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Nitrate Uptake Capacity and Efficiency of Upper Mississippi River Flow-Regulated Backwaters

by William F. James, William B. Richardson, and David M. Soballe

PURPOSE: In-stream uptake and processing of nitrate nitrite-N may be improved in large river systems by increasing hydrological connectivity between the main channel and adjoining backwaters, wetlands, and floodplain areas. Engineering designs to increase connectivity and loading to backwaters need to consider nitrate nitrite-N uptake capacity and efficiency in relation to hydraulic loading and residence time in order to optimize in-stream N processing. These relationships were examined during three summer periods for a series of backwater systems on the Upper Mississippi River that received flow-regulated nitrate nitrite-N loads via gated culverts.

BACKGROUND: Nitrogen (N) runoff to receiving streams and rivers, particularly in the form of nitrate-nitrite-N, has increased several-fold in recent decades (Justic et al. 1995, Vitusek 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 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 (Vitusek et al. 1997).

In addition to managing nitrate nitrite-N runoff 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 its in-stream uptake and removal by biological incorporation, bacterial denitrification, and burial in order to further reduce N transport to coastal systems (Mitsch et al. 2001). In-stream N transformation and removal does occur in large rivers, but it is typically low and represents 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 nitrate nitrite-N uptake might be a viable strategy for improving processing of nitrate nitrite-N loads and needs to be considered in integrated basin management of nitrate nitrite-N.

Although backwaters account for more 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 diversion of river water through coastal wetland complexes is an effective means of reducing nutrient concentrations before discharge into coastal waterways (Lane et al. 2004). Additional nitrate nitrite-N uptake and removal in large river systems may be achieved by re-establishing connectivity to backwater areas via culverts, dike diversion, and creation of channels to increase the rate of nitrate nitrite-N delivery for processing. However, information is needed regarding nitrate nitrite-N uptake capacity and efficiency of backwaters in relation to loading and water residence time in order to maximize uptake 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 nitrate nitrite-N uptake capacity and efficiency in a series of backwater lakes that are connected to the Upper Mississippi River via flow-regulated culverts.

METHODS: 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). The lakes have similar shallow morphometry (Table 1) and are eutrophic (chlorophyll = 55 $mg \cdot m^{-3}$; total P = 0.082 $mg \cdot L^{-1}$; soluble reactive P = 0.041$mg \cdot L^{-1}$). Nitrogen species entering the lakes are dominated by nitrate nitrite-N (> 75 percent of the total N). Dense stands of submersed and emergent aquatic macrophytes occupy large portions of the surface area of Lower Peterson, Third, Second, and First Lakes. In particular, American lotus (*Nelumbo lutea*) covers nearly 100 percent of the embayments located immediately south of the main basins of Second and Third Lakes. Other dominant macrophyte species include *Ceratophyllum demersum*, *Myriophyllum spicatum*, and *Nymphaea odorata*. In contrast, Clear and Schmokers Lakes exhibit less macrophyte coverage per unit surface area.

Clear, Lower Peterson, and Third Lakes receive regulated flows via individual gated culverts installed through the dike that allow source water from Navigation Pool 4 to flow into the system. First and Second Lakes receive regulated flows from a common culvert fitted with a junction box. Each culvert system was fitted with adjustable vertical slide gates to regulate flows within a range of 0 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).

During May of 2003, 2004, and 2005, vertical slide gates were adjusted to produce average summer flows ranging between 0.05 and 0.60 $m^3 \cdot s^{-1}$ into each of the five lakes to examine the effects of hydraulic loading and residence time on nitrate nitrite-N uptake capacity and efficiency. Mean summer culvert flows were set to be greater and theoretical residence time lower, in 2004 and 2005 than in 2003. Sampling stations were established at the culvert inflows and at various outflow points for all of the lakes (Figure 1). Sampling was conducted at weekly to biweekly intervals between June and August 2003 and between June and September 2004-2005. Water depths at the outflow stations were less than 0.4 m at nominal pool elevation. Culvert flows were measured at weekly to biweekly intervals using a Flo-Mate Model 2000 velocity meter (Marsh-McBirney Inc., Fredrick, MD). Flows were not directly measured at the outflow stations and 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 nitrate nitrite-N was performed on a Lachat QuikChem A/E

(Hach, Inc., Loveland, CO) using standard automated procedures (American Public Health Association (APHA) 1998).

