



The Causes

of Hypoxia in the Northern Gulf of Mexico



While information gaps still exist and several factors discussed below may contribute to hypoxia, the overwhelming scientific evidence indicates that excess nitrogen from the Mississippi River drainage basin coupled with hydrologic and climatic factors drives the onset and duration of hypoxia in the northern Gulf of Mexico. The following section summarizes this evidence, which is described in the detailed topic reports and the scientific literature upon which this assessment is based. Analysis of nutrient trends and sources, and the relative importance of specific human activities in contributing to these trends, are described here, providing the basis for the chapters that follow.

Coastal Eutrophication

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

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

Excess organic carbon and subsequent oxygen consumption alone do not necessarily lead to hypoxia: stratification is also necessary for the development of hypoxia in bottom waters. In most saltwater systems, the water stratifies (creating horizontal layers), with cold and/or saltier water at the bottom and warmer and/or fresher water at the surface. This layering separates bottom waters from the atmosphere and prevents re-supply of oxygen from the surface to replenish deficits created by the decomposing organic



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matter in the deeper waters. Thus, the extent of hypoxia is determined by the balance between the rate of delivery and decomposition of algae and other organic matter and the rate of oxygen re-supply, which is inversely related to the strength of stratification.

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

In the Gulf, hypoxic waters are most prevalent from late spring through late summer. Hypoxia is more widespread and persistent in some years than

in others, depending on river flow, winds, and other environmental variables. Hypoxic waters are distributed from shallow depths near shore (4 to 5 meters) to as deep as 60 meters but more typically appear between 5 and 30 meters.

Hypoxia occurs mostly in the lower water column but encompasses as much as the lower half to two-thirds of the entire column.

Continuous time-series data for the bottom

waters in the core of the hypoxia region show (1) the gradual decline in oxygen in the spring with interruptions due to wind-mixing events, (2) persistent hypoxia and often anoxia for extended parts of the record from May through September, (3)

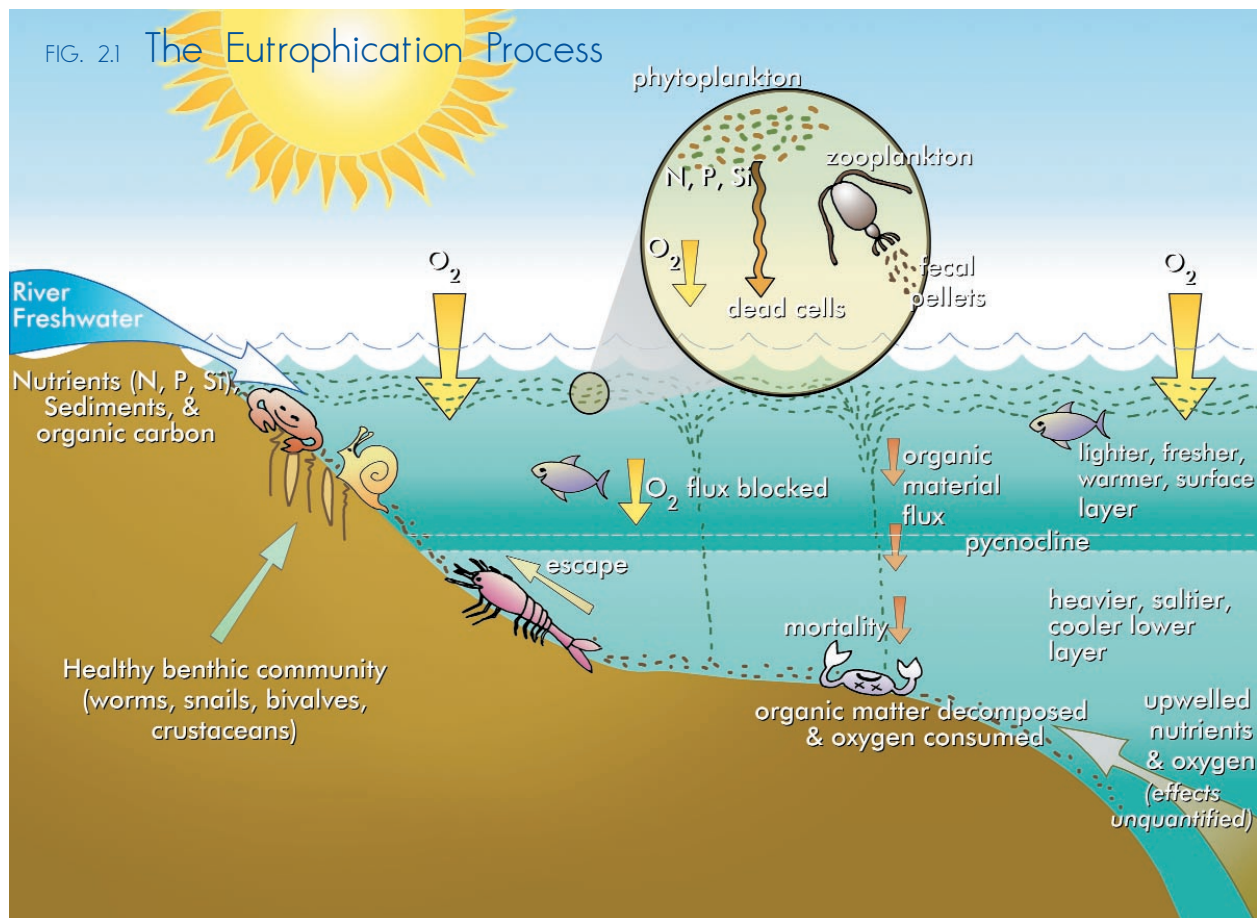
occasional summer upwelling of oxygenated water from the deeper shelf waters, and (4) the seasonal disruption of low oxygen in the fall by tropical storms or cold fronts.

Role of Nutrients

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

Role of Stratification

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



Eutrophication occurs when organic matter increases in an ecosystem. Eutrophication can lead to hypoxia when decaying organic matter on the seafloor depletes oxygen, and the replenishment of the oxygen is blocked by stratification. The flux of organic matter to the bottom is fueled by nutrients carried by riverflow or, possibly, from upwelling that stimulates growth of phytoplankton algae. This flux consists of dead algal cells together with fecal pellets from grazing zooplankton. Organic carbon from the Mississippi River can also contribute to the flux of organic matter.

