Anoxic and Oxic Release of P from Sediments in Minnesota Lakes

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Presentation Objectives

- Background on Internal P Release in Lakes
  - Sediment P sources
  - Release mechanisms
  - Shallow versus deep lakes

- Minnesota Lakes P Release
  - Release rate methods
  - Shallow and Deep Lakes
  - Anoxic and oxic P release

- TMDL Modeling
  - Estimating internal loads
What is a Total Maximum Daily Load (TMDL)?

- The maximum amount of a pollutant that a water body can receive and still meet water quality standards

- For lakes, focus is on the phosphorus budget
  - External sources
  - Internal P recycling
  - Atmospheric deposition

\[
\text{TMDL} = LC = \sum LA + \sum WLA + MOS
\]
Sediment P Release

Sondergaard et al. 2001

P-forms in the sediment:
- Dissolved (PO$_4$, organic P)
- Particulate
  - Iron: Fe (III) hydroxides, Fe (OOH), (ads.)
    Strengite, Fe PO$_4$
    Vivianite, Fe$_3$ (PO$_4$)$_2$ 8 H$_2$O
  - Alum: Al (OH)$_3$ (ads.)
    Variscite, Al PO$_4$
  - Calcium: Hydroxyapatite, Ca$_{10}$ (PO$_4$)$_6$ OH$_2$
    Monetite, Ca H PO$_4$
    Calcite (ads.)
  - Clay: (ads.)
  - Organic: "Labile"
    "Refractory"
## Sediment Phosphorus Fractions

<table>
<thead>
<tr>
<th>Variable</th>
<th>Extractant</th>
<th>Recycling Potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loosely-bound P</td>
<td>1 M Ammonium Chloride</td>
<td>Biologically labile; recycled via eH and pH reactions and equilibrium processes</td>
</tr>
<tr>
<td>Iron-bound P</td>
<td>0.11 M Sodium Bicarbonate-dithionate</td>
<td>Biologically labile; recycled via eH and pH reactions and equilibrium processes</td>
</tr>
<tr>
<td>Labile organic P</td>
<td>Persulfate digestion of the NaOH extraction</td>
<td>Biologically labile; recycled via bacterial mineralization of organic P and mobilization of polyphosphates stored in cells</td>
</tr>
<tr>
<td>Aluminum-bound P</td>
<td>0.1 N Sodium Hydroxide</td>
<td>Biologically refractory</td>
</tr>
<tr>
<td>Calcium-bound P</td>
<td>0.5 N Hydrochloric Acid</td>
<td>Biologically refractory</td>
</tr>
<tr>
<td>Refractory organic P</td>
<td>Determined by subtraction of other forms from total P</td>
<td>Biologically refractory</td>
</tr>
</tbody>
</table>

Redox-sensitive P
Generalized Lake Ecosystem
(Summertime Average Conditions)

Epilimnion (Mixed Layer) - warm, light water
Metalimnion - 0-4 meters
Hypolimnion (cool, heavy water) - 4-17 meters
Thermocline (prevents mixing)

Diagram not to scale
Internal Loading in Deep Lakes

Hafften DW 2004

TP (ug/L)

0  200  400  600  800  1000  1200

1/1  2/1  3/3  4/3  5/4  6/4  7/5  8/5  9/5  10/6  11/6  12/7
Internal Nutrient Cycles in Shallow Lakes

- Complex oxygen cycles in shallow lakes
  - Increased sediment area
- Shallowness makes phosphorus release readily available for algal production
  - Increased interaction with photic zone
  - Readily mixed due to lack of temperature stratification
- Internal loading in clear water, submersed vegetation dominated shallow lakes poorly understood
Bottom and Surface Dissolved Phosphorous

<table>
<thead>
<tr>
<th>Date</th>
<th>Bottom DP (mg/l)</th>
<th>Surface DP (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-May</td>
<td></td>
<td></td>
</tr>
<tr>
<td>31-May</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30-Jun</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30-Jul</td>
<td></td>
<td></td>
</tr>
<tr>
<td>29-Aug</td>
<td></td>
<td></td>
</tr>
<tr>
<td>28-Sep</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Why Laboratory Experiments?