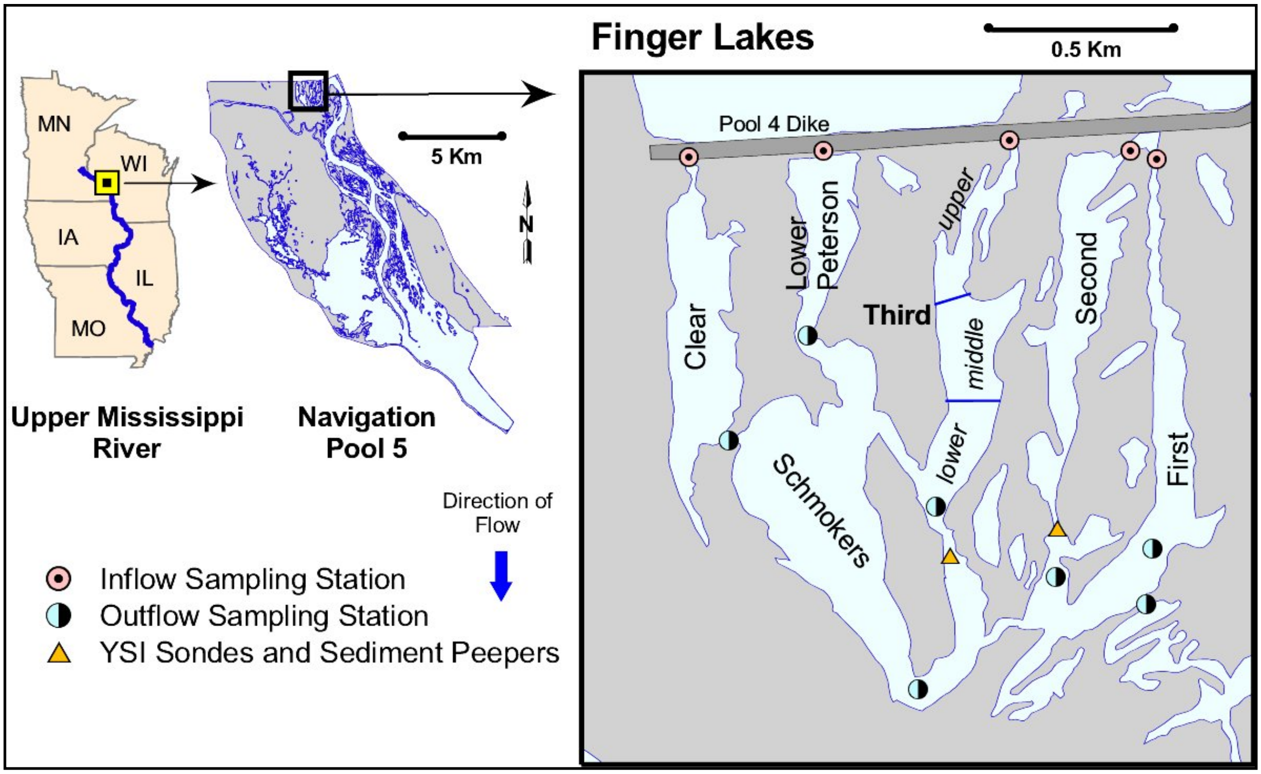

Figure 1. Map of the Finger Lakes backwater system showing inflow and outflow sampling locations.

