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Nitrogen in the Mississippi Basin—Estimating Sources and Predicting Flux to the Gulf of Mexico

Nitrogen from the Mississippi River Basin (fig. 1) has been implicated as one of the principal causes for the expanding hypoxic zone that develops each spring and summer on the Louisiana-Texas shelf of the Gulf of Mexico. Hypoxia refers to dissolved oxygen concentrations less than 2 mg/L (milligrams per liter). Hypoxia can cause stress or death in bottom-dwelling organisms that can not leave the zone. The midsummer extent of the hypoxic zone has more than doubled since it was first systematically mapped in 1985 (Rabalais and others, 1999). The largest hypoxic zone measured to date occurred in the summer of 1999, (fig. 2) when its size was reported to be 20,000 km^2 (square kilometers), or about the size of the State of New Jersey (Rabalais, 1999). In the summer of 2000, following drought conditions in the basin, the area of the hypoxic zone was about 4,400 km^2, one of the smallest sizes measured to date (Rabalais, 2000).

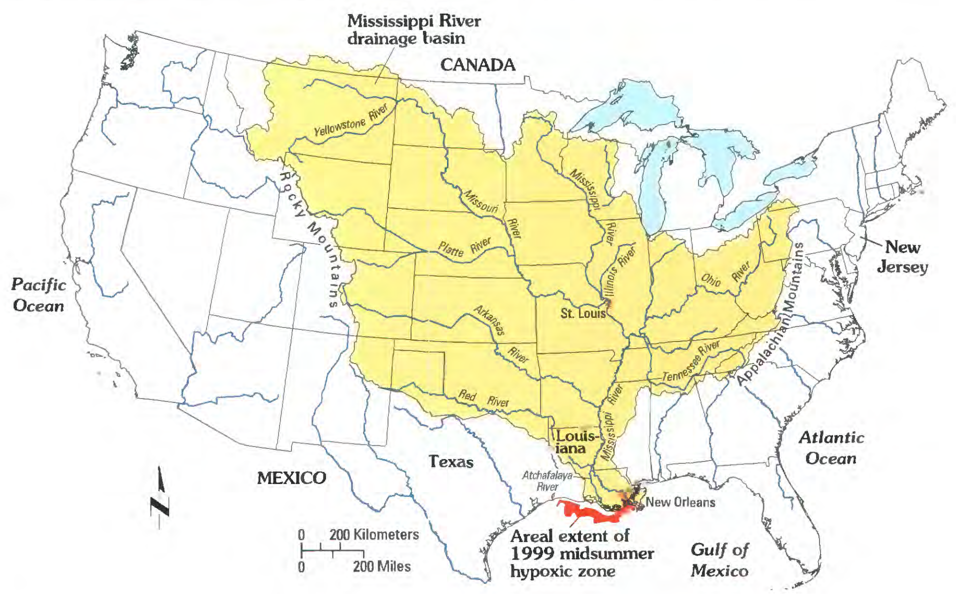

Figure 1. Mississippi River drainage basin, major tributaries, and areal extent of 1999 midsummer hypoxic zone.

Two conditions are necessary for the formation of hypoxia—stratification of the water column in the Gulf and the presence of organic matter to consume oxygen. The Mississippi River produces both conditions through large inputs of freshwater and nutrients. High streamflow in the spring and summer provides a large influx of freshwater, which promotes stratification in the Gulf with warmer, less dense water overlying colder, more dense salt water. Nutrients from the Mississippi River fuel the production of algae in the surface water of the Gulf. Organic material from the algae and other organisms settles into the bottom water of the Gulf where it is decomposed by bacteria, which consume oxygen in the process. Stratification blocks the replenishment of oxygen from the surface, and hypoxia develops. Hypoxia may persist until late fall when stratification breaks up because of reduced freshwater inputs, cooler temperatures, and mixing by storms.