Role of Other Potentially Contributing Factors

In addition to high levels of nutrients, other factors potentially contribute to hypoxia in the Gulf. The most significant of these other factors are described in the box on the next two pages. Only increased nitrogen loads from the Mississippi–Atchafalaya River system can account for the magnitude of the hypoxic zone and its increase over time. While other factors may contribute to the growth, dynamics, and decline of the hypoxic zone, none of them alone can explain its overall size and persistence.

Internally produced organic carbon, stimulated by nutrients

(from the land, air, or sea), externally supplied organic carbon, horizontal stratification, ocean circulation, and river hydrology are not competing hypotheses. Rather, they are interacting factors within the eutrophication process as it takes place in the Gulf of Mexico. These factors have been discussed in the six technical background papers, in the comments on those papers, at a science meeting on these issues held December 3, 1999,² and in recent reports on this subject sponsored by the Fertilizer Institute (Carey et al. 1999) and the Council for Agricultural Science and Technology (Downing et al. 1999), as well as the wide range of previous work

summarized in such volumes as the *1995 Proceedings of the First Gulf of Mexico Hypoxia Management Conference* (EPA 1997) and the December 1994 and June 1996 special issues of *Estuaries*.

Nutrient Over-Enrichment

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

Scientific investigations over the last several decades indicate

² Notes from the December 3, 1999, science meeting can be found at <http://www.nos.noaa.gov/products/pubs_hypox.html>

overwhelmingly that oxygen stress in the northern Gulf of Mexico is caused primarily by excess nutrients delivered to Gulf waters from the Mississippi–Atchafalaya River drainage basin, in combination with the stratification of Gulf waters.

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

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

Analysis of river discharge data and sediment cores from the Louisiana shelf in the Mississippi River delta might indicate that



Factors Potentially Contributing to Hypoxia in the Gulf

Landscape changes in the drainage basin. Wetlands and riparian zones can improve water quality and reduce nitrogen flux down the Mississippi River by enhancing denitrification (the conversion of nitrate to nitrogen gas, with subsequent loss from the aquatic system) and by incorporating nitrogen into vegetation. However, the natural capacity of the river basin to remove nutrients has diminished. Many of the original freshwater wetlands and riparian zones that were connected to streams and rivers are gone. Ohio, Indiana, Illinois, and Iowa have had over 80 percent of their wetlands drained. Indiana, Illinois, Iowa, Minnesota, Missouri, Ohio, and Wisconsin collectively have lost the equivalent of 14.1 million ha (35 million acres) of wetlands over the past 200 years. Louisiana, Mississippi, Arkansas, and Tennessee have also experienced wetland losses that collectively exceed 50 percent.

Organic loading from the Mississippi River. Externally supplied organic carbon from the Mississippi River has been proposed as a cause of the formation of hypoxia in the Gulf. For river-borne organic carbon to be an important contributor to the rise in hypoxia since the 1950s, significantly increasing quantities would have to be delivered to the bottom waters of the

hypoxic zone and would have to be decomposed by bacteria. Only the particulate organic carbon (POC) fraction of the total organic carbon load could contribute directly to hypoxia because only that fraction would sink to the bottom waters. The dissolved fraction would remain in the river-freshened surface waters and would have to be biologically assimilated and deposited as newly formed POC, with large attendant respiratory losses, to reach hypoxic zones extending 100–200 km from the river discharges. Suspended sediment in the river has declined by about half since the 1950s, so the POC load that can settle on the Louisiana shelf has also most likely decreased since then. Also, nutrient cycling affords nitrogen the ability to stimulate production of organic carbon at rates that far surpass that supplied by the river. Whereas decomposition of river-supplied organic carbon consumes oxygen only once, river-supplied nitrogen can be recycled and thus provides a continuous source of comparatively easily decomposed organic carbon (Ryther and Dunstan 1969). Scientists reviewed evidence about the role of organic carbon at a December 1999 meeting and agreed that it is a relatively small factor driving hypoxia—nitrogen-driven carbon production is approximately an order of magnitude greater.

eutrophication and hypoxia in the northern Gulf increased coincidentally with increases in nitrogen loads from the Mississippi River. The data exhibit both long-term trends and short-term variations. One particularly important factor is that peak river flows have

increased over the past 150 years due primarily to land-use changes, flood-control and navigation projects in the river, and climate (precipitation) changes.

Long-term Records—Gulf Ecosystem Changes. Since there are no com-

prehensive, direct measurements of oxygen in the northern Gulf of Mexico prior to 1985, evidence for long-term changes in hypoxia is based on indirect analysis from sediment records. While it is possible to explore temporal changes in water-column production,

Channelization of the delta and loss of coastal wetlands. Although in some years over-bank flow has been significant, flooding through coastal wetlands has been reduced since the 1927 flood, but geochemical and biological indicators show that hypoxia has intensified only since the 1950s. Coastal wetland loss rates exceeded 100 km² (about 40 sq mi) per year between 1950 and 1980. Recent wetland protection and restoration programs helped reduce losses in the 1990s to 65–90 km² (about 25–35 sq mi) per year. Both the loss of wetland filtering capacity and the direct contribution of organic matter eroded from wetlands and carried to the Gulf may contribute to the problems of hypoxia; however, the total contribution is relatively small compared with the nitrogen-related factors. Further, carbon isotope analysis shows that the sources of carbon over the broad area affected by hypoxia is produced by marine phytoplankton and is distinct from carbon close to shore.

Intrusion of deeper offshore waters. Some have suggested that flow of low-oxygen water from water layers in the deeper Gulf on to the continental shelf was the source of shelf hypoxia. However, these features are always physically distinct, with the shelf hypoxic zone at depths of less than 60 meters, and the deep low-oxygen layer at depths of 400–700 meters. Further,

oxygen concentrations and consumption rates, salinity, and temperature of the deep low-oxygen layer differ considerably from the waters of the hypoxic zone. Flow of nitrate from deeper waters may be important at the shelf edge (at depths of approximately 100 meters); however, all data indicate that the Mississippi and Atchafalaya Rivers contribute substantially more nutrients to the inner shelf and hypoxic region.

