# Total nitrogen inflow and outflow from a large river swamp basin to the Gulf of Mexico

**Y. JUN XU**

*School of Renewable Natural Resources, Louisiana State University Agricultural Center, Baton Rouge, Louisiana 70803, USA*

yjxu@lsu.edu

**Abstract** River corridor wetland restoration and freshwater diversion from the lower Mississippi River are being considered as two major options to reduce nitrogen input to the Gulf of Mexico. However, it is largely uncertain how much nitrogen can actually be retained from the overflowing waters by these wetland systems. This study quantified the nitrogen inflow and outflow for the largest distributary basin of the Mississippi River, the Atchafalaya River Swamp basin. The goal of the study was to seek answers to three critical questions: (a) Does the Atchafalaya River Swamp remove a significant amount of nitrogen from the overflowing water, or is it releasing more nitrogen into the Gulf? (b) How do the nitrogen removal or release rates fluctuate seasonally and annually? (c) What are the relationships between the nitrogen removal capacity and the hydrological conditions in the basin such as river stage and discharge? By utilizing the long-term (1978–2002) river discharge and water quality data, monthly and annual nitrogen fluxes were quantified, and their relationships with the basin hydrological conditions investigated. A total nitrogen—sum of the total Kjeldahl nitrogen (TKN) and nitrate plus nitrite nitrogen ($NO_3$+$NO_2$)—mass input–output balance between the upstream (Simmesport) and downstream (Morgan City and Wax Lake Outlet) locations was established to examine the nitrogen removal potential for this, the largest freshwater swamp basin in North America. The results from this study showed that, over the past 25 years, the Atchafalaya River Swamp basin acted as a source for $NO_3$+$NO_2$ nitrogen, although the average annual output of $NO_3$+$NO_2$ nitrogen (174 584 Mg) was only slightly higher (2.3%) than the average annual input of $NO_3$+$NO_2$ nitrogen (170 721 Mg). The higher $NO_3$+$NO_2$ mass outflow occurred throughout summer and autumn, indicating an active role of biological processes on nitrogen in the overflowing waters of the Atchafalaya. However, this swamp basin has served as a major sink for organic nitrogen: the annual averages of TKN mass input and output were 200 323 and 145 917 Mg year$^{-1}$, respectively, presenting a 27.2% removal rate by the basin. This large TKN reduction appeared high during springs and low during late summers, corresponding with the fluctuation of the hydrological conditions of the river.

**Key words** Atchafalaya swamp basin; Gulf of Mexico; hypoxia; nitrate nitrogen; nitrite nitrogen; nutrient enrichment; organic nitrogen

## Flux d'azote total entrant et sortant d'un grand bassin fluvial marécageux vers le Golfe du Mexique

**Résumé** La restauration des zones humides du corridor fluvial et la dérivation d'eau douce depuis le Mississipi inférieur sont considérées comme étant deux options majeures pour réduire les flux d'azote vers le Golfe du Mexique. Cependant, une grande incertitude persiste sur la capacité de ces zones humides à effectivement atténuer la charge en azote des eaux d'inondation. Cette étude quantifie les flux d'azote entrant et sortant du plus grand basin riverain du Mississipi, le bassin du Marais de la Rivière Atchafalaya. L'objectif de cette étude est de chercher à répondre aux trois questions critiques suivantes: (a) Le Marais de la Rivière Atchafalaya atténue-t-il de manière significative la charge en azote des eaux d'inondation, ou rejette-t-il plus d'azote dans le Golfe? (b) Comment les taux d'atténuation ou de rejet d'azote fluctuent-ils selon les saisons et les années? (c) Quelles sont les relations entre la capacité d'atténuation de l'azote et les conditions hydrologiques dans le basin, comme le niveau et le débit de la rivière? Grâce à de longues séries (1978–2002) de données de débit et de qualité d'eau de la rivière, les flux d'azote mensuels et annuels ont été quantifiés, et leurs relations avec les conditions hydrologiques du bassin ont été étudiées. Un bilan massique entrée–sortie de l'azote total Kjeldahl (ATK) et de l'azote sous formes nitrate et nitrite ($NO_3$+$NO_2$) a été établi entre les points amont (Simmesport) et aval (Morgan City et l'exutoire du Lac Wax) afin d'examiner la capacité d'atténuation de l'azote de ce qui est le plus grand bassin marécageux d'eau douce d'Amérique du Nord. Les résultats de cette étude montrent que, sur les 25 dernières années, le Marais de la Rivière Atchafalaya s'est comporté comme une source d'azote $NO_3$+$NO_2$, avec un flux sortant moyen annuel d'azote $NO_3$+$NO_2$ (174 584 Mg) juste un peu supérieur au flux (2.3%) entrant moyen annuel d'azote $NO_3$+$NO_2$ (170 721 Mg). Le flux massique sortant d'azote $NO_3$+$NO_2$ est apparu comme supérieur pendant l'été et l'automne, indiquant un rôle actif des processus biologiques sur l'azote des eaux d'inondations de l'Atchafalaya. Cependant, ce bassin marécageux s'est comporté comme un important puits d'azote organique: les moyennes

 Copyright © 2006 IAHS Press

annuelles des flux massiques entrant et sortant d'ATK ont atteint respectivement 200 323 et 145 917 Mg $an^{-1}$, ce qui correspond à un taux d'atténuation par le bassin de 27.2%. Cette diminution importante de l'ATK s'est révélé être forte en automne et faible en fin d'été, ce qui correspond aux fluctuations des conditions hydrologiques de la rivière.

**Mots clefs** bassin du Marais Atchafalaya; Golfe du Mexique; hypoxie; nitrate; nitrite; enrichissement en nutriment; azote organique

## INTRODUCTION

A dead zone of water with dissolved oxygen less than 2 mg $L^{-1}$ has developed off the shore of Louisiana in the northern Gulf of Mexico, USA. Studies on the hypoxia have shown that an average midsummer hypoxic zone of 8000–9000 $km^2$ during 1985–1992 increased to 16 000–20 700 $km^2$ during 1993–2001 on the Louisiana/Texas continental shelf (Rabalais & Turner, 2001; Rabalais *et al*., 2002). The two-fold increase in the hypoxic zone over a relatively short period of time has been attributed to the increase in river-borne nutrients that can exacerbate coastal water eutrophication, favour harmful algal blooms, aggravate oxygen depletion and alter marine food webs (e.g. Goolsby *et al*., 1999, 2001; Rabalais *et al*., 1996, 1998, 2002). Nitrogen, especially nitrate nitrogen (Turner & Rabalais, 1991, 1994), is the most probable cause; 90% of the nitrogen input originates from the 3-million-$km^2$ Mississippi River basin, which comprises 41% of the contiguous USA (van der Leeden *et al*., 1990; Dunn, 1996). The control of this hypoxia is both ecologically and economically important because the continental shelf fishery in the Gulf of Mexico comprises approximately 25% of the USA total (Mitsch & Gosselink, 2000).