Table 1
Lake Morphological Characteristics at Nominal Pool Elevation (201.65 m MSL) and Culvert Dimensions

Lake	Mean depth (m)	Surface area (m^2)	Volume (m^3)	Culvert dia. (m)
Clear	0.8	108381	86705	0.91
Lower Peterson	1.2	74759	89711	1.22
Third	0.6	112477	67486	0.91
Second	0.3	126921	38076	0.76
First	0.6	94806	56884	0.91

Information on daily stage elevations for navigation pools 4 and 5 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 in 2005 using a data logging system equipped with a pressure transducer (ISCO Model 4120; Teledyne ISCO, Inc., Lincoln, NE). Relationships between stage elevation at Third Lake and the Lock and Dam 4 tailwaters were used to estimate water volumes for the Finger Lakes in 2003 and 2005. Theoretical water residence time for each lake was calculated as volume divided by culvert flow (days). Hydraulic loading ($m \cdot d^{-1}$) was calculated as mean summer flow divided by the area of each backwater.

Nitrate nitrite-N uptake capacity and efficiency were examined as a function of relationships between summer average inflow (C_{inflow}) and outflow concentration ($C_{outflow}$) versus residence time (τ) or hydraulic loading (q) using the first-order rate equations

$$C_{outflow} = C_{inflow} e^{-k_v \tau} \tag{1}$$

$$C_{outflow} = C_{inflow} e^{-k_a / q} \tag{2}$$

where k_v (d^{-1}) and k_a ($m \cdot d^{-1}$) are the volumetric and areal uptake rate constants, respectively. The nitrate nitrite-N change rate constant, k_c (m^{-1}), was calculated as

$$C_{outflow} = C_{inflow} e^{-k_c x} \tag{3}$$

where x is the length of the backwater (m). The nitrate nitrite-N uptake length (i.e., distance a molecule travels before being removed from the water; Newbold et al. 1981), another measure of uptake efficiency, was calculated as $1/k_c$ (m). Concentration-based nitrate nitrite-N uptake capacity, estimated as the difference between average summer C_{inflow} and $C_{outflow}$ and uptake efficiency (R, percent), was calculated as

$$R = \left(\frac{\left(C_{inflow} - C_{outflow} \right)}{C_{inflow}} \right) \cdot 100 \tag{4}$$

RESULTS AND DISCUSSION: The grand mean C_{inflow} of 2.055 $mg \cdot L^{-1}$ (± 0.063 SE) during the summers of 2003 through 2005 was near the 13-year (1992-2005) summer mean of 2.019 $mg \cdot L^{-1}$ (± 0.128 SE).[1] In addition, it was nearly constant as a function of the various hydraulic loading rates and residence times maintained in the different lakes (Figure 2), indicating that nitrate nitrite-N loading rate differences were due to differences in culvert inflow to the individual lakes. Thus, increased flow resulted in higher load (i.e., $mg \cdot m^{-2} \cdot d^{-1}$) but lower residence time because mean source nitrate nitrite-N concentrations were relatively constant. In contrast, $C_{outflow}$ varied over these differing summer hydraulic characteristics. It was minimal at the lowest hydraulic loading rate and increased in a logarithmic pattern as a function of increasing hydraulic loading rate, approaching C_{inflow} as the hydraulic loading rate exceeded 1.0 $m \cdot d^{-1}$. Uptake capacity and efficiency were greatest at the lowest hydraulic loading rate and decreased in a logarithmic pattern with increasing hydraulic loading rate. At the highest measured hydraulic loading rate, uptake capacity was < 0.5 mg L^{-1} and uptake efficiency was ~ 20 percent. Opposite patterns for $C_{outflow}$, uptake capacity and efficiency occurred as a function of residence time. Thus, uptake capacity and efficiency were low at the lowest residence times and increased logarithmically as residence time increased.

