Restoration of wetlands in the Mississippi–Ohio–Missouri (MOM) River Basin: Experience and needed research

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Abstract

An ecological and hydrologic restoration of the Mississippi–Ohio–Missouri (MOM) Basin in the United States is proposed as the solution to the recurring hypoxic conditions in the Gulf of Mexico. Nitrate–nitrogen is the cause of this eutrophication in the Gulf and its source is mainly due to increased fertilizer use in the American Midwest. In that same Midwest, the land has also been artificially drained and 80–90% of the original wetlands have been lost. Our proposed restoration involves the strategic creation and restoration of 2.2 million ha of wetlands in the MOM basin where in-field wetlands intercept agricultural runoff and diversion wetlands are overflowed by flooding river water. Case studies that total 50 wetland-years of data from Illinois, Ohio, and Louisiana are summarized as the basis for the restoration area estimate. Benefits of this restoration, in addition to solving the Gulf hypoxia, include water quality improvement, reduction of public health threats, habitat creation, and flood mitigation that will accrue to the locations in the MOM basin where the restoration occurs. Before the restoration commences, there is a need for formal and rigorous large-scale research in the basin to reduce uncertainties.

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1. Introduction

The low oxygen conditions (hypoxia) in the Gulf of Mexico are but one sign that America’s 3 million km² watershed that feeds the Gulf—The Mississippi–Ohio–Missouri (MOM) River Basin—needs to be restored. Humans have dramatically increased nitrogen fertilizer use in the basin since the 1950s and significant amounts of this excessive nitrogen are transported as nitrate–nitrogen via drainage tile, ditches, streams, and rivers to the Gulf, leading to eutrophication and episodic and persistent hypoxia (dissolved oxygen <2 mg/L) in the Gulf; the hypoxic zone routinely covers 20,000 km² or more (National Research...
The connection between coastal eutrophication in the Gulf of Mexico and the nitrate–nitrogen released from the 3 million km² Mississippi River Basin that feeds the Gulf is well established (Goolsby et al., 1999; Rabalais et al., 2002; McIsaac et al., 1999). The hypoxia in the inner continental shelf of the Gulf of Mexico off Louisiana and Texas is also related to large loss of wetlands in the Basin (Mitsch et al., 2001), more rapid drainage and efficient drainage, and the separation of the Mississippi River from its floodplain and deltaic plain. Whereas the higher order streams and rivers once spread out over floodplains and delta during floods, flow is now mostly shunted directly to the sea (Baumann et al., 1984; Day et al., 2000a, 2003; Mitsch et al., 2001, 2005b).

A comprehensive series of studies sponsored by NOAA, USEPA, USDA, and other Federal agencies described the extent of the Gulf of Mexico problem (Rabalais et al., 1999), the sources of nutrients in the Mississippi River Basin (Goolsby et al., 1999), model predictions of the connect between the extent of the hypoxia and nutrient reductions (Brezonik et al., 1999), economic analysis of both the effect in the Gulf and the solutions to the problem (Diaz and Solow, 1999; Doering et al., 1999) and, most important for this paper topic, the potential solutions (Mitsch et al., 1999). These report findings were summarized by CENR (2000) and an “action plan for reducing, mitigating, and controlling hypoxia in the northern Gulf of Mexico” (Mississippi River Task Force, 2001) was formally transmitted to the U.S. Congress as a result of these studies.

The subject of this paper is the ecological restoration of MOM to solve the Gulf nutrient problems but also to improve the environment throughout the basin. Three general approaches for reducing agriculturally derived nitrogen that would otherwise reach the Gulf of Mexico were summarized in a Federal report and subsequent article by Mitsch et al. (1999, 2001): (1) change farming practices to minimize nitrate loss by reducing the use of nitrogen fertilizer and through a suite of management practices; (2) intercept laterally moving groundwater and surface water with nitrogen-sink ecosystems, particularly created and restored wetlands and (3) provide a system of river diversion backwaters along rivers and in the Mississippi River delta for interception of large fluxes of nitrogen associated with flood events. This paper discusses the use of the second and third options as part of a major hydrologic restoration of the Mississippi–Ohio–Missouri River Basin and points out the potential benefits to both the Gulf of Mexico and to those living in the basin itself. But this restoration must be done with lessons learned from previous large-scale restorations in the Everglades and Louisiana delta. We outline a research program of “big science” (see Mitsch and Day, 2004 for definition) that is needed to reduce uncertainties in the restoration approaches before it is attempted on a large-scale.