In order to reduce the frequency, duration, size and degree of oxygen depletion of the hypoxic zone of the northern Gulf of Mexico, a national action plan (http://www.epa.gov/msbasin/taskforce/pdf/actionplan.pdf) was cleared in 2001 by the state, tribal and federal agencies and delivered to the US Congress. The action plan called for a 30% nitrogen load reduction that will reduce the 5-year running average of the Gulf hypoxia zone to less than 5000 $km^2$ by 2015. Among several options that are being considered for controlling nitrogen discharge from the Mississippi-Atchafalaya River into the Gulf are: modifying agricultural practices (e.g. reduced fertilization, conservative tillage) and tertiary treatment of point sources and landscape restoration (e.g. wetland restoration and creation). Mitsch & Gosselink (2000) postulated that the approach which appears to have the highest probability of success, with a minimum impact on farming in the midwestern USA, is landscape restoration. It has been suggested that $2 \times 10^6$ ha of restored and created wetlands and about $7.7 \times 10^6$ ha of restored riparian buffers would be necessary to provide enough denitrification to substantially reduce the amount of nitrogen entering the Gulf of Mexico (Mitsch, 1999; Mitsch *et al*., 1999).

Freshwater diversion from the Lower Mississippi River into the region's wetlands has been considered as another possible means of reducing nutrient input to the Gulf of Mexico. In a recent study on riverine carbon transport, Xu & Patil (2006) found a 16% removal of total organic carbon by the Atchafalaya River Swamp basin. It is, however, largely unknown how much nitrogen can be retained from the overflowing waters in those natural wetlands. Generally, there is a knowledge gap in what tools are available for accurate assessment of nitrogen inflow, outflow and removal potential for the complex and diverse coastal flood-plain systems.

Copyright © 2006 IAHS Press

Total nitrogen is reduced in most wetland treatment systems with an average mass reduction of between 46 and 72% (Kadlec & Knight, 1996). However, the removal rate is highly variable. Based on analysis of the North American Treatment System Database (Knight *et al*., 1993; Knight, 1994), Kadlec & Knight (1996) reported an average total nitrogen mass removal rate of 1.89 kg $ha^{-1}$ $day^{-1}$ for natural surface wetlands, 3.46 kg $ha^{-1}$ $day^{-1}$ for constructed surface flow wetlands and 15.63 kg $ha^{-1}$ $day^{-1}$ for subsurface flow wetlands. These removal rates appear to be much higher than those (0.1–2.0 kg $ha^{-1}$ $day^{-1}$) reported by Nixon & Lee (1986) for natural wetlands that do not receive wastewaters. It has also been reported that some natural surface flow wetlands release nutrients rather than remove them (e.g. Devito *et al*., 1989; Soranno *et al*., 1996). Researchers have attributed nitrogen removal efficiency to a variety of factors, including watershed size (e.g. Arheimer & Wittgren, 1994), mass loading rate (e.g. Knight *et al*., 1985), water depth (e.g. Kadlec & Knight, 1996), or a combination of climate, soil characteristics and plant communities (e.g. Nixon & Lee, 1986; Kadlec & Knight, 1996).

The purpose of this study was to seek answers to three critical questions: (a) Does the Atchafalaya River Swamp remove a significant amount of nitrogen from the overflowing water, or does it release more nitrogen into the Gulf? (b) How do the nitrogen removal or release rates fluctuate seasonally and annually? (c) What are the relationships between the nitrogen removal capacity and the basin hydrological conditions, such as river stage and discharge? Answers to these questions can provide critical information for developing strategies to maximally reduce nitrogen discharge from the Mississippi River. The information is also needed to guide coastal resource planners and managers in maintaining desirable environmental conditions within the Atchafalaya basin, as well as in the coastal waters of the Gulf of Mexico.

## METHODS

### Study area

The Atchafalaya River is formed where the flow from the Red River is combined with about 30% of that of the Mississippi River, which is diverted through the Old River Control Structure into the Old River outflow channel. This system is part of a flood-control project designed to provide a diversion for extreme flooding on the Mississippi River. Hence, the excessive nutrients found in the Atchafalaya River originate from the Upper Mississippi River Basin states. The Atchafalaya basin is well defined by a system of levees that surround it on the north, east and west (Fig. 1). The 4678 $km^2$ drainage basin is predominantly wooded lowland and cypress-tupelo surface flow swamp with some freshwater marshes in the lower distributary area. It is the largest contiguous freshwater swamp in the USA. The basin area is home to a variety of wildlife, which includes more than 170 bird species, more than 40 mammalian species and more than 100 finfish and shellfish species (Demas *et al*., 2002). The major uses of the basin include recreation and crawfish harvesting.

Climate in the Atchafalaya River basin is humid, subtropical with typically mild winters, hot summers and abundant rainfall (up to over 1500 mm $year^{-1}$). Soils in the