- **Controlled conditions**
  - Temperature
  - Dissolved oxygen and redox
  - pH (primarily for P release under oxic conditions)
  - Manipulations

- **Insufficient lake data to build a P budget**
  - Lack good watershed data
  - No hypolimnetic monitoring
  - Rapid results from lab estimates

- **Questions about the results of a mass balance or modeling effort**
Sediment Core Collection
Core Processing

- Upper 10 cm transferred to an incubation sleeve
- Preconditioned filtered lake water slowly siphoned onto the sediment
Diffusive Phosphorus Flux

- Aerobic versus anaerobic conditions
  - Gas air stones with a nominal pore size
  - Gas flow rate control
  - Uniformly mixes overlying water column
  - Creates a diffusive boundary layer
  - Oxic-anoxic conditions created by gentle purging with air or nitrogen gas

- Incubated under “summer” temperature conditions
- Temperature-controlled environmental chambers
Anoxic P Release

Upper Lunsten
Anoxic P Release Rate

Lower Lunsten
Anoxic P Release Rate

East Auburn
Anoxic P Release Rate
Oxic P Release

Marsh
Oxic P Release Rate

Mud
Oxic P Release Rate

Wasserman
Oxic P Release Rate

Phosphorus (mg)

Phosphorus (mg/L)

Days
Study Lakes

- 61 Lakes Sampled
  - 70 Anoxic release sites
  - 25 Oxic release
- Lakes sampled as a part of TMDL studies or other lake diagnostic studies
- Majority Fall in North Central Hardwood Forest Ecoregion
Anoxic versus Oxic P Release

Sediment Phosphorus Release

P Release Rate (mg/m²/day)

- Anoxic Release
- Oxic Release
Sediment Phosphorus Release under Anoxic Conditions

Anoxic P Release (mg/m²/day)

- Shallow Lakes Winter
- Shallow Lakes Summer
- Deep Lakes Winter
- Deep Lakes Summer
Sediment Phosphorus Release under Oxic Conditions

Oxic P Release (mg/m²/day)

- Shallow Lakes Winter
- Shallow Lakes Summer
- Deep Lakes Winter
- Deep Lakes Summer
Sediment Phosphorus Release under Anoxic Conditions

Shallow Lakes vs Deep Lakes
# Shallow Lakes with Healthy Plant Community

<table>
<thead>
<tr>
<th>Lake</th>
<th>County</th>
<th>State</th>
<th>Ecoregion</th>
<th>Oxic P Release (mg/m²d)</th>
<th>Anoxic P Release (mg/m²d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower Lunsten</td>
<td>Carver</td>
<td>MN</td>
<td>NCHF</td>
<td>0.3</td>
<td>2.2</td>
</tr>
<tr>
<td>Oneka</td>
<td>Washington</td>
<td>MN</td>
<td>NCHF</td>
<td>--</td>
<td>0.2</td>
</tr>
<tr>
<td>McKusick</td>
<td>Washington</td>
<td>MN</td>
<td>NCHF</td>
<td>--</td>
<td>2.4</td>
</tr>
<tr>
<td>Neill</td>
<td>Hennepin</td>
<td>MN</td>
<td>NCHF</td>
<td>--</td>
<td>3.5</td>
</tr>
<tr>
<td>Schmidt - Shallow</td>
<td>Hennepin</td>
<td>MN</td>
<td>NCHF</td>
<td>--</td>
<td>1.3</td>
</tr>
<tr>
<td>Marsh</td>
<td>Carver</td>
<td>MN</td>
<td>NCHF</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>
Healthy Plant Community

Turbid Water State

Shallow Lake Anoxic Phosphorus Release

P Release Rate (mg/m²/day)
Importance of Internal Loading in Lake TMDLs

- Important source of phosphorus to surface waters
  - Often as-large or larger than external loads
  - Need to identify magnitude of source
  - Need to identify cause of internal loading

- Need to establish load allocation
  - What is a sustainable load? Background load?
  - Can the lake meet water quality standards without internal load reduction?
Initial modeling identified a residual load of >800 lbs/year
- Initially attributed to internal loading
- Evidence supported this conclusion due to high bottom water concentrations of TP