2. Source of the hypoxia problem

The Mississippi–Ohio–Missouri (MOM) Basin (Fig. 1) is 3.2 million km² or about 40% of the lower 48 United States. The Ohio, Missouri, and Upper Mississippi Rivers combined, which account for 80% of the Mississippi River Basin, contribute 90% of the nitrate–nitrogen flux to the Gulf of Mexico (Table 1). The Upper Mississippi and Ohio Rivers account for 43 and 34%, respectively of this flux, from comparable-sized basins. The Missouri River, although more than twice the area of the other two sub-basins, contributes only 13% of the nitrates to the Gulf. The shaded area in Midwestern USA shown in Fig. 1 is the region of highest nitrate–nitrogen flux, generally greater than 1000 kg N km⁻² yr⁻¹, in the basin. This area stretches from southern Minnesota southward through Iowa then eastward through Illinois, Indiana, and Ohio. Much of this area is the “corn belt” of Midwestern USA and historically one of the most productive agricultural areas in the world. That agricultural prosperity has led to the development of many large urban complexes in the region—Chicago, Minneapolis-St. Paul, Indianapolis, Cincinnati, and Columbus—where a large portion of the human population of the upper basin resides.

The increase in the hypoxia in the Gulf of Mexico in the past 20 years appears to reflect the increased nitrate–nitrogen flux to the Gulf and the increased use of nitrogen fertilizer in the Mississippi River Basin since the late 1950s. Nitrogen fertilizer use in the Mississippi–Ohio–Missouri Basin (as estimated by the sale of fertilizer in 20 basin states from 1951–1996) increased seven-fold from 1960 to 1990s, from 1 to 7 million Tons yr⁻¹ (Goolsby et al., 1999). Most of that...
increase occurred in 1960–1980. Other major sources of nitrogen to waterways in the basin include legume, especially soybean, nitrogen fixation, animal manure, soil mineralization, atmospheric inputs, and municipal and industrial wastewater. Goolsby et al.’s (1999) data do not show any significant rise in any of these sources in the period of the 1950–1990s and suggest that atmospheric and wastewater inputs are low compared to fertilizer inputs to the basin. Release of nitrogen by soil mineralization in the basin is poorly understood and was assumed by Goolsby et al. (1999) to be constant.

Nitrate–nitrogen concentrations in the streams of the MOM Basin show a clear seasonal pattern. From August through November, nitrate–nitrogen concentrations are generally low in most major streams in the basin as in-stream degradation of nitrates occurs, during low-flow periods with warm stream and river temperatures of late summer and fall (Fig. 2). High concentrations of nitrate–nitrogen occur in January–June during the wet season of high runoff and river flow and especially in May through early June immediately after fertilizer is applied. Concentrations as high

<table>
<thead>
<tr>
<th>Basin</th>
<th>Area (km²)</th>
<th>Flow (cm yr⁻¹)</th>
<th>Nitrate flux (Tons)</th>
<th>Nitrate yield (kg km⁻² yr⁻¹)</th>
<th>Percentage of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ohio</td>
<td>526000</td>
<td>50.2</td>
<td>323500</td>
<td>620</td>
<td>54.0</td>
</tr>
<tr>
<td>Missouri</td>
<td>1357700</td>
<td>6.5</td>
<td>125900</td>
<td>80</td>
<td>13.2</td>
</tr>
<tr>
<td>Upper Missouri</td>
<td>489500</td>
<td>22.7</td>
<td>41100</td>
<td>840</td>
<td>43.2</td>
</tr>
<tr>
<td>Total “Upper” Mississippi River Basin</td>
<td>2373200</td>
<td>860500</td>
<td>362</td>
<td>90.4</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 2. Patterns of weekly nitrate–nitrogen concentrations measured in the Olentangy River, Ohio, 1996–2001.

Concentrations of nitrate–nitrogen of 5–10 mg N/L are the norm in third and fourth order streams, such as the Olentangy River in Ohio during the wet season and drop to 2 mg N/L or less during the dry season of August–November (Fig. 2). Concentrations of nitrate–nitrogen in the Mississippi River in Louisiana just before it flows into the Gulf of Mexico average <2 mg N/L for most of the year (Fig. 3) but are sufficient to cause the Gulf hypoxia in this coastal system, particularly since the highest concentrations are seen April–July.