Copyright © 2006 IAHS Press

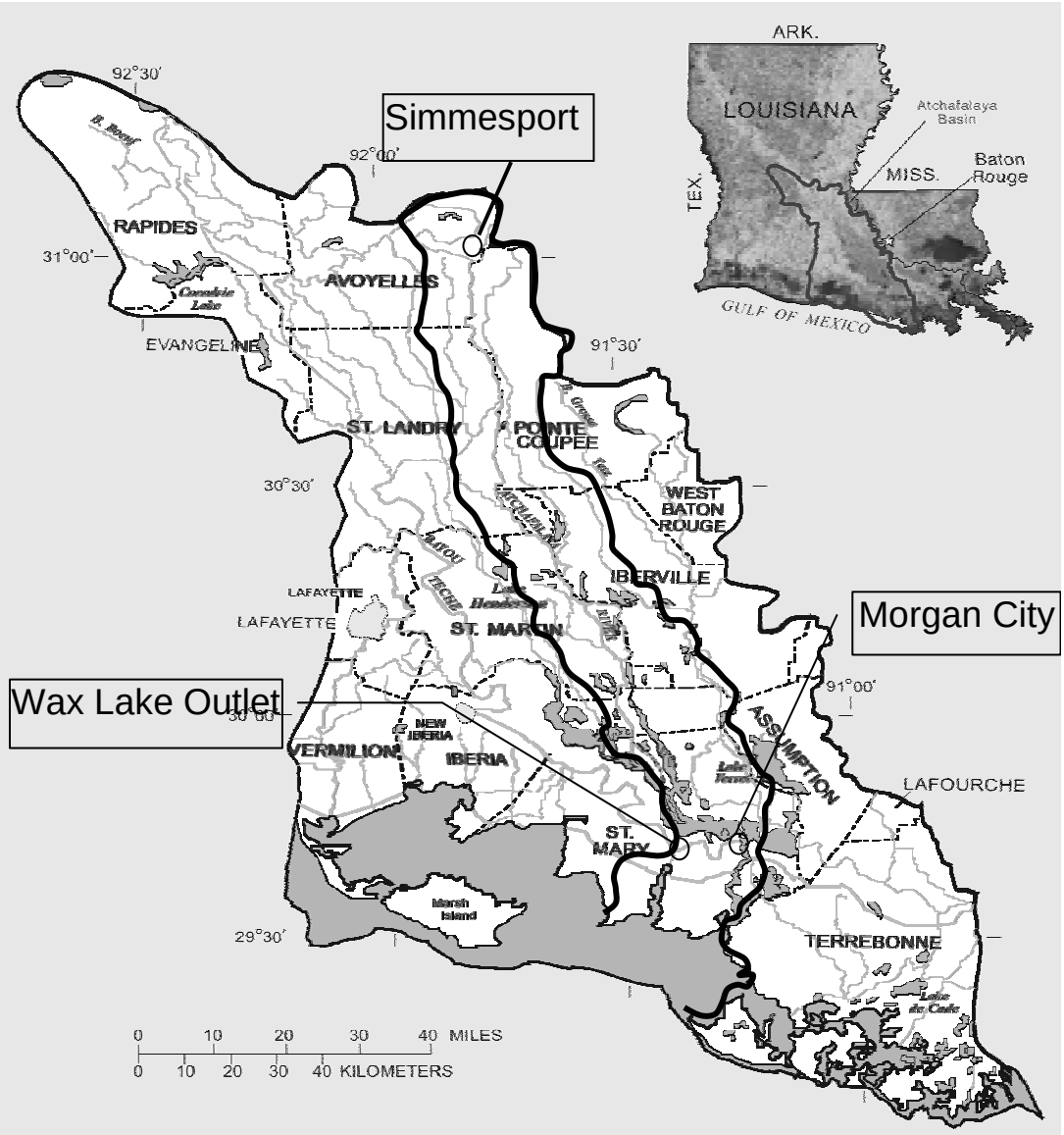


**Fig. 1** The Atchafalaya River Swamp basin in the northern Gulf of Mexico (the thick line denotes the levees on the north, east and west sides of the Atchafalaya floodway).

high and intermediate areas on the natural levees range from very fine sandy loams and silty loams, to silty clay loams (Murphy *et al*., 1977). Poorly drained loamy and clayey soils are present in the lower positions on natural levees and in back-swamps on the flood plain of the Atchafalaya River. The surface hydrology of the basin plays a vital role for the diversity, health and dynamics of the swamp ecosystems.

## Data collection

To estimate total nitrogen mass input, output and input–output budget in the Atchafalaya River Swamp basin, long-term historical data on river discharge and water quality were collected. Daily discharge data at Simmesport, Morgan City and Wax

Copyright © 2006 IAHS Press

Lake Outlet from 1978 to 2002 were obtained from the New Orleans District Office of the US Army Corps of Engineers and the Louisiana District Office of the US Geological Survey in Baton Rouge. Water quality data were obtained from the Louisiana Department of Environmental Quality. The water quality data included monthly measurements on a series of chemical and physical parameters, of which concentrations of total Kjeldahl nitrogen (TKN) and nitrate plus nitrite nitrogen ($NO_3$+$NO_2$) were used in this study. The measurements covered the period 1978–2002 at the Morgan City monitoring station, but, at the Simmesport monitoring station, data were only available for the years 1978–1990 and 2002. No water quality data were available for Wax Lake Outlet. Estimation of the nitrogen flux for the outflow used the data from Morgan City, under the assumption that there was no difference in nitrogen concentration of the overflowing waters between the two outlets.

## Estimation of nitrogen loading and inflow–outflow balance

Nitrogen fluxes were calculated by multiplying discharge with corresponding TKN and $NO_3$+$NO_2$ concentrations at the inflow (Simmesport) and outflow (Morgan City and Wax Lake Outlet) locations. Using all the available records on TKN and $NO_3$+$NO_2$ concentrations, log-linear regression functions were developed to estimate daily TKN and $NO_3$+$NO_2$ inputs and daily TKN and $NO_2$+$NO_3$ outputs, as given in equations (1)–(4), respectively:

$$\ln(S) = -12.3421 + 1.2984 \ln(Q) \quad (1)$$

$$\ln(S) = -10.4305 + 1.1223 \ln(Q) \quad (2)$$

$$\ln(S) = -14.9401 + 1.2847 \ln(Q) \quad (3)$$

$$\ln(S) = -10.8356 + 1.1402 \ln(Q) \quad (4)$$

where $S$ is daily loading (g) and $Q$ is daily discharge (L). The model parameters were determined using the SAS software package (SAS Institute, 1996), whereby use of equations (1)–(4) resulted in the following values of regression coefficients ($r^2$): 0.82 ($n$ = 146), 0.65 ($n$ = 157), 0.79 ($n$ = 229) and 0.65 ($n$ = 241), respectively.

The mass inputs and outputs estimated from the models were converted into Megagrams (1 Mg = 1 × $10^6$ g = 1 metric tonne) and were summed over time to provide monthly and annual total nitrogen (TKN and $NO_3$+$NO_2$) fluxes for the 25-year period 1978–2002. Annual nitrogen removal rates ($N_R$) were calculated by:

$$N_R = \frac{N_{\text{in}} - N_{\text{out}}}{N_{\text{in}}} \times 100 \quad (5)$$

where $N_{\text{in}}$ is total nitrogen (TKN and $NO_3$+$NO_2$) mass input in the overflowing water at Simmesport, and $N_{\text{out}}$ is total nitrogen mass output in the overflowing waters at Morgan City and Wax Lake Outlet.

A paired $t$ test was used to evaluate the significance of differences in TKN and $NO_3$+$NO_2$ concentrations between the inflowing water at Simmesport and outflowing water at Morgan City and Wax Lake Outlet. Regression analysis was used to determine relationships between nitrogen removal and the basin hydrology. All statistic analyses were performed with the SAS software (SAS Institute, 1996).

