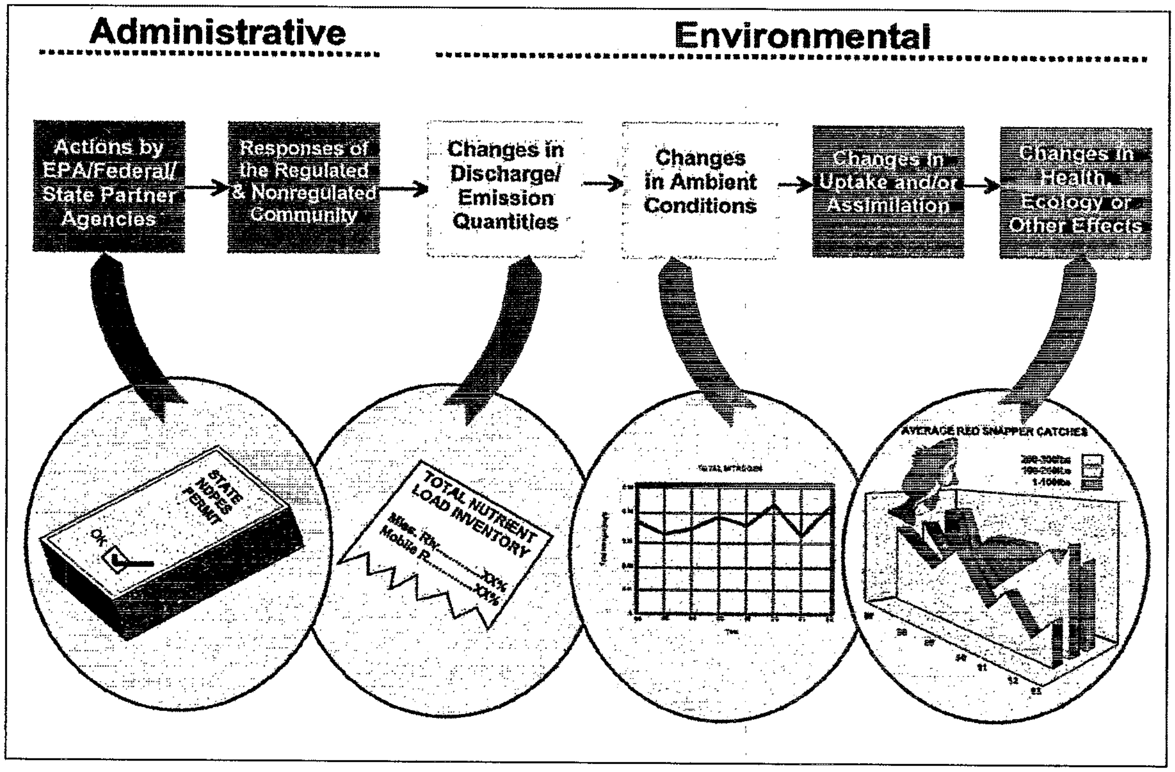


Figure 102.
An illustration of a hierarchy of indicators that can be used to track progress toward an environmental goal before results are measurable in the field.

What is Being Done in the Basin Now to Control Nutrient Loads?

Charles Spooner
Environmental Protection Agency
Office of Water
Washington, DC 20460

Abstract

Nutrients have been identified as problems in many places in the Mississippi River Basin making them one of the most ubiquitous and complex categories of water pollution. Control efforts tend to be localized and tend to focus on controlling phosphorus, the most important nutrient in freshwater systems. Concerns for nitrogen are found where nitrate's toxicity in drinking water and ammonia's toxicity to fish are noted.

Nutrient concerns are always expressed in their relationship to specific water bodies, and these concerns are seldom seen as issues that affect more than one water body. Examples of projects in the watershed and examples drawn from successful programs in other areas will be cited.

No Manuscript Submitted.

Presentation Discussion

Charles Spooner (Environmental Protection Agency/Office of Water)

Beverly Ethridge ***(U.S. Environmental Protection Agency, Water Quality Division—Baton Rouge, LA)*** commented that the Biennial State Water Quality Reports attribute about 60 or 70 percent of the Nation's water pollution to nonpoint sources. She asked Charles Spooner if that percentage is correct, and if the nonpoint source budget is about $100 million, how it compares to the remainder of the water budget which is presumably targeted for point source control.

Charles Spooner stated that Beverly Ethridge was making the point that the Section 319 Program is relatively small. He said that it was explained early in the conference that one of the reasons they reacted negatively to the Section 319g petition was because the remedy for a Section 319 petition is to invoke controls on the Section 319 Program which would, ultimately, lead to the EPA leveraging a small program within the agency. The major capital funding for the state revolving fund is large. Therefore, it is not difficult to list two states that have construction loan subsidies that would equal the nonpoint source program nationwide. It is encouraging that the rules are allowing greater flexibility to access those funds to support nonpoint source control capital costs.

What is Being Done in the Basin to Control Nutrient Loads from Agricultural Sources?

John P. Burt and Klaus Alt
USDA/Natural Resources Conservation Service
Washington, DC 20013

Abstract

The 1985 and 1990 Farm Bill has produced a conservation revolution across the country. Farmers are using conservation systems to reduce erosion, almost eliminating wetland drainage, restoring wetlands, and using space technology to refine nutrient and herbicide application for maximum efficiency. These efforts have reduced erosion on highly erodible land by 70 percent and on all cropland by 33 percent. In addition, the combination of drastically reduced drainage and wetland restoration and creation has begun to show a net gain in wetland acreage in agriculture areas. The Mississippi River Basin should be yielding less nutrients and sediments from agricultural nonpoint sources.

Introduction

Agricultural sources of nonpoint source pollution are a major nutrient load to the Gulf of Mexico as indicated in various water quality reports. While the storm water runoff carries natural nutrient loads and a mix of nonpoint source loads, it is generally agreed that agricultural sources are significant contributors.