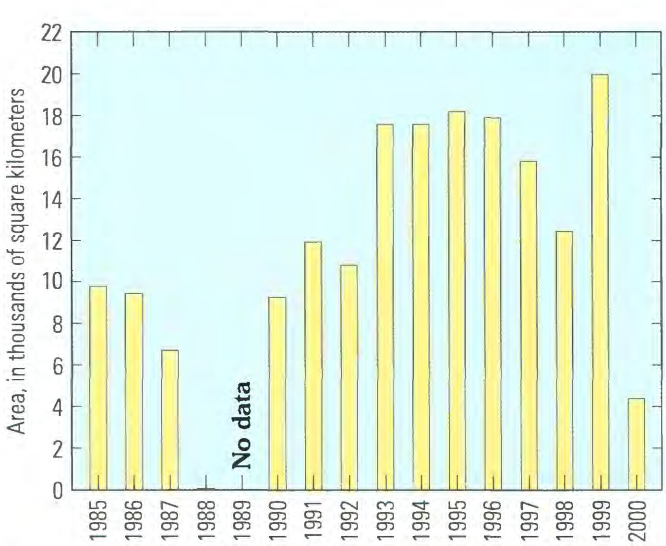

Figure 2. Area of hypoxic zone, 1985–2000 (source: N.N. Rabalais, Louisiana Universities Marine Consortium).

One of the principal causes for the increasing size of the hypoxic zone is believed to be the increasing supply of nitrogen, particularly nitrate, delivered to the Gulf each year from the Mississippi River Basin. Nitrate concentrations have increased several fold during the past 100 years in streams draining some parts of the Mississippi Basin, and the annual delivery of nitrate from the Mississippi River to the Gulf has nearly tripled since the late 1950's (Goolsby and others, 1999). The increased delivery of nitrate can magnify the production of organic carbon in the Gulf, which can lead to increased hypoxia. For example, one atom of nitrate-N can be responsible for producing 6.6 atoms of organic carbon through photosynthesis (Redfield, 1958). Further, some of the nitrogen is recycled to produce more organic carbon. Rabalais and others (1999) suggest that an atom of nitrogen from the Mississippi River is recycled about four times, on average, in the Gulf before it is lost from the water column. Therefore, the approximately 0.95 million metric tons of nitrate as nitrogen discharged annually from the Mississippi River Basin (Goolsby and others, 1999) could potentially produce more than 20 million metric tons of organic carbon annually in the Gulf of Mexico.

Mississippi River Basin

The Mississippi River and its distributary, the Atchafalaya River, drain an area of nearly 3,208,700 km^2 or about 41 percent of the conterminous United States. It is the largest river basin in North America and the third largest river basin in the world. The basin drains all or parts of 30 States and extends from the Appalachian Mountains in the east to the Rocky Mountains in the west, and from southern Canada to the Gulf of Mexico. About 70 million people live in the basin. The climate, land use, soils, and population vary widely across the basin. The annual runoff ranges from less than 5 cm/yr (centimeters per year) in the arid western part of the basin to more than 60 cm/yr in the humid eastern part. The basin contains one of the most productive farming regions in the world. About 58 percent of the basin is in cropland. Other significant land uses and their percentage of the basin include woodland (18 percent), range and barren land (21 percent), wetlands and water (2.4 percent), and urban land (0.6 percent). The central part of the basin produces the majority of the corn, soybean, wheat, cattle, hogs, and chickens in the United States.

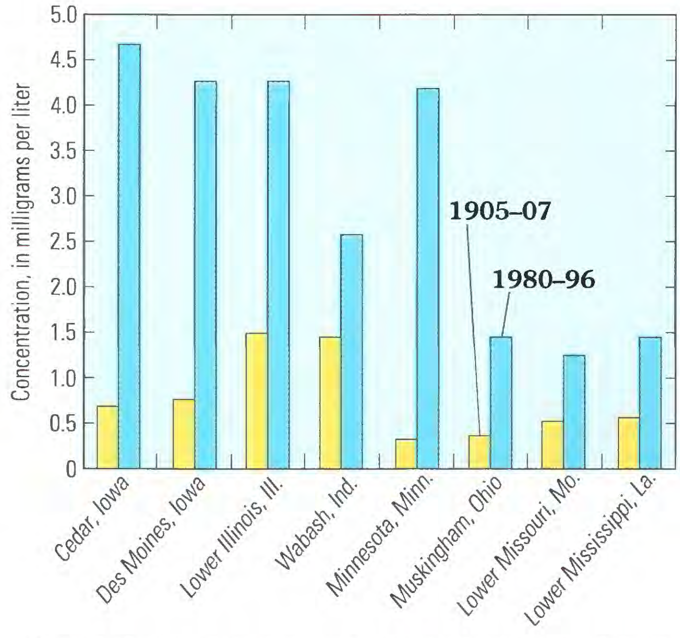

Figure 3. Average annual nitrate concentrations in selected rivers during 1905–07 and 1980–96.