Copyright © 2006 IAHS Press

## RESULTS AND DISCUSSION

### River discharge of the Atchafalaya

From 1978 to 2002, annual discharge at Simmesport (inflow) averaged 6559 $m^3 s^{-1}$, varying from 1246 to 19 255 $m^3 s^{-1}$. Annual average discharge at Morgan City and Wax Lake Outlet (outflow) was 6228 $m^3 s^{-1}$, varying from 626 to 17 283 $m^3 s^{-1}$. The results for the Atchafalaya River basin indicate that the annual inflow was higher by $1.04 \times 10^{10}$ $m^3$ than the annual outflow. The difference, however, varied from $-1.2 \times 10^{10}$ $m^3$ to $4.4 \times 10^{10}$ $m^3$ $year^{-1}$ and appeared to be positively correlated to the annual

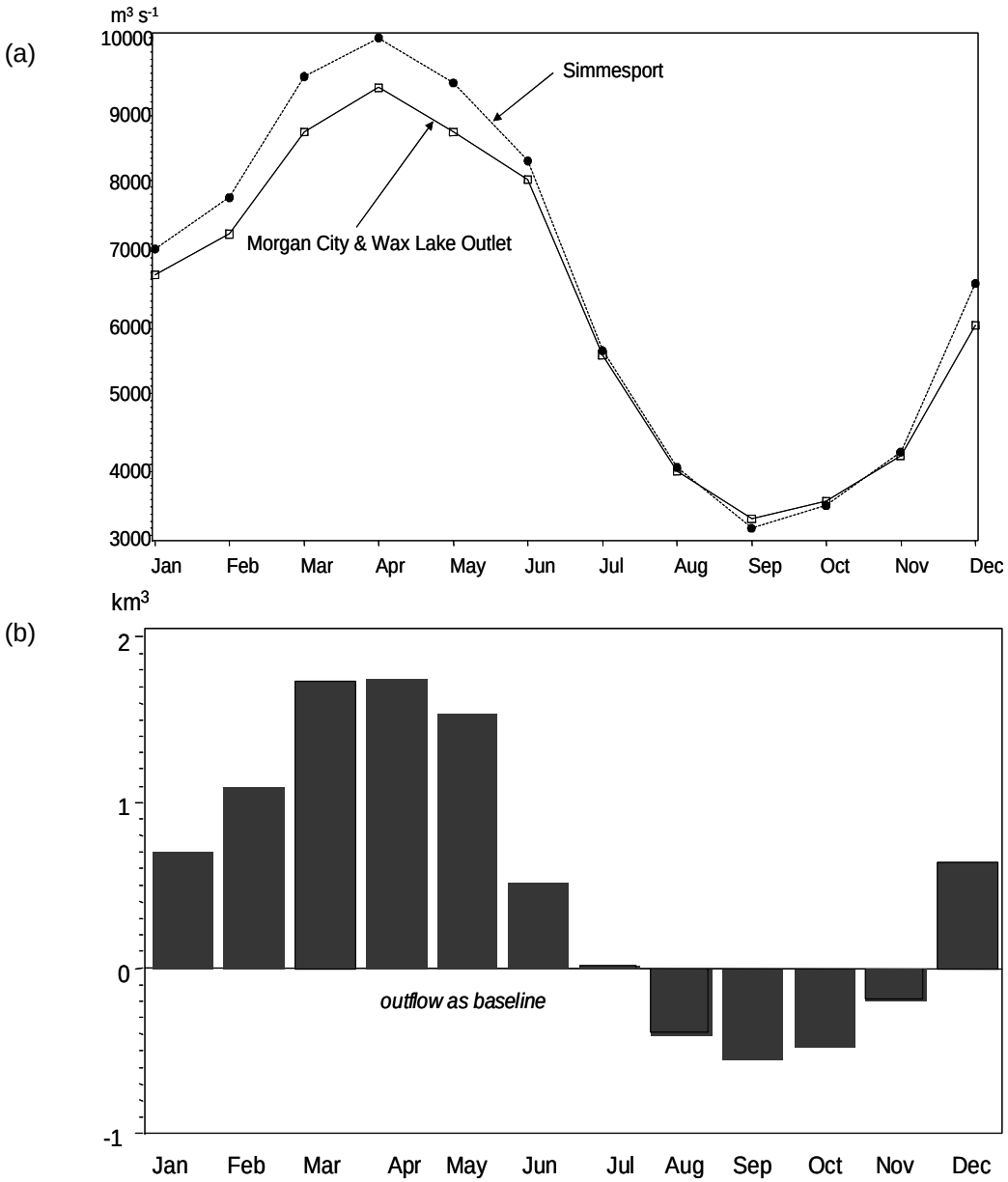


**Fig. 2** Monthly average inflow (a) at Simmesport and outflow at Morgan City and Wax Lake Outlet, and (b) the inflow–outflow budget.

Copyright © 2006 IAHS Press

inflow. Seasonally, both inflow and outflow were high from March to June and low from August to November (Fig. 2). During the wet season (December–June) the inflows were significantly higher than the outflows, suggesting that the basin served as a recharge zone from winter to late spring (Fig. 2). In the dry months from August to November, however, the outflows were higher than the inflows, indicating that the basin served as a discharge zone.

It has been widely assumed that inflow and outflow of the Atchafalaya River Swamp basin are approximately equal at any given time. The assumption has been a fundamental basis in many studies (e.g. Lambou & Hern, 1983; Sabo *et al.*, 1999; Turner, 1999) on water quality and biogeochemical processes in the basin. The findings from this study that point to the invalidity of this assumption may have important implications for the ongoing projects that are designed to maintain water resources and water quality conditions in the basin.

## Seasonality of nitrogen concentrations

The Atchafalaya showed consistently higher TKN concentrations in its inflow than that in its outflow during a year (Fig. 3). However, the $NO_3$+$NO_2$ concentrations in the water leaving the basin appeared to be higher than those in the inflowing water during three winter months (December–February) and three summer months (June–August). The TKN nitrogen concentrations in both inflow and outflow were highest in the late winter and spring, corresponding with the trend of the river discharge, while the $NO_3$+$NO_2$ concentrations showed a more or less parabolic trend over the year.

