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Reducing Hypoxia in the Gulf of Mexico: Advice from Three Models

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ABSTRACT: Summer hypoxia in the bottom waters of the northern Gulf of Mexico has received considerable scientific and policy attention because of potential ecological and economic impacts from this very large zone of low oxygen and because of the implications for management within the massive Mississippi River watershed. An assessment of its causes and consequences concluded that the almost 3-fold increase in nitrogen load to the Gulf is the primary external driver stimulating the increase in hypoxia since the middle of the last century. Results from three very different models are compared to reach the consensus that large-scale hypoxia likely did not start in the Gulf of Mexico until the mid-1970s and that the 30% nitrogen load reduction called for in an Action Plan to reduce hypoxia, agreed to by a federal, state, and tribal task force, may not be sufficient to reach the plan's goal. Caution is also raised for setting resource management goals without considering the long-term consequences of climate variability and change.

Introduction

Summer hypoxia in the bottom waters of the northern Gulf of Mexico has received considerable scientific and policy attention because of potential ecological and economic impacts from this very large zone of low oxygen and because of the implications for management within its massive watershed (Turner and Rabalais 1994; Committee on Environment and Natural Resources [CENR] 2000; Mississippi River/Gulf of Mexico Watershed Nutrient Task Force [Task Force] 2001; Mitsch et al. 2001; Rabalais et al. 2002). These regions of oxygen concentrations below 2 mg l^{-1} that form off the Louisiana coast each spring and summer increased from an average of 8,300 km^2 in 1985–1992 to over 16,000 km^2 in 1993–2001 (Rabalais et al. 2002), and reached a record 22,000 km^2 in 2002. There is significant interannual variability and no comprehensive records of areal extent prior to 1985. An assessment of its causes and consequences (CENR 2000; Rabalais et al. 2002) concluded that the almost 3-fold increase in nitrogen load to the Gulf (Goolsby et al. 2001) is the primary external driver that stimulated the increase in hypoxia since the middle of the last century. This riverine nitrogen input stimulates coastal algal production and the subsequent settling of organic matter below the pycnocline. Because the pycnocline inhibits vertical oxygen flux, decomposition of organic matter below the pycnocline consumes oxygen faster than it is replenished, resulting in declining oxygen concentrations during the period of stratification.

Two key questions were asked during development of the Federal-State-Tribal Action Plan to reduce, mitigate, and control Gulf hypoxia, called for in the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 (Task Force 2001; Rabalais et al. 2002). The first question was ''when did large-scale hypoxia start in the Gulf of Mexico?'' Knowing the answer to this question is important both for understanding its underlying causes and for identifying reasonable and practical goals for reducing its size. If large-scale hypoxia was common before the significant increase in nitrogen loads, it would not have been reasonable to consider those loads as a primary cause. If large-scale hypoxia was common in the sufficiently distant past, then reducing its size might not be an appropriate or practical societal goal. The Action Plan included a goal to reduce the five-year running average size of the hypoxic zone to below 5,000 km^2 by 2015.

The second question debated during development of the Action Plan was ''what nitrogen load reduction would be needed to reach the societal goal set for hypoxia?'' Being able to answer this question allows one to connect the hypoxia goal to