The majority of all agricultural chemicals used in the United States are applied to cropland within the basin. For example, about 7 million metric tons of nitrogen in commercial fertilizers are applied annually in the basin. In addition, the central part of the basin has been subjected to extensive agricultural drainage during the past 125 years (Zucker and Brown, 1998) to lower the water table and make the land suitable for farming. This practice "short circuits" the flow of ground water by draining the top of the saturated zone directly into agricultural drains and then to nearby streams. Nitrate concentrations in agricultural drains can be very high—20 to 40 mg/L or more (Zucker and Brown 1998).

Concentrations and Flux of Nitrate

Nitrogen occurs principally in two forms in streams—nitrate and organic nitrogen (dissolved and particulate). Nitrate is the most soluble and mobile form of nitrogen. Historical records (Palmer, 1903; Dole, 1909) show that the average concentrations of nitrate in the Mississippi River and some of its tributaries have increased several fold since the early 1900's in parts of Iowa, Illinois, Indiana, Minnesota,

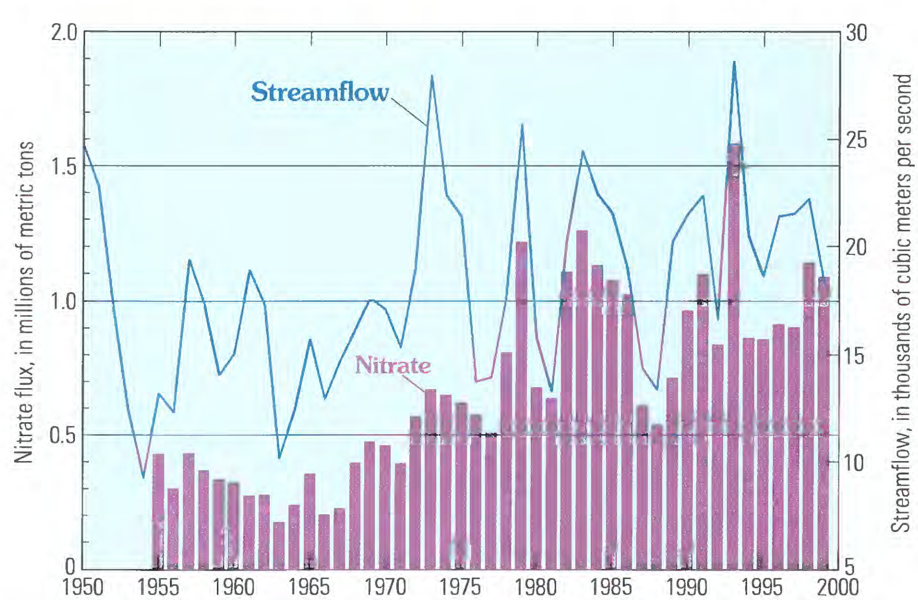

Figure 4. Annual nitrate flux and mean annual streamflow from the Mississippi River Basin to the Gulf of Mexico.

and Ohio (fig. 3). Although the increase in average nitrate concentrations in the lower Mississippi River main stem has not been as dramatic as in some smaller streams, concentrations still increased by a factor of about 2.6 between 1905–07 and 1980–96. Most of the increase in the lower Mississippi River main stem occurred between the late 1960's and the early 1980's. During that period, the average annual nitrate concentration in water flowing to the Gulf of Mexico more than doubled (Goolsby and others, 1999).