Agriculture is by far the dominant land use in the Mississippi River Basin. Before 1985, the basin contained approximately 56 percent of the Nation's land in farms and 80 percent of the Nation's cropland. After the Conservation Reserve Program (CRP) contracts converted cropland to permanent cover, the area still contained 65 percent of the Nation's cropland. This area produces 84 percent of the Nation's corn, 81 percent of the soybeans, 59 percent of the wheat and 57 percent of the hay. Often, the upper Mississippi River Basin is referred to as the Nation's "Bread Basket," relating to the large grain production.

Mississippi River Basin Production

- 84 percent of national corn production.
- 81 pecent of national soybean production.
- 59 percent of national wheat production.
- 65 percent of the Nation's cropland.

For agriculture to remain profitable and efficient, agricultural chemicals—both pesticides and fertilizers—are necessary. These chemicals vary from pre- and post-herbicides, to insecticide and fungicides, to nutrients from animal manure and fertilizer. Since nutrients are the major concern in the Gulf of Mexico, this paper will concentrate on nutrient availability and soil erosion, which is an indicator of nutrient movement from agricultural land.

Basic Transport Mechanisms

While reviewing the following information, the basic nonpoint source transport mechanisms should be kept in mind. These mechanisms are:

availability, transport, and in-stream integration.

The availability of agricultural nutrients is related to soil erosion and the presence of nutrients on the surface or in the soil. If soil erosion and excess nutrients are reduced, a similar reduction in downstream nutrient load should occur.

The transport is the movement of the available material —soil, chemicals, organic matter, manure, and so forth—from the field to the stream. The actual amount of nutrients and soil transported depends upon the transporting forces and interceptions in the transport path. If the runoff flow is interrupted due to terraces in the field, filter strips, or wetlands, some eroded soil and nutrients will be removed.

The in-stream integration is the assimilation of the transported material into the stream, lake, or estuary environment, creating some impact—good or bad depending upon many aquatic factors.

Basic Transport Mechanism

- *Availability*—Soil erosion, chemical use, concentrated manure production.

- *Transport*—Energy of sheet and concentrated flow from precipitation.

- *Instream integration*—Effects on the aquatic environment.

Once the flow enters a water body, the potential for managing the nonpoint source loads is lost. However, the effects on the water body must be understood to determine if additional load reductions are necessary.

With the 1985 and 1990 farm bills, improved technology, and farmers better-educated on environmental issues, the nutrient loads to the Gulf from agriculture should be declining.

1985 and 1990 Farm Bills

The 1985 Farm Bill, known as the Food Security Act (FSA), set in motion some major conservation policy that has generated a revolution across the agriculture community. These policies are embedded in the Conservation Title of the Farm Bill.

1985 Farm Bill, Conservation Title

- Conservation Compliance Provisions
- Conservation Reserve Program
- Swampbuster Provisions
- Wetland Reserve Program

Common names are applied to these provisions and programs rather than the actual Farm Bill terms. Briefly, these programs and provisions had the following conditions.

Conservation Compliance

If farmers were participating in any USDA program—commodity deficiency payments, loans, and so forth—they had to provide soil conservation treatment on their *highly erodible land* (hel).

Conservation compliance provisions were implemented in two stages. From 1985 until 1990, conservation compliance plans were developed. This plan scheduled the cultivating systems, structures, and crop management systems that would be necessary to adequately reduce erosion on the highly erodible land. The implementation schedule must have all the plan installed by December 31, 1994.

Visual

1985 → 1990 → 1994

Develop Conservation Compliance Plan (1985–1990)

Implement Conservation Compliance Plan (1990–1994)

The Natural Resources Conservation Service (NRCS) (formerly the Soil Conservation Service) has a soil loss tolerance, commonly called "T" value, assigned to each soil in the United States. The "T" value is expressed in tons/acre allowed for sustainable agricultural production. In the development of the conservation compliance plans, the agency had to develop conservation systems that meet four primary criteria as described below.

Criteria for Conservation Compliance Systems

1. 50 percent or more soil erosion reduction
2. Economically feasible
3. Locally practical
4. Socially acceptable

Produced Alternative Conservation Systems

These criteria often required conservation systems with soil loss higher than the "T" value for the soil. However, the system, called ***alternative conservation systems,*** had to achieve at least 50 percent or greater soil erosion reduction.

By the deadline of Dec. 31, 1994, over 90 percent of the farmers had implemented their compliance plan. This has been a major conservation revolution in the country-side and the farm community is very proud of its accomplishment. Everyone worked together to get the job done. Not only farmers but also equipment dealers, farm organizations, chemical dealers, and, above all, the farm press had a major impact on reaching the conservation goals.

To meet the goals of Conservation Compliance, 1.7 million conservation compliance plans were developed on 143 million acres of the Nation's most highly erodible cropland. This is about one-third of all cropland in the United States. A major portion of this land is located in the Mississippi River Basin.

Conservation Compliance

- 1.7 conservation compliance plans.
- 143 million acres of highly erodible land.

Conservation Reserve Program

- 36.4 million acres
- Cost—1.8 billion per year

As part of treating highly erodible land, the Conservation Reserve Program was offered to retire land for 10 years. Through 12 sign-ups, 36.4 million acres of cropland was placed under contract and planted into permanent vegetation, which essentially eliminates herbicide and fertilizer use on those acres (Figure 103).

Results of Conservation Compliance and Conservation Reserve Program

The combination of conservation compliance along with the conservation reserve program reduced erosion rates by 70 percent on the highly erodible land based on 1994 status reviews and by one-third on all cropland based on the 1992 National Resources Inventory (NRI). The NRI is a sample of the Nation's resources from 800,000 points across the country (Figures 104, 105, 106).

The reduction in nutrient availability must be having a significant effect eventually on the Gulf. However, immediate response is not anticipated when the complexity of the transport mechanism, the entire Mississippi River system, is considered. It takes time for the streams to purge the current loads and make adjustments.

