Effects of Water Residence Time on Nitrate Removal in Flow-Regulated Backwater Lakes of the UMR Flood Plain

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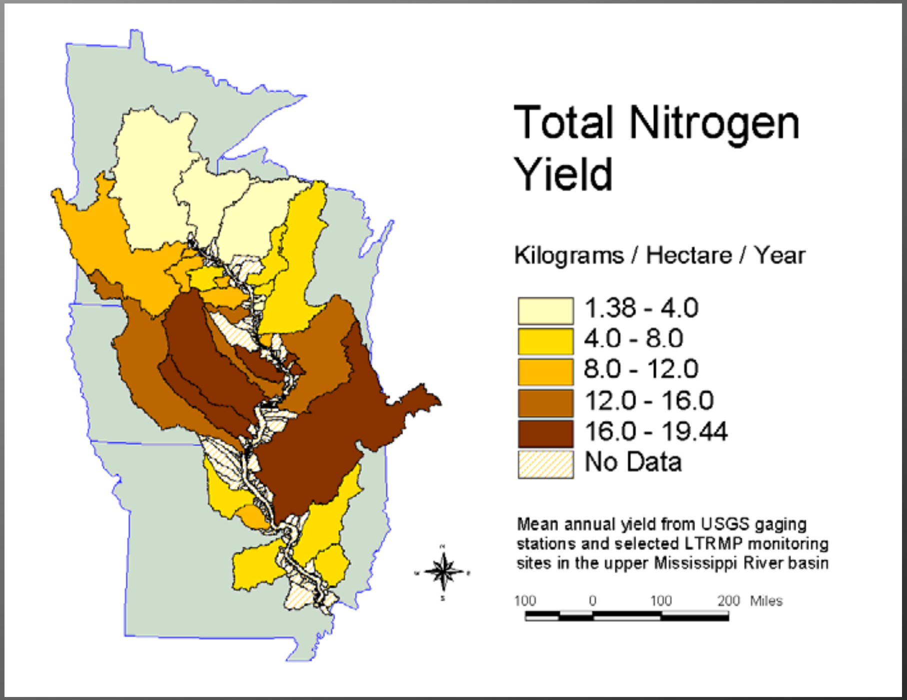
High Nitrate Delivery to Coastal Waters

- Accelerated agricultural N runoff in recent decades
- Receiving tributaries saturated with nitrate
- In-stream nitrate processing efficiency is typically low
- Large river systems essentially act as conduits for nitrate



Promoting In-Stream Nitrate Processing

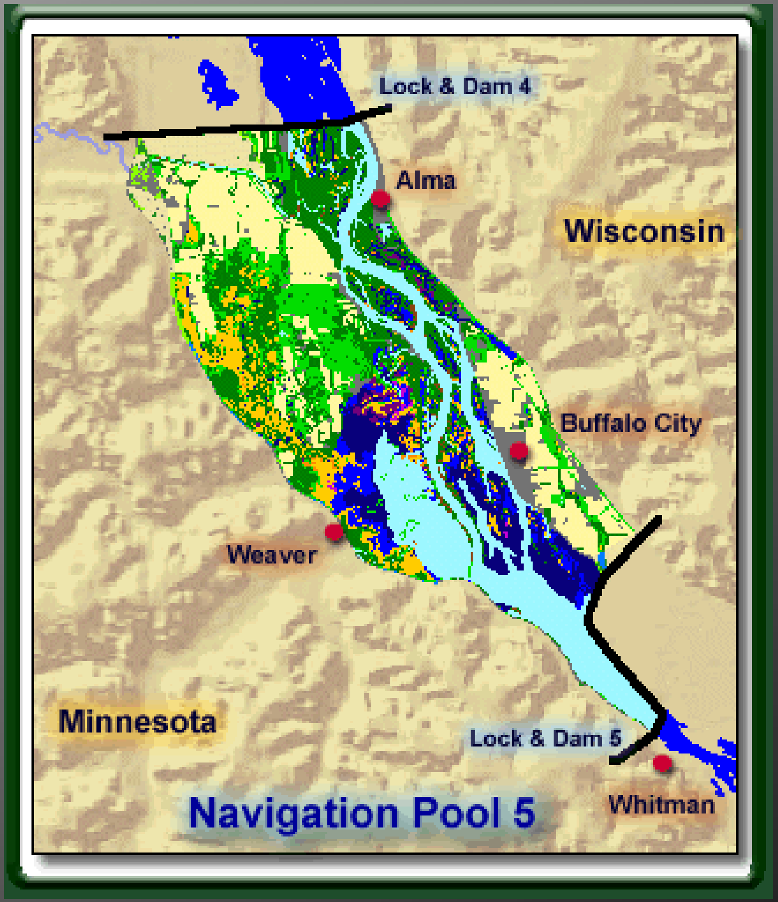
- Backwaters account for 30% of the surface area of the UMR
- Support abundant macrophyte growth and attached microbial communities
- Suitable habitat for nitrification-denitrification
- Accrete organic carbon-rich anaerobic sediment
- Biological uptake, bacterial denitrification, and burial of N in backwaters may be a viable strategy for reducing nitrate delivery to coastal waterways

Backwater N Processing Efficiency Limited by Nitrate Delivery

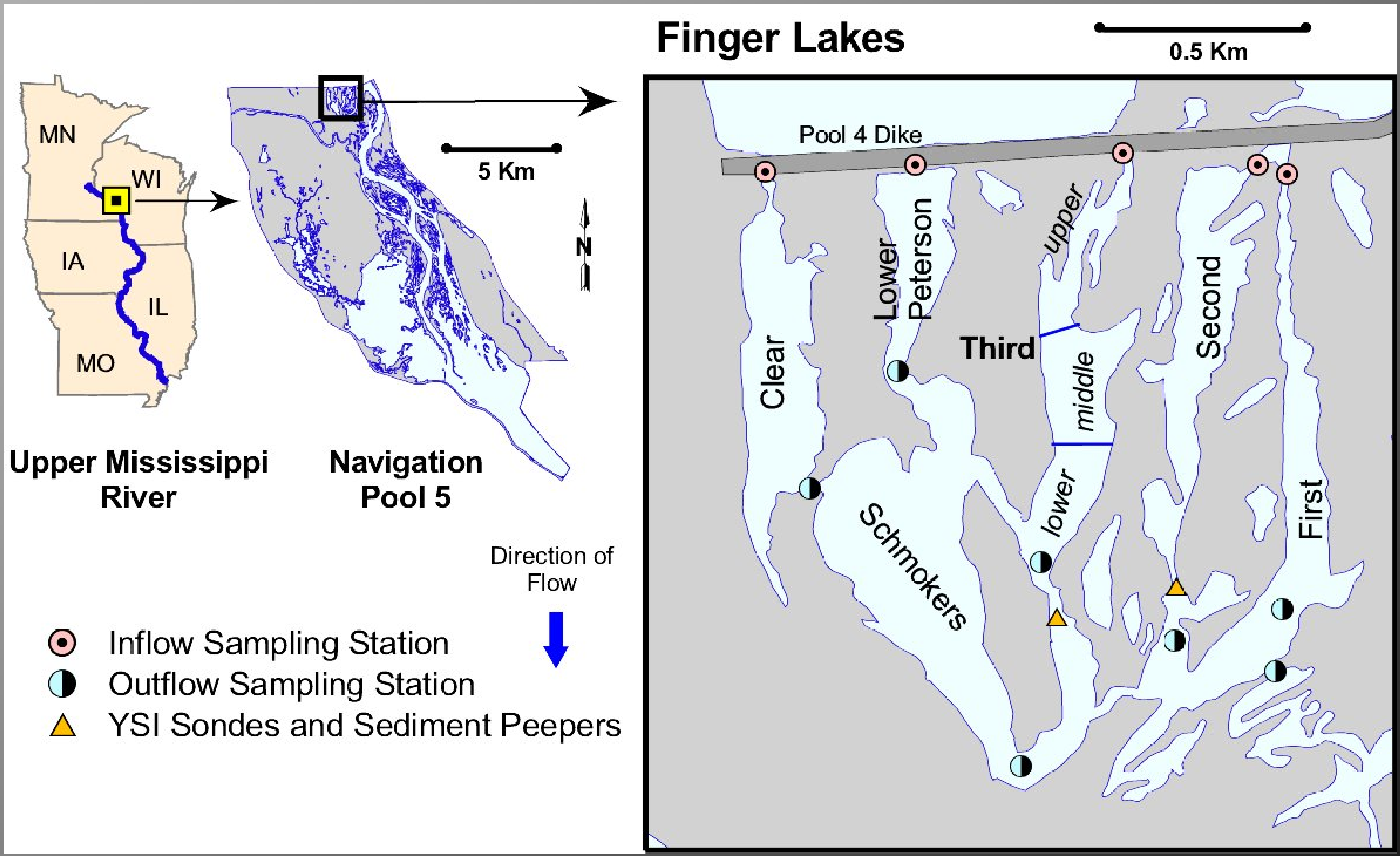
- Richardson et al. (2004)
- Pool level regulation and dampened flooding cycled impede flows to backwaters
- Re-establishing hydrological connectivity to backwaters of large river systems may improve overall nitrate processing efficiency

Knowledge Gaps

- How efficient are backwaters in retaining and processing N?
- Can efficiency be optimized by considering load and residence time?
- What maximal nitrate retention capacities can we expect?