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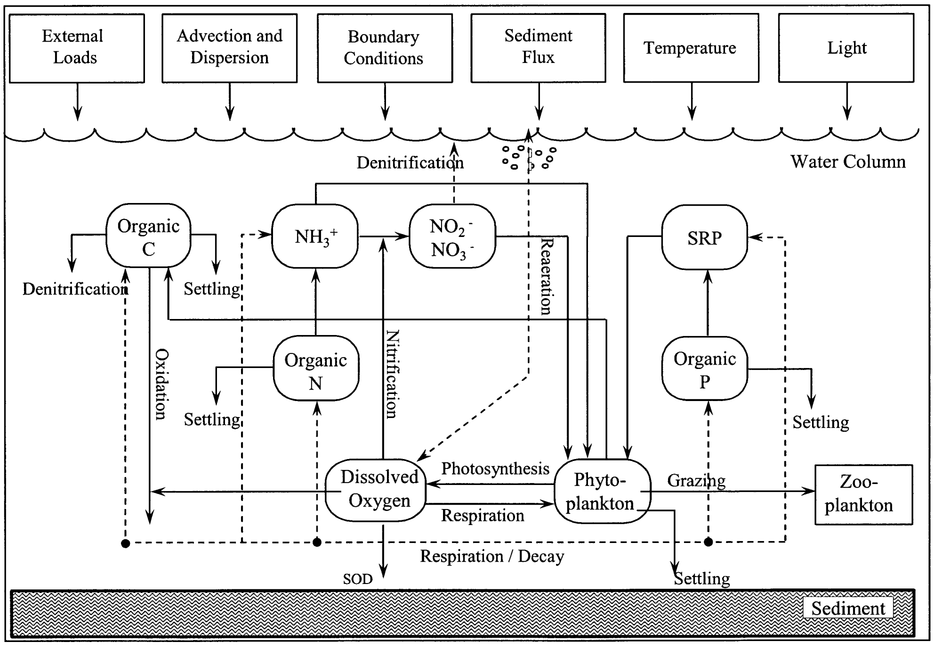

Fig. 1. Bierman et al. (1994) model conceptual framework.

potential management actions within the basin. The drafters of the Action Plan appropriately set a quantitative, end-point goal for hypoxia; but without being able to connect that goal to a measurable control parameter (nutrient loads), there would be little basis for management action. As Boesch (2002, p. 892) recently summarized, nutrient reduction goals are transitioning from ones based on ''professional judgment and political art'' to ones based on quantitative, often model-based analyses. We compared how three very different numerical models answered these two fundamental questions and discuss their implications for future management.

Methods

Several models have been developed, calibrated, tested, and used to simulate, hindcast, and forecast the effects of alterations in river nitrogen loads and other environmental variables on Gulf of Mexico oxygen concentrations. The three models compared in this analysis (Bierman et al. 1994; Justić et al. 1996, 2002; Scavia et al. 2003) capture very different aspects of the physics, chemistry, biology, and ecology of the northern Gulf.

The most complex model (Bierman et al. 1994) simulates summer steady-state, three-dimensional, food-web-nutrient-oxygen dynamics (Fig. 1). This model is based on a version of the U.S. Environmental Protection Agency Water Analysis Simulation Program adapted to a 21-segment, three-dimensional spatial grid on the Louisiana inner shelf. State variables include salinity, phytoplankton, phosphorus, nitrogen, dissolved oxygen, and carbonaceous biochemical oxygen demand. The model is driven by externally-specified values for nutrient loadings, water circulation, seaward and sediment boundary conditions, temperature, incident solar radiation, and underwater light attenuation. Water circulation was derived from a salinity mass balance. The model was initially calibrated to a comprehensive set of field data collected during July 1990 at over 200 stations in the northern Gulf of Mexico. Reasonable comparisons were obtained between computed and observed values for model state variables, primary productivity, and particulate carbon and nitrogen settling fluxes (Fig. 2). The model calibration was extended to include data collected during 1985 and 1988; results indicated no significant differences between overall mean values for model output and field data for almost all state variable-year combinations for 1985, 1988, and 1990. The calibrated model was used to forecast potential responses of dissolved oxygen concentrations to reductions in nutrient loads from the Mississippi-Atchafalaya River (LimnoTech, Inc. 1995).