The effect of increased use of fertilizer on flux of nitrate–nitrogen to the Gulf is exacerbated by the increased drainage of the landscape—including the drainage of wetlands—that occurred in the past century in the MOM basin (Fig. 4). About 30 million ha of land has been drained in the Mississippi River Basin in the 20th century (Mitsch et al., 2001). The portion of the basin where drainage tiles have been used for more than a century (Fig. 4), correspond closely to the “red zone” high nitrate areas (Fig. 2). Seven states in the upper half of the MOM basin (Indiana, Illinois, Iowa, Minnesota, Missouri, Ohio, and Wisconsin) accounted for about 19 million ha of that drainage. In those same states, 14 million ha of wetlands were lost over the past 200 years (Dahl, 1990). Thus, not only has the landscape lost part of its ability to maintain a biogeochemical balance by shortening the time that water spends on the land, but the streams and rivers and ultimately the coastal areas are no longer buffered from upland regions by wetlands and riparian forests. Added to the increased use of fertilizers, the drainage systems in place in much of the MOM Basin are the reasons for the hypoxia in the Gulf of Mexico.

3. The ecological solution

Our national “problem-solving committee” (Mitsch et al., 1999, 2001) that was part of the hypoxia study described above recommended that to help solve the persistent problem of the hypoxia, the flux of nitrate–nitrogen to the Gulf of Mexico must be significantly reduced. Since the source and rapid transport of nitrogen to the Gulf is due to a combined effect of two human actions—the use of nitrogen fertilizer in excess of what is required by crops, and artificial drainage of much of the Upper Mississippi/Ohio River basins that accelerates the flow of fertilizer-rich waters to adjacent streams and rivers—our ecological solution suggests landscape changes that both remove the nitrate–nitrogen from runoff and rivers alike but also slow the speed by which the runoff reaches streams and rivers and streams and rivers subsequently reach the coast.

The agricultural community is already responding by identifying and implementing some management practices, such as changing cropping systems, reducing fertilizer application, controlled drainage, and manag-
Fig. 4. Mississippi–Ohio–Missouri (MOM) River Basin in the United States, showing location of land drainage (from Mitsch and Gosselink, 2000). Each dot represents 8000 ha of drained land.

Ining manure spreading and timing of nitrogen application. These practices, by themselves, are estimated to be able to reduce nitrogen discharge to streams by up to 20% (Mitsch et al., 2001). If other solutions are not found, mandated reductions in fertilizer use or water quality standards may be the only options left to solve the problem—these regulations could result in reduced farm production.

We recommended that in addition to the above agro-nomic practices already being explored there are two fundamental approaches that are needed to allow agriculture to maintain its productivity:

1. farm runoff wetlands—creation and restoration of wetlands and riparian buffers between farms and adjacent streams and rivers, and
2. river diversion wetlands—diversion of river water into adjacent constructed and restored wetlands along main river channels and in the Mississippi River delta during flood periods.

Nitrate-nitrogen retention has been effective in both types of wetlands (Table 2). Case studies of each type of wetland are described here.

3.1. Farm runoff wetlands

The ability of natural and constructed wetlands to remove nutrients and organic loads from farm runoff has been well demonstrated (e.g. Hammer, 1992; Knight, 1992; Arheimer and Wittgren, 1995; Kadlec and Knight, 1996; Comin et al., 1997; Peterson, 1998; Kovacic et al., 2000; Fink and Mitsch, 2004). This wetland function is especially effective if the wetlands are located in the headwaters of small watersheds and downstream from farm runoff (Fig. 5).

3.1.1. Illinois agricultural runoff wetlands

Four surface-flow wetlands were constructed in 1994 on the Embarras River floodplain in east-central Illinois, USA, to demonstrate if wetlands could inter-
Table 2
Nitrate–nitrogen retention in farm and river diversion wetlands in the Mississippi River Basin