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

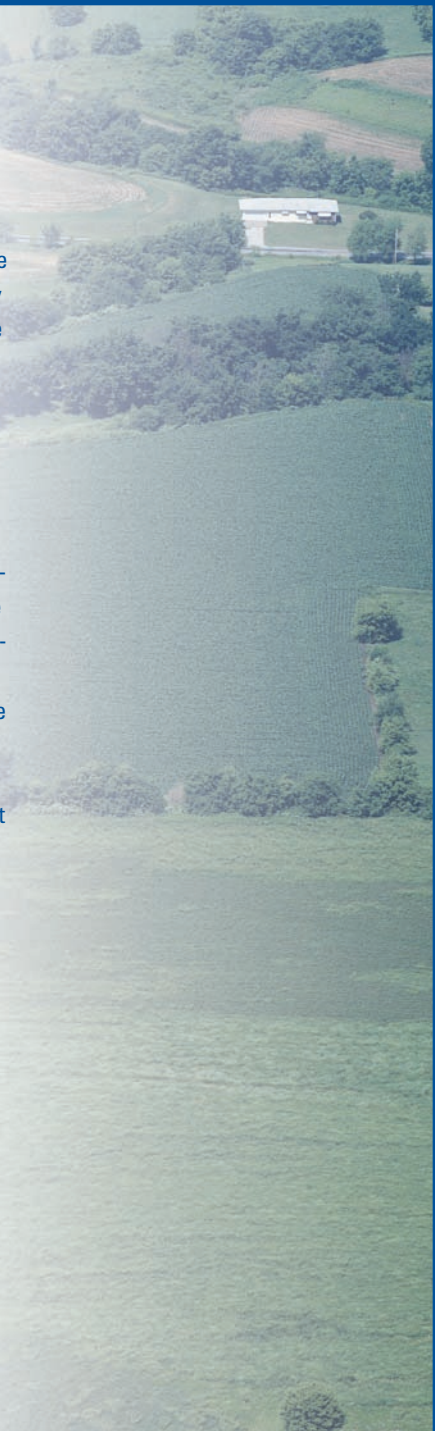
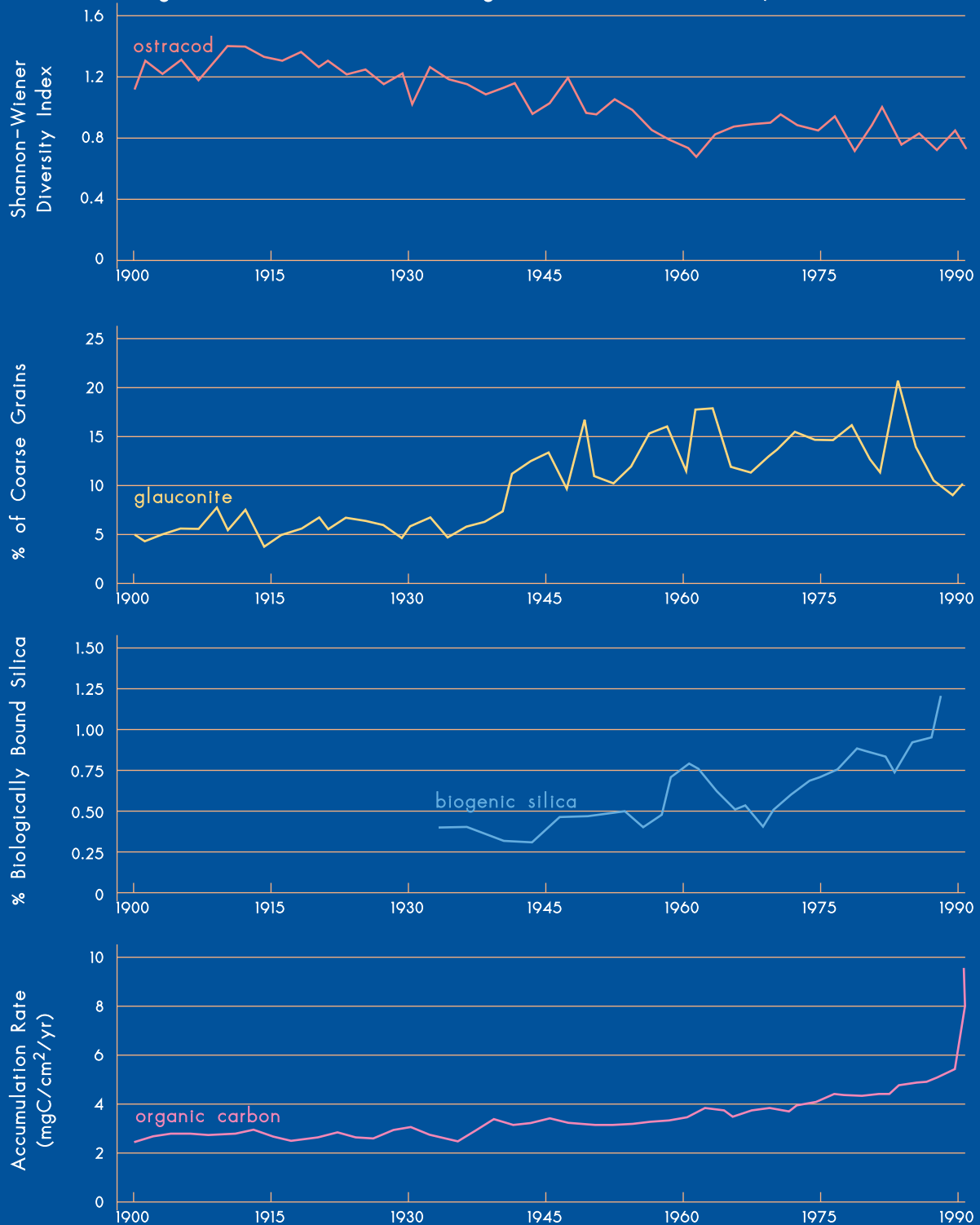


FIG. 2.2 Long-term Records of Changes in the Gulf Ecosystem: 1900-90



Sources: Figures 7.6, 7.7, and 7.9 in the Topic 1 Report for the Integrated Assessment.