A simpler model (Justić et al. 1996, 2002) simulates two-layer, time-dependent, oxygen dynamics (Fig. 3) for one location off the Louisiana coast, driven by meteorological conditions and nitrogen loads. Model forcing functions include monthly values of the Mississippi River runoff, nitrate concentration, nitrate flux, ambient water column

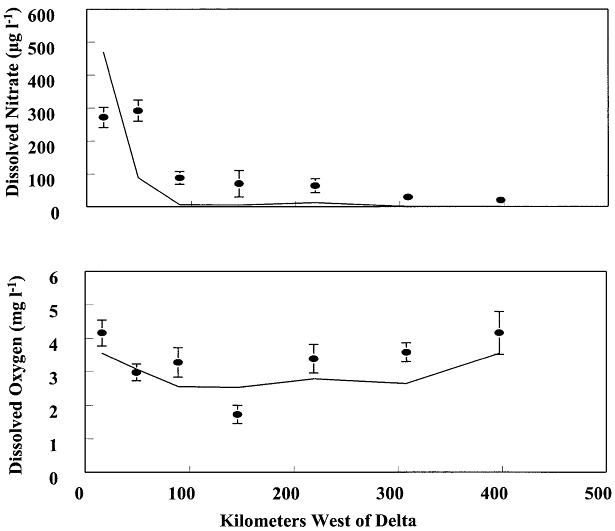

Fig. 2. Bierman et al. (1994) model calibration results for mid-summer surface nitrate and bottom water dissolved oxygen concentrations.

temperature, and surface winds. The model was calibrated using the 1985–1993 time series for a station within the core of the Gulf's hypoxic zone (Fig. 4). This period included three average hydrologic years (1985, 1986, and 1989), a record flood year (1993), two years with above average discharge (1990 and 1991), three years with below average discharge (1987, 1988, and 1992), and a record drought year (1988). Given this time span and range of hydrologic variability, this data set was deemed appropriate for model calibration. A sensitivity analysis revealed that the model is highly sensitive to external forcing, yet sufficiently robust to remain stable and reproduce observed dynamics under an order of magnitude change in the nitrate flux between successive months, such as those en-

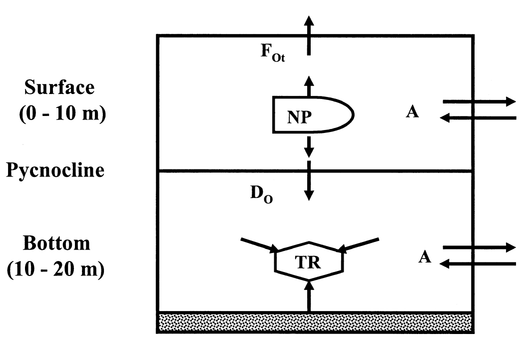

Fig. 3. A conceptual model of oxygen cycling in the core of the Gulf's hypoxic zone (from Justić et al. 1996, reprinted with permission from Elsevier). The F_{Ot} denotes the total air-sea oxygen flux, NP is the net productivity of the upper layer, D_O is the diffusive oxygen flux through the pycnocline, A is the horizontal oxygen transport by advection and diffusion, and TR is the total oxygen uptake in the lower water column.

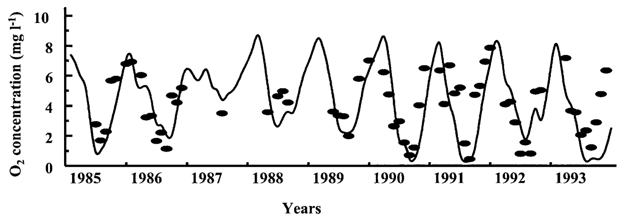

Fig. 4. Observed (dots) and predicted (solid line) monthly averages (June 1985–November 1993) of bottom (10–20 m) oxygen concentrations at station A within the core of the Gulf's hypoxic zone (from Justić et al. 2002, reprinted with permission from Elsevier).

countered during the flood of 1993 (Justić et al. 2002). After calibration, the model was used to simulate and hindcast seasonal oxygen concentrations from 1955 to 2000, linking decadal changes in the Mississippi River nutrient load to eutrophication near the Mississippi River Delta. It was also extended and used (Justić et al. 2003) to simulate potential impacts of climate change on the development of annual hypoxia.