In contrast, it is estimated that the concentration of particulate organic nitrogen in the lower Mississippi River has decreased about 50 percent since the early 1900's, primarily because of reduced suspended sediment flux caused by construction of several large reservoirs on the Missouri River in the 1950's and 1960's (Meade, 1995). The dissolved organic nitrogen concentration is believed to have changed very little during the last 100 years.

In an average year the Mississippi River discharges 1.57 million metric tons of nitrogen into the Gulf of Mexico. This includes about 0.95 million metric tons as nitrate and 0.58 million metric tons as organic nitrogen (Goolsby and others, 1999). About three-fourths of the nitrogen is discharged to the Gulf through the Mississippi River channel and the remainder is diverted into the Atchafalaya River, which also discharges to the Gulf.

The annual flux of nitrate to the Gulf from the Mississippi River Basin increased significantly during the period 1955–99 (fig. 4). A Kendall's tau test for trend shows the increase in nitrate flux to be highly significant (p less than 0.001), with a trend slope of approximately 19,000 metric tons per year. During 1955–70, nitrate flux averaged 328,000 metric tons per year. However, during 1980–99 the nitrate flux averaged 969,000 metric tons per year, almost a threefold increase. Nearly all of this increase in nitrate flux occurred between 1970 and 1983. There was no statistically significant trend, upward or downward, in nitrate from 1980 to 1999. Part of the increase in flux can be attributed to an increase in precipitation and streamflow (fig. 4). The average annual streamflow during 1980–99 was about 30 percent higher than during 1955–70. Higher precipitation during the latter period may have caused more leaching and transport of nitrate from soil and ground-water systems in the basin. On a seasonal basis, the period of highest nitrate flux to the Gulf is usually the spring and early summer, preceding the development of hypoxia in the Gulf.

Estimating Sources of Nitrogen

The principal sources of nitrogen inputs to the Mississippi Basin are summarized in figure 5. They include soil mineralization, fertilizer, legumes and pasture, animal manure, atmospheric deposition, and municipal and industrial point sources. Some of these represent new inputs of nitrogen to the basin, and some represent recycling of nitrogen already in the basin. However, all are potential sources of nitrogen that can enter the Mississippi River and the Gulf of Mexico. The largest annual inputs are from commercial fertilizer and soil mineralization. The largest change in annual nitrogen input has been in fertilizer, which has increased more than sixfold since the 1950's.

The geographic distribution of the combined annual nitrogen inputs from the known major sources is shown in figure 6*A* for the 133 hydrologic accounting units in the basin. The estimated total nitrogen (nitrate plus organic and ammonia nitrogen) yields in streams draining the accounting units are shown in figure 6*B*. The yields are the nitrogen outputs from the basins normalized to basin drainage areas. The similarities in the patterns of nitrogen inputs and outputs are striking. As might be expected, the higher nitrogen yields in streams (1,001–3,050 kg/km^2/yr) are from basins where the nitrogen inputs are higher. These basins also tend to be in areas of the Mississippi Basin where precipitation is high and subsurface drainage is used extensively. The high nitrogen inputs coupled with high precipitation and the associated runoff, generally high water tables, and extensive subsurface

