ERDC TN-SWWRP-06-1
February 2006

Effect of Residence Time on Net Nitrate Retention in Flow-Regulated Backwaters of the Upper Mississippi River

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PURPOSE: This research investigated relationships between water residence time and net nitrate retention (i.e., loading minus discharge) in flow-controlled backwater systems of the Upper Mississippi River (UMR). Goals were to gain a better understanding of the management potential for removing nitrogen in large river systems by increasing connectivity between nitrogen-rich main channel areas and backwater habitats.

BACKGROUND: Nitrogen (N) runoff to receiving streams and rivers, particularly in the form of nitrate-nitrite (NO_3NO_2-N), has increased several-fold in recent decades (Justic et al. 1995, Vitousek et al. 1997, Goolsby and Battaglin 2001). A consequence of accelerated N mobilization and transport has been water quality degradation of coastal areas and estuaries which are sensitive to N inputs (Nixon 1995). For instance, increased N loading from the Mississippi River basin has been associated with the development of extensive areas of anoxia and hypoxia (Rabalais et al. 1994) and declines in fish and invertebrate abundance (Pavela et al. 1983) in the Gulf of Mexico. Continued unchecked N loading to coastal systems could lead to significant declines in the diversity and abundance of higher trophic levels and increased bloom frequency of noxious and toxic algae (Vitousek et al. 1997).

In addition to managing NO_3NO_2-N runoff input to large river systems (i.e., watershed N source and transport control, wetland detention, riparian buffers, restored bottomland hardwood floodplains), there is a need to promote in-stream removal of NO_3NO_2-N by biological uptake, bacterial denitrification, and burial in order to reduce N transport to coastal systems (Mitsch et al. 2001). In-stream N transformation and removal do occur in large rivers, but are typically low and represent a small percentage of the overall load (5 to 20 percent, Seitzinger 1988). Shallow backwaters of large river systems can support abundant submersed and emergent macrophyte growth with attached microbial communities and accrete anaerobic organic sediments that provide suitable habitat for bacterial denitrification (Richardson et al. 2004). Rehabilitation and management of these aquatic habitats to encourage greater in-stream NO_3NO_2-N retention might be a viable strategy for improving processing of NO_3NO_2-N loads and needs to be considered in integrated basin management of NO_3NO_2-N.

Although backwaters account for greater than 30 percent of the surface area of the Upper Mississippi River, many of these systems have become isolated from main channel flows and delivery of associated N loads due to regulated pool elevation and dampened hydrological flooding cycles that impede natural water exchange (Richardson et al. 2004). Recent research has demonstrated that diverting river water through coastal wetland complexes is an effective means of reducing nutrient concentrations before discharge into coastal waterways (Lane et al. 2004). Additional NO_3NO_2-N retention and removal in large river systems may be achieved by reconnecting to backwater areas via culverts, dike diversion, and creation of channels to increase the rate of NO_3NO_2-N delivery for processing. However, information is needed regarding NO_3NO_2-N retention efficiency of backwaters in relation to loading and water residence time in order to maximize retention potential by connection to main channel loads. For engineered and natural wetland systems, water residence time has been shown to be an important factor in nutrient processing efficiency (Kadlec 1994). It should also play an important role in backwater systems. Objectives of this study were to examine NO_3NO_2-N retention capacity and efficiency in a series of flow-controlled backwater lakes that are connected to the Upper Mississippi River via flow-controlled culverts.

STUDY SITE: The Finger Lakes backwater system (Clear, Lower Peterson, Schmokers, Third, Second, and First Lakes) is located in navigation pool 5, immediately downstream of the Lock and Dam 4 dike on the Upper Mississippi River (Figure 1). In 1965, a 1.2-m-diam culvert was installed through the dike to allow discharge from navigation pool 4 into Lower Peterson Lake (Johnson et al. 1998). Concerns over lack of water exchanges and poor dissolved oxygen conditions during winter periods led to the installation of additional culverts in 1994 to supply flow to Clear, Third, Second, and First Lakes, which abut the dike. Each culvert system was fitted with adjustable vertical slide gates to control flows within a range of zero to 1.4 $m^3 \cdot s^{-1}$, depending on culvert size. Culvert engineering design was based on the need to provide low flows (0.02 to 0.14 $m^3 \cdot s^{-1}$) to the lakes in order to optimize dissolved oxygen and temperature conditions for overwintering centrarchid fish (Johnson et al. 1998). Clear, Lower Peterson, and