The simplest model (Scavia et al. 2003) simulates summer steady-state, one-dimensional horizontal dynamics of nutrient-dependent production, respiration of organic matter, and resulting oxygen balance (Fig. 5). It is driven by May–June total nitrogen loads, calibrated to 17 years of data between 1985 and 2002, and used to simulate, hindcast, and forecast hypoxic zone length and area in response to changes in nitrogen loads. This model was the first to successfully predict effects of variable nutrient loads directly on the areal extent of hypoxia on this shelf. An adaptation of a model used extensively for rivers and estuaries (e.g., Chapra 1997), the model simulates concentrations of subpycnocline oxygen-consuming organic matter and dissolved oxygen downstream from the Mississippi and Atchafalaya Rivers. Scavia et al. (2003) discussed the validity of assumptions of steady-state and no dispersion, as well as those of surface and bottom water movement being constrained such that the subpycnocline water move-

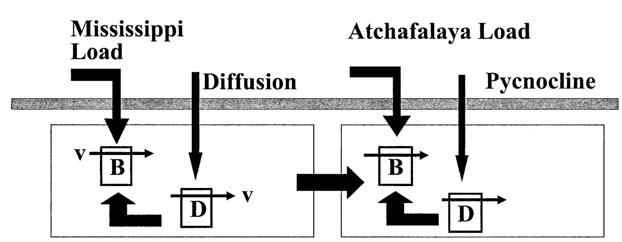

Fig. 5. Scavia et al. (2003) model conceptual framework. B represents biological oxygen demand, D represents dissolved oxygen, and v is net downstream advection. Reprinted with permission of the American Society of Limnology and Oceanography.

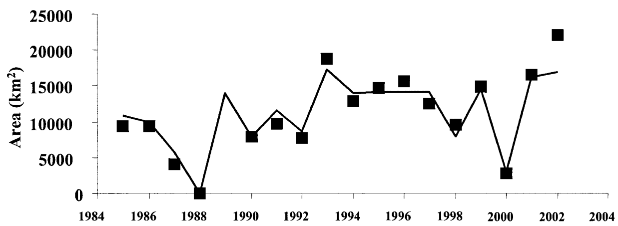

Fig. 6. Observed (solid boxes) and predicted (solid line) hypoxia area from Scavia et al. (2003). Reprinted with permission of the American Society of Limnology and Oceanography.

ment can be modeled as one-dimensional flow, May–June river total nitrogen load can be used as a surrogate for the organic matter load below the pycnocline, and subpycnocline oxygen consumption and cross-pycnocline oxygen flux can be modeled as first-order processes. The calibrated model explains 95% of 1985–2002 interannual variation in hypoxic zone length and 88% of hypoxic zone area (Fig. 6). Because they could not fully parameterize historical oceanographic effects and because it is impossible to determine future values for that effect, Scavia et al. (2003) developed probabilistic hindcasts and forecasts based on assumed probability distributions for subpycnocline, net long-shore advection, and Monte Carlo analysis.

Results

All three models provided simulations, calibrated to observations relevant for their spatial and temporal scales and model structures, and they all captured key system properties and processes. Scavia et al. (2003) captured interannual variability in hypoxic zone length and area in response to nutrient loads and oceanic variability and provided probabilistic hindcasts (Fig. 7a) and forecasts (Fig. 8a) in response to changes in observed past and potential future nutrient loads. Justić et al. (2002) captured seasonal dynamics of oxygen production, consumption, and flux for two layers at a single location, and provided hindcasts of oxygen concentrations based on observed nutrient loads (Fig. 7b). Bierman et al. (1994) captured key features of the three-dimensional summer structure of primary production, nutrient cycling, plankton, and oxygen concentrations and provided forecasts (LimnoTech, Inc. 1995) of changes in average subpycnocline oxygen concentrations in response to a range of potential reductions in nutrient loads (Fig. 8b). Results of these computations can be used to address the two questions outlined in the introduction.

When did Large-scale Hypoxia Start in the Gulf of Mexico?