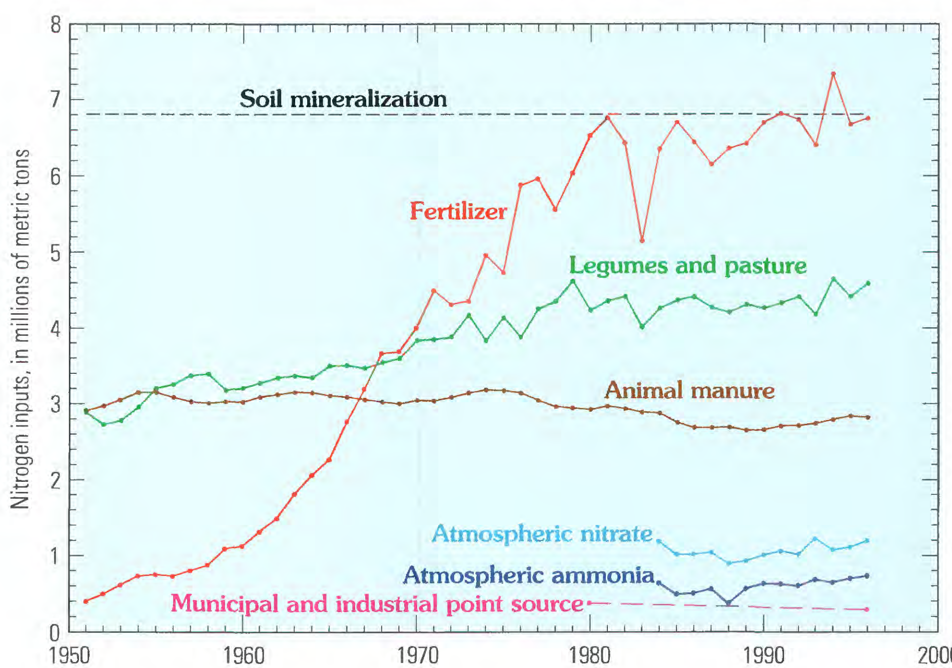

Figure 5. Annual nitrogen inputs to the Mississippi Basin from major sources.