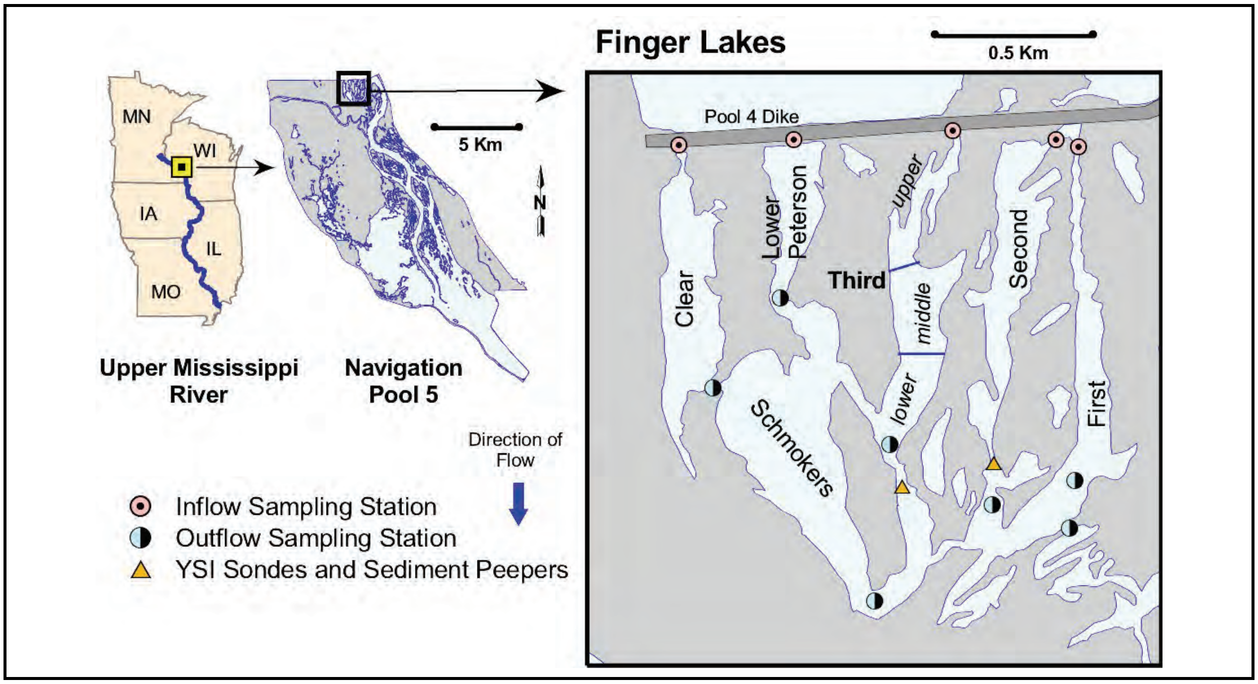

Figure 1. Map of the Finger Lakes backwater system showing station inflow and outflow sampling locations

Third Lakes receive controlled flows via individual gated culverts. First and Second Lakes receive controlled flows from a common culvert fitted with a junction box. Second Lake generally receives much lower flow than First Lake due to the configuration of the junction box.

The lakes are very shallow, eutrophic (chlorophyll = 55 $mg \cdot m^{-3}$; total P = 0.082 $mg \cdot L^{-1}$; soluble reactive P = 0.041$mg \cdot L^{-1}$) and nitrogen species entering the lakes are dominated by nitrate-nitrite-N (total N = 3.53 $mg \cdot L^{-1}$; NO_3NO_2-N = 2.56 $mg \cdot L^{-1}$). Dense stands of submersed and emergent aquatic plants occur in Lower Peterson, Third, Second, and First Lakes and occupy a large portion of the lakes' surface areas. In particular, dense stands of American lotus (*Nelumbo lutea*) occur over nearly 100 percent of the embayments located immediately south of the main basins of Second and Third Lakes. In contrast, Clear and Schmokers Lakes exhibit less macrophyte coverage per unit surface area. Other dominant macrophyte species include *Ceratophyllum demersum*, *Myriophyllum spicatum*, and *Nymphaea odorata*.

METHODS: In late April 2004, vertical slide gates were adjusted to allow flows of ~ 0.75 $m^3 \cdot s^{-1}$ to discharge into each of the five lakes (i.e., ~50 percent of full flow capacity). This culvert discharge flow target was maintained throughout most of the summer of 2004 (May through September) for Clear, Lower Peterson, and First Lakes. However, mean culvert discharges into Second and Third Lakes were significantly lower than the target (see results). Balanced flows between First and Second Lakes were difficult to obtain due to the design of the junction box. Thus, First Lake received greater flow than Second. Debris trapped in the grate protecting the intake structure may have been responsible for diminished flows discharging into Third Lake.

Sampling stations were established at the culvert inflows and at various outflow points for all of the lakes (Figure 1). Biweekly sampling was conducted between May and September 2004. Water depths at the outflow stations were less than 0.4 m at nominal pool elevation. Culvert flows were measured using a Flo-Mate Model 2000 velocity meter (Marsh-McBirney Inc., Fredrick, MD). Flows were not directly measured at the outflow stations and thus were assumed to be equal to the culvert inflows. Surface water grab samples collected at each station were filtered through a 0.45-μm membrane filter in the field and preserved on ice until analysis. Chemical analysis of NO_3NO_2-N was performed on a Lachat QuikChem A/E using standard procedures (American Public Health Association (APHA) 1998).

Information on daily navigation pool 4 and 5 stage elevations and tailwater flows and elevations for Lock and Dam 4 were obtained from the U.S. Army Engineer District, St. Paul (St. Paul, Minnesota). Stage elevation was monitored on the Third Lake at 15-min intervals between late June and September 2004, using a data logging system equipped with a pressure transducer (ISCO Model 4120; Teledyne ISCO, Inc., Lincoln, NE). Theoretical water residence time for each lake was calculated as volume divided by mean culvert flow (days). NO_3NO_2-N discharges from navigation pool 4 were estimated using concentration information collected as part of another study from Upper Peterson Lake near its discharge into First Lake.