During the past 25 years, TKN concentrations in the overflowing waters at Simmesport varied from 0.31 to 2.80 mg $L^{-1}$, with an average concentration of 0.97 mg $L^{-1}$. This was significantly higher than the average TKN concentrations in the outflowing waters at Morgan City of 0.74 mg $L^{-1}$ (varying from 0.16 to 1.86 mg $L^{-1}$). The $NO_3$+$NO_2$ concentrations in the river water at Simmesport averaged 0.89 mg $L^{-1}$ (0.15–2.56 mg $L^{-1}$), which was slightly lower than the average measured at Morgan City of 0.94 mg $L^{-1}$ (0.17–2.38 mg $L^{-1}$). The monthly averages of TKN concentration were 0.81–1.23 mg $L^{-1}$ in the inflow and 0.55–0.91 mg $L^{-1}$ in the outflow waters, whereas the monthly averages of $NO_3$+$NO_2$ concentration varied between 0.63 and 1.17 mg $L^{-1}$ in the inflow and between 0.74 and 1.23 mg $L^{-1}$ in the outflow.

Nitrogen can enter streams and rivers through direct surface runoff, subsurface leaching and agricultural drains. More than $20 \times 10^6$ ha have been drained through use of subsurface tile drainage, ditches and streams in many states of the Upper Mississippi River Basin (USDA, 1987). This drainage practice can result in the leaching of large amounts of nitrate nitrogen stored in soils (Goolsby *et al.*, 1999, 2001). Soil tillage and fertilization during the late winter and spring may have been another reason for the higher TKN concentrations during these seasons. In a simulation study on the impact of agricultural practices on the doubled nitrogen export from the Upper Mississippi River Basin since the 1960s, Donner *et al*. (2004a) found three most critical factors: (a) an increase in fertilizer application, (b) an increase in runoff across the basin, and (c) the expansion of soybean cultivation. In this present study, the decrease of TKN concentrations from the spring towards the summer and autumn may have exposed the direct influence of the runoff from the Upper Mississippi River Basin

Copyright © 2006 IAHS Press

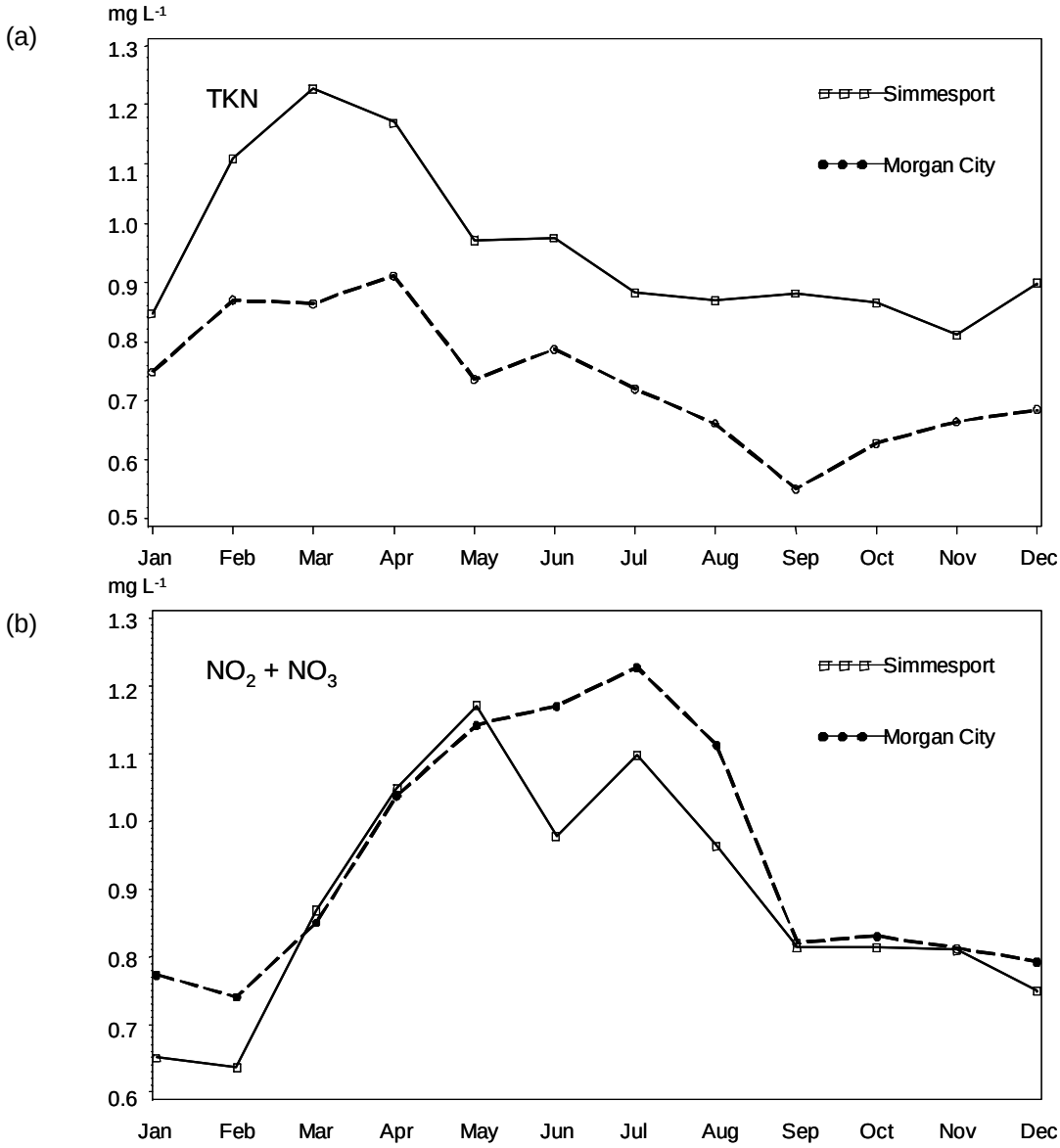


**Fig. 3** (a) Long-term averages of total Kjeldahl nitrogen and (b) nitrate + nitrite nitrogen concentrations in the overflowing waters at Simmesport and Morgan City.

to organic nitrogen fluxes. On the other hand, the concentrations of nitrate and nitrite nitrogen in the Atchafalaya River appeared to follow the seasonal trend of temperature (Fig. 3), which clearly indicates biological effects on riverine nitrogen transformation in the river swamp basin.

## Nitrogen mass inflow, outflow and removal rates

From 1978 to 2002, on average, a total amount of 371 044 Mg nitrogen entered into the Atchafalaya River Swamp basin annually, of which 170 721 Mg (or 46%) was nitrate and nitrite nitrogen (Table 1). The average annual nitrogen output leaving the basin was 320 500 Mg, of which 174 584 Mg (or 54%) was nitrate and nitrite nitrogen.