Swampbuster

Another program that should be helping to reduce nutrient loads is the swampbuster provisions. Simply stated farmers cannot drain or fill wetlands and still receive USDA program benefits. This provision has drastically reduced wetland drainage. The remaining wetlands will continue to serve as a major nutrient and sediment trapping system in the transport process. Based on the 1992 NRI, the rate of wetland drainage due to agriculture has been reduced to 31,000 acres per year (Figure 107).

Wetland Reserve Program

The wetland reserve program has restored almost 134,000 acres of cropland back to wetlands under perpetual easements. The landowners have offered seven times as many acres for the wetland reserve program as funds are available to accept.

The restored wetland acres are often in a position to receive some drainage from agricultural land and serve as a trap in the transport mechanism.

The combination of Swampbuster and Wetland Reserve Program has probably turned the wetland acreage in agricultural areas to a net gain rather than a loss.

Impact on Water Quality in the Mississippi River

Some of the papers presented at this conference may estimate change in water quality within the Gulf or Mississippi River. The U.S. Geological Survey (1) data for 1980 to 1989 shows nitrate level dropped 0.4 percent per year in the Upper Mississippi River Region, and the Lower Mississippi River Region dropped 1.6 percent per year. The phosphorus levels decreased from 1 to 1.7 percent per year in the northern parts of the Mississippi River Basin and decreased yearly from 3.1 to 3.8 percent in the lower Mississippi River Basin. Clearly, this reduction is not due solely from nonpoint sources. Reductions in point source discharges and different weather patterns could be the major reasons for the nutrient level reductions. However, a significant reduction from agricultural nonpoint sources should continue this trend.

New Technology

New technology that is being implemented will offer an additional reduction in nutrient movement from the fields. Some refer to this technology as "Prescription Farming" while others refer to it as "Precision Farming." The technology is still in its infancy, but it is operational, proving profitable, expanding rapidly, and optimizes nutrient consumption by the plants.

With the use of Geo-Positioning Systems (GPS), a small four-wheeler can move across the field and take soil samples on a grid while recording the exact position in a compute file using GPS.

While the harvesting equipment moves across the field, it is collecting data continuously on crop yields and recording the data with GPS markers. The farmer has a color coded record of the crop yield variability across the field and the file is stored for computer use. The crop yield can be overlaid with soil types to determine potential crop yields.

With this information, the data are loaded into a computer mounted on a fertilizer and herbicide application truck, which applies fertilizers based on potential yield and nutrient content of the soils and applies herbicides to weedy spots in the field rather than the entire field. When the seed is planted, the seed density per area is also varied based on soil potential yield and the nutrients applied.

It is space-age technology applied to farming. In most cases, the more efficient use of chemicals and chemical savings will off set the cost of using the equipment on a custom fee basis. Now, rather than applying the herbicides and fertilizers across the field based on average field conditions, the chemicals can be precisely applied for the most efficient use (Figures 108, 109, 110).

New Technology

- Using GPS technology and computers.
- Grid sampling for nutrient analyses.
- Yield monitoring with GPS markers.
- Pest weed problems identified with GPS markers.
- Computer controlled herbicide and fertilizer application truck linked to GPS.
- Seeding based on soil potential yield and linked to GPS.

This technology is not available everywhere due to lack of equipment and trained staff, but it is rapidly expanding. On the horizon, this technology has the potential of being the best method for reducing nutrients from the field and still maintaining a productive agriculture.

Farmers, in general, have been striving for better nutrient utilization, and the trend of lower nutrient consumption per unit of production for some commodities supports their success.

When animal manure is used for part or all the nutrient needs of the plants, farmers are still having some difficulty estimating nutrient availability during the growing season. This is especially a problem with nitrogen. Annual soil and manure testing helps build confidence on accuracy of estimates.

What Does the Future Hold?

Much of the progress described above is dependent upon the 1995 Farm Bill and Budget Reconciliation. Although neither bill has been passed into law, it is obvious some major changes will occur. Commodity payments may be reduced significantly in Budget Reconciliation. Due to commodity payments and loan reduction, Congress feels that some regulator relief is warranted. Therefore, some of the farming constraints that were a condition for receiving commodity support, loans, and so forth, will be reduced. In addition, farmers will be released to plant any crop and not be constrained by the Farm Bill. In addition, set-aside land will be released for planting. The entire process is to move agriculture to a more free market-based economy.

Based on the current debate, the following conditions *may occur.*

- *Conservation Compliance*—Farmers out of compliance will have reduced penalties. Plus the penalty will be limited to the field out of compliance.
- *Conservation Reserve*—Acreage enrollment will probably drop to 50-70 percent of the current enrolled acres. Enrollments in Conservation Reserve started in 1986 with the big enrollments in 1987 and 1988. These 10-year contracts will soon expire.
- *Swampbuster*—Some wetlands will be exempt from swampbuster. The wetlands farmed 6 out of 10 years and 1 acre or less may be exempt from swampbuster. This will exempt 6 to 10 million acres of wetlands

Wetland Reserve Program (WRP)

The program will still be supported but at a lower funding level. Perpetual easements may not be allowed. Instead, WRP contracts will be used and they may vary from 15 to 30 years depending upon who wins during Budget Reconciliation conference.

The bottom line is a much weaker Conservation Title in the farm bill.

1995 Farm Bill Potential Impacts

- *Conservation Compliance*—Penalties reduced. Penalties limited to field not in compliance.
- *Conservation Reserve*—Funding reduced. Fewer acres in reserve.
- *Swampbuster*—Frequently cropped wetlands and small wetlands exempt. 90 percent of pothole wetlands are vulnerable.
- *Wetland Reserve Program*—No perpetual easements—only contracts. Funding reduced. Acreage capped at 975,000 acres.