[1] Personal Communication, 2006. Dr. David Soballe, Research Biologist, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

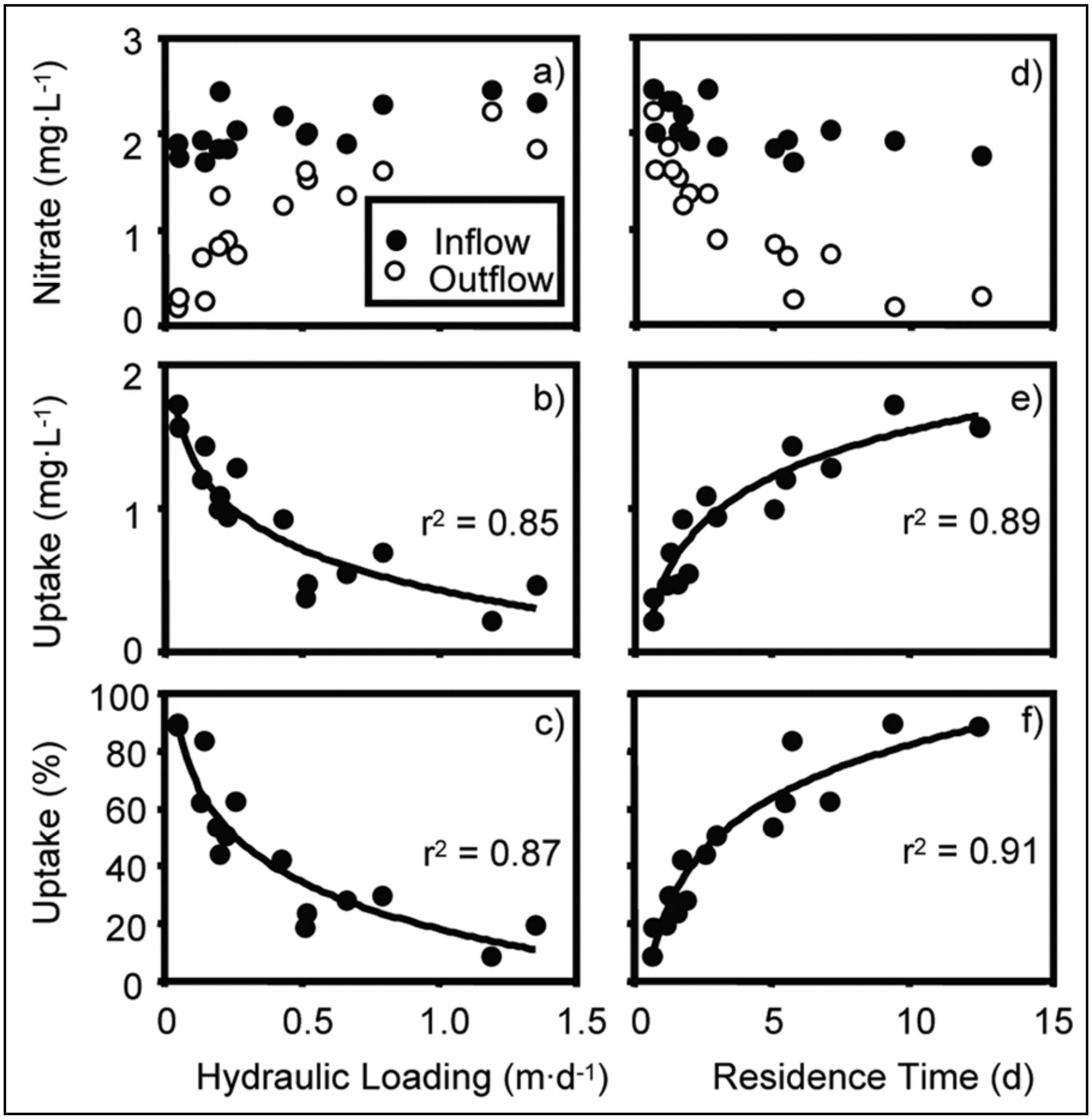

Figure 2. Relationships between hydraulic loading or residence time and nitrate nitrite-N concentrations in the inflow versus outflow, uptake capacity, and uptake efficiency. Values represent means over the summer period (May-September) for 2003-2005.