Copyright © 2006 IAHS Press

**Table 1** Annual nitrogen mass input–output budget for the Atchafalya River Swamp basin.

| Nitrogen species | Input (Mg year$^{-1}$) | Output (Mg year$^{-1}$) | Change (%) (Mg year$^{-1}$) |
|---|---|---|---|
| $NO_3$+ $NO_2$ | 170 721 | 174 584 | –3 863 (–2.3) |
| TKN | 200 323 | 145 917 | 54 406 (27.2) |
| Total | 371 044 | 320 500 | 50 544 (13.6) |

The mass input–output budget of total nitrogen represents a 50 544 Mg (or 13.6%) nitrogen reduction in the basin, while the input–output budget of nitrate + nitrite nitrogen shows a 3863 Mg (or 2.3%) nitrogen increase leaving the basin.

During the 25-year study period, a total of $5 \times 10^6$ Mg of Kjeldahl nitrogen entered into the Atchfalaya River Swamp basin, whereas a total of $3.6 \times 10^6$ Mg of Kjeldahl nitrogen discharged from the basin into the Gulf of Mexico, resulting in an average removal of 27%. The removal rates were high during the winter and spring and low during the summer and autumn (Fig. 4), corresponding with the basin hydrological conditions (Fig. 2). During the same 25-year period, a total of $4.3 \times 10^6$ Mg of nitrate and nitrite nitrogen entered into the basin, whereas a total of $4.4 \times 10^6$ Mg of nitrate and nitrite left the basin. The difference between the input and output of nitrate and nitrite nitrogen was found mainly during the five summer months (June–October) (Fig. 4) when the river flow was low (Fig. 2) and water temperature was high.

Riverine nitrogen can undergo a series of transformations during flooding. It can be retained by river and wetland systems through filtration, sedimentation, chemical absorption, microbial interactions and uptake by vegetation (Watson *et al*., 1989). In the Atchafalaya, all of these processes may have occurred simultaneously in the past, because it is a large river system with flood plains, backwater swamps and bottomland hardwood ecosystems. A recent study by Donner *et al.* (2004b) showed that benthic denitrification may play a significant role in nitrogen removal of the Mississippi River. From another recent study on sediment inflow and outflow (1978–2002) in the Atchafalaya, Xu (2004) reported a 20-million-t year$^{-1}$ deposition of solids in the basin. The high removal rate of organic nitrogen (TKN) found in this study may have resulted from both denitrification and sedimentation processes in this large river swamp basin.

Many wetlands along the Atchafalaya are backwater cypress-tupelo swamps. Hydrologically, these swamps serve as a retention basin when the water level in the channel rises, but when the water level falls they become a discharge area. Biogeochemically, the swamps are active ecosystems in nitrogen cycling. The findings from this study that the mass output of nitrate and nitrite nitrogen was higher than their mass input during the summer and autumn months indicates the complexity of biological and hydrometeorological impacts on nitrogen transformation and nitrate plus nitrite discharge from this swamp basin.

## Relationship between nitrogen removal and river discharge

Both monthly and annual Kjeldahl nitrogen mass removals in the Atchafalaya River Swamp basin were closely correlated with the river inflow at Simmesport. About 78% of the variation in annual TKN removal (Fig. 5) and about 83% of the variation in monthly removal (data not shown) could be explained by the amount of inflow in a

Copyright © 2006 IAHS Press

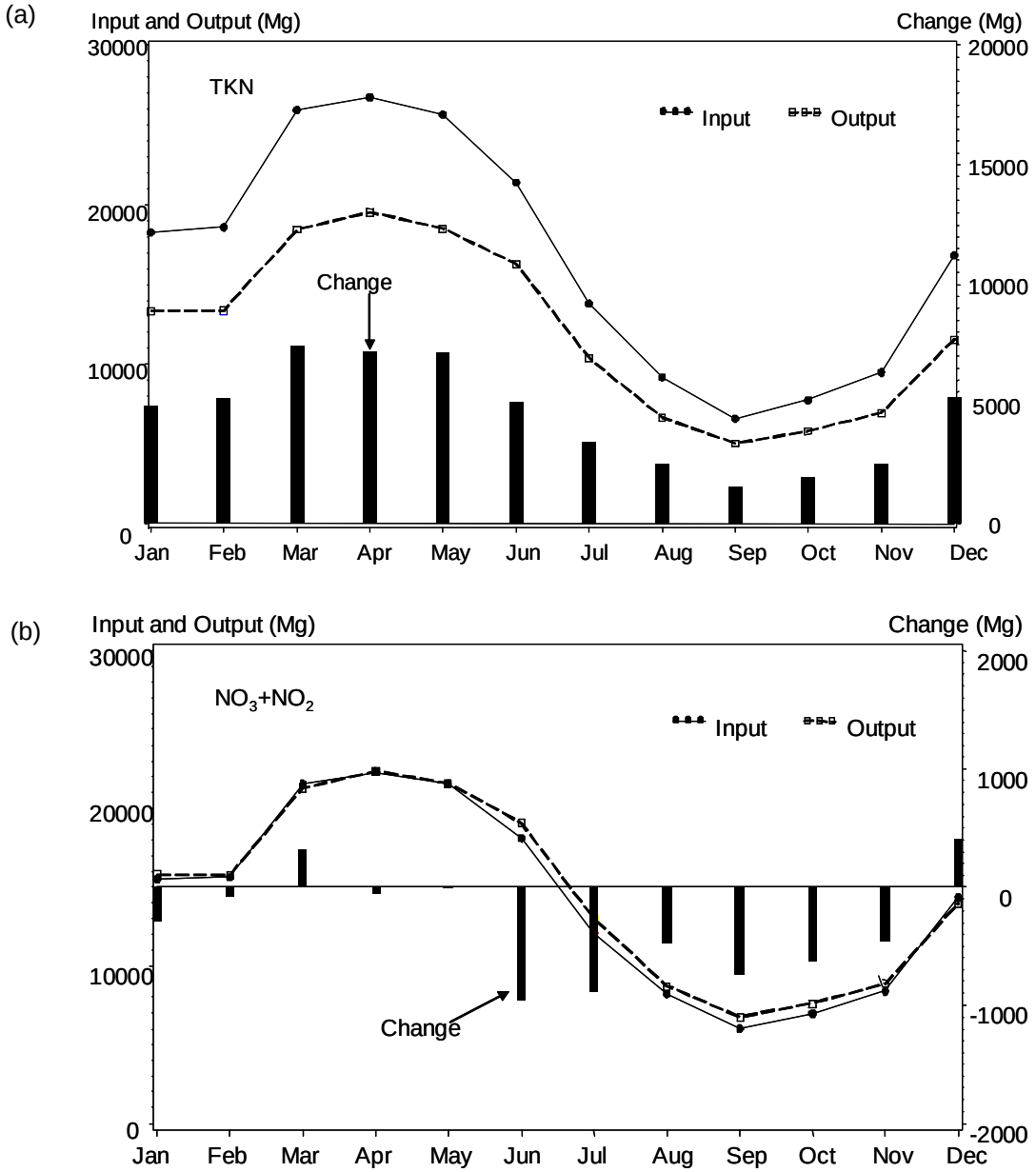


**Fig. 4** (a) Long-term averages of monthly total Kjeldahl nitrogen and (b) nitrate + nitrite nitrogen inputs, outputs and input–output budgets.