Commodity Prices

American agricultural products are and will continue to be major contributors to world trade. Bad weather in some regions of the world and increased demand from countries such as China, have increased the prices of commodities in recent months. Commodity payments for wheat and loans for cotton will probably not be necessary for the 1995 crop year due to the increased prices. It is anticipated that upward pressure will continue on commodity prices through 1996 and possibly beyond. However, if the 1995 Farm Bill completely releases the farmers from all restrictions and weather is good, a big crop yield from the United States could reduce the commodity prices, but at some additional cost to the environment.

Increased demand and prices for certain crops combined with a weaker Conservation Title in the 1995 farm bill presents the possibility for a setback to the environment. One major hope, and a valid hope, is that the farmers realize their accomplishments, retain their conservation ethic and continue conservation farming.

It would help to reinforce the conservation ethic if the farmers had a clear understanding of the potential impact of their actions on the Gulf. They are witnessing local improvement in water quality and wildlife but connecting that improvement to the Gulf is difficult to recognize from a farm in the upper Mississippi River Basin. Communications between the Gulf and the farmers in the Mississippi River Basin needs improvement.

However, to get major reductions in nonpoint sources over a large area like the Mississippi River Basin, Farm Bill policy must be compatible with the environmental objectives for the basin.

Summary

Agricultural nonpoint source loads in the Mississippi River Basin have been reduced due to the programs and provisions of the 1985 and 1990 Farm Bills. The future of these accomplishments rests in the 1995 Farm Bill and Budget Reconciliation. These two bills will determine if this country is willing to maintain the present accomplishments, possibly make some improvements, or allow for some backsliding. With the decline in current world grain supply reserves, the opportunity is present for some reversal from the current accomplishments.

Reference

Smith, R.A., Alexander, R.B., and Lanfear, K.J., 1993, National Water Summary 1990–1991, Page 129.

Presentation Discussion

John Burt (U.S. Department of Agriculture/Natural Resources Conservation Service—Washington, D.C.)

No questions/discussion after John Burt.

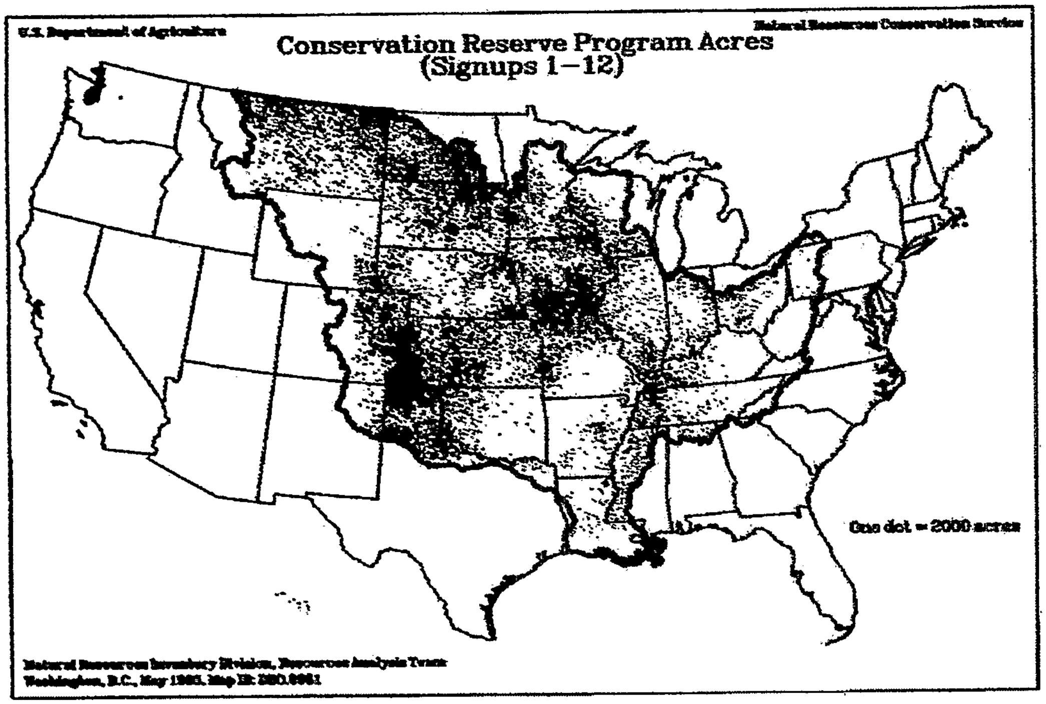


Figure 103.