<table>
<thead>
<tr>
<th>Wetland, location and type</th>
<th>Wetland size (ha)</th>
<th>Nitrate–nitrogen retention (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farm wetlands</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Agricultural wetlands, OH (one basin over 2 years)</td>
<td>1.2</td>
<td>40</td>
<td>Fink and Mitsch (2004)</td>
</tr>
<tr>
<td>Agricultural wetlands, IL (three basins over 3 years and one basin for an additional year)</td>
<td>0.3–0.8</td>
<td>44±4</td>
<td>Kovacic et al. (2000) and Larson et al. (2000)</td>
</tr>
<tr>
<td>River diversion wetlands</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Created river diversion wetlands, IL (three basins over 3 years)</td>
<td>1.8–2</td>
<td>43–94</td>
<td>Mipps and Crompton (1994)</td>
</tr>
<tr>
<td>Low-flow conditions</td>
<td>2.3</td>
<td>75–95</td>
<td>Unpublished data</td>
</tr>
<tr>
<td>Created diversion wetlands, OH (two basins over 8 years)</td>
<td>1</td>
<td>33±2</td>
<td>Mitsch et al. (1998, 2005a,b) and Spieles and Mitsch (2000)</td>
</tr>
<tr>
<td>Oxbow diversion wetland, OH (one basin over 4 years)</td>
<td>3</td>
<td>42±13</td>
<td>This study</td>
</tr>
<tr>
<td>Caernarvon diversion, LA (one basin in 5 years)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zone 1</td>
<td>1000</td>
<td>39</td>
<td>Lane et al. (1999)</td>
</tr>
<tr>
<td>Zone 2</td>
<td>3000</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>Zone 3</td>
<td>5000</td>
<td>72</td>
<td></td>
</tr>
<tr>
<td>Entire wetland, 1991–1994</td>
<td></td>
<td>76–95</td>
<td></td>
</tr>
</tbody>
</table>

cept tile drainage from farm fields, temporarily hold the water, remove pollutants, and then pass the water to the adjacent stream (Kovacic et al., 2000; Larson et al., 2000; Hougland et al., 2001). The four wetlands, 0.3–0.8 ha in size, were created by construction of a berm 15 m from the river. The wetlands were designed to intercept flow from field drainage tiles from corn and soybean fields. Outlet weir structures were installed on the downstream end of the wetlands to measure outflow. Overall, with 10 wetland-years of data, these wetlands decreased nitrate-nitrogen export from 32 to 66%, with an average retention of 23 g N m⁻² yr⁻¹.

3.1.2. Ohio agricultural runoff wetland

An agricultural runoff wetland was constructed in the spring of 1998 in Logan County, Ohio, USA, several kilometers upstream of a popular recreational lake in northwestern Ohio called Indian Lake (Fink and Mitsch, 2004). The multi-celled 1.2 ha “Indian Lake Demonstration Wetland” receives drainage from a 17 ha watershed, 14.2 ha of which was used for intensive row-crop agriculture and 2.8 ha of which was forested. Thus, the wetland had a watershed:wetland ratio of 14:1. Surface inflow in 2000 was 6.64 m yr⁻¹ and groundwater inflow to the wetland was 4.2 m yr⁻¹. Surface water levels over a 2-year period of study varied over 40 cm in depth and muskrat activity in one of the cells actually led to a 30 cm water level decrease in the second year of study. Major storm events led to dramatic but short increases in water level of over 20 cm. These storm events, primarily in the late winter and early spring, led to rapid flow-through and poorer water quality enhancement. Surface inflow had 2-year-average concentrations of 0.8 mg N/L for nitrate+nitrite while groundwater had much higher concentrations (2.0 mg N.L⁻¹). Interestingly, concentrations of nitrate-nitrite discharging from the wetlands did not increase significantly during precipitation events even though inflow concentrations were generally higher then. Overall, the wetlands retained 40% of nitrate-nitrite and retained a mass of 39 g N m⁻² yr⁻¹ (Table 2). The overall design of this wetland, with multiple cells and a watershed:wetland ratio of 14:1, appeared to be appropriate to buffer storm pulses of
A river diversion wetland is a wetland on the adjacent floodplain or behind artificial levees that receives water by pumping or flood flow from the main channel of a river (Fig. 6). River diversion wetlands, both at a small-scale in the upper half of the MOM Basin in Illinois and Ohio, and large-scale on the Mississippi River itself in Louisiana, illustrate the potential of this approach for improving water quality. Each river diversion system was the site of significant research with similar sampling and analytical methodologies for several years. Each project involves diverting nutrient-laden river water into adjacent riparian wetlands. In all cases, some infrastructure (diversion gates, retention valves, check valves, and pumps) was used to control and measure flows into adjacent riparian wetlands.