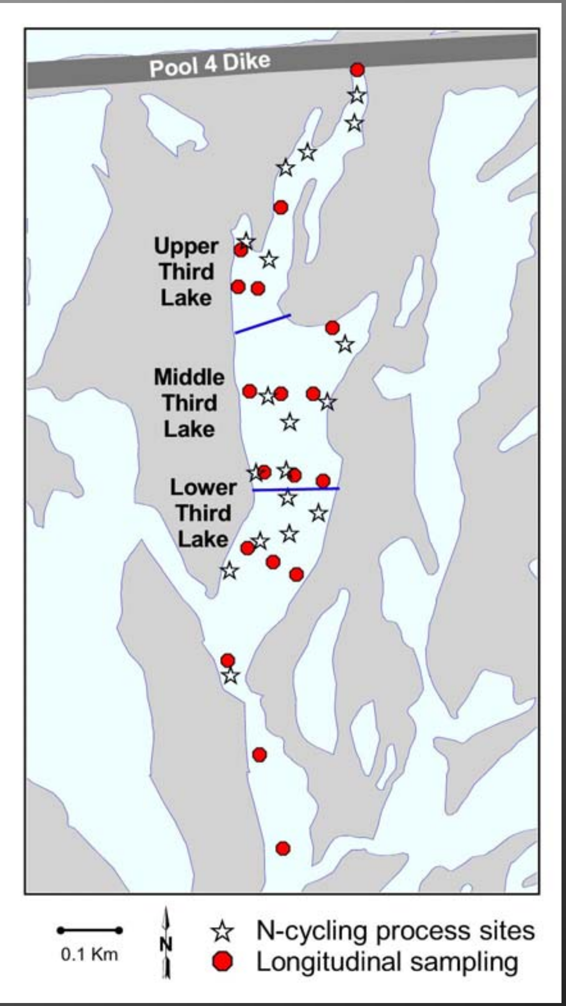
Flow-Controlled Backwaters in Pool 5 of the UMR



Net Nitrate Retention

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

- Internal nitrate inputs via nitrification were not included in the calculation (i.e., gross nitrate retention)



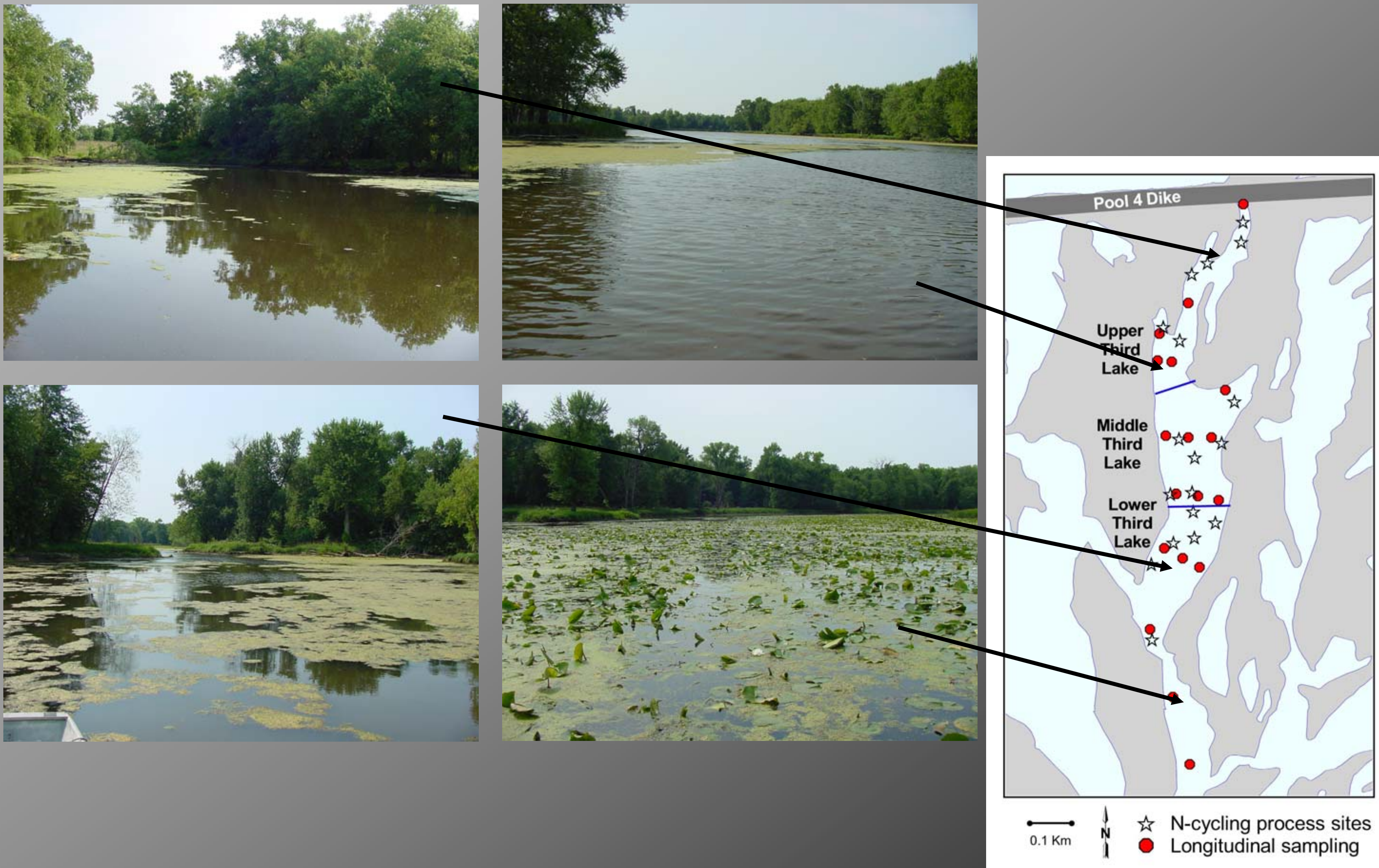
Controlled flow range = 0 to ~ 1.5 $m^3\ s^{-1}$