Hindcasts of the areal extent of hypoxia in the Gulf of Mexico (Fig. 7a; Scavia et al. 2003) suggest

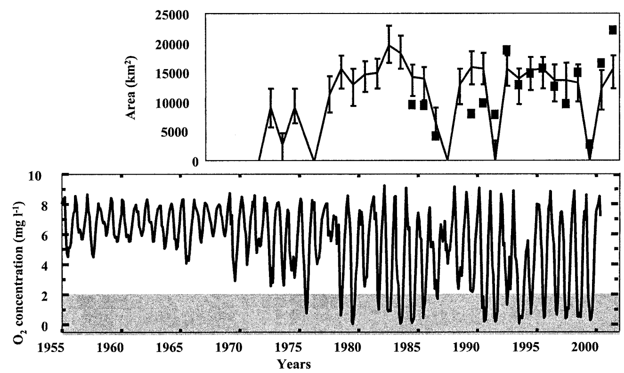

Fig. 7. Upper panel: Simulated changes in the areal extent of hypoxia during 1968–2000 (from Scavia et al. 2003). Reprinted with permission of the American Society of Limnology and Oceanography. Lower panel: changes in the average bottom (10–20 m) oxygen concentration at a station within the core of the Gulf's hypoxic zone during 1955–2000 (from Justić et al. 2002). Shaded area in the lower chart denotes hypoxic conditions (< 2 mg O_2 l^{-1}) in bottom waters. Note that both models identified the mid-1970s as a start of the recurring hypoxia.

that, within the spatial resolution of the model (ca., 10–20 km), large hypoxic regions were not likely to have occurred prior to the mid-1970s, that the size of those regions grew to a maximum in the 1980s, and then fluctuated between the mid-1980s and present. Hindcasts of subpycnocline oxygen concentrations (Justić et al. 2002) suggest that subpycnocline summer-minimum oxygen concentrations offshore of Terrebonne and Timbalier Bays were fairly constant at approximately 6 mg l^{-1}

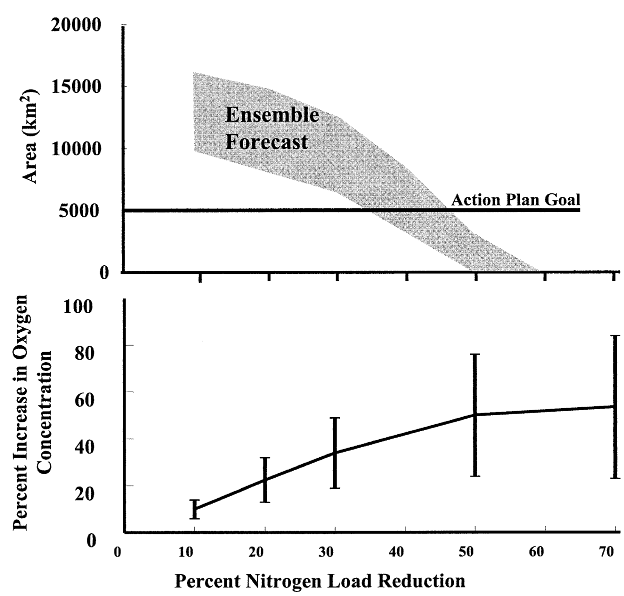

Fig. 8. Upper panel: Forecasts from Scavia et al. (2003). Lower panel: Forecasts from LimnoTech, Inc. (1995). Reprinted with permission of the American Society of Limnology and Oceanography.

between 1955 and 1969 (Fig. 7b), decreased during the 1970s until after 1978 when summer concentrations consistently dropped below 2 mg l^{-1} in most years. Taken together, these models suggest that large-scale regions of hypoxia were not likely to be present prior to the 1970s.