For inflow-outflow budgetary analysis, culvert loading was calculated as the product of flow and concentration. Outflow constituent discharge was estimated as the product of culvert flow (i.e., culvert inflow ~ water discharge from the lake) and concentration measured at the outflow station. Groundwater influx and dike seepage to the system were not measured and these possible fluxes were not included in mass balance determinations. Net retention of NO_3NO_2-N culvert loads was calculated as inflow load minus outflow discharge. Retention is defined as the net retention and/or loss of NO_3NO_2-N as a result of bacterial denitrification, adsorption, uptake by phytoplankton, deposition, and uptake by microbial communities attached to submersed macrophytes. Net NO_3NO_2-N retention efficiency (R, %) was calculated as:

$$R = \left(\frac{(Load - Discharge)}{Load} \right) \bullet 100 \tag{1}$$

and does not include internally derived NO_3NO_2-N loads via nitrification. Inflow-outflow budgetary analysis was examined for Clear, Lower Peterson, Third, and First Lakes; Second and Schmokers Lakes were not included in the analysis. The outflow location of the former lake was not accessible due to a shallow water column and dense *N. odorata* beds. Flows into Schmokers Lake could not be directly measured because it was not connected to the lock and dam 4 dike by a culvert. Means in loading, discharge, and retention were estimated over the summer period of nominal pool elevation (i.e., May and late June through September; see below).

Table 1
Morphological Characteristics at Nominal Pool Elevation (201.65 m MSL)

Lake	Mean Depth (m)	Surface area (m^2)	Volume (m^3)	SA:Volume
Clear	0.8	108381	86705	1.25
Lower Peterson	1.2	74759	89711	0.83
Third	0.6	112477	67486	1.67
Second	0.3	126921	38076	3.33
First	0.6	94806	56884	1.67

RESULTS AND DISCUSSION: During most of May and between late June and October, water income to the Finger Lakes system was via culvert inflows (Figure 2). During late May through late June, flows and tailwater elevations increased on the Mississippi River due to storm-related runoff, causing flooding of the Finger Lakes. NO_3NO_2-N concentrations entering the Finger Lakes system from the Mississippi River fluctuated as a result of storm-related flows (Figure 2). The concentration was less than 0.5 $mg \cdot L^{-1}$ in early May and increased substantially in late June and, to a lesser extent, in late July and late September in conjunction with storm-related peaks in Mississippi River flow. As flows subsided in late July through August, NO_3NO_2-N declined in concentration to a minimum in early September.

During periods of nominal pool elevation (i.e., May and late June through September), NO_3NO_2-N loadings to individual lakes were regulated by culvert flow over the summer, as the Mississippi River source water and, thus, mean NO_3NO_2-N concentrations were similar for the five lakes (Figure 3a). The grand mean NO_3NO_2-N concentration of Mississippi River source water over the summer period was 2.51 $mg \cdot L^{-1}$ (± 0.05 S.E.). Mean summer flow was lowest for Third Lake and higher for Clear, Lower Peterson, and First Lakes (Figure 3b). Third Lake exhibited the greatest mean water residence time (1.6 days ± 0.1 S.E.) due to intermediate flows in relation to the volume of the lake. Clear and Lower Peterson Lakes, which exhibited similar volume and flow, had nearly identical mean water residence times (1.1 days ± 0.1 S.E.). First Lake had the lowest mean water residence time. Thus, lakes with greater culvert flows received greater NO_3NO_2-N culvert loading but these loads resided in the lake for a shorter period of time (Figure 4). Conversely, lower culvert flows were associated with less NO_3NO_2-N culvert loading but a greater water residence time for that load to be processed in the lake.

Mean NO_3NO_2-N discharge and net retention also varied as a result of differences in flow and residence time characteristics between the lakes (Table 2). Although First Lake received the greatest NO_3NO_2-N culvert loading, it retained very little and had the lowest mean net retention efficiency of all the lakes. Third, Clear, and Lower Peterson Lakes had higher mean net NO_3NO_2-N retention rates relative to First Lake. Overall, Third Lake exhibited both the highest mean net NO_3NO_2-N retention rate and a mean net retention efficiency of approximately 42 percent versus Clear and Lower Peterson, which exhibited intermediate retention efficiencies.

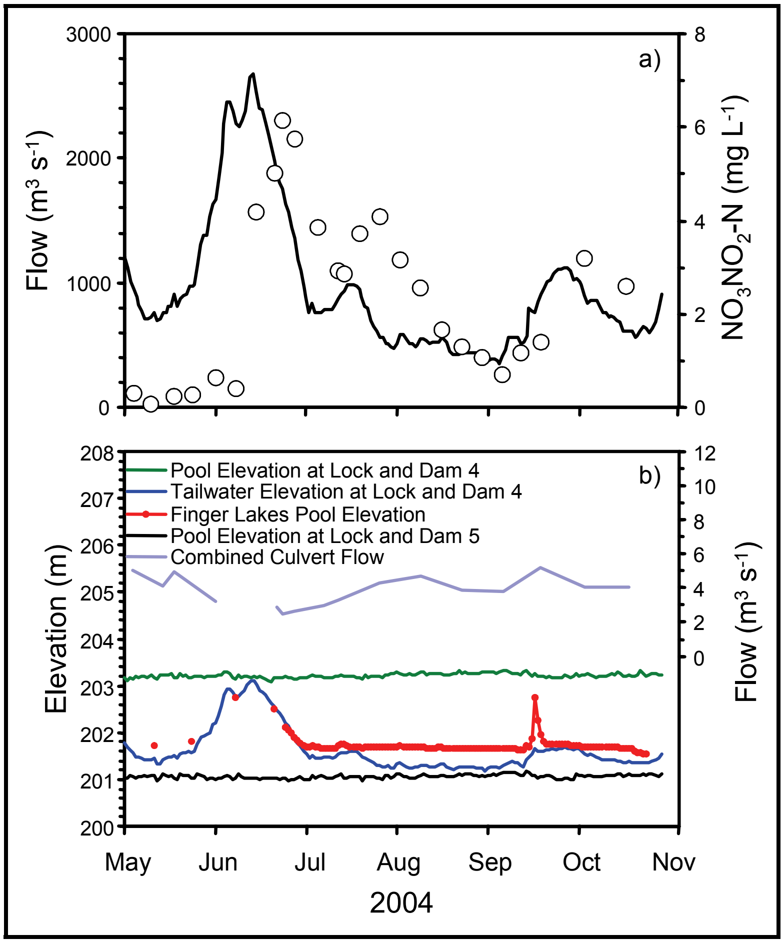

Figure 2. Seasonal variations in (a) flow and nitrate-nitrite-N (NO_3NO_2-N) concentration of the Mississippi River at Lock and Dam 4, and (b) pool elevation and combined culvert flow into the Finger Lakes