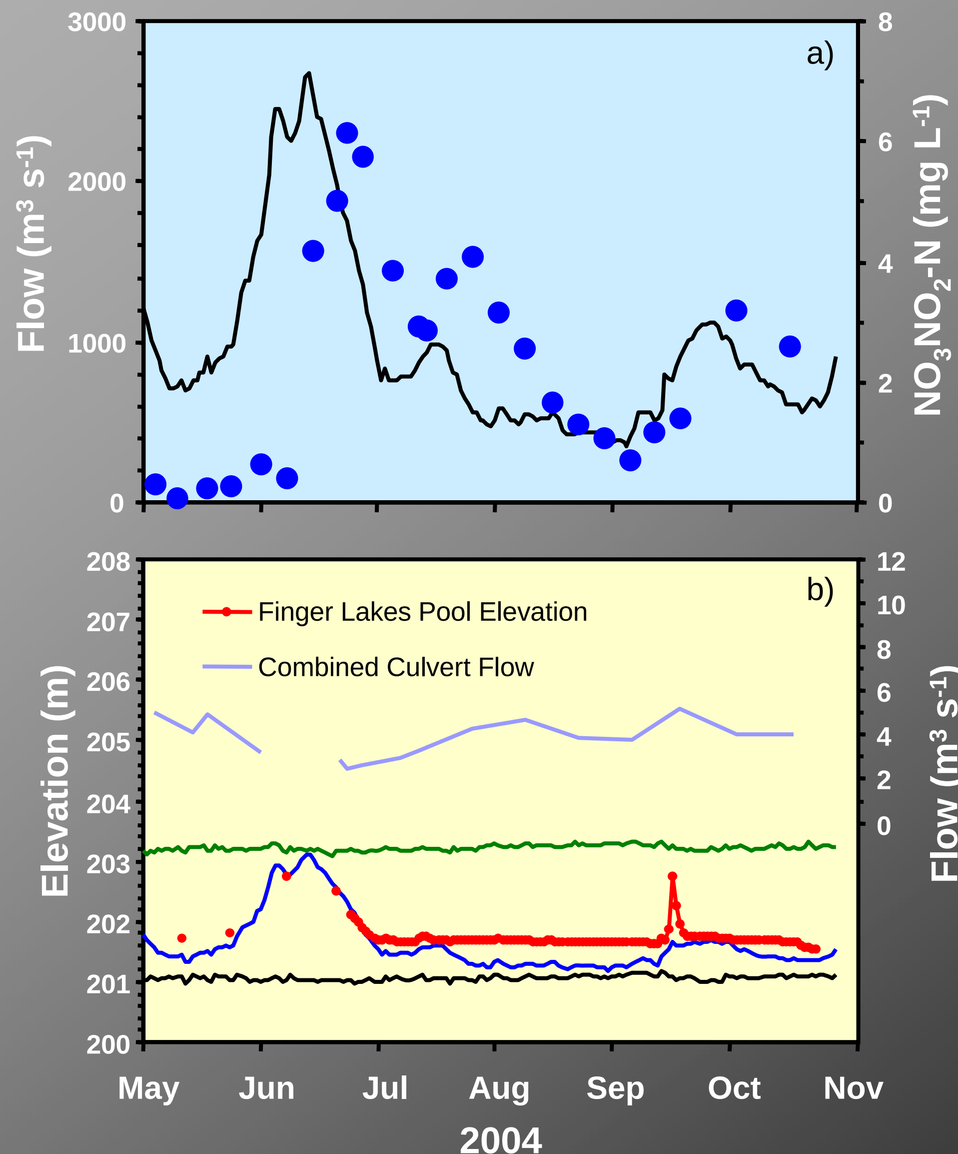
Lake	Culvert dia. (m)	Mean depth (m)	Area (ha)
Clear	0.91	0.8	10
Lower Peterson	1.22	1.2	8
Third	0.91	0.6	15
Second	0.76	0.3	7
First	0.91	0.6	10
Schmoker’s	None	0.9	19


Intake structure above dike


Discrete flow measurements

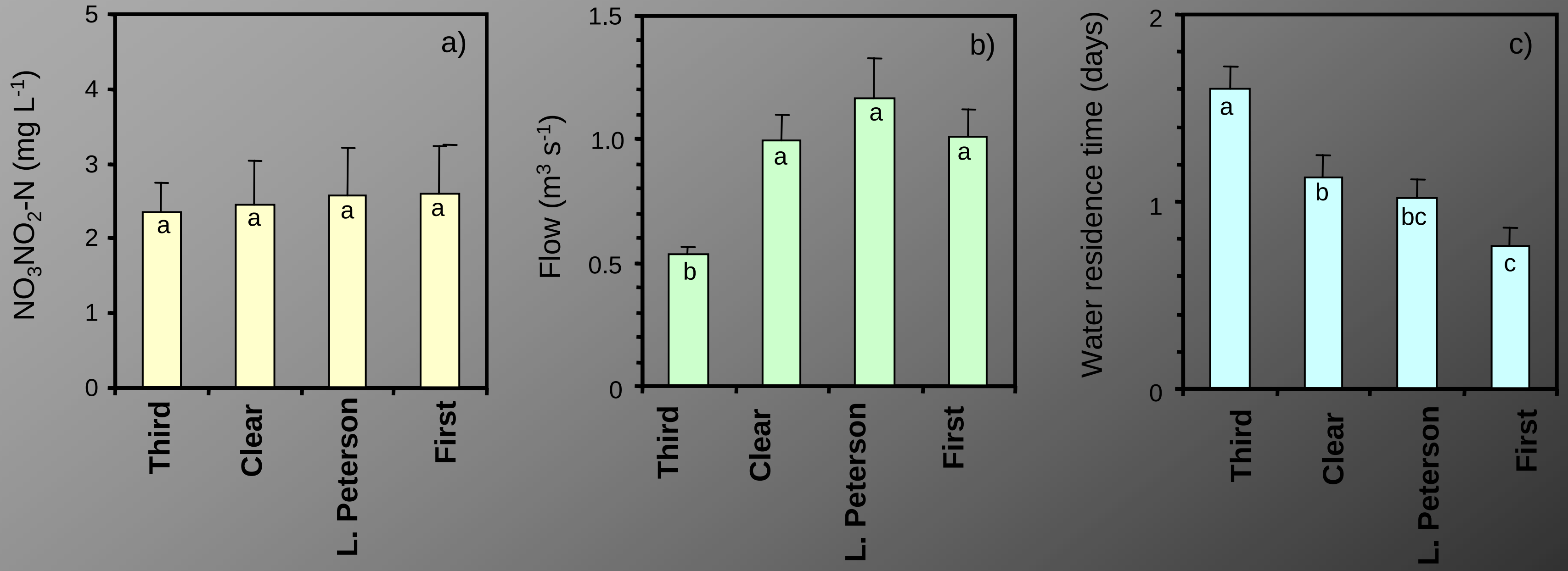

Lower Peterson culvert inflow

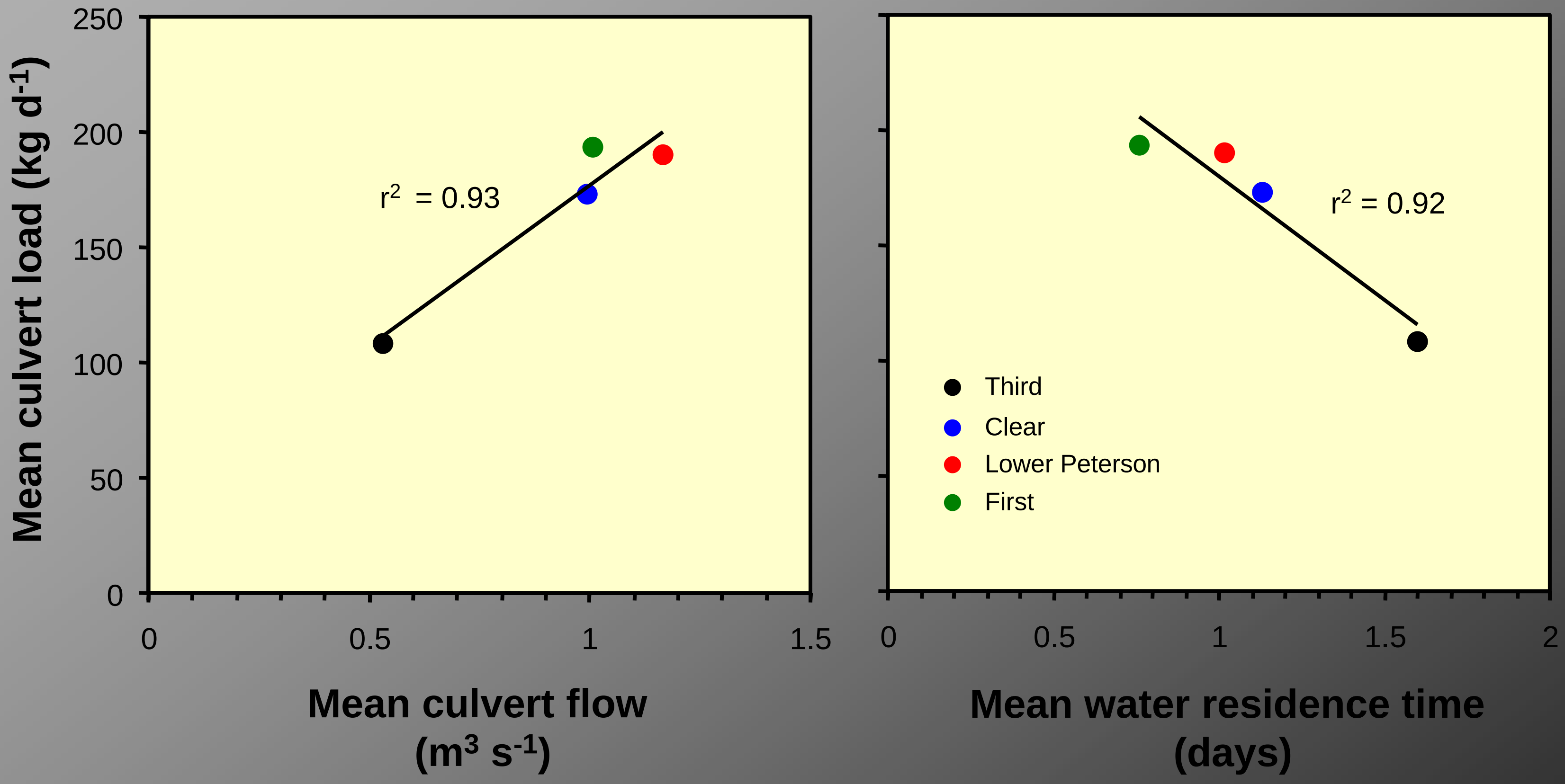

Pool 4 Dike
Upper Third Lake
Middle Third Lake
Lower Third Lake
0.1 Km
N
N-cycling process sites
Longitudinal sampling