Profiles from cores taken in the Mississippi River bight in an area of persistent seasonal bottom-water hypoxic conditions revealed the following trends related to the growth of bottom-water hypoxia in the area: (1) a steady decrease in the number of species of ostracods, a family of minute shelled organisms; (2) an increase in the abundance of the mineral glauconite, which forms only under low-oxygen conditions; (3) an increase in the average concentration of biologically bound silica, indicating changes in algal community composition; and (4) an increase in the organic carbon accumulation rates, indicating growth in algal production.

oxygen-relevant geochemistry, and biology because such properties are preserved sequentially down a sediment core, it is important to recognize that bottom mixing and sediment reworking limits the resolution of temporal change to scales approaching decades, as opposed to years.

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

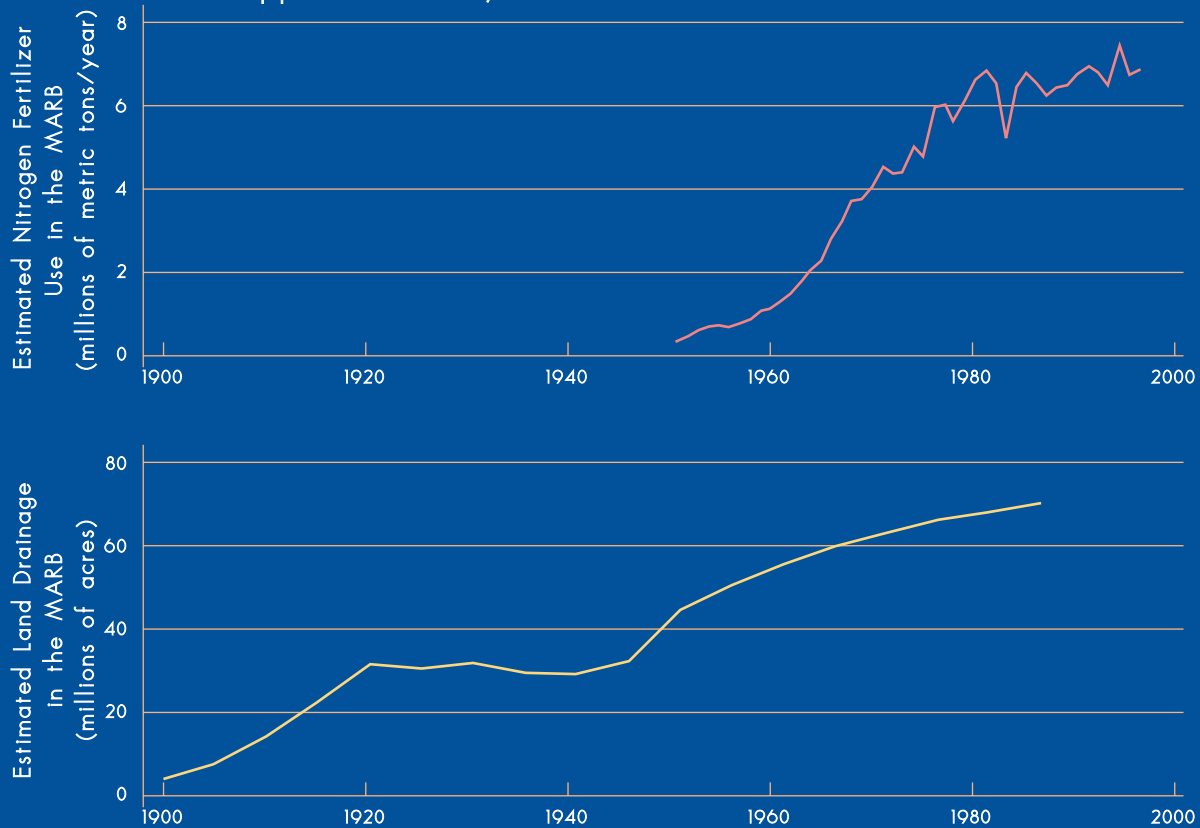
The sediment record clearly shows significant increase in algal production beginning around the 1950s. Accumulation of organic carbon and biogenic silica (a measure of diatom abundance) both increased significantly after that time period. Because there have been no significant increasing trends in either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

The sediment geochemistry record indicates that while there was likely some oxygen stress on the Louisiana shelf as early as the beginning of the twentieth century, there was a striking increase in that stress starting roughly dur-

ing the 1940s and 1950s. Because the mineral glauconite forms only under reducing conditions, its presence in the sediment is an indication of low oxygen conditions. Sediment cores show the history of glauconite formation from sediments as they were deposited on the seafloor. As shown in the core profile in Figure 2.3, glauconite abundance was relatively low in the early 1900s, but increased dramatically in the 1940s and 1950s, indicating increased low oxygen stress.

Another indirect indicator of a significant change in the relative magnitude of hypoxia during this same transition period is the biodiversity of benthic foraminifera and ostracods preserved in the sediments. These single-celled

FIG. 2.3 Long-term Records of Changes in the Mississippi-Atchafalaya River Basin: 1900-99



Sources: Figure 5.7 of the Topic 3 Report for the Integrated Assessment; and Figure 1.2 of the Topic 5 Report.

The amount of nitrogen fertilizer used in the Basin increased dramatically between the 1950s and 1980s (enabling a large increase in crop production). The area of cropland fitted with artificial subsurface drains has also increased, reducing the capacity of the landscape to remove nitrogen.

organisms and metazoans, respectively, produce carbonate shells which remain intact in buried sediments. After a transition period in the 1940s through 1950s, the diversity of these organisms decreased significantly, which is typical of stressed environments. Also, the types of organisms that remained after the transition period were those that are more tolerant of low oxygen conditions.

Long-Term Records—Drainage Basin Changes.