MCWD initiated a Diagnostic study to:
- Confirm internal loading key driver in Parley Lake
- Develop internal load control options
Parley Lake Conclusions

- Internal load was determined to be <20% of the total P budget
  - Verified by internal release rate study and good DO data
- Focus of restoration shifted to upstream lakes and tributaries and biological conditions
Ann and Fish Lake TMDL

- 2 years continuous flow and water quality data
  - Average inflow to Ann Lake was 49 µg/L TP

- Large model residual in Ann and Fish Lake
  - Internal load in Ann Lake validated by release rate study
    - 15 mg/m2/day
  - Only partially explained residual in Fish Lake
    - Decreased settling due to depth and flushing
<table>
<thead>
<tr>
<th>Ann Lake</th>
<th>Fish Lake</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface Area (acres)</strong></td>
<td>773</td>
</tr>
<tr>
<td><strong>Average Depth (ft)</strong></td>
<td>6.5</td>
</tr>
<tr>
<td><strong>Maximum Depth (ft)</strong></td>
<td>17</td>
</tr>
<tr>
<td><strong>Volume (acre-feet)</strong></td>
<td>5,029</td>
</tr>
<tr>
<td><strong>Residence Time (years)</strong></td>
<td>0.18</td>
</tr>
<tr>
<td><strong>Littoral Area (acres)</strong></td>
<td>710</td>
</tr>
<tr>
<td><strong>Littoral Area (%)</strong></td>
<td>92%</td>
</tr>
<tr>
<td><strong>Watershed (km2/ounces)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Mixing Depth (ft)</strong></td>
<td>17</td>
</tr>
<tr>
<td><strong>Volume (acre-feet)</strong></td>
<td>2,009</td>
</tr>
<tr>
<td><strong>Residence Time (years)</strong></td>
<td>0.05</td>
</tr>
<tr>
<td><strong>Littoral Area (acres)</strong></td>
<td>418</td>
</tr>
<tr>
<td><strong>Littoral Area (%)</strong></td>
<td>100%</td>
</tr>
<tr>
<td><strong>Watershed (km2/ounces)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Mixing Depth (ft)</strong></td>
<td>10</td>
</tr>
</tbody>
</table>

Ann Lake flushes about 6 times a year
Every 2 months

Fish Lake flushes almost 22 times a year
Every 2 weeks
## Internal Load Estimate

### Ann Lake

<table>
<thead>
<tr>
<th>year</th>
<th>Release Rate (mg/m²/day)</th>
<th>AF</th>
<th>Gross Load (mg/m²/summer)</th>
<th>kilograms</th>
<th>pounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993</td>
<td>15</td>
<td>2</td>
<td>29</td>
<td>92</td>
<td>202</td>
</tr>
<tr>
<td>2008</td>
<td>15</td>
<td>6</td>
<td>90</td>
<td>282</td>
<td>620</td>
</tr>
<tr>
<td>2009</td>
<td>15</td>
<td>12</td>
<td>184</td>
<td>576</td>
<td>1,267</td>
</tr>
<tr>
<td>Oxic</td>
<td>0.2</td>
<td>NA</td>
<td>24</td>
<td>76</td>
<td>168</td>
</tr>
<tr>
<td>Shallow</td>
<td>15</td>
<td>52</td>
<td>783</td>
<td>2449</td>
<td>5,388</td>
</tr>
</tbody>
</table>

### Fish Lake

<table>
<thead>
<tr>
<th>year</th>
<th>Release Rate (mg/m²/day)</th>
<th>AF</th>
<th>Gross Load (mg/m²/summer)</th>
<th>kilograms</th>
<th>pounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>5.4</td>
<td>16</td>
<td>85</td>
<td>144</td>
<td>317</td>
</tr>
<tr>
<td>2009</td>
<td>5.4</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Oxic Release</td>
<td>0.3</td>
<td>NA</td>
<td>37</td>
<td>62</td>
<td>136</td>
</tr>
<tr>
<td>Shallow</td>
<td>5.4</td>
<td>64</td>
<td>343</td>
<td>581</td>
<td>1,277</td>
</tr>
</tbody>
</table>
Conclusions