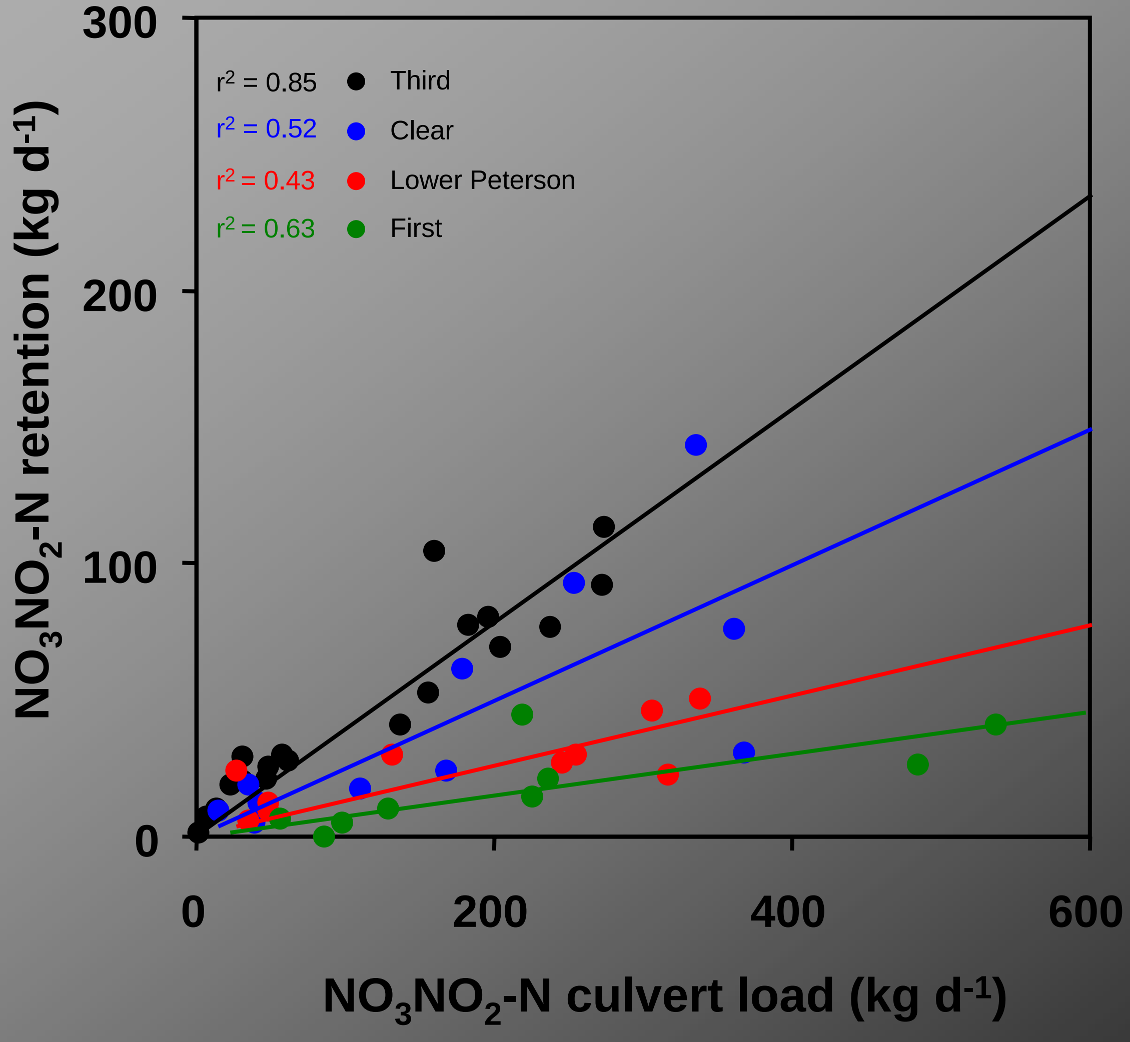
a)
Flow (m^3 s^{-1})
NO$_3$NO$_2$-N (mg L^{-1})
0
1000
2000
3000
0
2
4
6
8
b)
Finger Lakes Pool Elevation
Combined Culvert Flow
Elevation (m)
Flow (m^3 s^{-1})
200
201
202
203
204
205
206
207
208
0
2
4
6
8
10
12
May
Jun
Jul
Aug
Sep
Oct
Nov
2004

Summer Mean Inflow Characteristics

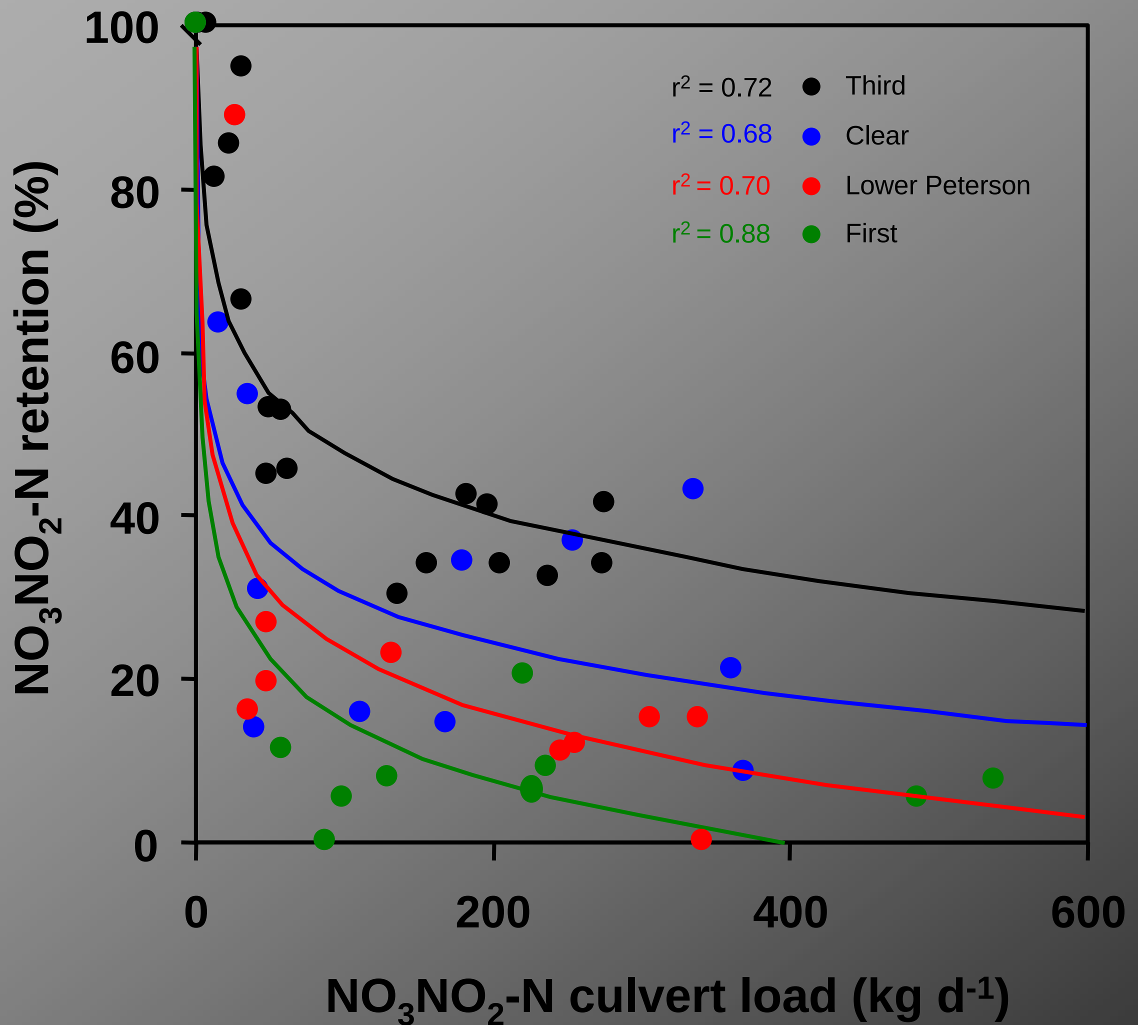




Mean culvert load (kg d-1)
250
200
150
100
50
0
r2 = 0.93
0
0.5
1
1.5
Mean culvert flow
(m3 s-1)
r2 = 0.92
Third
Clear
Lower Peterson
First
0
0.5
1
1.5
2
Mean water residence time
(days)