Regression analysis of NO_3NO_2-N culvert loading versus net retention indicated that at equivalent NO_3NO_2-N loading levels (range = 0 to 400 kg·d^{-1}), Third Lake exhibited the greatest net NO_3NO_2-N retention rates followed by Clear Lake (Figure 5a). Lower Peterson and First Lakes exhibited the lowest net NO_3NO_2-N retention rates at equivalent loading rates. Net NO_3NO_2-N retention efficiencies followed a negative logarithmic pattern and a similar trend to that of net NO_3NO_2-N retention rates was observed among lakes (Figure 5b). Overall, maxima in mean net retention mass and mean retention efficiency of NO_3NO_2-N culvert loads occurred in conjunction with a mean water residence time of 1.6 days (i.e., Third Lake).

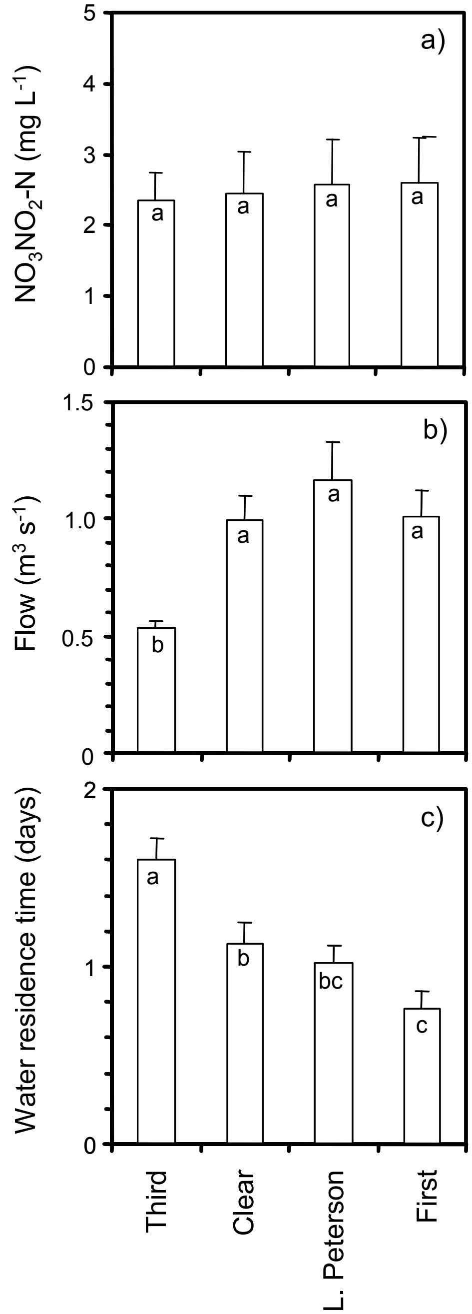

Figure 3. Mean summer (a) nitrate-nitrite-N (NO_3NO_2-N) concentration, (b), culvert flow, and (c) water residence time for various backwater lakes. Vertical lines represent 1 standard error. Letters represent significant differences in the mean at the 5-percent level or less (ANOVA; Statistical Analysis System (SAS) 1994)

One unknown is the maximum possible NO_3NO_2-N retention capacity that can be realistically expected and achieved for backwater systems that are connected to large rivers (e.g., Finger Lakes). NO_3NO_2-N retention can be quite high for wetland complexes and freshwater diversion structures on large river systems (range of 30 to near 100 percent; Phipps and Crumpton 1994,