linear regression function. In the annual relationship, an inflow threshold value of $2.3 \times 10^{-11}$ $m^3$ appeared, from which the increase of TKN nitrogen mass removal was higher with increasing river inflow.

Unlike with TKN, changes in annual mass input–output balance of nitrate and nitrite nitrogen were not related to the basin discharge (Fig. 5). The lack of relationship indicates that riverine nitrogen within the Atchafalaya may undergo a considerable variability in residence time. A thorough study on spatial hydrological conditions in the basin is needed to better understand nitrogen dynamics in this large river swamp basin.

Copyright © 2006 IAHS Press

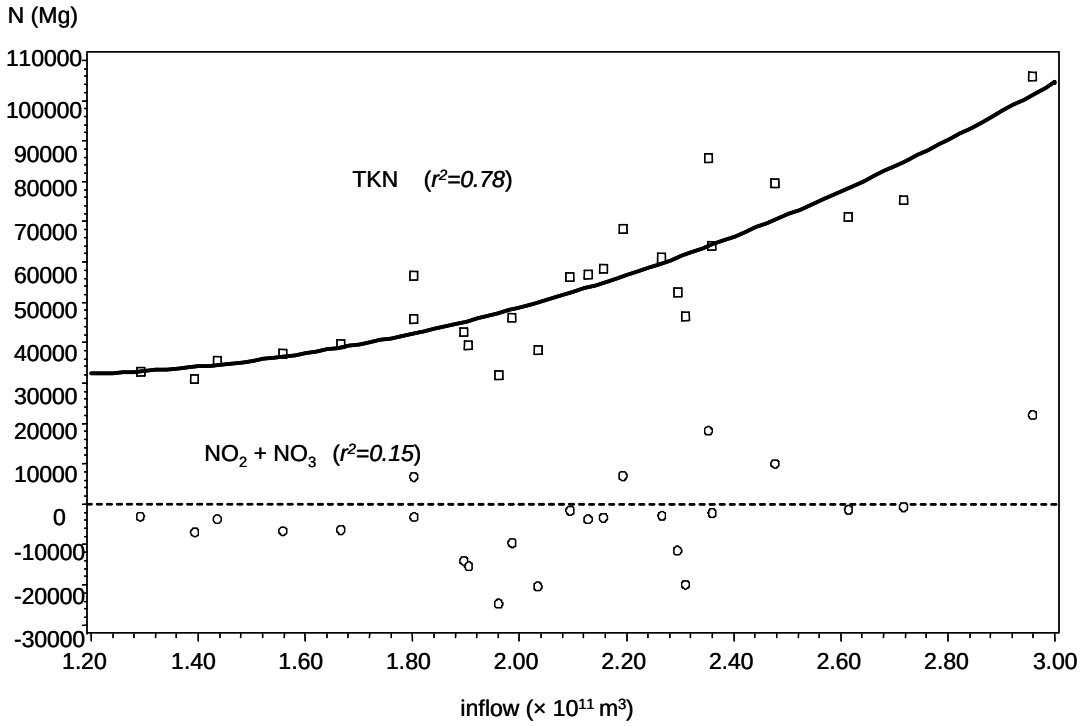


**Fig. 5** Nitrogen input–output mass balance as a function of the basin's inflow.

## CONCLUSIONS

Over the past 25 years, the Atchafalaya River Swamp basin as a whole acted as a significant sink for organic nitrogen. The removal rate of the riverine organic nitrogen was closely related to the basin hydrological conditions: the higher the river inflow, the more organic nitrogen was removed from the overflowing water. However, this large swamp basin showed a 2.3% higher mass output than input of nitrate and nitrite nitrogen. The negative input–output balance occurred throughout the summer and autumn months, when the river flow was normally low and the water temperature high, indicating biotic effects on riverine nitrogen transformation in the large swamp basin. In total, the basin retained nearly 14% of the nitrogen inflow, suggesting that previous studies may have overestimated nitrogen discharge from the Mississippi-Atchafalaya River system. Furthermore, this study challenged the widely-held assumption that the river inflow at the upper-basin location (Simmesport) is equal to the river discharge from the two basin outlets (Morgan City and Wax Lake Outlet).

**Acknowledgements** The author would like to acknowledge funding support by the Louisiana Board of Regents/National Science Foundation Pilot Fund Program (Contract: NSF/LEQSF2005-Pfund-12). The long-term river discharge and water quality data were made available by the Louisiana District of the US Geological Survey and the Louisiana Department of Environmental Quality.

## REFERENCES

Arheimer, B. & Wittgren, H. B. (1994) Modelling the effects of wetlands on regional nitrogen transport. *Ambio* **23**(6), 378–386.

Copyright © 2006 IAHS Press

Demas, C. R., Brazelton, S. R. & Powell, N. J. (2002) The Atchafalaya Basin—river of trees. *US Geol. Survey Fact Sheet FS–021-02.*

Devito, K. J., Dillon, P. J. & Lazerte, B. D. (1989) Phosphorus and nitrogen retention in five Precambrian shield wetlands. *Biogeochem.* **8**(3), 185–204.

Donner, S. D., Kucharik, C. J. & Foley, J. A. (2004a) Impact of changing land use practices on nitrate export by the Mississippi River. *Global Biogeochemical Cycles* **18**(1) Art. no. GB1028, doi:10.1029/2003GB002093.

Donner, S. D., Kucharik, C. J. & Oppenheimer, M. (2004b) The influence of climate on in-stream removal of nitrogen. *Geophys. Res. Lett.* **31**(20), Art. no. L20509, doi:10.1029/2004GL020477.

Dunn, D. D. (1996) Trends in nutrient inflows to the Gulf of Mexico from streams draining the conterminous United States, 1972–93. *US Geol. Survey Water Resour. Invest. Report 96–4113*.