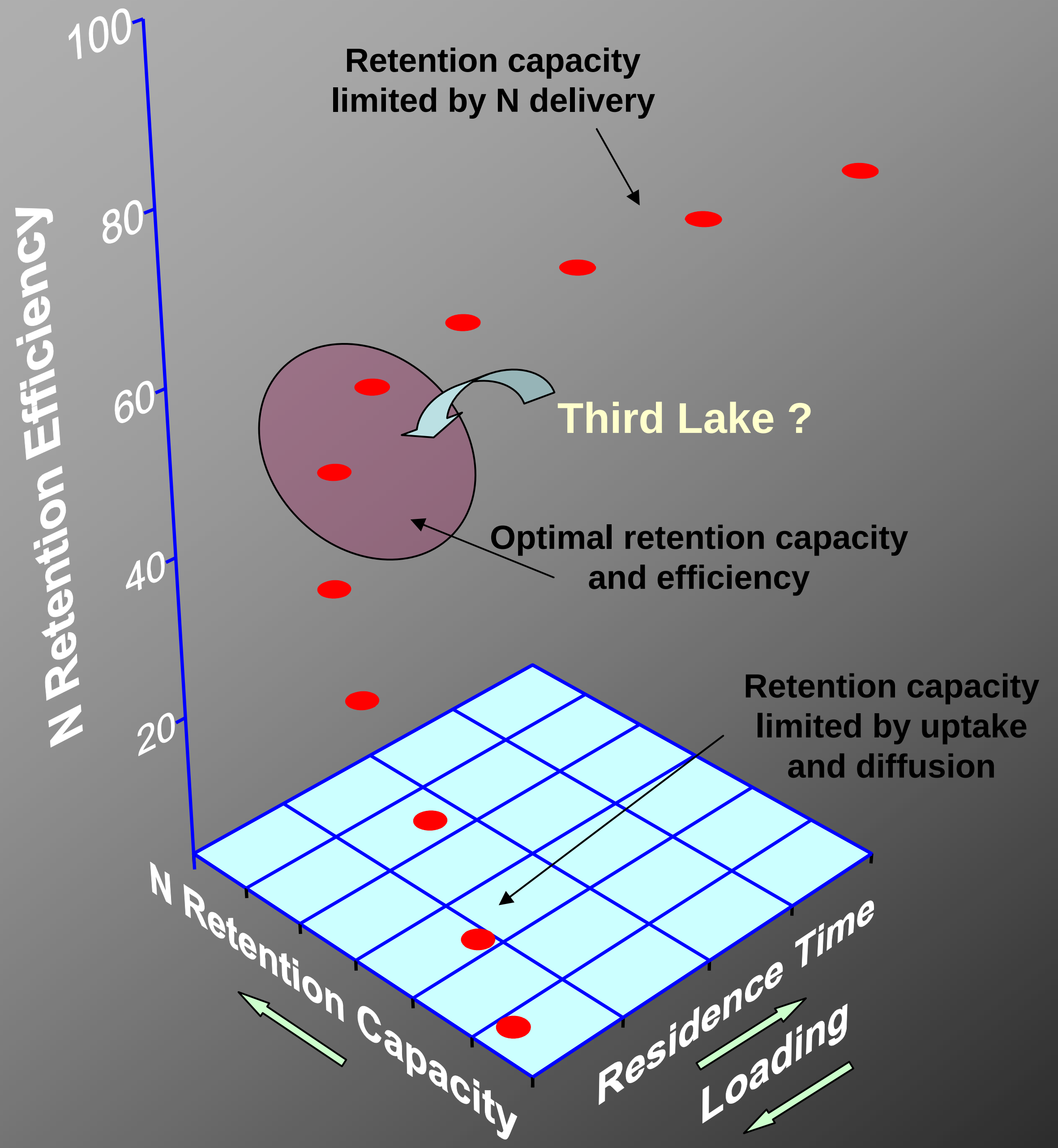


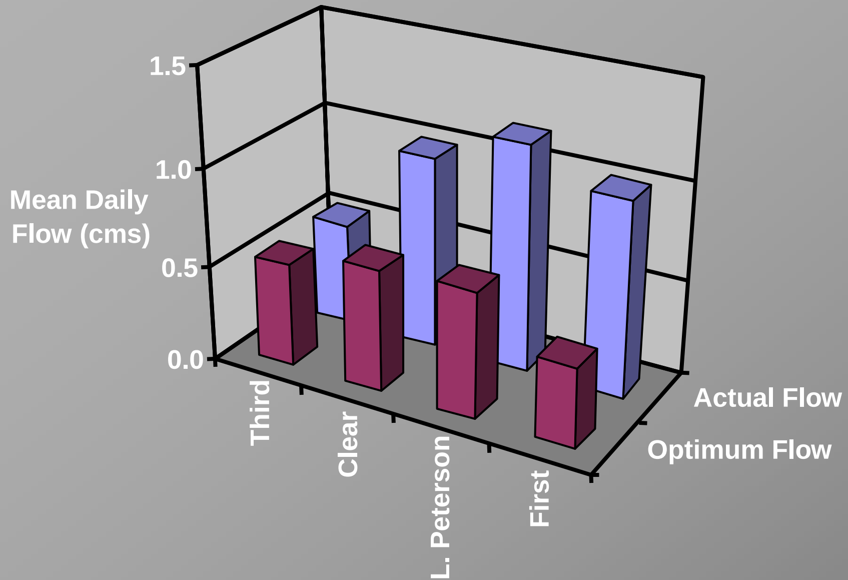
300
200
100
0
0
200
400
600
NO_3NO_2-N retention (kg d^{-1})
NO_3NO_2-N culvert load (kg d^{-1})
r^2 = 0.85
Third
r^2 = 0.52
Clear
r^2 = 0.43
Lower Peterson
r^2 = 0.63
First

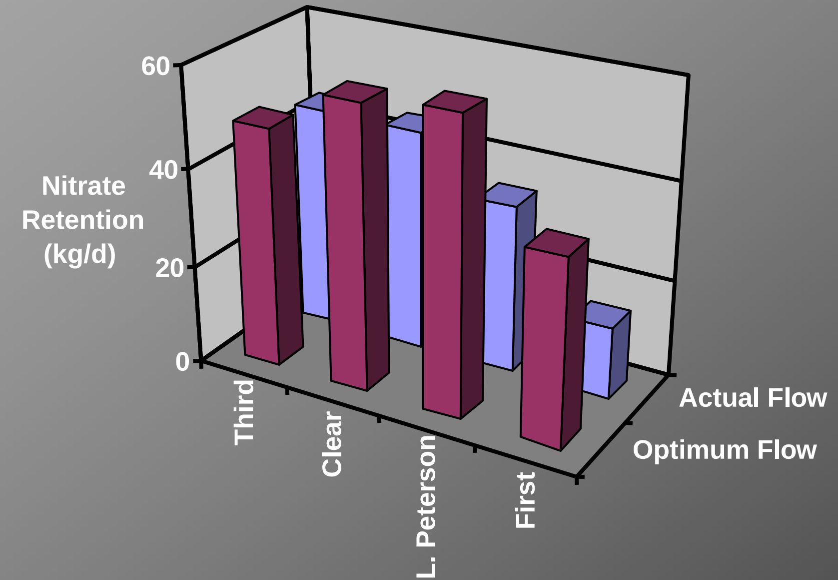


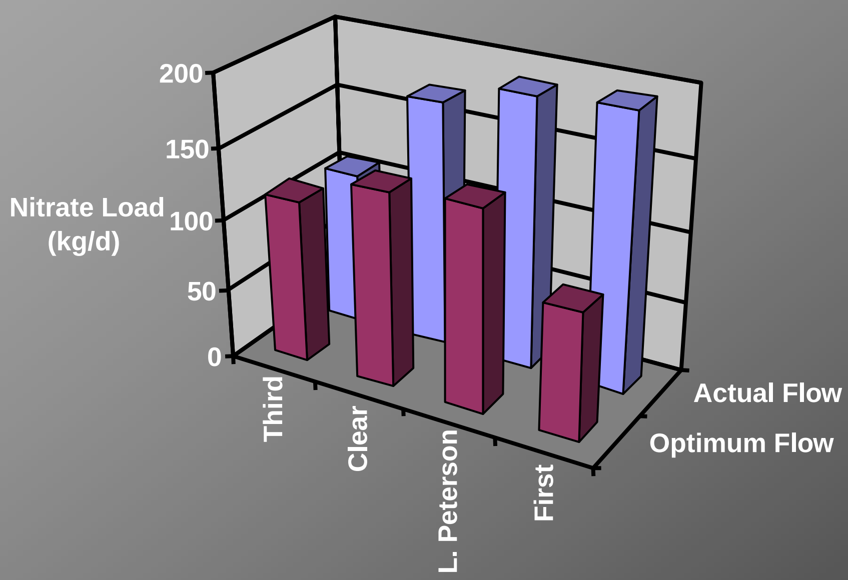
r2 = 0.72
Third
r2 = 0.68
Clear
r2 = 0.70
Lower Peterson
r2 = 0.88
First
100
80
60
40
20
0
0
200
400
600
NO3NO2-N retention (%)
NO3NO2-N culvert load (kg d-1)