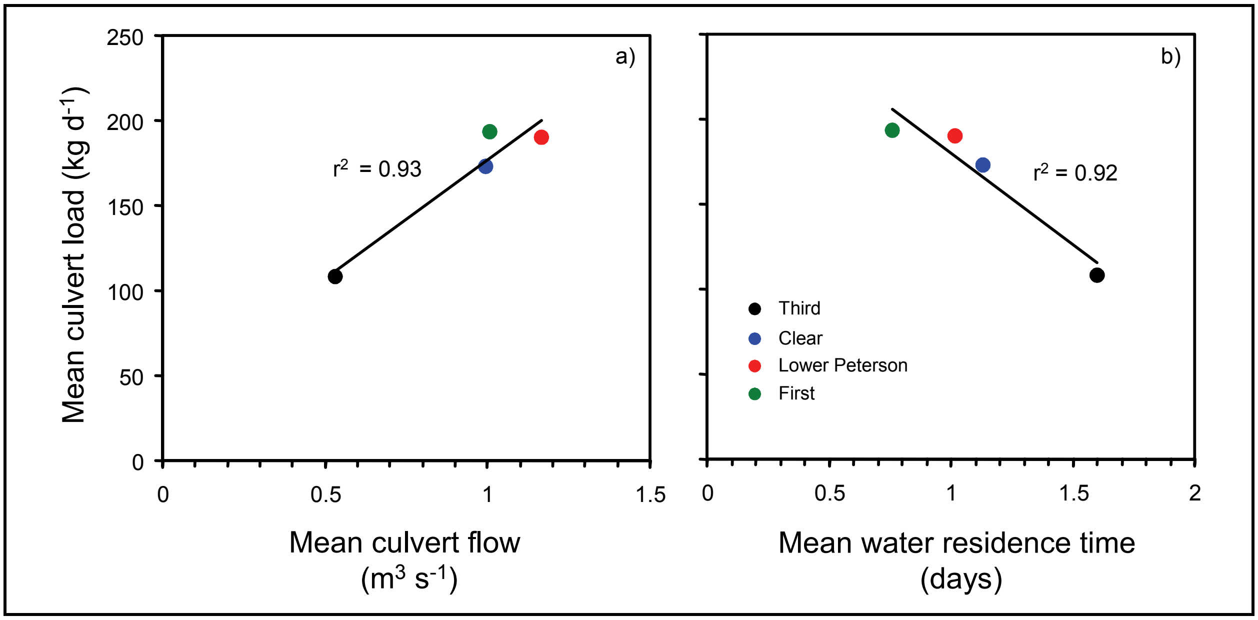

Figure 4. Linear relationships between mean summer nitrate-nitrite-N culvert loading and (a) mean summer flow; (b) mean summer water residence time

Table 2
Mean Summer Nitrate-Nitrite Nitrogen Inputs (via culvert flows), Outputs, and Net Retention

Lake	Input (kg d^{-1})	Output (kg d^{-1})	Net retention (kg d^{-1})	Net retention(%)
Third	108.3 (21.1)^{a}	63.4 (13.9)^{bc}	44.9 (7.9)^{a}	41.5
Clear	173.3 (41.5)^{a}	128.5 (33.2)^{ab}	44.8 (13.2)^{a}	25.8
Lower Peterson	190.2 (39.9)^{a}	155.8 (34.4)^{ab}	34.4 (9.5)^{ab}	18.1
First	193.4 (52.7)^{a}	178.7 (48.7)^{a}	14.7 (5.1)^{c}	7.6
Letters indicate significant differences at the 5-percent level or less (ANOVA; SAS 1994)				

Spieles and Mitsch 2000, Lane et al. 2004). NO_3NO_2-N loading, backwater surface area:volume ratio and mean depth, extent of submersed and emergent aquatic macrophyte and periphyton growth, and organic carbon availability are important variables in NO_3NO_2-N retention capacity in addition to water residence time. However, results suggested that under 2004 NO_3NO_2-N loading conditions and mean water residence times, NO_3NO_2-N mass retention for Third Lake was probably near maximal, especially given the constraints of source water NO_3NO_2-N load and backwater morphometry in relation to flow. Since the other study lakes exhibited similar mean depths and surface area:volume ratios as Third Lake, it was hypothesized that net NO_3NO_2-N retention could be improved in the other lakes by altering flows and, thus, water residence time to optimize exposure of NO_3NO_2-N loads for uptake and processing.

Hypothetical adjustments in water residence time (while maintaining observed mean NO_3NO_2-N concentration of the source water at 2004 levels) resulted in estimated culvert flow and NO_3NO_2-N loading decreases to Clear, Lower Peterson, and First Lakes over conditions observed in 2004 (Table 3). In particular, the estimated optimal NO_3NO_2-N culvert loading to First Lake represented less than 50 percent of the actual loading observed in 2004. The sum of all estimated optimal NO_3NO_2-N culvert loadings was about 27 percent less than observed loads. However,assuming that net NO_3NO_2-N retention efficiency improved to greater than 40 percent as a result of hypothetical water residence time adjustments, estimates suggested that net NO_3NO_2-N retention could improve by approximately 46 percent over 2004 conditions, with First and Lower Peterson Lakes exhibiting the greatest net NO_3NO_2-N mass retention and efficiency improvements. The mean summer 2004 NO_3NO_2-N concentration of source water to the Finger Lakes was high relative to the 10-year average by about 25 percent (Figure 6). Thus, backwater NO_3NO_2-N retention would need to be reevaluated under these mean long-term conditions in order to optimize efficiency.