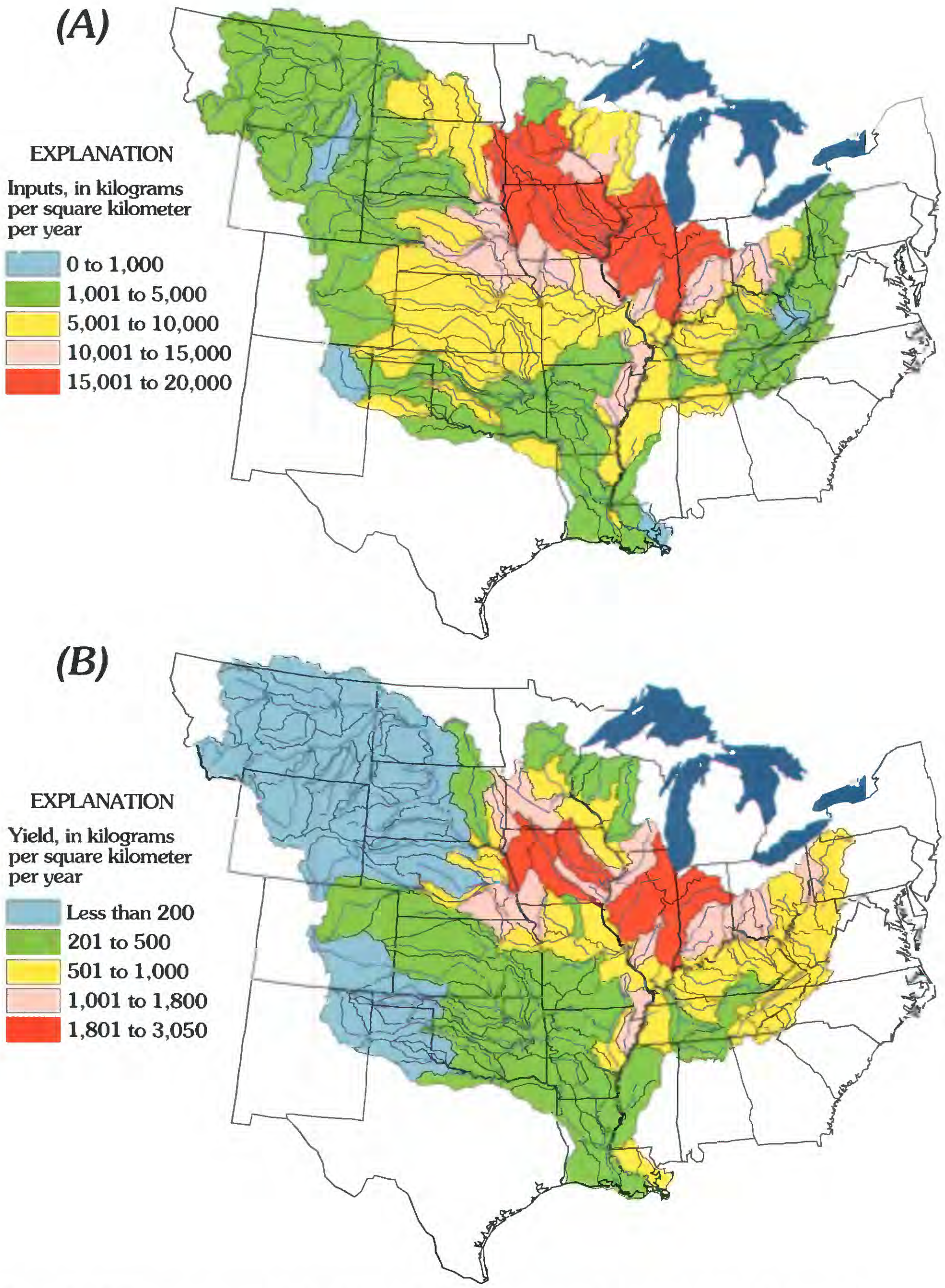

Figure 6. ***(A)*** **Nitrogen inputs during 1992 and** ***(B)*** **average annual nitrogen yields of streams for 1980–96 (modified from Goolsby and others, 1999).**

drainage result in high rates of transport of soluble nitrate into streams and, eventually, to the Mississippi River and the Gulf of Mexico.

Linking Nitrogen Flux to Nitrogen Sources

Relations between nitrogen inputs from various sources and nitrogen yields for 42 large drainage basins were analyzed using multiple regression techniques (Goolsby and others, 1999). This analysis showed that about 89 percent of the annual total nitrogen flux to the Gulf (1.57 million metric tons) was from nonpoint sources, and the remaining 11 percent was from municipal and industrial point sources. The estimated contributions of both nitrate and total nitrogen from specific sources are given table 1. Alexander and others (2000) obtained similar values for total nitrogen flux to the Gulf using a model referred to as SPARROW.

Predicting Nitrate Flux to Gulf of Mexico

A number of factors are important in determining the annual flux of nitrate from the Mississippi River Basin to the Gulf of Mexico. These include nitrogen inputs to the Mississippi Basin, nitrogen removal in harvested crops, and precipitation, which affects the storage and leaching of nitrogen from the soil/ground-water system. Most of the annual nitrogen input is removed in harvested crops or lost through denitrification, volatilization, and soil immobilization. The difference between the annual nitrogen inputs and nitrogen removal by these various processes is referred to here as the residual nitrogen and represents nitrogen potentially available for transport into ground water, streams, and eventually the Gulf. The residual nitrogen can be stored in the soil/ground-water system, where some can be used by crops in subsequent years and some (mostly nitrate) can be leached into streams by precipitation. High amounts of precipitation leach more nitrogen to streams than low amounts.

Goolsby and others (1999) estimated the annual nitrogen inputs, removal, and residuals for the Mississippi Basin for 1955–96. These variables and a number of related variables, which could be quantified through this time period including those in figure 5, were examined in statistical models to determine which ones could best explain the observed annual nitrate flux to the Gulf. The three most statistically significant variables were, in order of importance, annual basinwide nitrogen fertilizer use 2 years

Table 1. Estimated nitrogen contribution to the Gulf of Mexico from specific sources in the Mississippi Basin (1980–96)

[Nitrate flux = 0.95 million metric tons per year; total nitrogen flux = 1.57 million metric tons per year]

Source of nitrogen	Percentage of nitrate flux from source	Percentage of total nitrogen flux from source
Fertilizer and mineralized soil nitrogen	58 +/-9	50 +/-9
Animal manure	16+/-9	15 +/-10
Other, including atmospheric deposition, ground water, soil erosion, and urban runoff	16 +/-6	24 +/-6
Municipal and industrial point sources	9 +/-2	11 +/-2

previous, mean annual streamflow for the current year, and the basinwide residual nitrogen for the previous year. The regression model shown below has an R^2 of 0.89.

$$N_{flux} = 0.049*F_2 + 36*Q - 0.094*R_1, \quad (1)$$

where N_{flux} is nitrate flux to the Gulf, in metric tons per year;

F_2 is fertilizer use in the entire basin 2 years previous, in metric tons;

Q is the current year mean annual discharge to the Gulf, in cubic meters per second;

R_1 is the nitrogen residual for the previous year, in metric tons.