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**


100
80
60
40
20
N Retention Efficiency
Retention capacity
limited by N delivery
Third Lake ?
Optimal retention capacity
and efficiency
Retention capacity
limited by uptake
and diffusion
N Retention Capacity
Residence Time
Loading



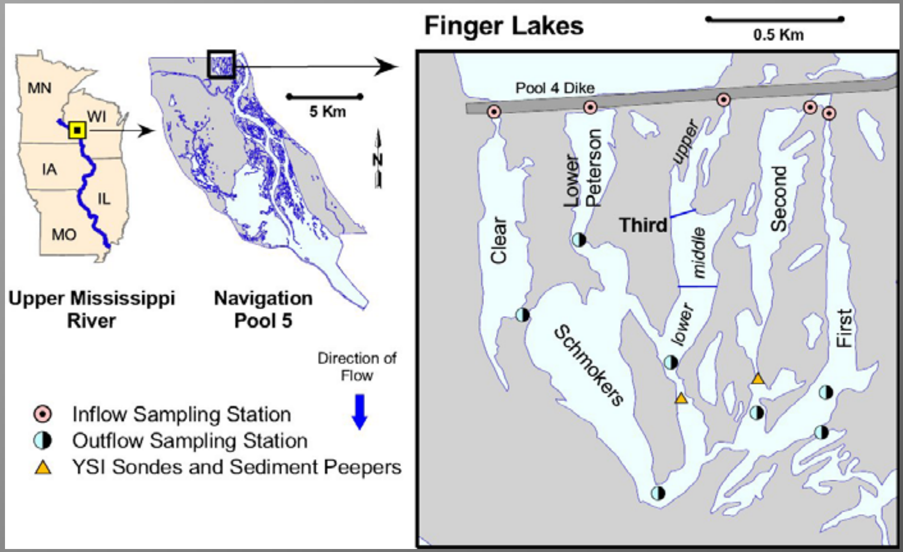




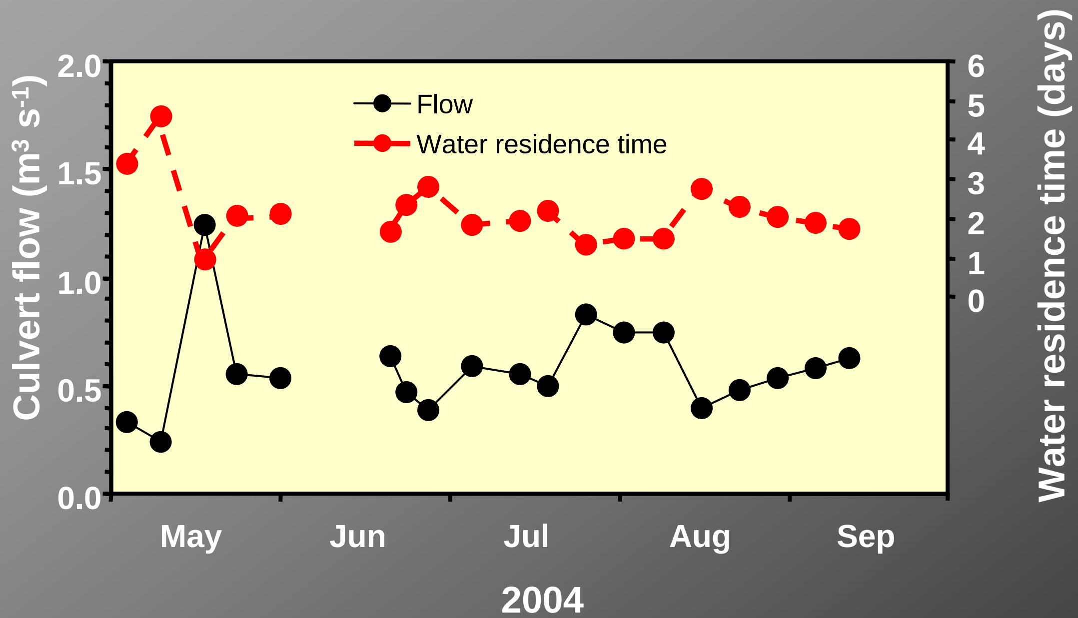
66% overall improvement in net nitrate retention capacity

Contrasts in Backwater Nitrate Retention

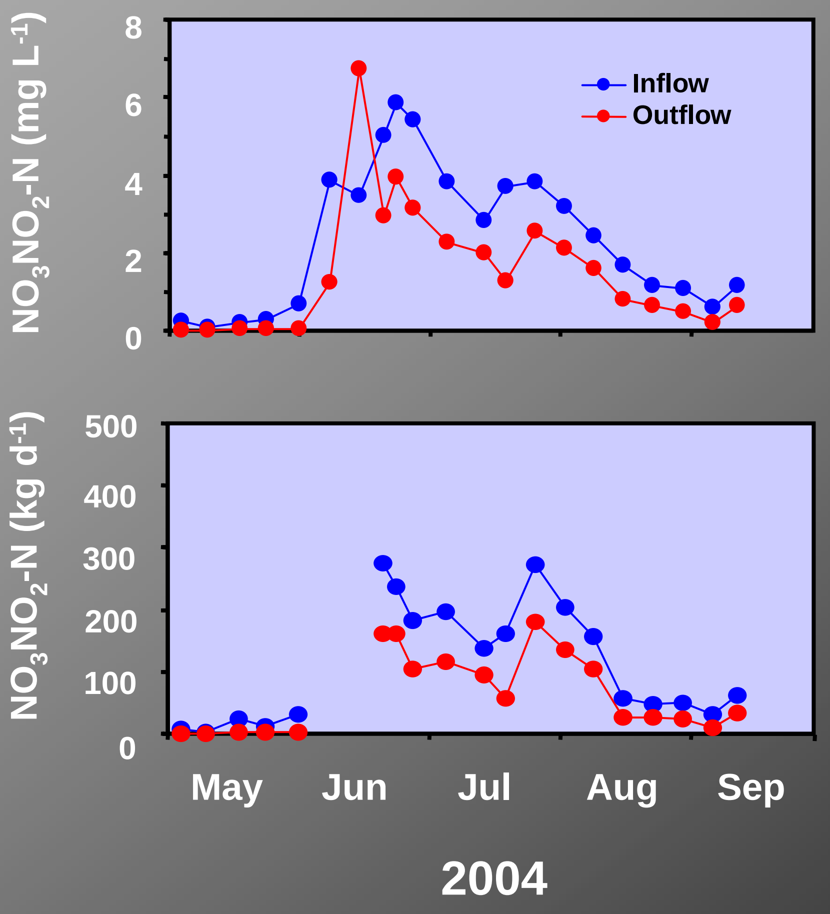
- Effects of varying mean residence time on mean nitrate retention efficiency and capacity (between-lake differences).
- Effects of varying nitrate load over a constant residence time on mean nitrate retention efficiency and capacity (within-lake variations).