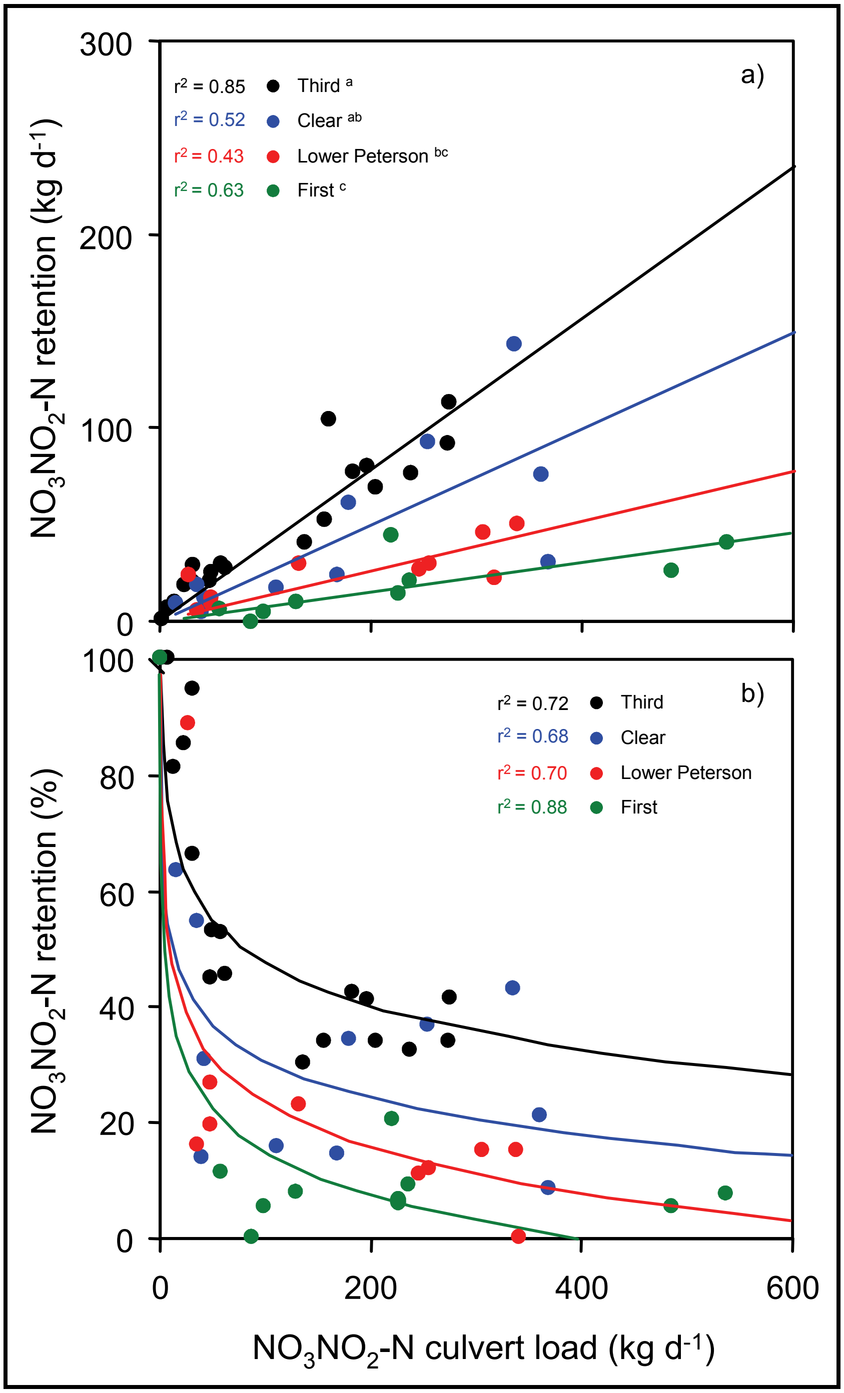

Figure 5. Nitrate-nitrite-N (NO_3NO_2-N) culvert load versus (a) net NO_3NO_2-N retention rate and (b) percent of culvert load removed for various backwater lakes. Letters next to lake names in the legend of panel (a) denote significant differences in the slope of the regression line (SAS 1994)

Table 3
Actual and Hypothetical Values for 2004[1]

(a) Lake	(b) Actual flow ($m^3 s^{-1}$)	(c) Adjusted flow ($m^3 s^{-1}$)	(d) Adjusted load ($kg\ d^{-1}$)	(e) Adjusted net retention ($kg\ d^{-1}$)	(f) Net retention improvement (%)
Third	0.531	0.531	108.3	44.9	0
Clear	0.994	0.627	136.5	57.3	128
Lower Peterson	1.166	0.649	141.3	59.3	173
First	1.008	0.411	89.5	37.6	256

[1] Actual mean summer 2004 flows (Column b) were hypothetically adjusted (Column c) to maintain a mean water residence time of ~1.6 days for which lake. Adjusted nitrate-nitrite-N (NO_3NO_2-N) loads (Column d) were calculated as the product of adjusted flow and the actual mean summer 2004 NO_3NO_2-N concentration of the source water (2.51 mg L^{-1}) . Adjustments in residence time were assumed to lead to an optimum net retention efficiency of ~42 percent of the adjusted NO_3NO_2-N load (Column e). The percent change in the net NO_3NO_2-N retention rate (Column f) was calculated as the adjusted net NO_3NO_2-N retention divided by the actual net NO_3NO_2-N retention rate (Table 2).