- Internal P release is an important P source to lakes
  - Must be quantified as a part of any TMDL or diagnostic study
- Laboratory P release studies provide measured estimates of internal loading
  - Better prediction than using model residuals
  - Provide reference release rates for setting TMDL allocations
Questions?
Hypolimnetic Oxygenation in Lake Vadnais

By: Roger Scharf, John Blackstone, John Borghesi, James Bode, Paul Gantzer, David Austin
Outline

- Background
- Old Aeration System
- Hypolimnetic Oxygenation System Design
- New Hypolimnetic Oxygenation System Performance
Background: SPRWS

- St Paul Regional Water Services (SPRWS)
  - McCarrons Water Treatment Plant
  - Average Daily Flow = 43 MGD
  - Maximum Flow = 126 MGD
  - ~92,000 Metered Accounts
  - 400,000+ People Served
Background: SPRWS Supply

- **Source Water**
  - Mississippi River (80-95%)
  - Local Watersheds (5-20%)
Background: Lake Vadnais

- Lake Vadnais
  - Area 385 Acres
  - Average depth 7.7 m
  - Max depth 17.6 m
  - HRT 69 days
Project Objectives

control nutrients $\rightarrow$ control cyanobacteria $\rightarrow$ control taste and odor

Nutrient Release from Sediments

Blue-Green Algae

Intake Pipe

Taste and Odor Compounds
Redox management (for sediments rich in Fe)

FeO(OH):PO$_4$

D.O. > 2 - 5 mg/L

Inject O$_2$ or NO$_3$ ...

to create F(III) cap

... and keep these compounds in sediment.
Historical Aeration System

- Partial Lift Aeration System with Ferric Iron Injection
- Installed in 1988
- Required Divers for Maintenance
- Aerators recycle hypolimnion every 4 days
Summer 2010 Dissolved Oxygen Performance

Lake Vadnais - Aerator Operational

Pleasant Lake - Aerator NOT Operational
Summer 2010 ORP Performance

Lake Vadnais - Aerator Operational

Pleasant Lake - Aerator NOT Operational
Historical Aeration System Performance

1984-1996 10 m Lake Vadnais Orthophosphate Concentration

Orthophosphate (ug/L)

Date


Hypolimnetic aeration started
Hypolimnetic Oxygenation Design

- Key Design Parameter is Hypolimnetic Oxygen Demand
  - *In Situ* Sediment Oxygen Demand
  - *Ex Situ* Sediment Oxygen Demand
  - Hypolimnion Oxygen Mass Regression Analysis
Sediment Oxygen Demand

- Isolation chamber
- D.O. probe
- Mixer
- Meter, data logging

Graph:
- D.O. (mg/L) vs. Time (minutes)

Images:
- People working on a barge
- Lake and wooded area
Hypolimnetic Oxygen Demand

- **SOD**
  - 3.7 g-O$_2$/m$^2$ d

- **HOD = SOD x Area of Hypolimnion**
  - 3,444 kg/d
  - 4,374 kg/d with Sediment and Community Oxygen Demand

- **HOD: Mass Regression**
  - 700 kg/d
  - 2,660 kg/d with Turbulence from Diffusers Induced Demand
Linear Diffuser Layout

- Advantages
  - Wide operating range (0-200% of design)
  - Experience with zebra mussels
  - All maintenance can be done on shore or from a boat
  - Well documented project history
  - Minimal mechanical equipment
  - Minimal power use with LOX
  - Lowest equipment cost
Oxygen Supply

• 9,000 Gallon Oxygen Storage

• Twin 10,000 SCFH Vaporizers
Flow Control
Constructed On Site
Supply Lines
Diffusers Checked for Damage
Diffusers Moved Into Position
Controlled Sinking of Diffusers
Operational
Project Objectives

control nutrients → control cyanobacteria → control taste and odor
Dissolved Oxygen Performance

2010 – Partial Lift Aerator Operational  2012 – Linear Diffuser Operational
Lake Vadnais Hypolimnion Total Iron

New System Installed
Lake Vadnais Hypolimnion Total Phosphorus

New System Installed
Lake Vadnais Epilimnion Total Phosphorus

New System Installed
Questions?