Finger Lakes
0.5 Km
MN
WI
IA
IL
MO
5 Km
N
Upper Mississippi River
Navigation Pool 5
Direction of Flow
Inflow Sampling Station
Outflow Sampling Station
YSI Sondes and Sediment Peepers
Pool 4 Dike
Clear
Lower Peterson
upper
Third
middle
lower
Second
First
Schmokers

THIRD LAKE

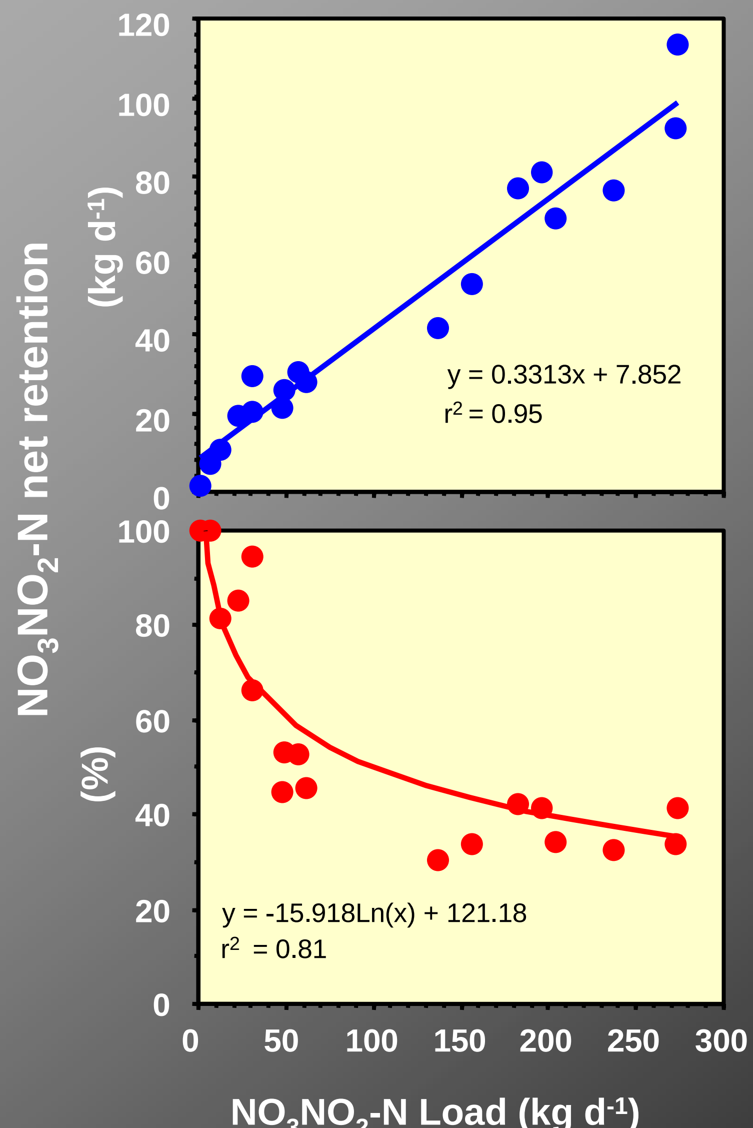

Flow
Water residence time
Culvert flow (m3 s-1)
Water residence time (days)
2.0
1.5
1.0
0.5
0.0
6
5
4
3
2
1
0
May
Jun
Jul
Aug
Sep
2004

THIRD LAKE

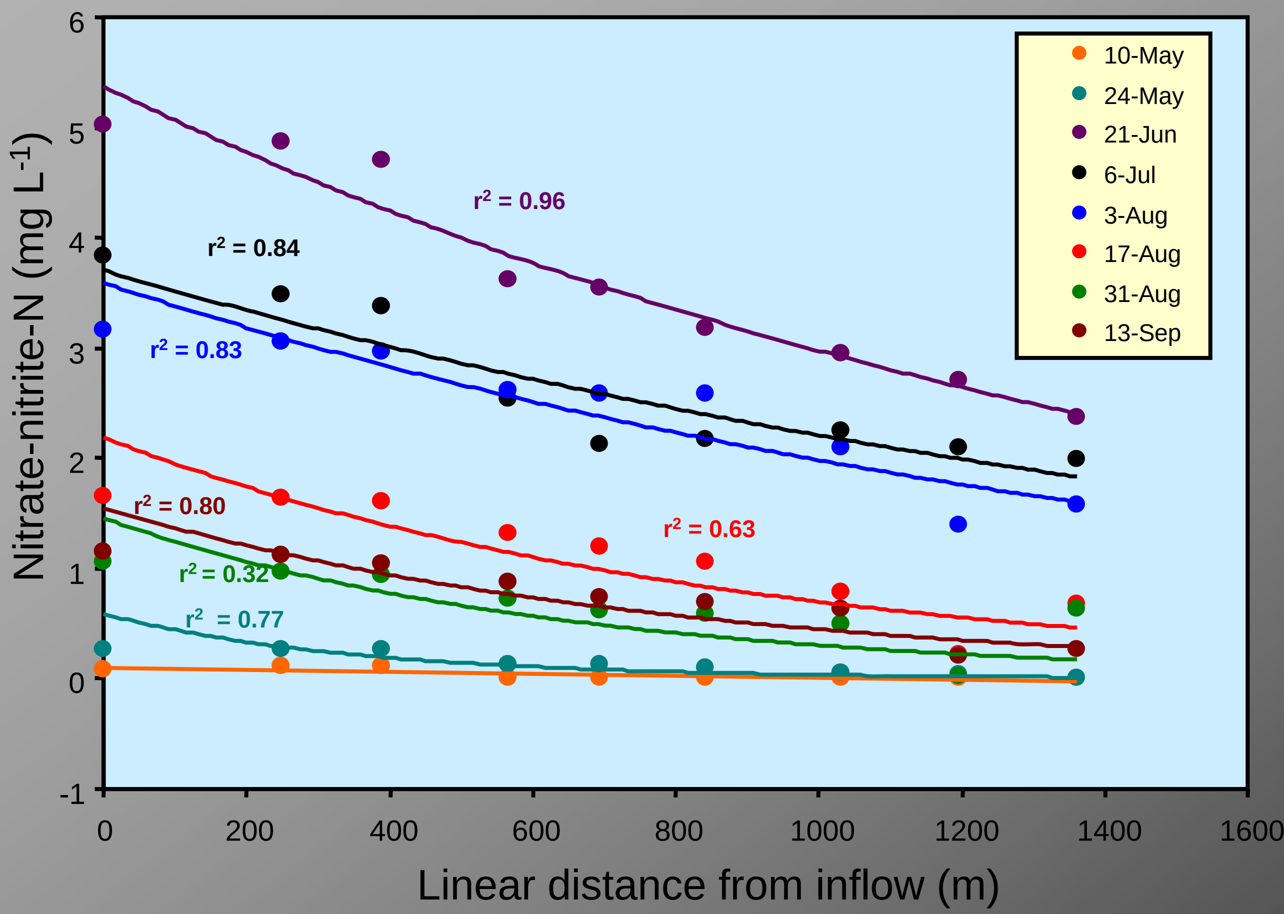


NO3NO2-N (mg L-1)
8
6
4
2
0
Inflow
Outflow
NO3NO2-N (kg d-1)
500
400
300
200
100
0
May
Jun
Jul
Aug
Sep
2004

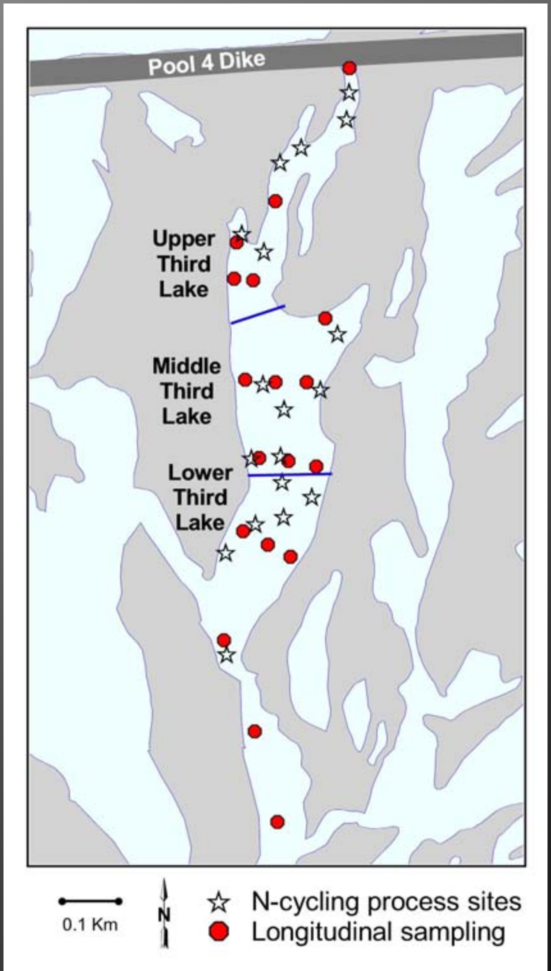
THIRD LAKE



NO3NO2-N net retention
(kg d-1)
(%)
120
100
80
60
40
20
0
y = 0.3313x + 7.852
r2 = 0.95
100
80
60
40
20
0
y = -15.918Ln(x) + 121.18
r2 = 0.81
0
50
100
150
200
250
300
NO3NO2-N Load (kg d-1)