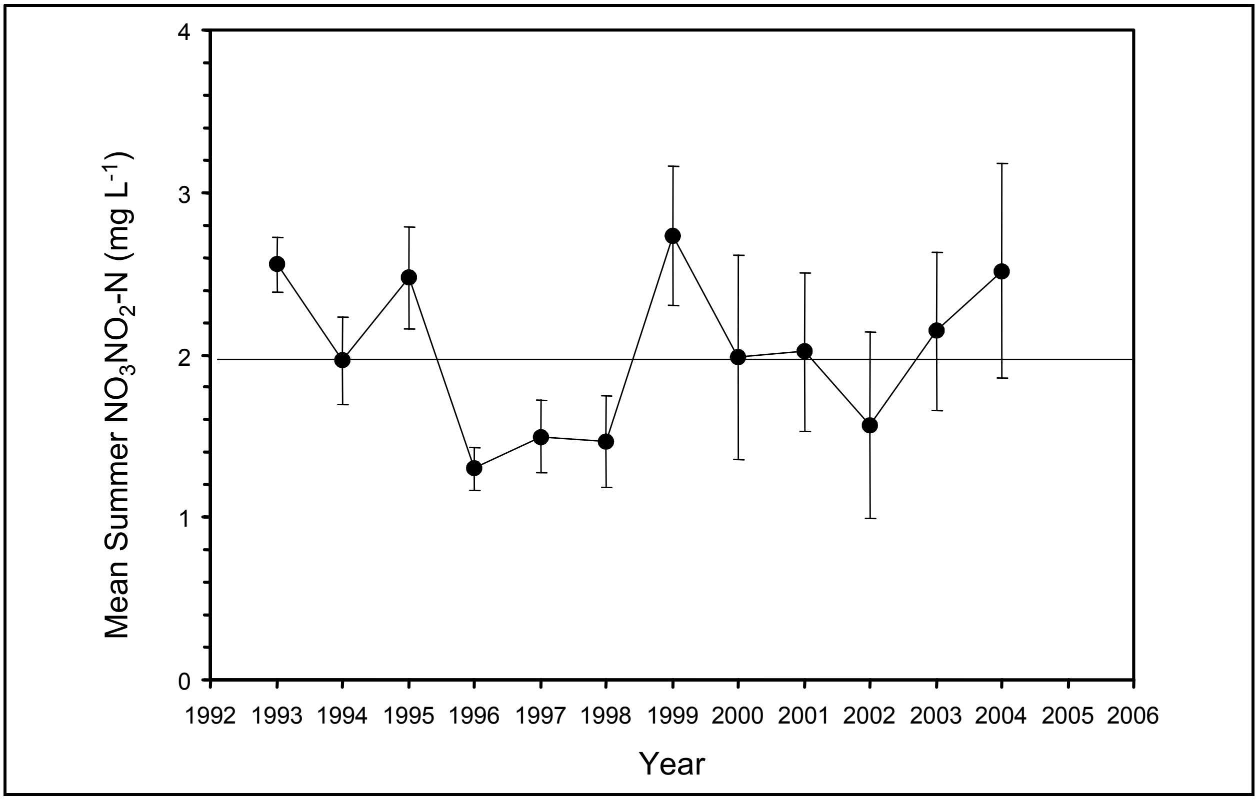

Figure 6. Annual variations in the mean (± 1 SE) summer nitrate-nitrite-N concentration of the Mississippi River at Lock and Dam 4 (horizontal line represents the 10-year average)

For the Finger Lakes, NO_3NO_2-N loading and water residence time co-varied in an inverse pattern as a function of culvert flow for each lake, constraining the ability to maximize net NO_3NO_2-N retention (i.e., by increasing concentration and decreasing flow to the lakes independently, for instance). Thus, unlike engineered wetlands that can be designed to maximize nutrient retention, natural backwater regions of large rivers will likely be less efficient in their ability to remove NO_3NO_2-N. Within these constraints, however, a mean water residence time on the order of 1-2 days appeared to be associated with the greatest net NO_3NO_2-N retention of loads for the Finger Lakes. At water residence times of less than 1 day (i.e., First Lake), NO_3NO_2-N loading was high, but net retention was probably limited by diffusive flux of NO_3NO_2-N into the sediment (i.e., for denitrification; Golterman 2000) and periphyton uptake in relation to advective delivery and flushing rate. Conversely, diffusive flux into the sediment and periphyton uptake could exceed advective delivery at higher water residence times (i.e., >2 days) resulting in a greater net retention efficiency, but low overall net mass retention (James, unpubl. data). These results suggest a general conceptual model for flow-controlled backwaters of large rivers that describes net NO_3NO_2-N retention capacity and efficiency in relation to residence time within NO_3NO_2-N loading and concentration ranges (Figure 7).

Unlike main channel reaches of large river systems, biological uptake and N retention are enhanced in backwater complexes due to lower flows which promote the deposition of nutrient and carbon-rich sediments, creating suitable substrate for bacterial denitrification (Richardson et al. 2004). For large river systems like the Mississippi River, NO_3NO_2-N processing and retention may be improved by increasing connectivity to backwater complexes like the Finger Lakes system. Connectivity could be increased by dredging channels to isolated backwaters, using diversion structures (i.e., wing dams constructed islands, etc.) to promote greater flows into side channels, and installing culverts. Analogous to engineered wetlands, results indicate that water residence time needs to be considered in connectivity design issues in order to maximize NO_3NO_2-N retention in backwater systems. This goal is perhaps more difficult to achieve for natural backwater systems given the more complex interrelationships between flow, load, morphology, and water residence time. Ecological models would be useful in evaluating scenarios to increase main channel connectivity and NO_3NO_2-N loading to backwaters for net overall improvement in NO_3NO_2-N retention.

More detailed information is needed regarding relationships among NO_3NO_2-N loading, water residence time distribution (RTD, days; Kadlec 1994), and water displacement (water contact time with the sediment, m d^{-1}; Seitzinger et al. 2002) in order to improve understanding of backwater NO_3NO_2-N retention as a function of hydraulic efficiency. Flow and mixing patterns through backwater systems like the Finger Lakes are typically not at steady state or fully mixed reactors (Holland et al. 2004). Bathymetric complexity, embayments, dendritic shoreline features, and submersed and emergent macrophytes affect the distribution of flow patterns, resulting in spatial differences in NO_3NO_2-N delivery that would be a determinant in overall NO_3NO_2-N retention efficiency. In addition, the roles that emergent and submersed aquatic macrophyte abundance play in backwater NO_3NO_2-N retention need to be evaluated within the framework of hydraulic efficiency. Aquatic macrophytes would be expected to improve overall NO_3NO_2-N retention efficiency in the following ways:

- Provide substrate for attached microbial uptake and denitrification (Eriksson and Weisner 1996, Toet et al. 2003).

- Affect NO_3NO_2-N delivery by modifying local flow patterns.
- Contribute organic carbon to fuel denitrification.
- Alter the local redox environment to facilitate nitrification and denitrification (James et al. 1996, Eriksson and Weisner 1999).