3.2. Illinois experimental riverine wetlands

Experimental wetlands at the Des Plaines River Wetlands in northeastern Illinois were among the first sites in the country to investigate the idea of river diversions through small constructed floodplain wetlands (Sanville and Mitsch, 1994; Wang and Mitsch, 2000). Initially four constructed wetland basins, ranging in size from 1.8 to 3.8 ha were constructed in Lake County in northeastern Illinois on the floodplain of the Des Plaines River. Excavation of the four wetland basins began in 1986 in the alluvium of the Des Plaines River floodplain. Water was delivered to each wetland basin through a pipe network fed by a submersible pump at the river. Pumping began in 1989 and most of the useful data at the site were obtained in water years 1990 and 1991. During that period, a whole-ecosystem experiment was established whereby two of the wetlands had a high rate of flow (18–20 m yr$^{-1}$) while the other two wetlands had a much lower rate of flow (5–8 m yr$^{-1}$) (Hey et al., 1994). Nitrate–nitrogen budgets were developed for three of the four wetland basins in 1991 (Phipps and Crumpton, 1994; Table 2). All of the wetlands were sinks for nitrate–nitrogen, removing 78–84% of the inflowing nitrate by mass in that study. Over a 3-year period, retention by concentration ranged from 46 to 95%, with retention only slightly related to the flow rates. Retention rates ranged from 2 to 43 g N m$^{-2}$ yr$^{-1}$.

3.2.2. Ohio experimental riverine wetlands

A pair of 1 ha experimental diversion wetlands basins were created in 1994 at the Olentangy River Wetland Research Park on Ohio State University’s campus and used in a whole-ecosystem wetland experiment from 1994 to 2002 (Mitsch and Wilson, 1996; Mitsch et al., 1998, 2005a; Mitsch and Jørgensen, 2004). Continuously pumped inflows have averaged 20–30 m yr$^{-1}$ to each basin with day-to-day flow patterns corresponding to Olentangy River flow. The water passes through the wetlands in about 3–4 days and discharges to a common swale that in turn flows back to the Olentangy River. For 16 wetland-years of measurements (2 wetlands × 8 years), the Ohio wetlands retained an average of 34% of nitrate–nitrogen by concentration and 33% by mass (Fig. 7; Table 2). In years of high nitrate concentration (1996, 1997, 2000, and 2001), nitrates decreased from approximately 4 to 3 mg N L$^{-1}$ in the 1 ha wetlands. In low-nitrate concentration years (1994, 1995, 1998, and 1999), nitrates decreased from approximately 2 to 1 mg N L$^{-1}$.
3.2.3. Ohio created oxbow

A 3 ha river diversion wetland was constructed in the summer of 1996 at the Olentangy River Wetland Research Park. The wetland was created on the river floodplain as mitigation for the loss of 1.1 ha of wetlands lost about 30 km south of the site in the same major river basin. This freshwater oxbow wetland was designed to receive water from the Olentangy River during flood pulses similar to the flow pattern shown in Fig. 6b. When the river level is higher than the wetland water level, water passively flows into the wetland through a check valve at the inflow. When the river pulse decreases to where its water level is below that of the wetland, the check valve closes, keeping the water from spilling back to the river. Thus all of the floodwater is “pushed through” the wetland and eventually returns to the Olentangy River through a control weir at the outflow about 300 m from the inflow. Fig. 8 shows a typical hydroperiod for the wetland compared to the adjacent river hydroperiod. Water level trends of the oxbow follow a pattern of high water levels in winter and early in the growing season, followed by drier conditions in late summer. Frequent winter and spring flooding followed by summer drawdowns is typical of Midwest USA wetlands. For example, 11 flood events occurred between January and July in 2002 into the wetland. These flood events provide nutrients and introduce seeds and small organisms from across the watershed. The spring/early summer flooding also provides a period of standing water in the wetland considerably longer than the number of hydrologic critical days that were given by National Research Council (1995) for wetland delineations; thus, the design of this wetland was successful in establishing hydrologic conditions conducive to development of a functioning wetland.