Three key historical trends are important to consider in relationship to the above long-term trends in hypoxia. First, most of the significant flood-control and navigation channelization occurred prior to the 1950s. Second, significant alterations in the landscape (e.g., deforestation and expansion of artificial agricultural drainage) removed much of the “buffer” for runoff into the Mississippi tributaries and main stem. The greatest rates of change occurred in the 50-year period straddling the beginning of the twentieth century, with another burst in drainage development during 1945–60. Third, there was a dramatic increase in nitrogen input into the Mississippi River drainage basin, primarily from fertilizer applications, between the 1950s and 1980s. This,

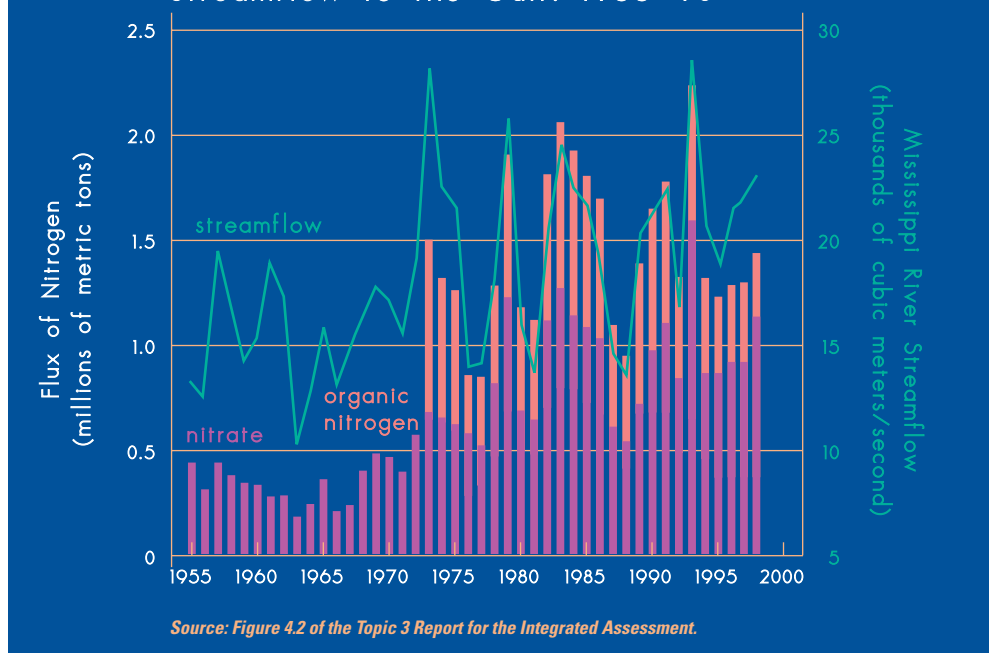
in turn, has led to significant increases in the flux of nitrogen from the Mississippi River system to the Gulf.

Shorter-Term Records. Extensive monitoring of the hypoxic zone did not begin until 1985, and areal estimates (see Figure 1.2) since then have been primarily from a single shelf-wide survey taken during the mid-summer of each year. Thus, for any given year, the maximum extent of hypoxia could have been significantly greater. Despite this limitation, three significant extreme events illustrate the nature of the variation in this record:

- First, during the summer of 1988, following a severe regional drought and subsequent low nitrogen load (see Figure 2.4), the hypoxic zone covered only 40 km² (15 sq mi), compared to 5,000–20,000 km² (2,000–8,000 sq mi) in other years. The hypoxic zone had developed in the spring but was not maintained into the summer because of reduced flow of fresh water and resulting lack of stratification.
- Second, the size of the hypoxic zone nearly doubled during the summer following the 100-year flood of 1993.

The annual flux of nitrate nitrogen from the Basin to the Gulf of Mexico has almost tripled between the periods 1955-70 and 1980-96. Organic nitrogen measurements were not regularly made before 1973 but show no trend. Both streamflow and nitrate flux have become much more variable in the last 25 years.

FIG. 2.4 Annual Nitrogen Loads and Streamflow to the Gulf: 1955-98



Source: Figure 4.2 of the Topic 3 Report for the Integrated Assessment.

While it is not clear why this larger area has persisted in years following 1993, nitrogen recycling and resuspension of recently deposited, algal-produced organic material are likely important factors.

- Third, the year 1999 was somewhat unusual in that both streamflow and nitrate concentrations during the spring and summer were above normal in the upper Mississippi. The streamflow of the Mississippi River at Thebes, above the Ohio River confluence for January–June 1999 averaged 9,300 m³/s, as compared with a January–June 1980–98 mean of 8,054 m³/s. The mean nitrate concentrations for January–June 1999 were 3.4 mg/L, versus a 1980–98 mean for these months of 2.7 mg/L. However, drought conditions were developing in the upper Ohio Basin, which produced below-normal streamflow in 1999 of 10,650 m³/s, versus a mean of 12,070 m³/s for January–June 1980–96. Nitrate concentrations (1.2 mg/L for January–June) were near normal for this period. The combination of above-normal flows and nitrate concentrations from the upper Mississippi and below-normal flows from the Ohio River produced higher-than-normal nitrate concentrations and flux in the lower Mississippi River, and may have contributed to the record large extent of the hypoxic zone measured in July 1999.

Model Simulations

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

and oxygen depletion change significantly when modeled river loads were changed.

Sources, Loads, and Trends of River Nutrients

Analyses were conducted to determine the flux and sources of nutrients transported from the Mississippi–Atchafalaya River Basin (MARB, or the Basin) to the Gulf of Mexico. These analyses aimed to identify where in the Basin the nutrients came from and to estimate the relative importance of specific human activities—such as agriculture, point-source discharges, and atmospheric emissions—in contributing nutrient flux to the Mississippi River and the Gulf.

Nutrient Trends

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

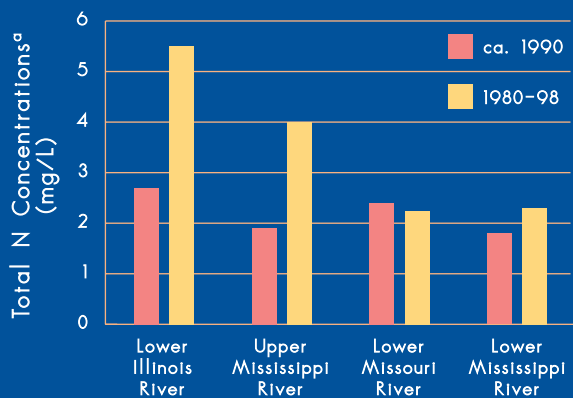
Nitrogen is present primarily in three forms in the Mississippi River and its tributaries: dissolved inorganic nitrogen (nitrate and ammonium), dissolved organic nitrogen, and particulate organic nitrogen. Total nitrogen is the sum of these three forms. For 1980–96 the average total nitrogen flux from the MARB to the Gulf was estimated to be 1,567,900 metric tons per year. Of this amount,

Scientific investigations indicate that oxygen stress in the northern Gulf of Mexico is caused primarily by excess nutrients delivered to Gulf waters from the Mississippi–Atchafalaya River drainage basin, in combination with the stratification of Gulf waters.