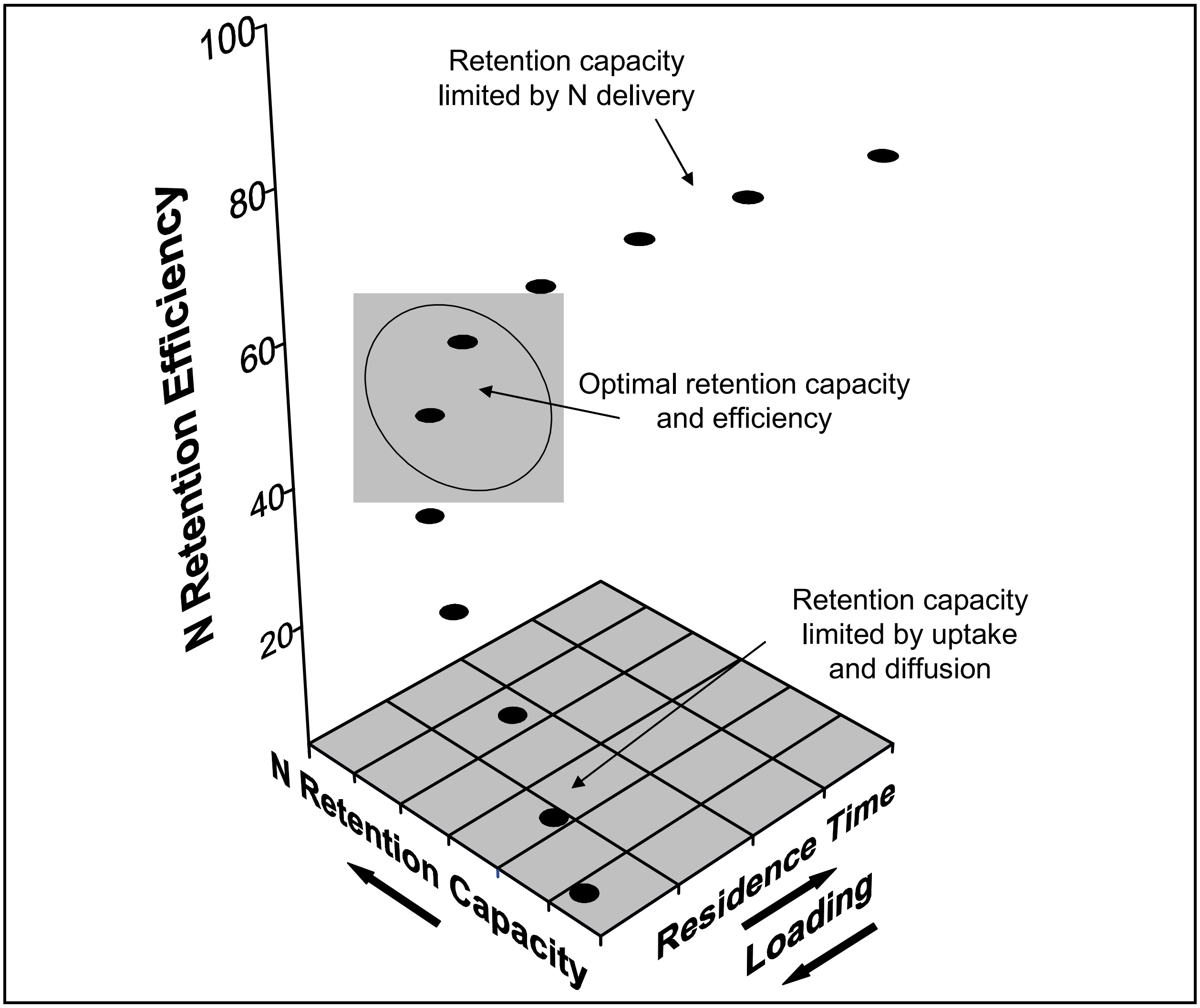

Figure 7. Conceptual diagram of net nitrate-nitrite (N) retention capacity and efficiency in relation to residence time and external N loading for a hypothetical flow-regulated backwater system. Arrows denote the direction of increasing values. External nitrate-nitrite loading is constrained by source river water concentrations. Thus, external loading and residence time vary inversely due to variation in culvert flow (x-axis). As external loading increases, residence time declines to the point where both retention capacity and efficiency are limited by contact time for uptake and diffusion into the sediment. Increasing the residence time via culvert flow adjustment results in decreased external loading to the system. At an optimal residence time range, however, retention capacity becomes maximal due to sufficient contact time for uptake and diffusion into the sediment in relation to N delivery. As residence time increases beyond this optimum, retention efficiency approaches 100 percent. However, retention capacity is limited by low external loading and approaches zero

ADDITIONAL INFORMATION: This technical note was prepared by William F. James, William B. Richardson, David M. Soballe, John W. Barko, and Harry L. Eakin , U.S. Army Engineer Research and Development Center. For information on the System-Wide Water Resources Program (SWWRP), please consult https://swwrp.usace.army.mil/ or contact the Program Manager, Dr. Steven L. Ashby at Steven.L.Ashby@erdc.usace.army.mil. This technical note should be cited as follows:

James, W. F., Richardson, W. B., Soballe, D. M., Barko, J. W., and Eakin, H. L. (2006). "Effect of residence time on net nitrate retention in flow-regulated backwaters of the upper Mississippi River," *SWWRP Technical Notes Collection*, ERDC TN-SWWRP-06-1, U.S. Army Engineer Research and Development Center, Vicksburg, MS. https://swwrp.usace.army.mil/

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