Nitrate–nitrogen and hydrology measurements at the inflow and outflow of this created oxbow wetland illustrate a consistent pattern of nitrate retention by concentration and mass (Table 3). Nitrate–nitrogen concentrations were statistically lower in the outflow compared to the inflow in three of the 4 years for which data are available, with an average nitrate–nitrogen concentration decrease of 42%. When hydrology data are added to the evaluation, the wetland was shown to retain about 46% of the inflowing nitrate–nitrogen or 20 g N m\(^{-2}\) yr\(^{-1}\). Overall, this type of wetland is a prototype for how diversion wetlands can be created or restored along floodplains throughout the MOM Basin. The wetland is effective in retaining floodwater, in removing nitrate–nitrogen from that water, and in establishing a habitat particularly suitable for migratory waterfowl during spring migrations and for herons (e.g. Great Blue Heron, Ardea herodias) in the late summer dry season. In some years, the standing water in the wetland is only a fraction of the 3 ha basin, thus causing a concentration of fish and a feast for the herons.

3.2.4. Louisiana river diversions

In Louisiana, river diversions are designed along the main stem of the Mississippi River to restore deteriorating wetlands in the Mississippi Delta by delivering sediments meant to compensate for sinking land (Day et al., 1997). One such diversion at Caernarvon on the east bank of the river south of New Orleans is a five-box culvert with vertical lift gates with a maximum flow of 280 m\(^3\) s\(^{-1}\). River diversion began in August 1991; average minimum and maximum flows are 14 and 114 m\(^3\) s\(^{-1}\), respectively, with summer flow.
rates generally near the minimum and winter flow rates 50–80% of the maximum (Lane et al., 1999, 2004). The diversion delivers river water to a the 260 km² Caernarvon freshwater/brackish wetland that eventually discharges into the brackish/saline Breton Sound estuary which is part of coastal Gulf of Mexico. The Caernarvon wetland retained 39–72% of nitrate by concentration, depending on the sampling location (Table 2) and 31–90 g N m⁻² yr⁻¹. Earlier studies at Caernarvon (1991–1994) showed a long-term reduction of nitrate of 76–95% nitrate reduction by concentration (Lane et al., 1999). In a related study in Louisiana, Lane et al. (2002) reported that nitrate concentrations in the Atchafalya River outflow were reduced by 40–50% as the water flowed into the Gulf of Mexico.

4. Restoring MOM

We recently re-estimated that creation or restoration of 2.2 million ha of wetlands will be required to remove 40% of the total nitrogen discharging to the Gulf of Mexico (Mitsch et al., 2005b). This estimate is based on the relationship between loading and retention rates for wetlands determined from several wetland-years of data from several independent wetland basins in the MOM Basin. If bottomland hardwood riparian forests are included as “wetlands” in this management strategy, the area required may be more; our analysis has shown that bottomland hardwood forests generally retain less nitrogen per unit area than wetlands do (Mitsch et al., 2001). This ecologically engineered nitrogen reduction of the MOM basin, combined with a 20% nitrate reduction we estimated that could be done by appropriate agronomic practices (Mitsch et al., 2001) would assure a sufficient reduction in nitrates entering the Gulf of Mexico to ensure a decrease in the size of the Gulf of Mexico hypoxia.

The restoration in agricultural areas might involve a combination of wetlands intercepting surface drain tiles and bottomland hardwood forests along streams and rivers intercepting subsurface drainage. Along river systems, natural and constructed backwaters can be reconnected to the river system in a manner similar to the created oxbow on the Olentangy River in Ohio, but on a larger scale and at many locations. An illustration of a potential river diversion site along the lower Mississippi River is shown in Fig. 9.
Our recommendation of setting aside less than 1% of the Mississippi River Basin is an ecological solution to the Gulf of Mexico hypoxia and provides a reasonable complement to a major reduction in fertilizer use that could reduce agricultural output and cause an economic impact in the Basin. Doering et al. (1999) agreed with this assessment when they found that restoring 2 million ha of wetlands in the Mississippi River Basin would have minimal impact on agricultural production in the basin. Furthermore, they argued that if nitrogen...
fertilizer use is restricted within the Mississippi River Basin, then the crop production and hence nitrogen pollution would simply be transferred to somewhere else and some other coastal system might be affected. Our solution to the nitrate problem prevents that transfer of pollution to another watershed and maintains agricultural production in the MOM Basin.