A nonlinear relationship existed between ln(C_{inflow}/$C_{outflow}$) and hydraulic loading or residence time (Figure 3). Maximum k_a and k_v were 0.301 m·d^{-1} and 0.327 d^{-1}, respectively. The latter value was greater than the mean k_v 0.18 d^{-1} (±0.16 Standard Deviation) for total N determined for wetlands worldwide (Water Pollution Control Federation (WPCF) 1990; range = 0.008 to 0.63 d^{-1}) and higher than the total N k_v reported for the Cache River wetland (0.048 d^{-1}; Dortch 1996), indicating that the backwaters were behaving similarly to wetlands and capable of efficiently retaining nitrate nitrite-N loads. Results suggested that first-order models may be applicable for screening-level assessment of uptake improvement in large river systems by routing water into backwaters via a channel or culvert and out to the main channel. One caveat to this approach is that backwater systems can be interconnected with each other as well as with the main channel, making model requirements more complex. For instance, the five backwaters examined in this study feed into another backwater (Schmoker's Lake) before flowing back into the Mississippi River main channel.

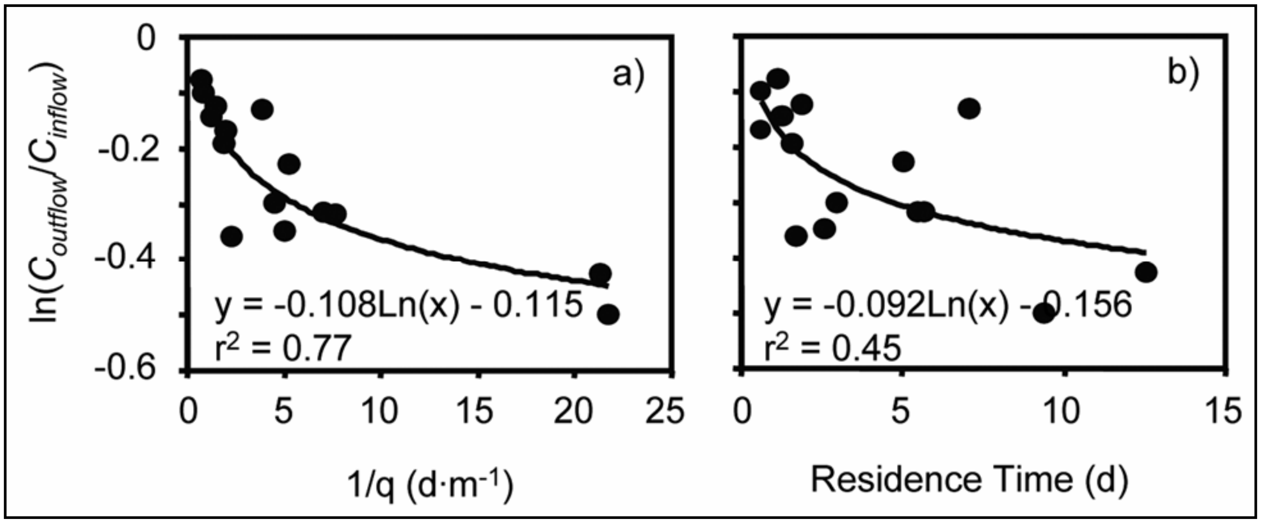

Figure 3. Relationships between hydraulic loading or residence time and $\ln(C_{inflow}/C_{outflow})$, where C is the summer mean nitrate nitrite-N concentration ($mg{\cdot}L^{-1}$) of the inflow or outflow.