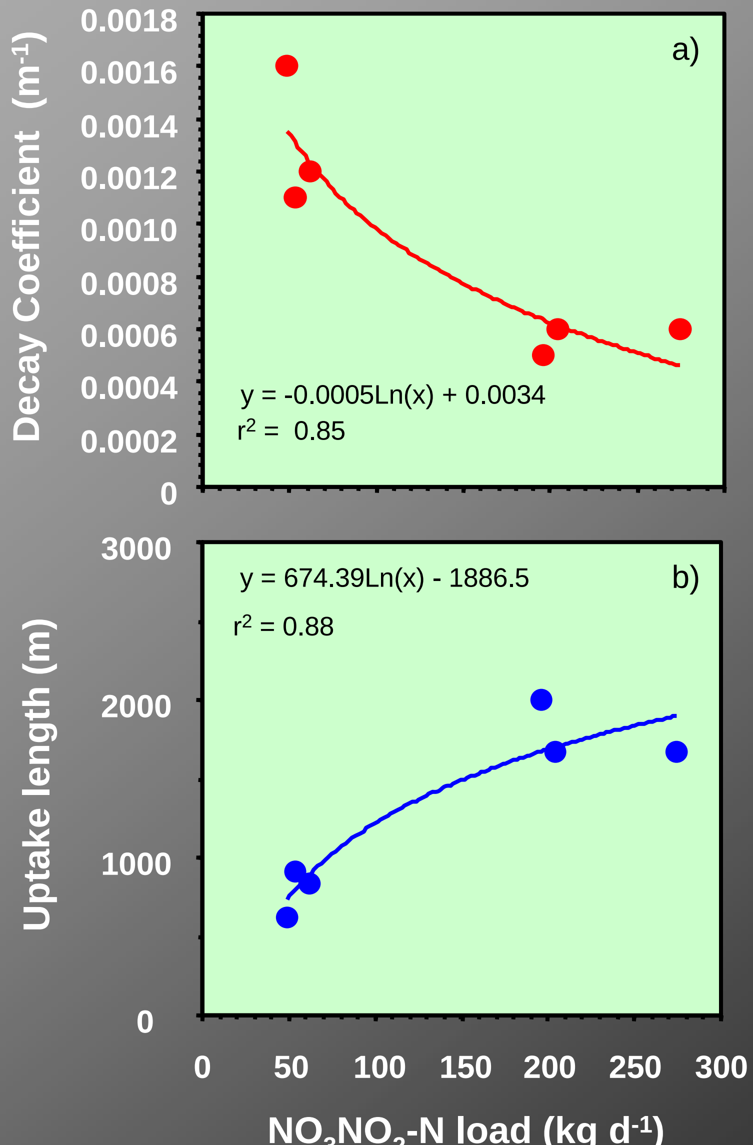


Nitrate-nitrite-N (mg L-1)
Linear distance from inflow (m)
10-May
24-May
21-Jun
6-Jul
3-Aug
17-Aug
31-Aug
13-Sep
r2 = 0.96
r2 = 0.84
r2 = 0.83
r2 = 0.80
r2 = 0.63
r2 = 0.32
r2 = 0.77



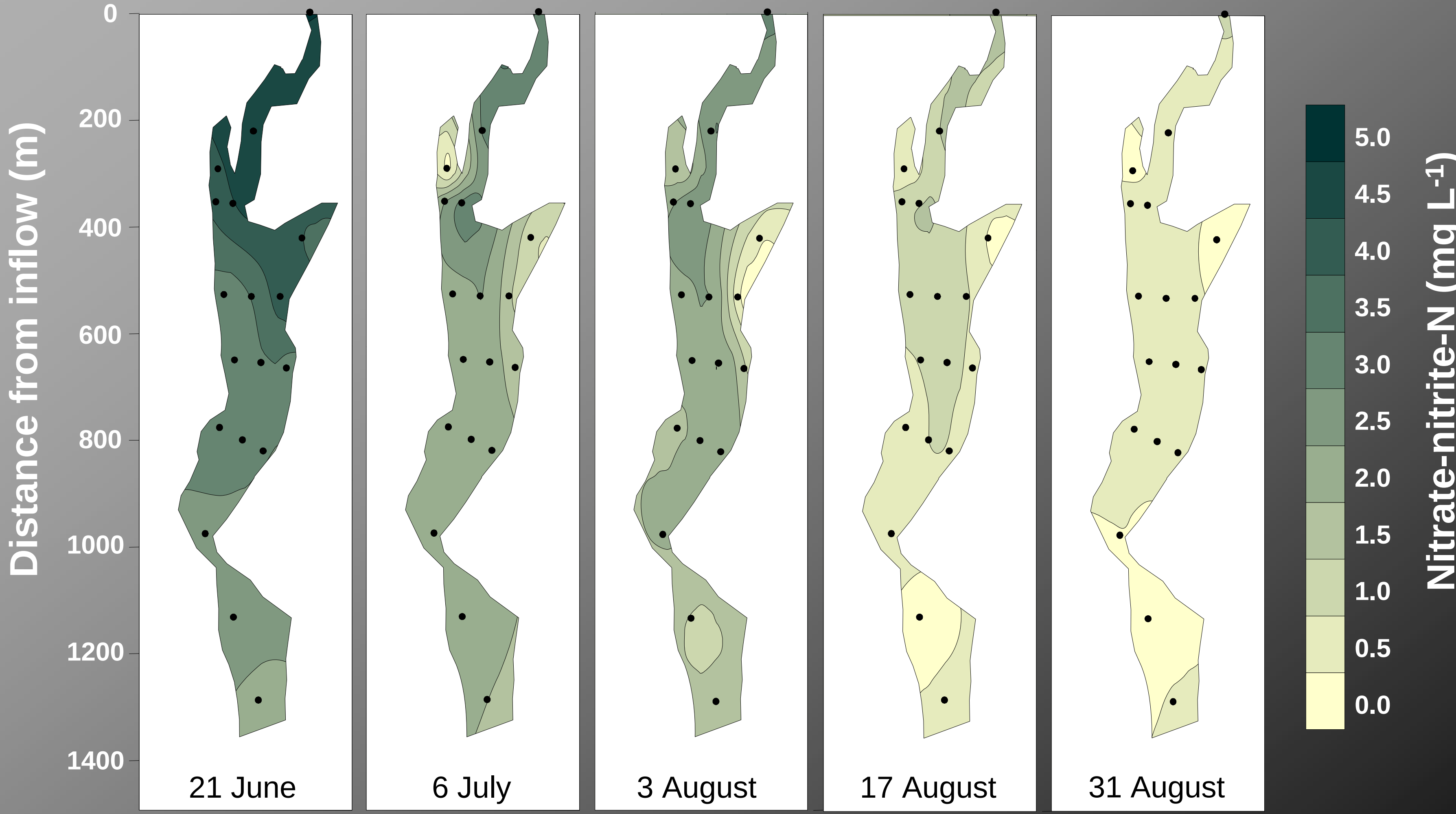
Pool 4 Dike
Upper Third Lake
Middle Third Lake
Lower Third Lake
0.1 Km
N
N-cycling process sites
Longitudinal sampling

THIRD LAKE



Decay Coefficient (m-1)
0.0018
0.0016
0.0014
0.0012
0.0010
0.0008
0.0006
0.0004
0.0002
0
a)
y = -0.0005Ln(x) + 0.0034
r2 = 0.85
Uptake length (m)
3000
2000
1000
0
y = 674.39Ln(x) - 1886.5
r2 = 0.88
b)
0
50
100
150
200
250
300
NO3NO2-N load (kg d-1)

SPATIAL VARIATIONS



2004

CONCLUSIONS

- N processing efficiency is high (> 40%) in backwaters of large river systems versus in the main channel (5 to 20%).
- Increasing connectivity between main channels and backwaters may improve overall in-stream N processing efficiency.
- Residence time, nutrient uptake length, and contact time regulate N processing efficiency in backwaters. These variables need to be considered in engineering designs to increase connectivity.

FUTURE RESEARCH

- The role of macrophyte structure and backwater morphometry in affecting residence time distribution and water displacement in backwaters.
- Improvement and use of hydrological and water quality models to explore management scenarios to increase large river-backwater connectivity and N processing efficiency