This ecological restoration would return the MOM basin to a functioning that is more akin to how the system functioned under natural conditions. Understanding river ecosystems has evolved from the River Continuum Concept (Vannote et al., 1980) where the longitudinal pattern changes from upstream to downstream are emphasized, to the Flood Pulse Concept (Junk et al., 1989; Junk, 1999; Tockner et al., 2000) where exchange between a river and its floodplain is emphasized as the main factor determining the function of both the river and its adjacent riparian floodplains. For major river deltas, ideas have changed from a physical-based model of deltaic lobe formation forced mainly by mineral sediments (e.g. Kolb and Van Lopik, 1958) to the concept that deltas are sustained by a hierarchical series of pulses that include tides, storms, and floods as they interact with biological, chemical, and geological processes (Day et al., 1995, 1997, 2000b). The restoration plan we describe reconnects the rivers with the floodplain and delta through a series of pulsed introductions of water from runoff and flooding.

4.1. Local benefits of MOM restoration

One of the features that became apparent soon after discussion began on solving the Gulf of Mexico hypoxia with wetlands in the MOM Basin, was the fact that such an ecological restoration would have dramatic benefits to the Midwestern USA as well. These benefits are summarized below.

4.1.1. Public health and local water quality

Warnings occur from time to time in the newspapers and television in late spring in several Midwestern cities about the threat to public health posed by high concentrations of nitrate-nitrogen in streams and rivers. The chemical is known to cause methemoglobinemia (“blue baby” disease that can cause fatalities to babies <6 months old). Water supply companies are required to notify their customers when nitrate-nitrogen concentrations are greater than 10 mg N/L, a frequent occurrence in the “red zone” area shown in Fig. 1 during the first major rain events after fertilizers are applied to crops. Currently several communities in Midwestern USA use expensive water treatment processes to reduce the concentrations of nitrate-nitrogen in drinking water and thus avoid these warnings to the public. Other communities spend resources removing nitrate-nitrogen from wastewater to meet water quality standards. Creating wetlands to prevent nitrate-nitrogen from being discharged into streams or to remove nitrates that are already in the rivers and streams could reduce the number of nitrate water quality alerts in the Midwest and could save towns and cities a great deal of chemical treatment costs.

4.1.2. Habitat restoration

Most states in Midwestern USA have lost 80–90% of their wetlands. Many farmers cultivate their farms to the stream’s edge, leaving little room for forested riparian buffers that would protect the stream as well as provide some water quality improvement. The National Research Council (1992) described a goal for wetland restoration for the United States for which this hydrologic restoration would provide half of the goal “a gain of 10 million acres (4 million ha) of wetlands by the year 2010, largely through reconvertng crop and pastureland and modifying or removing existing water control structures”. The restoration and creation of 2.2 million ha of wetlands in the MOM basin would immediately bring the nation more than halfway towards that national goal presented by the NRC. Restored and created wetlands greatly enhance wildlife benefits to the region. Hickman (1994) found that the number of breeding bird species increased from 37 to 54 at the Des Plaines River Wetland Demonstration project after wetland creation. He also found a four-fold increase in the number of waterfowl species after the wetlands were created. There are now over 150 species of bird species identified at the Olentangy River Wetland Research Park, many of which came to this urban area after the wetlands were constructed.

4.1.3. Flood control

An additional advantage of creating and restoring wetlands in the Midwestern United States is the mitigation of floods. Hey and Phillip (1995) estimated
that restoration of about 5 million ha of wetlands and backwaters in the Upper Mississippi River Basin could have provided substantial flood control value, even for the 100-year flood conditions experienced in the Upper Mississippi River Basin in 1993. This potential benefit of wetlands in the Mississippi River Basin needs more research from flood control specialists but the concept of wetlands contributing to flood control has been frequently documented (Mitsch and Gosselink, 2000).

4.1.4. Protection of agricultural production

The productivity of the American heartland would be preserved if a small percentage of the landscape were converted to wetlands. Using only a small percent of the landscape to allow the rest of the landscape to remain productive farmland might be the best tradeoff that the agricultural community could possibly have. If the ecological solution that we propose here is not enacted and the Gulf hypoxia continues to grow worse, fertilizer limits and nitrate water quality standards and discharge permits may eventually become policy.