Uptake length varied logarithmically as a function of residence time (Figure 4). As residence time decreased below ~2 days, uptake length exceeded the maximum length of the backwater systems indicating that contact time was limiting uptake due to high flushing. As residence time increased, uptake length fell within the range of backwater length. At the highest residence times (> 8 days), uptake length was less than one-half the average length of the backwater systems. Since overall loading declined with increasing residence time as well, results suggested that uptake capacity was probably limited by N delivery at these high residence times, even though uptake lengths were almost two times the length of the backwaters.

These results suggested a general model for flow-through backwaters that describes net nitrate nitrite-N uptake capacity and efficiency in relation to hydraulic loading and residence time within nominal summer mean concentration ranges (Figure 5). At low water residence times, nitrate nitrite-N loading was high, but uptake was probably limited by diffusive flux of nitrate nitrite-N into the sediment (i.e., for denitrification; Golterman 2000) and biological incorporation in relation to advective delivery and flushing rate. Uptake length exceeded the distance of the system at these higher flushing rates, resulting in low uptake efficiency as well as low uptake capacity. Conversely, rates of diffusive flux into the sediment and biological incorporation could exceed advective delivery at higher water residence times, resulting in greater uptake efficiency but low uptake capacity. Nitrate nitrite-N loading was low at the higher residence times due to source water concentration constraints. Uptake length was also low relative to backwater length indicating that most of the N was incorporated in the upper reaches of the backwaters with limited to minimal delivery of N for uptake at downstream locations. Uptake capacity was maximal, while net uptake efficiency ranged between 40 and 70 percent, at intermediate hydraulic loadings and residence times ranging between ~2 and 8 days. This pattern suggested that contact time for uptake of loads moving through the system was optimal given the constraints of source water concentrations which could not be controlled. Residence time above and below this range resulted in suboptimal uptake capacity. Consideration of uptake capacity-efficiency relationships would be applicable for engineering approaches to increase connectivity between backwaters and the main channel for purposes of maximizing in-stream nitrate nitrite-N processing of large river systems.

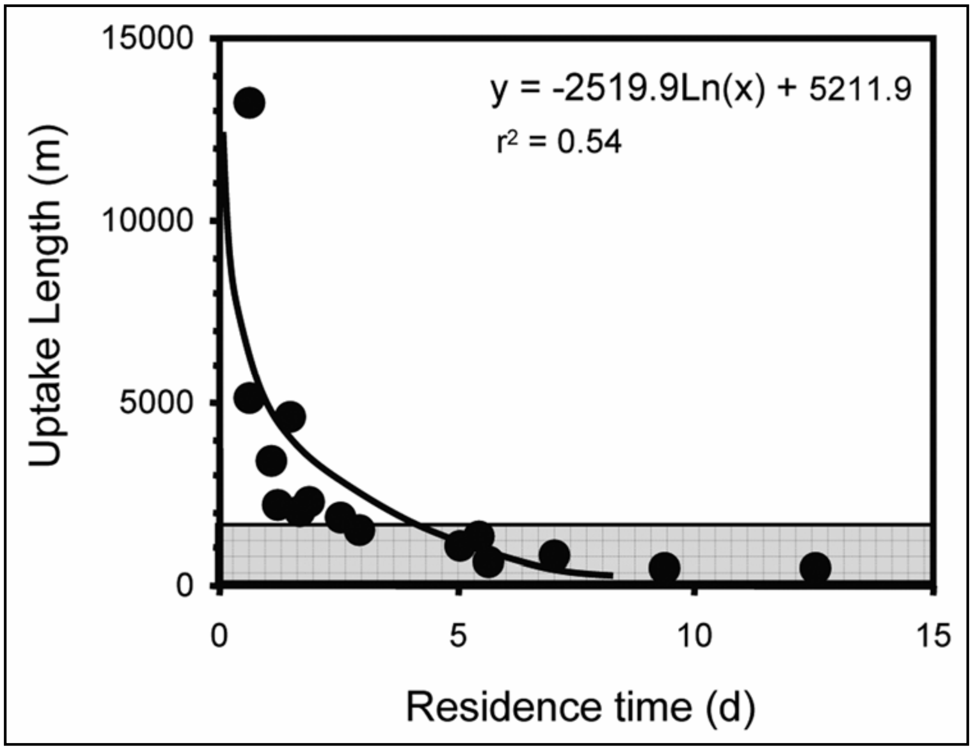

Figure 4. Relationships between residence time and uptake length. Shaded area represents the length of the backwater systems.