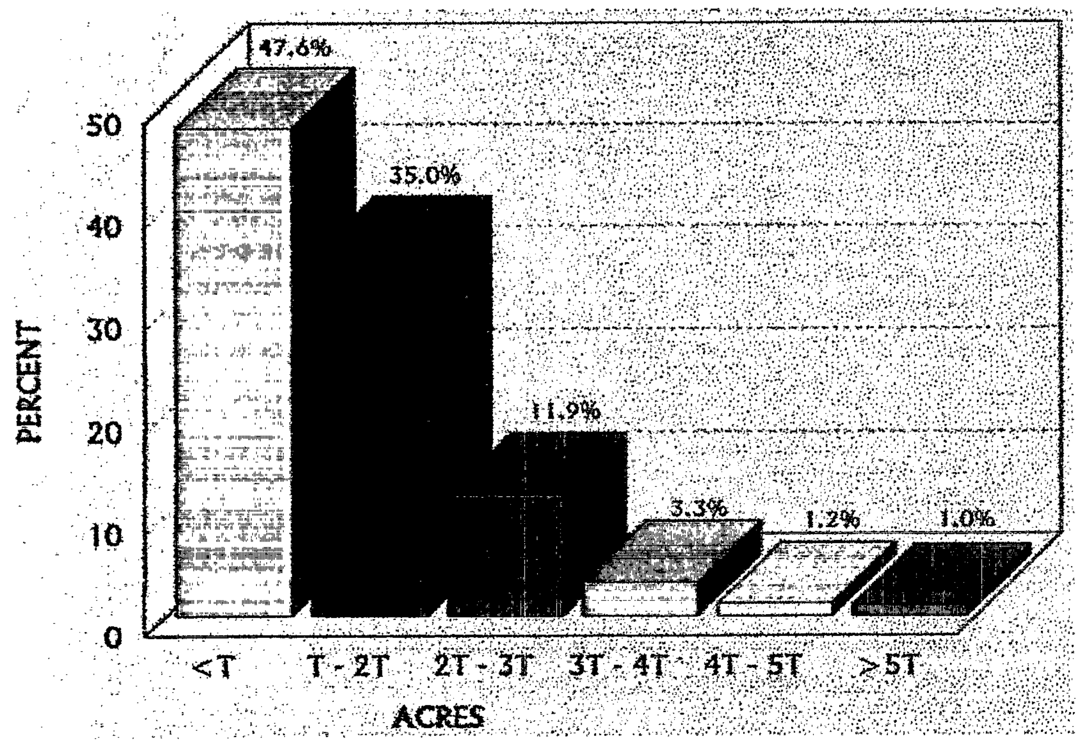


Figure 104.

Distribution of erosion rates before FSA, erosion rates with respect to soil loss tolerance values preliminary data as of February 9, 1995

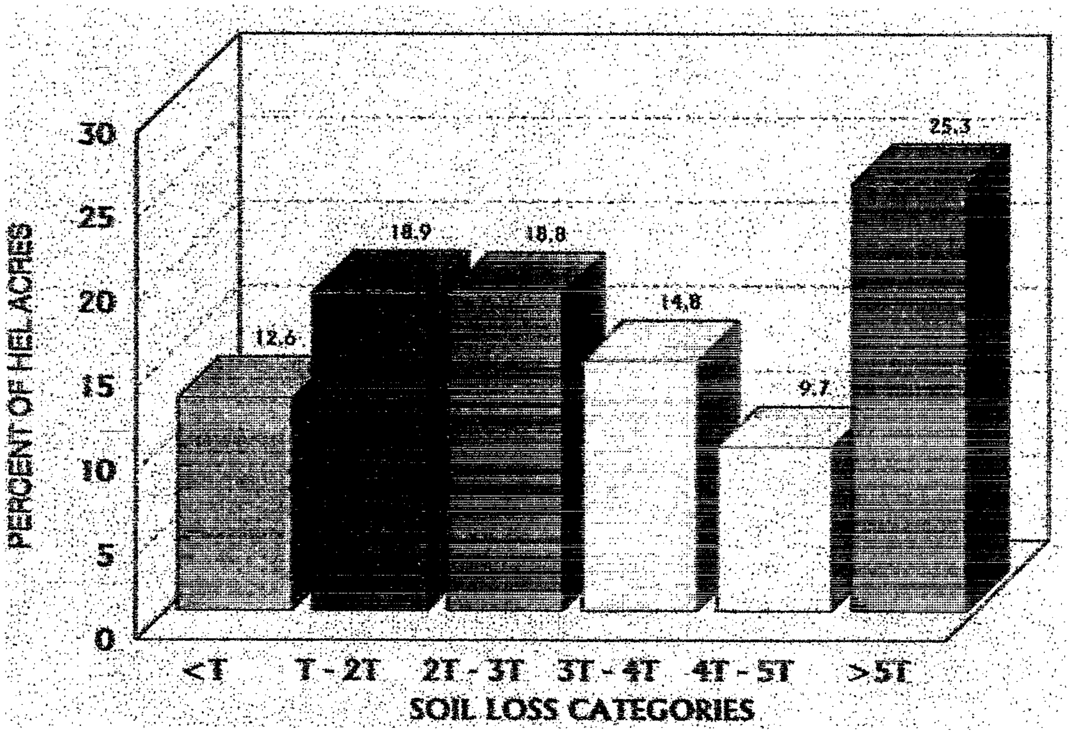


Figure 105.
Summary 1994 Status Review Results—Distribution of erosion rates after full implementation with respect to the soil loss tolerance values preliminary data as of February 9, 1995