A comparison of the nitrate flux predicted from the regression model and the observed nitrate flux (see annual flux in fig. 4) is shown in figure 7.

F_2 explains about 68 percent of the variation in nitrate flux and explains much of the increasing trend in nitrogen flux. Q explains an additional 18 percent of the variation in nitrogen flux and explains much of the observed year-to-year variability. R_1 explains another 3 percent of the variation in nitrogen flux. For most years, except 1972–74, the model shows excellent agreement between observed and predicted values. Streamflow was very high during these 3 years (see fig. 4), and nitrate flux is greatly over predicted. Results for 1961 are similar, although streamflow was considerably lower. Little excess nitrate may have been present in the soil/ground-water system for leaching during these periods.

The observed fluxes indicate that the nitrate transport to the Gulf has not increased appreciably since the early 1980's. However, the year-to-year variability has become large, probably because of variability in precipitation and an abundant reservoir of soluble nitrate in the soil/ground-water system. Thus, nitrate inputs to the Gulf appear to have stabilized for the current level of nitrogen inputs and outputs. However, in future years the flux of nitrate to the Gulf will likely respond quickly and perhaps dramatically to variations in precipitation and runoff. Because of the amount of nitrate stored in the soil/ground-water system, fluxes of nitrate will be low in dry years and high in wet years. Also, because of the huge storage capacity of the soil/ground-water system, the flux of nitrate will likely change very slowly in response to increases or decreases in nitrogen inputs to the basin.

—Donald A. Goolsby and William A. Battaglin

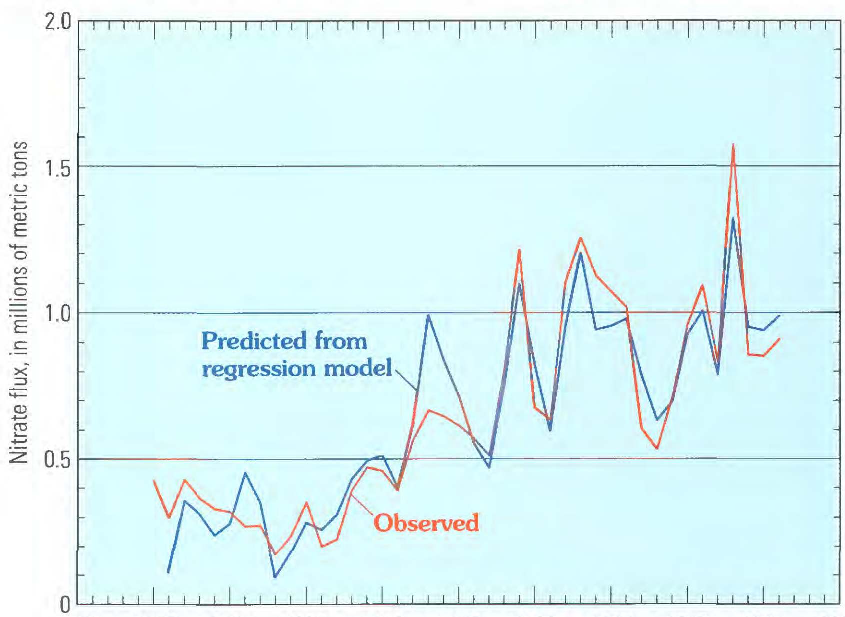

Figure 7. Annual nitrate flux to Gulf of Mexico and nitrate flux predicted from regression model.

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Additional information on hypoxia in the Gulf of Mexico and nutrients in the Mississippi Basin, including a downloadable graphics file, can be obtained at the following web sites:

http://wwwrcolka.cr.usgs.gov/midconherb/hypoxia.html (downloadable graphics files)

http://www.nos.noaa.gov/products/pubs_hypox.html

http://water.usgs.gov/nawqa/sparrow/

http://water.usgs.gov/nawqa/nutrient.html

http://water.usgs.gov/nasqan/

http://water.usgs.gov/pubs/circ1133/index.html

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