Unlike main channel reaches of large river systems, biological incorporation and N uptake is 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, Strauss et al. 2006). Backwaters also provide important habitat for aquatic macrophytes and associated epiphyton, which also play an important role in N uptake via biological uptake. For large river systems like the Mississippi River, nitrate nitrite-N processing and uptake may be improved by increasing hydrological connectivity to backwater complexes as was done for 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, installing culverts, and pulsing water into backwater regions via pool elevation manipulations. Analogous to engineered wetlands, the results of this study indicated that water residence time needs to be considered in connectivity design issues in order to maximize nitrate nitrite-N uptake capacity and efficiency in backwater systems. This goal is perhaps more difficult to achieve for natural backwater systems given the more complex interrelationships among flow, load, morphology, and water residence time. Ecological models would be useful in evaluating scenarios to increase main channel connectivity and nitrate nitrite-N loading to backwaters for net overall improvement in uptake capacity.

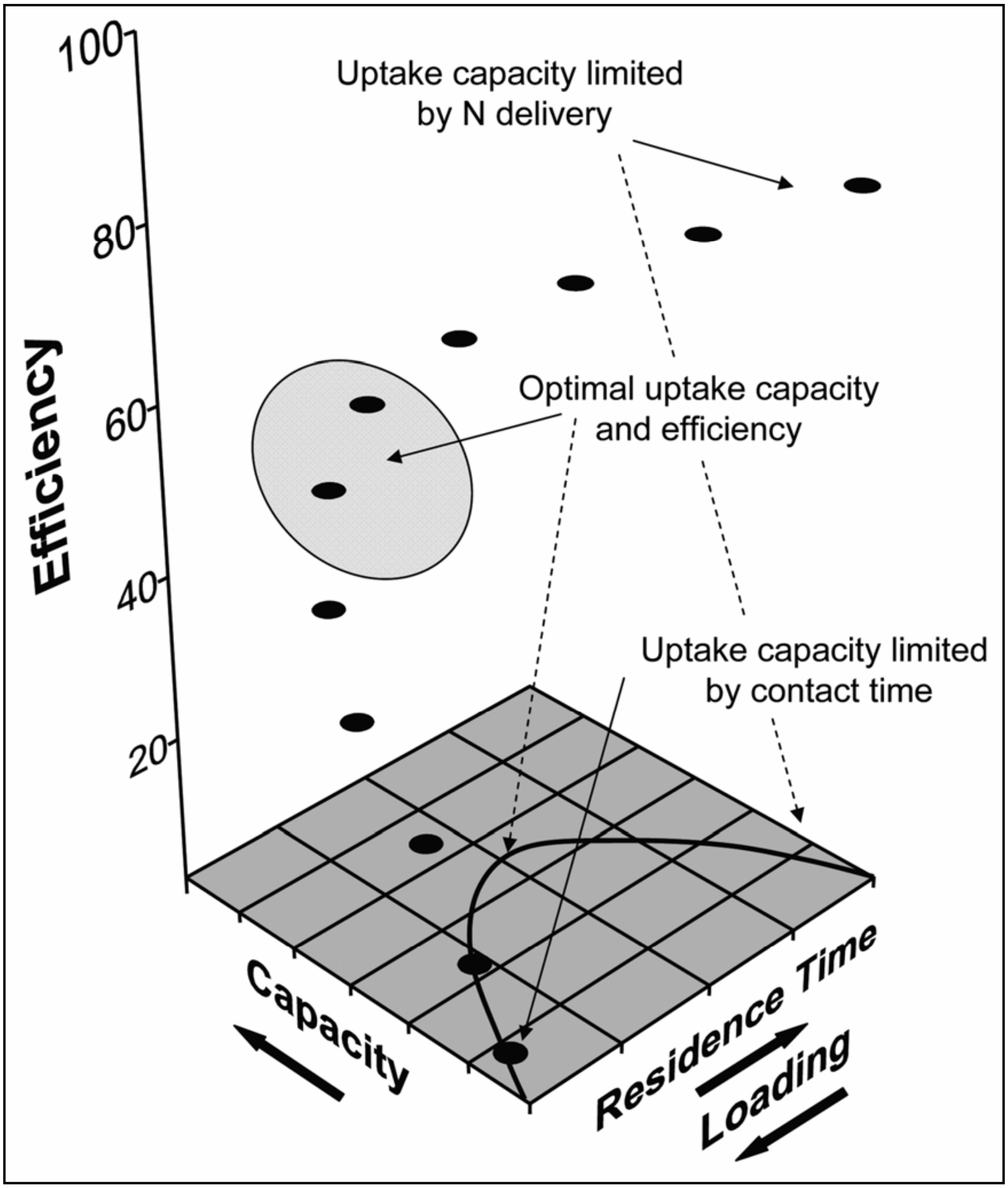

Figure 5. Conceptual diagram of nitrate-nitrite-N uptake capacity and efficiency in relation to residence time and N loading for a hypothetical flow-regulated backwater system. Arrows denote the direction of increasing values. Nitrate-nitrite-N loading is constrained by source river water concentrations. Thus, loading and residence time vary inversely due to variation in culvert flow and hydraulic loading (z-axis). As loading increases, residence time declines to the point where both uptake capacity and efficiency are limited by contact time for biological incorporation and diffusion into the sediment. Increasing the residence time via culvert flow adjustment results in decreased loading to the system. At an optimal residence time range, however, uptake capacity becomes maximal due to sufficient contact time for biological incorporation and diffusion into the sediment in relation to N delivery. As residence time increases beyond this optimum, uptake efficiency approaches 100 percent. However, uptake capacity is limited by low N delivery and approaches zero.