Goolsby, D. A., Battaglin, W. A., Lawrence, G. B., Artz, R. S., Aulenbach, B. T. & Hooper, R. P. (1999) Flux and sources of nutrients in the Mississippi–Atchafalaya basin: Topic 3. Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico. Decision Analysis Series no. 17, NOAA Coastal Ocean Office, Silver Spring, Maryland, USA.

Goolsby, D. A., Battaglin, W. A., Aulenbach, B. T. & Hooper, R. P. (2001) Nitrogen input to the Gulf of Mexico. *J. Environ. Qual.* **30**(2), 329–336.

Kadlec, R. H. & Knight, R. L. (1996) *Treatment Wetlands*. Lewis Publishers, New York, USA.

Knight, D. H., Fahey, T. J. & Running, S. W. (1985) Water and nutrient outflow from contrasting lodgepole pine forests in Wyoming. *Ecol. Monogr.* **55**(1), 29–48.

Knight, R. L. (1994) Treatment wetlands database now available. *Water Environ. Technol.* **6**(2), 31–33.

Knight, R. L., Ruble, R. W., Kadlec, R. H. & Reed, S. C. (1993) Database: North American wetlands for water quality treatment. Phase II Report, US Environ. Protection Agency.

Lambou, V. W. & Hern, S. C. (1983) Transport of organic-carbon in the Atchafalaya Basin, Louisiana. *Hydrobiologia* **98**(1), 25–34.

Mitsch, W. J. (1999) Hypoxia solution through wetland restoration in America's breadbasket. *National Wetlands Newsletter* **21**(6), 9–10, 14.

Mitsch, W. J. & Gosselink, J. G. (2000) *Wetlands* (third edn). John Wiley & Sons, Inc., New York, USA.

Mitsch, W. J., Day, J. W., Jr, Gilliam, J. W., Groffman, P. M., Hey, D. L., Randall, G. W. & Wang, N. (1999) Reducing nutrient loads, especially nitrate-nitrogen, to surface water, ground water, and the Gulf of Mexico—Topic 5 Report for the Integrated Assessment on Hypoxia in the Gulf of Mexico. US Dept of Commerce, National Oceanic and Atmospheric Administration (NOAA). Decision Analysis Series no. 19, NOAA Coastal Ocean Program, Silver Spring, Maryland, USA.

Murphy, K. E., Touchet, B. A., White, A. G., Daigle, J. J. & Clark, H. L. (1977) Soil survey of St Martin Parish, Louisiana. US Dept of Agriculture Soil Conservation Service, Washington DC, USA.

Nixon, S. W. & Lee, V. (1986) Wetlands and water quality: a regional review of recent research in the United States on the role of freshwater and saltwater wetlands as sources, sinks, and transformers of nitrogen, phosphorus, and various heavy metals. Technical Report Y-86-2, US Army Engng Waterways Experiment Station, Vicksburg, Mississippi, USA.

Rabalais, N. N. & Turner, R. E. (eds) (2001) *Coastal Hypoxia: Consequences for Living Resources and Ecosystems.* Coastal and Estuarine Studies 58, American Geophysical Union, Washington DC, USA.

Rabalais, N. N., Turner, R. E., Justic, D., Dortch, Q., Wiseman, W. J., Jr & Sen Gupta, B. K. (1996) Nutrient changes in the Mississippi River, and system responses on the adjacent continental shelf. *Estuaries* **19**(2b), 386–407.

Rabalais, N. N., Turner, R. E., Wiseman, W. J., Jr & Dortch, Q. (1998) Consequences of the 1993 Mississippi River Flood in the Gulf of Mexico. *Regulated Rivers: Res. Manage.* **14**(2), 161–177.

Rabalais, N. N., Turner, R. E. & Scavia, D. (2002) Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi river. *BioScience* **52**(2), 129–142.

Sabo, M. J., Bryan, C. F., Kelso, W. E. & Rutherford, A. (1999) Hydrology and aquatic habitat characteristics of a riverine swamp: I. Influence of flow on water temperature and chemistry. *Regulated Rivers: Res. Manage.* **15**(6), 505–523.

SAS Institute (1996) *SAS/STAT User's Guide, Version 6.12* (fourth edn). SAS Institute Inc., Cary, North Carolina, USA.

Soranno, P. A., Hubler, S. L., Carpenter, S. R. & Lathrop, R. C. (1996) Phosphorus loads to surface waters: a simple model to account for spatial pattern of land use. *Ecol. Applic.* **6**(3), 865–878.

Turner, R. E. (1999) Nitrogen losses in water flowing through Louisiana swamps. In: *Natural System Function and Response to Human Influence* (ed. by L. P. Rozas, J. A. Nyman, C. E. Proffitt, N. N. Rabalais, D. J. Reed & R. E. Turner ), 145–154. Louisiana Sea Grant College Program, Baton Rouge, Louisiana, USA.

Turner, R. E. & Rabalais, N. N. (1991) Changes in Mississippi River water quality this century. *Bioscience* **41**(3), 140–147.

Turner, R. E. & Rabalais, N. N. (1994) Coastal eutrophication near the Mississippi River Delta. *Nature* **368**(6472), 619–621.

USDA (1987) Farm drainage in the United States: history, status, and prospects. Economic Res. Serv. Misc. Publ. no. 1455. USDA, Washington DC, USA.

van der Leeden, F., Troise, F. L. & Dodd, D. K. (1990) *The Water Encyclopedia*. Lewis Publishers, Chelsea, Michigan, USA.

Watson, J. T., Reed, S. C., Kadlec, R. H., Knight, R. L. & Whitehouse, A. E. (1989) Performance expectations and loading rates for constructed wetlands. In: *Constructed Wetlands for Wastewater Treatment* (ed. by D. A. Hammer), 319–351. Lewis Publishers, Chelsea, Michigan, USA.

Xu, Y. J. (2004) Surface water and sediment inflow and outflow for the Atchafalaya River Basin. In: *Proc. 2004 AWRA Annual Conf.* (ed. by S. J. Nix). CD-ROM, AWRA, Middleburg, Virginia, USA.

Xu, Y. J. & Patil, A. (2006) Organic carbon fluxes from the Atchafalaya River into the Gulf of Mexico. In: *Coastal Environment and Water Quality* (ed. by Y. J. Xu & V. P. Singh), 217–226. Water Resources Publications, LLC, Highlands Ranch, Colorado, USA.

**Received 16 January 2005; accepted 1 March 2006**

Copyright © 2006 IAHS Press