5. Needed research

Funds have already been provided, through such mechanisms as the USDA’s Farm Bill and Wetland Reserve Program, to farmers and farming interests to implement some conservation methods including wetland creation and restoration. There are also several initiatives to provide funds to farmers to recreate and restore wetlands and riparian buffers in the Midwest through the Conservation Reserve Enhancement Program (CREP). There are also many projects for river diversion, flood management and wildlife protection in the basin. However, few of these projects are being monitored for their effectiveness and the research base is inadequate to model and estimate the effects of large-scale restoration of wetlands, riparian zones, and river diversions with a high degree of certainty to improve water quality in the Basin. Pilot- and full-scale projects, modeling, and technology transfer are needed before a restoration project on the scale of 2 million ha is undertaken.

We propose a comprehensive, coordinated applied research program to thoroughly investigate the uncertainties of these two general approaches (farm wetlands and river diversion wetlands) for helping to solve a major national pollution problem in the Basin and Gulf of Mexico. Our findings will be applicable to help solve inland and coastal pollution problems throughout the USA. Big science research projects (see Mitsch and Day, 2004) using a combination of multiple full-scale demonstration wetlands on farms, wetland research parks, and river diversions in the MOM basin and Mississippi delta are needed to test alternative water quality improvement strategies that use wetlands as permanent sinks for nutrients. These projects will allow development of design parameters, confidence intervals, and validated simulation ecosystem models to predict the behavior of these wetlands. A scale of the research is suggested here.

5.1. Farm wetlands

Ten to twenty full-scale, existing and new agricultural wetland demonstration projects should be located throughout the Midwest and instrumented to study agricultural runoff into wetlands in a variety of soil conditions. Most of these sites should be in the Ohio and Upper Mississippi “red zone” region shown in Fig. 1. Studies of the use of wetlands for reducing nitrogen and other pollutants should include timing of floodwater input, methods for retention of floodwaters, fate of nitrogen, and investigation of factors, such as temperature, soils, microbiology, etc., on loading-uptake relationships. Similar studies could be carried out using riparian buffer forests for water quality improvement. This will also provide flood control, sustainable forestry and wildlife habitat in these riverine systems.

5.2. River diversions

River diversions are being carried out in the Mississippi River delta for coastal restoration. Such studies should investigate the potential for managing these diversion systems for pollutant reduction and coastal fisheries enhancement. In addition, pilot and full-scale studies are needed of diversions into riparian systems along river channels throughout the MOM basin similar to the created oxbow project in Ohio described above. River diversions also need to be studied to determine that they do not result in any unacceptable water quality problems, such as eutrophication or harmful algal blooms.
5.3. Adaptive management research

These studies should use the same methodologies and approaches at all sites to determine if our recommendations of using agricultural wetlands, riparian ecosystems, and river diversions can be effective in controlling nutrients to the Gulf before embarking on a full-scale restoration in the Basin. Also, having multiple sites throughout the basin in different hydrologic, soil, and nutrient conditions will provide more certainty regarding ecological engineering design criteria for these systems.

6. Conclusions

- Ecologically engineered solutions should be the focus for solving problems that are watershed-scale. These solutions need to be sustainable and involve enhancing ecological processes.
- The restoration of the MOM Basin and the Gulf of Mexico will require a combination of agronomic and ecological techniques and strong collaboration among all stakeholders.
- Restoration of 2.2 million ha of wetlands is needed in the MOM basin to reduce the nitrogen load to the Gulf of Mexico sufficiently to ensure a reduction in the size of the hypoxia.
- Agronomic techniques, by themselves, are neither politically feasible, nor ecologically sufficient in scale to cause a significant reduction in the size of the hypoxic zone in the Gulf of Mexico.
- The benefits of wetland restoration in the MOM Basin, of and by themselves, are sufficient reasons for this large-scale restoration.
- Our eco-solution deals with three main causes of the problem: wetland/habitat loss; major drainage networks and hydrologic disruption; and excessive fertilizer use.
- Our eco-solution rehabilitates the natural functioning of riverine, wetland, and deltic ecosystems.
- Some large-scale riparian restoration projects are beginning in the MOM basin and are supported by U.S. Department of Agriculture. These projects need comprehensive monitoring to determine their effectiveness and applicability to other regions of the basin.

- A major, interdisciplinary research program, as a lead-in to the actual restoration of MOM, needs to take place with sufficient funding, study sites, and time to reduce remaining uncertainties about the efficacy of wetlands rebuilt in the MOM Basin to solve the coastal hypoxia problems in the Gulf of Mexico.

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