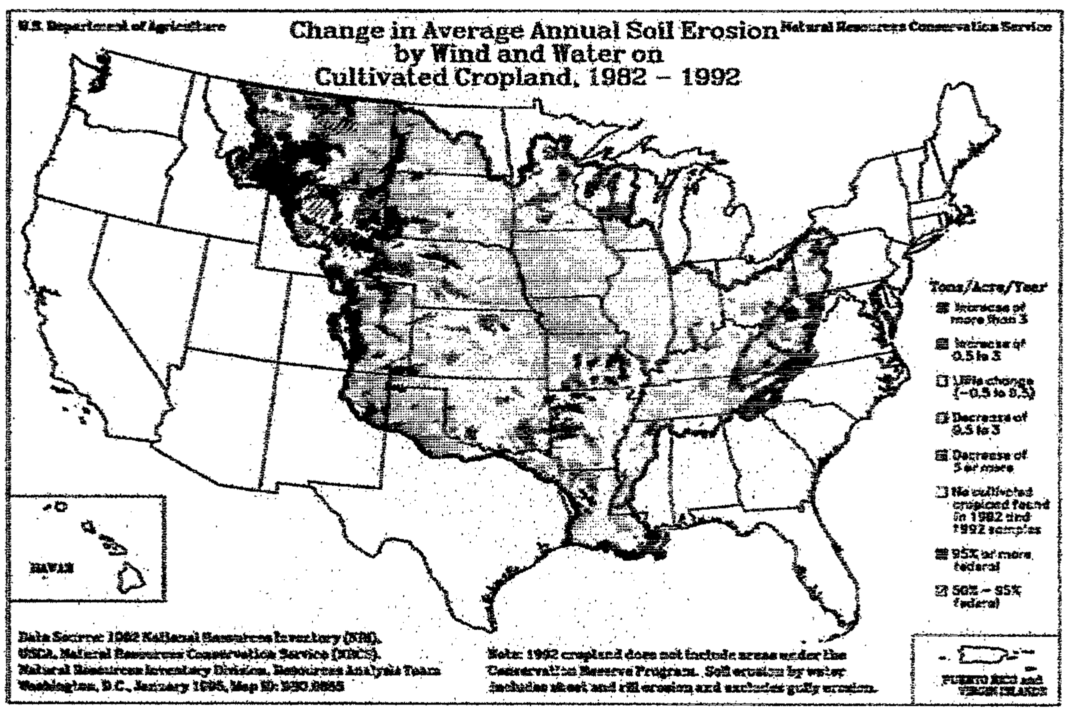
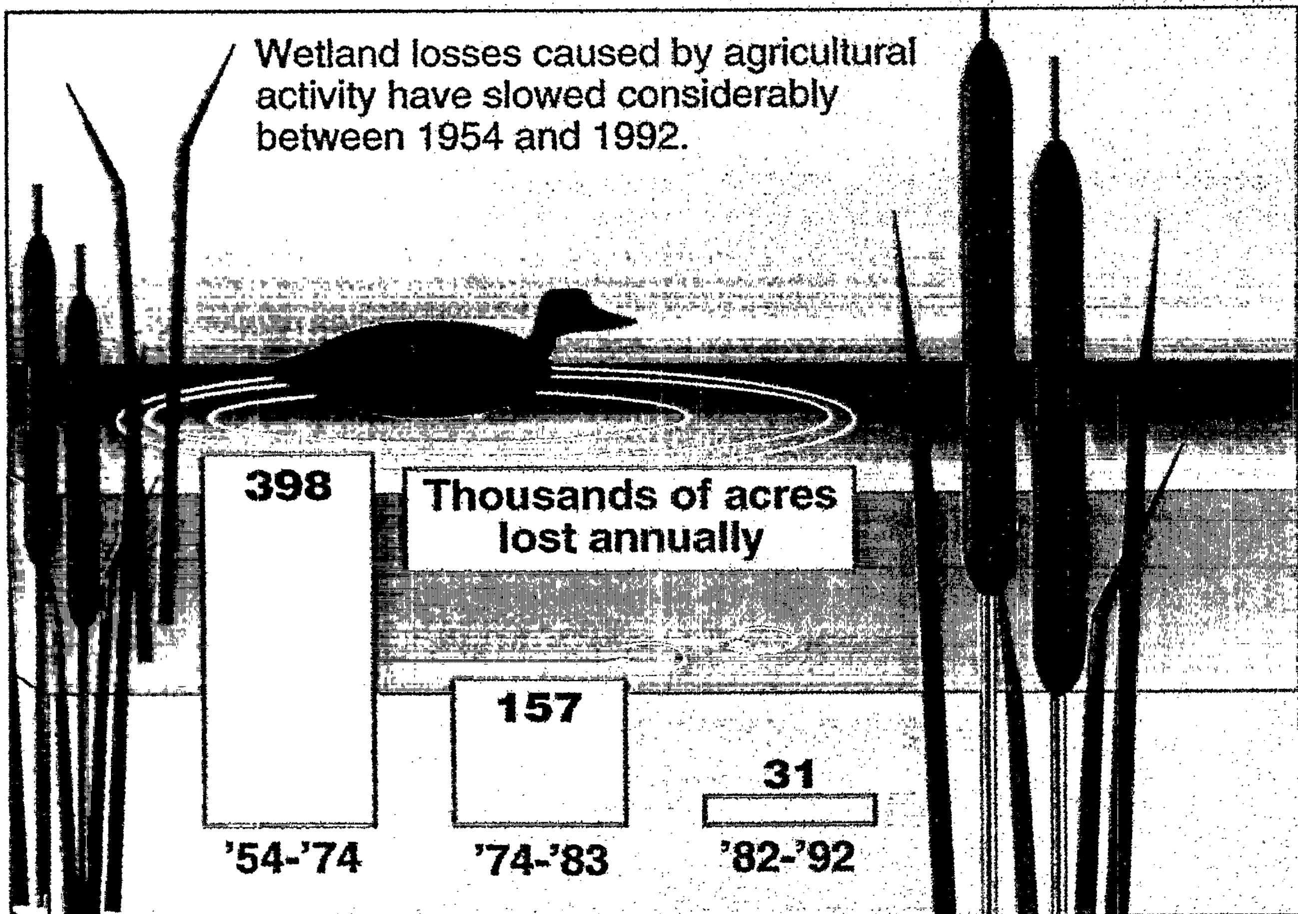


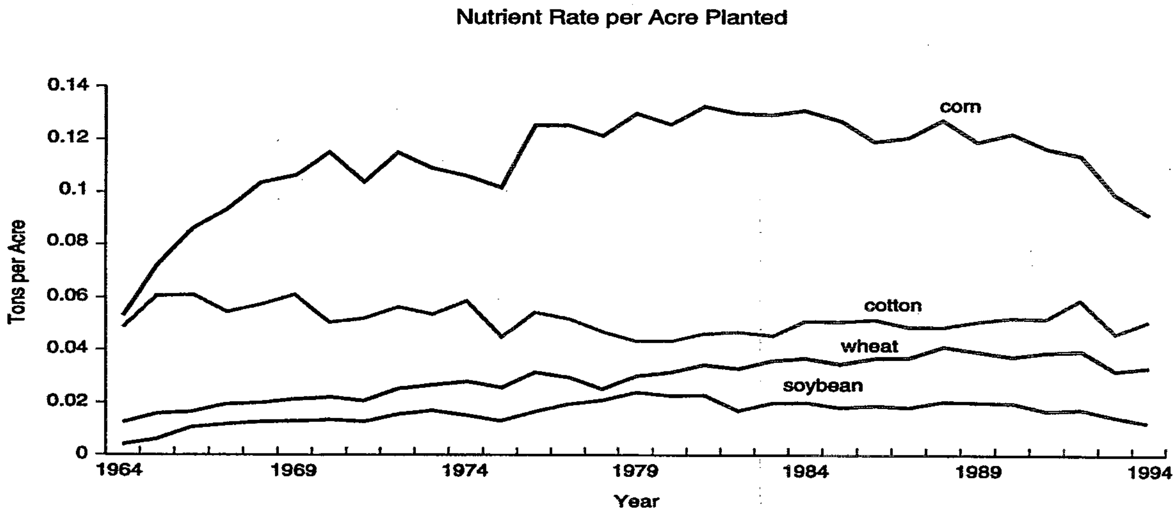
Figure 106.