Table 2.1 Historical and Recent Data on Nitrogen (N) Concentrations in the Mississippi River Basin

Location	Number of Samples	Organic N			Inorganic N			Total N ^a
		DON	PON	Total	Nitrate-N	NH ₄ -N	DIN	
Lower Illinois River								
1897–1902	weekly	0.59	0.42	1.01	1.25	0.38	1.63	2.64
1980–98	189	0.45	0.60	1.22 ^b	4.09	0.14	4.23	5.46
Upper Mississippi River near Grafton (below Illinois & above Missouri Rivers)								
1899–1900	70	0.48	0.62	1.10	0.59	0.13	0.72	1.82
1980–98	120	0.81	0.63	1.27	2.63	0.11	2.74	4.01
Lower Missouri River								
1899–1900	63	0.30	1.53	1.83	0.51	0.06	0.57	2.40
1980–98	186	0.51	0.69	1.03	1.23	0.05	1.28	2.24
Lower Mississippi River								
1905–06	52	0.40 ^c	0.76 ^d	1.16	0.56	0.10 ^c	0.66	1.82
1955–65	308	0.52 ^f	0.69 ^g	1.21	0.65 ^e	0.10 ^f	0.75	1.96
1980–98 ^e	104	0.52	0.38	0.92	1.45	0.06	1.51	2.40

FIG. 2.5 Nitrogen Concentrations in the Mississippi River Basin



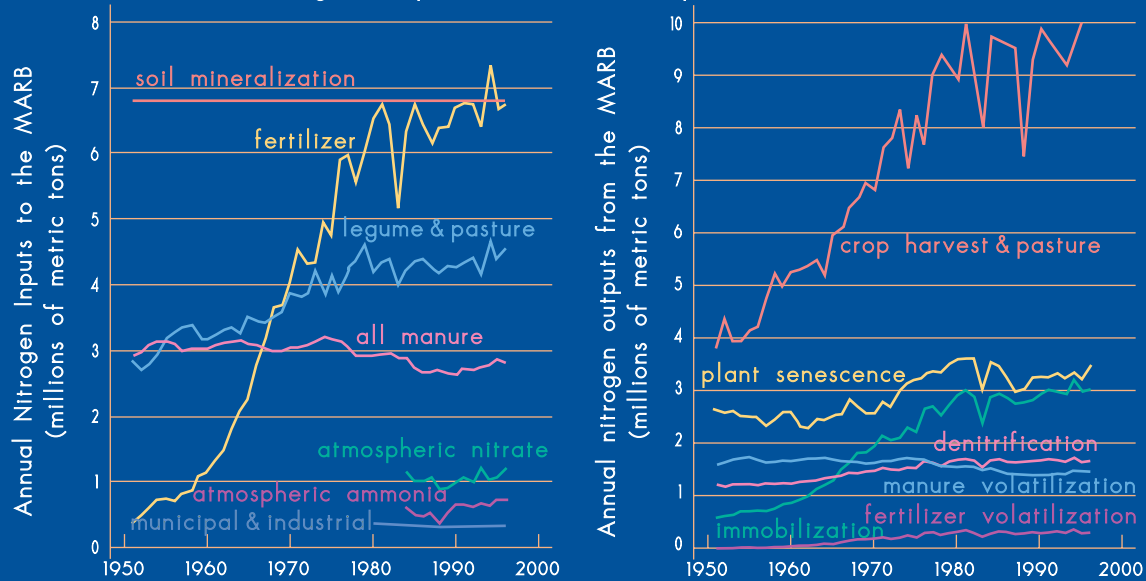
- ^a Total nitrogen calculated as the sum of total organic N + dissolved inorganic nitrogen (DIN).
- ^b Dissolved organic nitrogen (DON) and particulate organic nitrogen (PON) were not analyzed on all samples in 1980–98. Thus, DON + PON does not equal total organic nitrogen (N) for this time period.
- ^c Estimated from concentrations in the upper Mississippi River and lower Missouri River.
- ^d Estimated as two times the average 1980–98 PON concentration.
- ^e From Table 3.4 of the Topic 3 report.
- ^f Estimated.
- ^g Calculated from 1955–65 daily sediment concentration at Tarbert Landing (4,018 samples; mean = 460 mg/L) and estimated sediment nitrogen content of 0.15%; PON = 0.69 +/- 0.41 mg/L.

about 63 percent was dissolved inorganic nitrogen (61 percent nitrate and 2 percent ammonium), 24 percent was dissolved organic nitrogen, and 13 percent was particulate organic nitrogen. Most of the analysis of nitrogen changes (trends) discussed in the Committee on Environment and Natural Resources hypoxia topic reports focused on nitrate, which comprises most of the dissolved inorganic nitrate. The principal reason for the focus on nitrate, rather than total nitrogen, is that nitrate

is the most significant bioavailable form of nitrogen transported into the Gulf. Dissolved inorganic nitrogen concentration and flux have changed more than any other form of nitrogen and, therefore, potentially have a much larger effect on algal production and hypoxia than do dissolved and particulate organic nitrogen. Published data (Palmer ca. 1903; Leighton 1907; and Dole 1909) from the period 1897–1906 for four locations in the MARB show that both nitrate and total

nitrogen concentrations have increased significantly in the last 100 years (Table 2.1 and Figure 2.5). Mean nitrogen concentrations at these four sites for 1980–98 are also shown in the table for comparison. Concentrations of total nitrogen increased significantly at three of the four sites during the past 100 years, and essentially all of the increase can be attributed to dissolved inorganic nitrogen or nitrate. The total nitrogen concentration in the lower Mississippi is estimated to

FIG. 2.6 Annual Nitrogen Inputs to and Outputs from the Basin: 1951–96



Sources: Figures 5.7 and 5.9 of the Topic 3 Report for the Integrated Assessment.