More detailed information is needed regarding relationships between nitrate nitrite-N loading, water residence time distribution (RTD, days; Kadlec 1994), and water displacement (water contact time with the sediment, $m \cdot d^{-1}$; Seitzinger et al. 2002) in order to improve understanding of backwater nitrate nitrite-N uptake 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 aquatic macrophytes affect the distribution of flow patterns, resulting in spatial differences in nitrate nitrite-N delivery, which would be a determinant in overall nitrate nitrite-N uptake capacity and efficiency. In addition, the role that aquatic macrophyte abundance plays in backwater nitrate nitrite-N uptake needs to be evaluated within the framework of hydraulic efficiency. Aquatic macrophytes would be expected to improve overall nitrate nitrite-N uptake efficiency by 1) providing substrate for attached microbial uptake and denitrification (Eriksson and Weisner 1996; Toet et al. 2003), 2) affecting nitrate nitrite-N delivery through modification of local flow patterns, 3) contributing organic carbon to fuel denitrification, and 4) altering the local redox environment to facilitate nitrification and denitrification (Eriksson and Weisner 1999).

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POINTS OF CONTACT: This technical note was written by William F. James and Dr. David M. Soballe of the Eau Galle Aquatic Ecology Laboratory, Environmental Laboratory (EL), Engineer Research and Development Center (ERDC), and Dr. William B. Richardson of the U.S. Geological Survey, Upper Midwest Environmental Sciences Center. For additional information, contact the manager of the System-Wide Water Resources Research Program (SWWRP), Dr. Steven A. Ashby (601-634-2387, *Steven.A.Ashby@erdc.usace.army.mil*).

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