These findings are similar to the empirical water-column evidence collected between 1970 and 1985, before the shelf-wide surveys began, summarized by Turner and Allen (1982) and Rabalais et al. (1999, 2002). These results are also supported by retrospective analyses of sedimentary records. The analyses of ^{210}Pb-dated sediment cores collected in the vicinity of the Mississippi River Delta demonstrated a substantial increase in the organic carbon accumulation rates, from about 30 gC m^{-2} yr^{-1} in the 1950s to 50–70 gC m^{-2} yr^{-1} at present (Eadie et al. 1994), with the rate of carbon accumulation being significantly higher at a station within the area of chronic hypoxia (approximately 70 gC m^{-2} yr^{-1}) compared to another site at which hypoxia has not been documented (approximately 50 gC m^{-2} yr^{-1}). The δ^{13}C partitioning of organic carbon into terrestrial and marine fractions further indicated that the increase in accumulation for both cores is exclusively in the marine fraction. Parallel evidence of historical changes in the river-dominated coastal waters of the northern Gulf of Mexico has also been obtained from the skeletal remains of diatoms sequestered as biologically bound silica (BSi). BSi accumulation rates in sediments adjacent to the Mississippi Delta have doubled since the 1950s, indicating greater diatom flux from the photic zone (Turner and Rabalais 1994). Stratigraphic records of the benthic foraminifera, *Ammonia* and *Elphidium,* indicate an overall increase in the bottom oxygen stress in the same region (Sen Gupta et al. 1996). Translating these empirical lines of evidence into shelf-wide conditions is difficult because of the relatively few sampling locations and the significant horizontal spatial heterogeneity in the sediment record. The significant changes since the middle of the last century from locations where sediment cores have been taken is consistent with the model simulations and hindcasts suggesting significant expansion of the hypoxia area in the 1970s.

What Nitrogen Load Reduction Would be Needed to Reach the Societal Goal for Hypoxia?

Justić et al. (2002) analyzed the effects of alterations in nutrient loads in simulations of the region offshore of Terrebonne and Timbalier Bays. In their calibrated simulations, driven by measured nitrogen loads between 1955 and 2000, subpycnocline waters became hypoxic in 19 of the 45 years, all since 1975. In simulations with nitrogen loads reduced by 30%, this occurred in only 12 of the most recent years; a 37% decrease. While it is not possible to translate this result into average areal extent, it does suggest that more than a 30% nitrogen load reduction is needed for a significant reduction in hypoxia in most years. Forecasts of the areal extent of hypoxia under various load reduction scenarios (Fig. 8a; Scavia et al. 2003) suggest that reductions of 40–45% from the average 1980–1996 May–June total nitrogen load will be needed to reach the Action Plan's 5,000 km^2 goal in most years. The three-dimensional model (Bierman et al. 1994) did not have the spatial resolution required to forecast changes in hypoxic area; it did forecast increases in average subpycnocline oxygen concentrations in response to load reductions scenarios (LimnoTech, Inc. 1995; Bierman et al. 2003). Those analyses indicate that 30–50% decreases in nitrogen loads would result in a 35–50% increase in oxygen concentrations (Fig. 8b), values consistent with the areal extent forecasts (Scavia et al. 2003).

Discussion

Implications for the Action Plan

The Action Plan for reducing, mitigating, and controlling hypoxia in the northern Gulf of Mexico (Task Force 2001) included a goal of reducing the five-year running average size of the hypoxic zone to below 5,000 km^2 by 2015. The model analyses here underscore the importance of setting this goal as a running average. Significant interannual variability throughout the period of record for hypoxia, as well as through the hindcast period make it clear that reaching or breaching that goal in a particular year has limited meaning. For example, small areas of hypoxia in 1988 and 2000 were caused primarily by significant drought conditions yielding reduced nutrient loads, as opposed to changes in nutrient controls, within the Mississippi River Basin.

In any restoration effort, it is important to set reasonable and achievable goals. From these analyses it is apparent that the 5,000 km^2 goal represents conditions similar to those that were likely found in the mid-1970s. The mean hypoxic area hindcast for the period 1973–1975 is 6,400 km^2, corresponding to an average May–June total nitrogen load of 4,097 MT d^{-1} or about 36% of the average loads determined for the base period (1980–1996) used in the Integrated Assessment (CENR 2000) and Action Plan (Task Force 2001). Thus, one might consider this goal as reasonable because it represents conditions from the recent past. The remaining question, then, is whether the goal is achievable. The Action Plan suggests a 30% reduction in the annual nitrogen load would be needed to reach the goal. Because the appropriate model was not available when the Action Plan was being developed, the 30% target was selected as a reasonable estimate that would meet less resistance than the 40–50% used in other management plans. More recent analysis (Scavia et al. 2003) suggests that a 30% reduction (in the spring load) would result in hypoxic areas between 6,600 and 12,590 km^2 75% of the time (median of 9,940 km^2), and to achieve the 5,000 km^2 goal in most years, a 40–45% reduction would be needed. While larger than the reduction identified in the Action Plan, it is similar to those set for a wide range of coastal ecosystems (Boesch 2002).