Agriculture Wetlands Loss Down



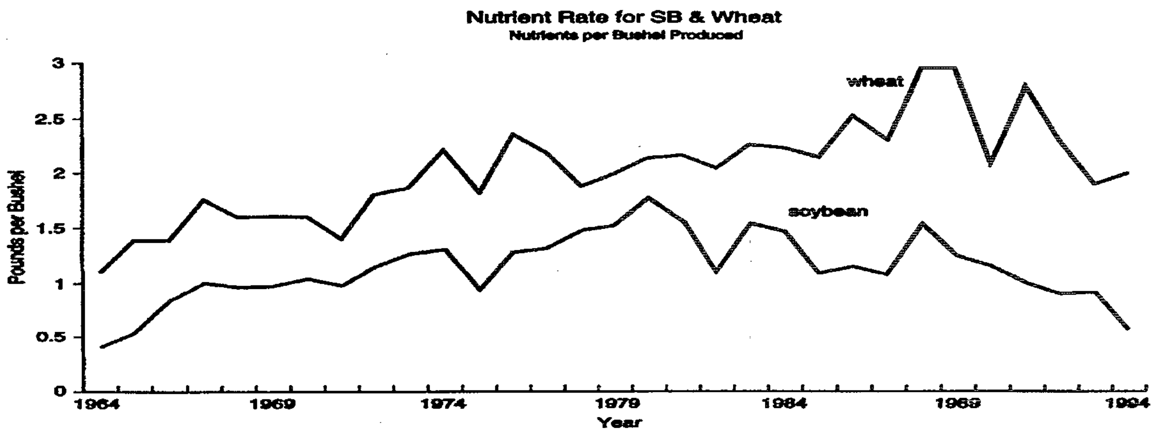
Source: USDA Natural Resources Conservation Service. National Resources Inventory, NRI.
NRI data cover the 48 contiguous states, Hawaii, Puerto Rico, and the U.S. Virgin Islands, but not Alaska.
Source for '54 - '74 and '74 - '83 data: U.S. Department of the Interior.

Figure 107.



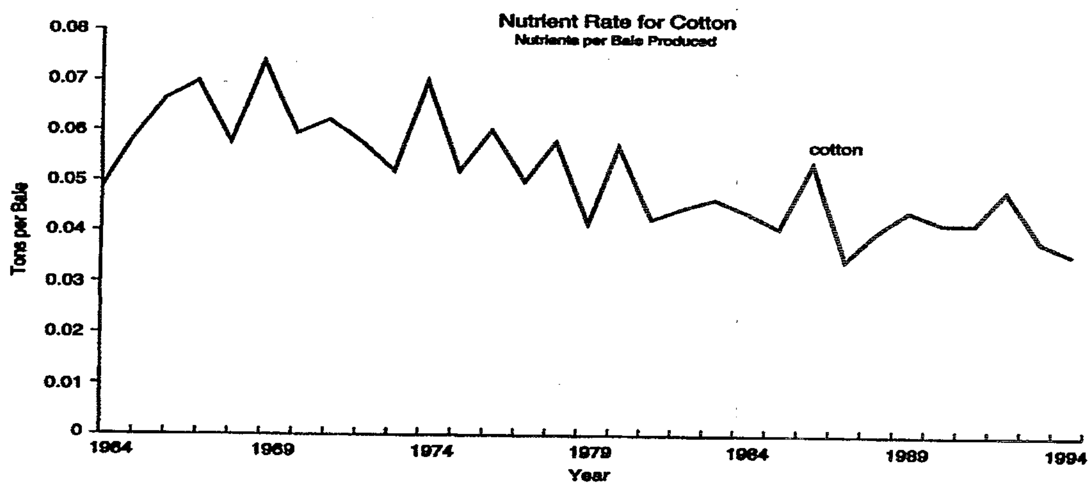
Sources: AER 717; Cropping Practices Survey Data

Figure 108.



Sources: AER 717; Cropping Practices Survey Data

Figure 109.



Sources: AER 717; Cropping Practices Survey Data

Figure 110.

Louisiana Activities and Programs in Nutrient Control and Management?

Dugan S. Sabins and Jan R. Boydstun
Louisiana Department of Environmental Quality
Baton Rouge, Louisiana

Abstract

Louisiana has implemented many activities and programs to address the problems of nutrient enrichment. For many years, most activity was associated with point source control programs for municipal and industrial discharges, many of which had significant nutrient discharges. These point source control activities have led to substantial reductions in the nutrient loadings to state water bodies and are continuing. Recently, however, it has been recognized that diffused rainfall runoff from a variety of "nonpoint" sources are now contributing to the majority of man-induced nutrient loadings to Louisiana water bodies. To address the nonpoint sources of nutrients, Louisiana, as have most states, has initiated an aggressive nonpoint source program designed to work cooperatively with the Environmental Protection Agency under Section 319 of the Clean Water Act. Louisiana's Nonpoint Source Program has sought to support and incorporate existing local, state, and federal agency programs and enter into a broad cooperative "interagency" approach to the problem.