The largest changes in nitrogen inputs to and outputs from the Mississippi Basin occurred between the 1950s and 1980s. Fertilizer nitrogen inputs increased from less than 1 million to more than 6 million metric tons per year, and crop harvest and pasture production more than doubled.

have increased by a factor of 1.3 since 1905–06, and nitrate has increased by a factor of about 2.5. Mean annual total nitrogen concentrations in the lower Illinois River and the Mississippi River at Grafton, Illinois, doubled in the last 100 years, while nitrate concentrations increased by factors of three to more than four. The exception is the lower Missouri River, where total nitrogen concentrations decreased slightly due to a large decrease in particulate organic nitrogen concentrations associated with construction of reservoirs on the Missouri River in the 1950s and 1960s. Trapping of sediment in the reservoirs has reduced the discharge of suspended sediment by more than 50 percent (Meade 1995), resulting in a similar reduction in particulate organic nitrogen. However, nitrate concentrations in the lower Missouri have more than doubled and make up for most of the decrease in particulate organic nitrogen.

The most significant trend in nutrient loads has been an increase in nitrate load, which has almost

tripled from 0.33 million metric tons per year during 1955–70 to 0.95 million metric tons per year during 1980–96 (see Figure 2.4).

Figure 2.6 shows trends in annual nitrogen inputs to and outputs from the MARB. The most significant changes in both inputs and outputs occurred between the 1950s and 1980s, when fertilizer input more than tripled, and crop harvest and pasture production increased by about 2.4 times. Total nitrogen inputs increased by about 9 million metric tons per year, from about 13 million to nearly 22 million metric tons per year. Outputs increased by about 11 million metric tons per year.

The difference between these inputs and outputs (the residual) represents nitrogen potentially available as loadings to the aquatic environment (see Figure 2.7). The rapid decline in residual corresponds to the period of rapid change in fertilizer application and crop harvests and may represent increased efficiency in the use of nitrogen in crop production. Residuals since around 1980

have exhibited no trend, although they have become highly variable from year to year. The leveling off of nitrogen fertilizer, crop outputs of nitrogen, and the nitrogen residuals may indicate that a new steady-state condition was established about 1980.

Seasonal Variability

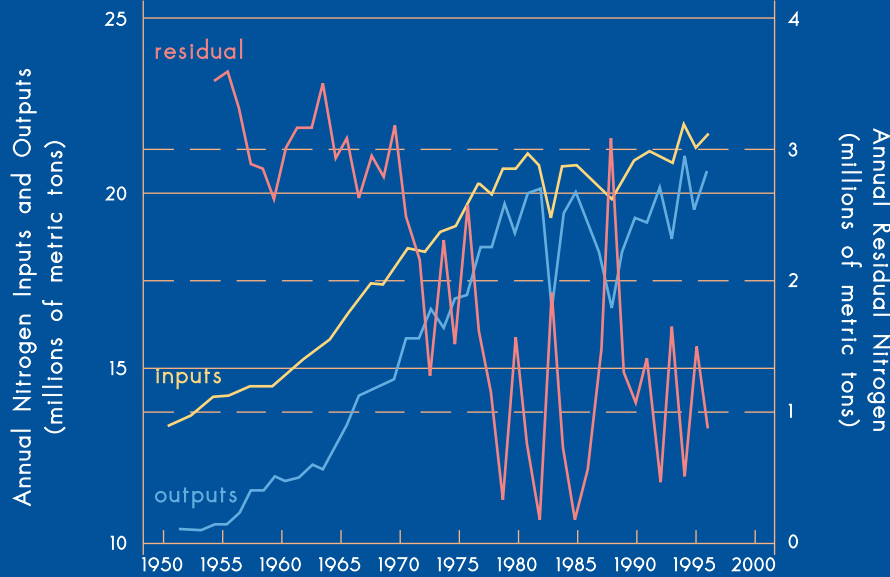
Nitrogen concentrations and loads vary seasonally. Loads and freshwater discharge are usually highest during the late winter, spring, and early summer when runoff is highest. The seasonal and annual cycles of nitrate transport are illustrated in Figure 2.8.

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

Nitrogen Sources

The principal sources of nitrate in the MARB are river basins that

FIG. 2.7 Nitrogen Mass Balance for the Basin: 1951-96



Sources: Figure 6.4 of the Topic 3 Report for the Integrated Assessment.

Both inputs to and outputs from the Basin have increased dramatically since about 1950. The difference between inputs and outputs—the residual—declined rapidly between 1969 and 1978, possibly indicating increased efficiency in the use of nitrogen in crop production. Essentially no change in residuals has occurred since 1980, although they have been highly variable from year to year.

Gulf of Mexico. About 56 percent of the nitrate transported to the Gulf enters the Mississippi River above the Ohio River. The Ohio basin subsequently adds another 34 percent of the nitrate load.

Since 1980, the Mississippi and Atchafalaya Rivers have discharged, on average, about 1.6 million metric tons of total nitrogen to the Gulf each year; 0.95 million metric tons of that is in the form of nitrate.

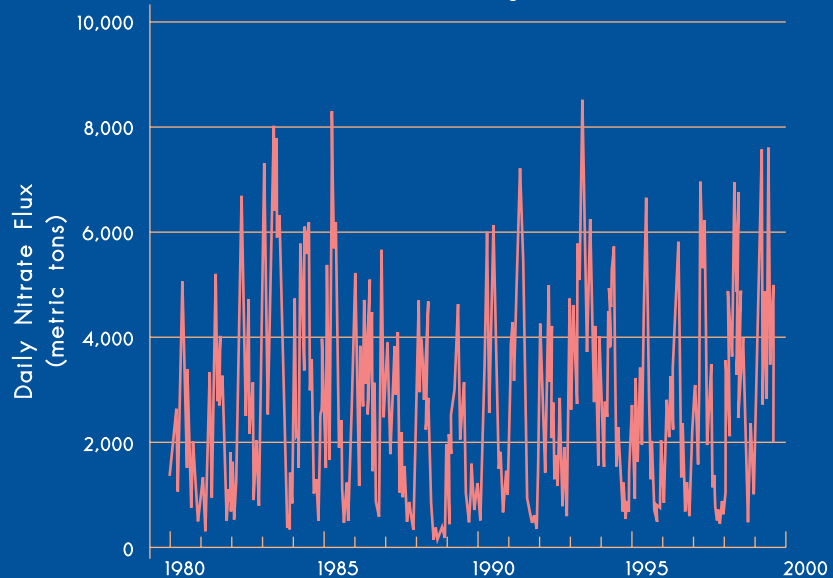
drain agricultural land in southern Minnesota, Iowa, Illinois, Indiana, and Ohio (see Figure 2.9). This is an area of intensive corn and soybean production, where large amounts of nitrogen from fertilizer and manure are applied to soils every year. Legumes and atmospheric deposition add nitrogen to the soils in this region, which also contain large amounts of organic nitrogen, some of which is converted to soluble nitrate each year. The nitrate accumulated from all sources and not used by crops or removed by biogeochemical processes is subject to being leached to streams and ground water by precipitation. Extensive use of tile drains in this region can intercept water with high levels of nitrate and accelerate its transport directly to ditches and streams. In addition, in