A 30% annual total nitrogen load reduction is 0.48 million metric tons per year less than the 1980–1996 mean loading of 1.6 million metric tons used in the assessment (CENR 2000). A 40–45% load reduction represents 0.64–0.72 million metric tons less per year. Options for reducing the loss of nitrogen from the land and for enhancing denitrification in this basin have been detailed by Mitsch et al. (1999, 2001). Implementing these options could reduce the load of nitrogen to streams and rivers by 1.9–2.4 million metric tons per year from agricultural nonpoint sources, by 0.6–1.6 million metric tons per year through creating and restoring wetlands and riparian buffers, by 0.05–0.1 million metric tons per year through river diversions in the Mississippi delta region, and by 0.02 million metric tons per year from point sources. While these estimated reductions at their primary sources do not necessarily translate to equivalent reductions in loading to the Gulf because of nutrient processing between these points of action and the lower Mississippi, it is clear that significant overall reductions above 30% are possible. It is also significant that recent re-analyses (McIsaac et al. 2001, 2002) of the effects of potential management actions on nitrogen loads from the Mississippi River Basin suggest that nonlinear effects within the basin could make those reductions easier to achieve and at less cost than estimated in the original studies supporting the Action Plan (Doering et al. 1999). For example, based on a statistical model of nitrate flux in the lower Mississippi River, McIsaac et al. (2001) conclude that if fertilizer application had been 12% lower between 1960 and 1998, there would currently be 33% less nitrate flux to the Gulf of Mexico. Innovative policy approaches, including nutrient trading among point and nonpoint sources (e.g., Greenhalgh and Faeth 2001; Faeth and Greenhalgh 2002; Greenhalgh and Sauer 2003), should further reduce the overall costs of nutrient load reduction.

A Climate Caveat

Potential management actions within this enormous basin will play out over decades and, because of significant time lags in physical transport and biogeochemical processes within the terrestrial landscape, these actions may not result in changes in nutrient loads to the rivers and the Gulf over even longer time scales. Mid-continental climate is likely to continue to change over this same time frame (National Assessment Synthesis Team 2001). Because riverine nitrate flux is well correlated with water discharge (Goolsby et al. 2001), changes in precipitation and runoff are likely to modify nitrate loads independent of management actions within the basin. After the significant increase between the 1950s and 1980s, lower-river nitrate concentrations are now relatively constant (Turner and Rabalais 1991; Goolsby et al. 2001) and discharge has become more important in determining interannual variation in loads. Variations in discharge and temperature will also affect the stability of the Gulf water column and vertical oxygen transport (Justić et al. 1996). These changes have the potential to alter both the stability of the water column and nutrient-enhanced productivity, the two compulsory factors for hypoxia.

Justić et al. (2003) examined hypothetical scenarios based on projected changes in the Mississippi River discharge and ambient water temperatures. In those analyses, a 20% increase in discharge, which may occur under some climate change scenarios (Miller and Russell 1992; Wolock and McCabe 1999), increased the annual frequency of hypoxia by 37% over the calibration simulations. Simulations with the increased flow and a 4°C warmer Gulf resulted in a 63% increase in frequency. Results from the simpler model (Scavia et al. 2003) indicate that a 20% increase in nitrate load over the 1980–1996 mean would increase the size of the hypoxic zone by 26%, from the 1980–1996 simulation mean of 12,900 km^2 to 16,200 km^2. While there is significant uncertainty in these climate scenarios, it is important to note that this potentially warmer-wetter scenario is capable of compensating for management-based nitrogen load reductions.

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