One of the first water bodies in the state that was targeted for nonpoint source implementation activities, which included nutrient controls, was Bayou Queue de Tortue in the Mermentau River Basin (Figure 111). Over a five year period, the program has seen the development of best management practices for rice cultivation that has benefited water quality. The state believes the Bayou Queue de Tortue experience shows that, working cooperatively, nutrient and water quality goals can be achieved (Figures 112 and 113). Other nonpoint source program activities addressing forestry practices and urban runoff, although not as far along in the development, are also showing promise in reaching water quality goals. The state is committed to pursuing whatever point and nonpoint source controls are necessary to address nutrient enrichment problems and believes its existing programs are achieving this goal.

No Manuscript Submitted.

Presentation Discussion

Dugan Sabins (Louisiana Department of Environmental Quality—Baton Rouge, LA)

There were no questions/discussion following Mr. Sabins' presentation.

Bayou Queue de Tortue
Gueydan, Louisiana
58010046

Post BMP : 1990 - 1995

Annual Average DO = 3.512 mg/L

Winter Average	***DO = 5.639 mg/L***
Spring Average	***DO = 3.316 mg/L***
Summer Average	***DO = 2.144 mg/L***
Fall Average	***DO = 2.938 mg/L***

Figure 111.

Bayou Queue de Tortue
Gueydan, Louisiana
58010046

Pre BMP : 1982 - 1989

Annual Average DO = 2.434 mg/L

Winter Average	***DO = 4.917 mg/L***
Spring Average	***DO = 2.083 mg/L***
Summer Average	***DO = 1.251 mg/L***
Fall Average	***DO = 1.483 mg/L***

Figure 112.

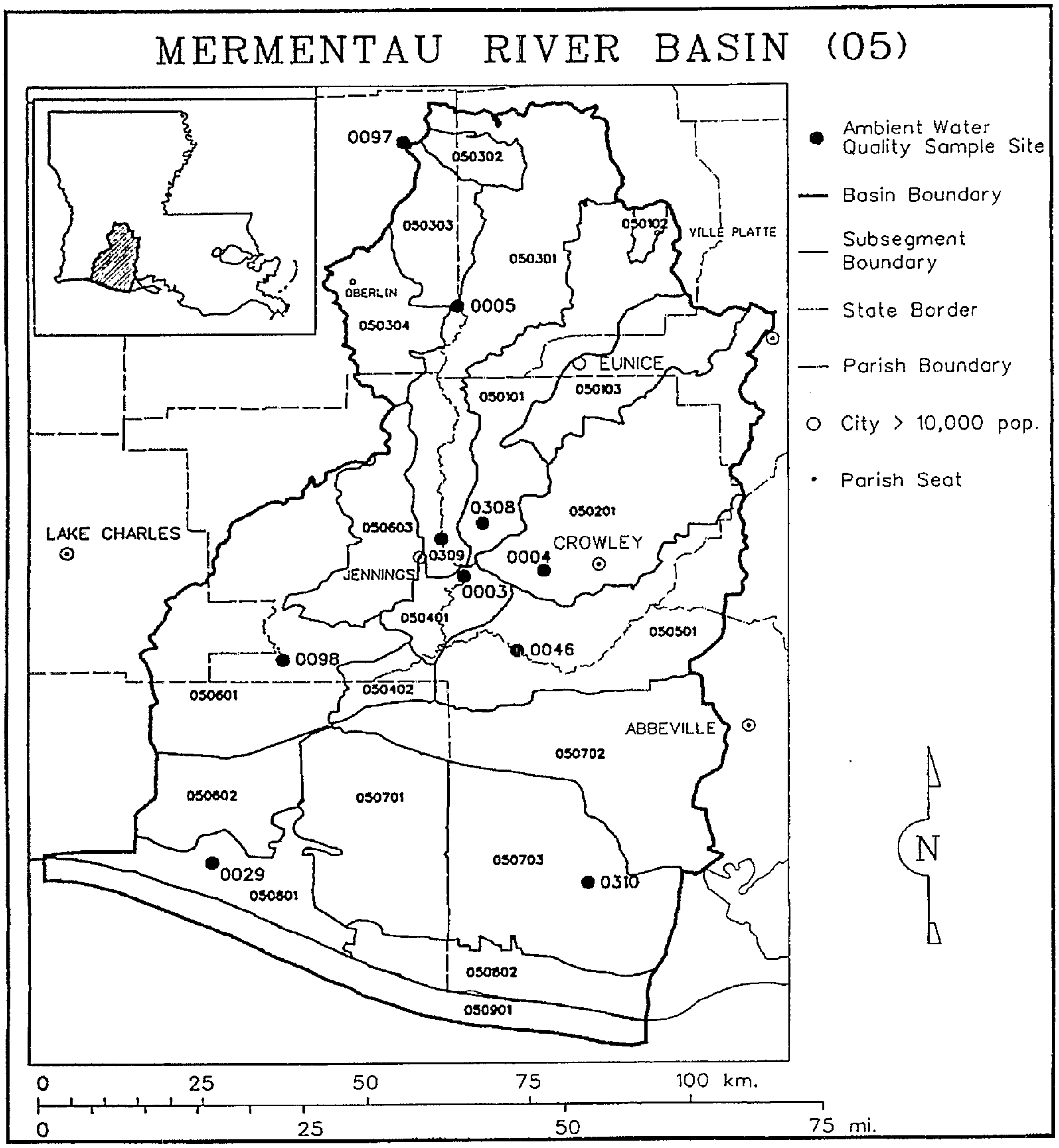

MERMENTAU RIVER BASIN (05)
Ambient Water Quality Sample Site
Basin Boundary
Subsegment Boundary
State Border
Parish Boundary
City > 10,000 pop.
Parish Seat
0097
050302
050303
050301
050102
VILLE PLATTE
OBERLIN
0005
050304
EUNICE
050101
050103
LAKE CHARLES
0308
050201
050603
0309
CROWLEY
0004
JENNINGS
0003
050401
050501
0098
0046
050601
050402
ABBEVILLE
050702
050602
050701
050703
0029
0310
050801
050802
050901
N
0 25 50 75 100 km.
0 25 50 75 mi.

Figure 113.