some basins sewage treatment plants and industrial sources add nitrogen directly to streams.

All of these sources contribute to the nitrogen load transported by the Mississippi River to the

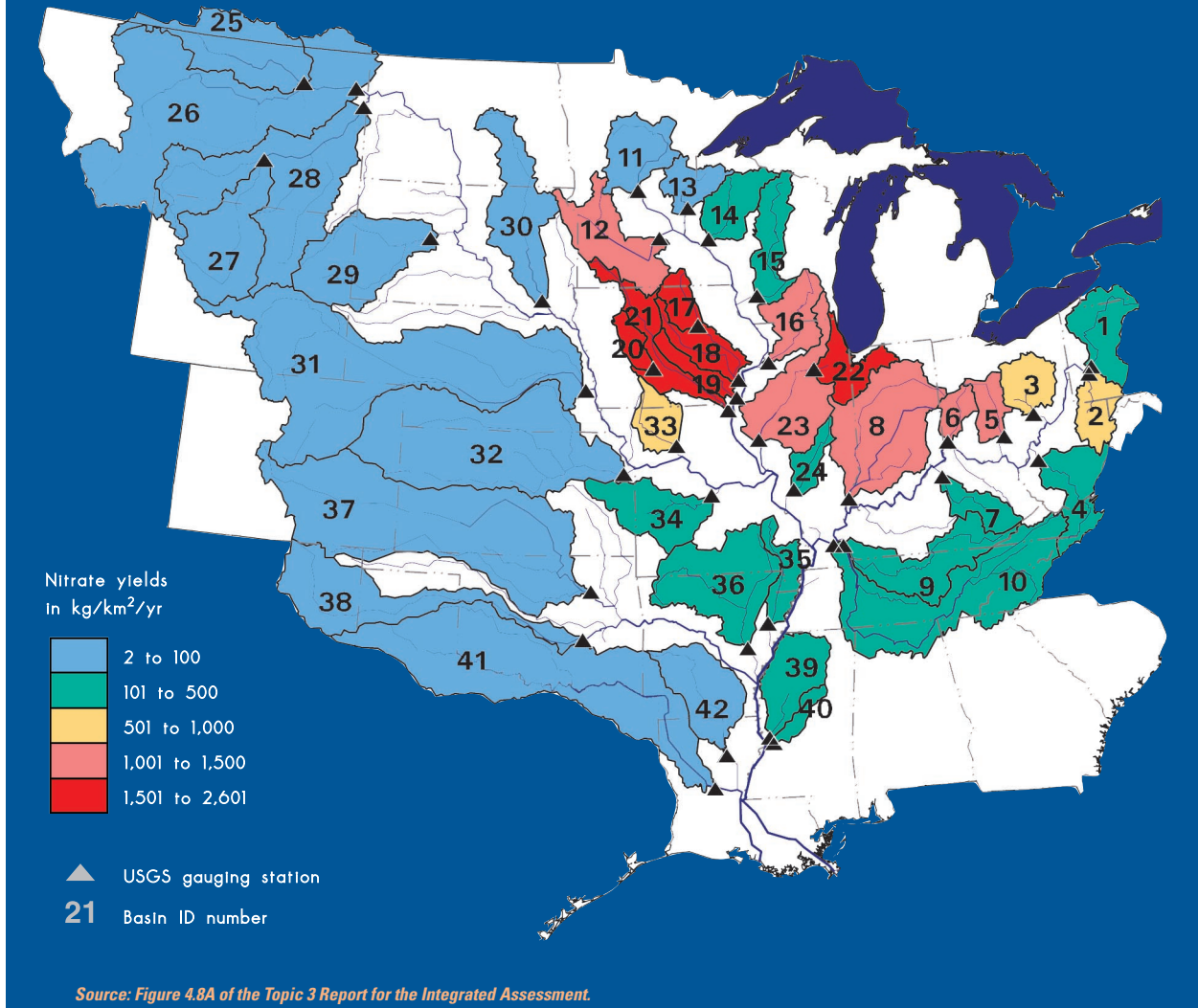
The daily flux of nitrate varies from a low of several hundred metric tons per day during low streamflow in the fall to several thousand metric tons per day during high streamflow in the spring.

FIG. 2.8 Daily Flux of Nitrate from the Basin to the Gulf: August 1980-1999



Sources: Figure 4.1 of the Topic 3 Report for the Integrated Assessment, with an update from Donald Goolsby, U.S. Geological Survey.

FIG. 2.9 Average Annual Nitrate Yields for the 42 Sub-basins within the Basin: 1980–96



The principal sources of nitrate are river basins that drain agricultural land in southern Minnesota, Iowa, Illinois, Indiana, and Ohio, where large amounts of nitrogen are applied to corn and soybean fields.

About 90 percent of the nitrogen comes from nonpoint sources, with the remainder coming from

point sources. Table 2.2 presents the estimated contributions of nitrate and total nitrogen from

the predominant sources in the Basin.

Table 2.2 Estimated Contributions of Nitrogen Input Sources to the Total Nitrogen and Nitrate Nitrogen Yield of the Mississippi-Atchafalaya River Basin and Flux to the Gulf of Mexico

Source of Nitrogen Transported to the Gulf	Percent of Nitrate	Percent of Total Nitrogen
Agricultural nonpoint sources	74	65
Other nonpoint sources	16	24
Municipal and industrial point sources	9	11