Phosphorus Dynamics in the Saginaw Bay Ecosystem

Presentation to Phosphorus Committee of the Saginaw Bay Coastal Initiative
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1970’s and 80’s: Meeting target phosphorus loads established by GLWQA

1990’s and 2000’s: Apparent reversion to historical problems
- Dreissenid invasion of Saginaw Bay beginning in 1991
- Reoccurrence of *Microcystis* cyanophyte blooms
- Reoccurrence of nearshore attached nuisance algae (*Cladophora*)
- Reoccurrence of “muck” washing up on shoreline

Evaluation of cause-effect relationships for recent observations
1970’s and 1980’s: Successful achievement of TP target load and associated water quality improvements
1972 Great Lakes Water Quality Agreement and Annex 3 Focused on Eutrophication

- Public concern leads to political action
- 1972 signing of Binational Great Lakes Water Quality Agreement (GLWQA)
  - “restore and maintain the chemical, physical, and biological integrity of the Great Lakes Basin Ecosystem.”
- Annex 3 (1978)
  - Implicated phosphorus as primary cause of nuisance algal growth
  - phosphorus concentrations “…should be limited to the extent necessary to prevent nuisance growths of algae, weeds and slimes that are or may become injurious to any beneficial water use.”
  - “year-round aerobic conditions in bottom waters of the central basin of Lake Erie”
  - Initiated efforts to reduce phosphorus loads
  - Established targets phosphorus loads to control eutrophic conditions
Task Group III models used to establish Annex 3 target P loads

- **Vollenweider (all basins)**
  - Empirical
  - Steady-state

- **Chapra (all basins)**
  - Semi-empirical
  - Dynamic TP mass balance
  - Chlorophyll $a$ and DO empirically correlated with TP

- **Thomann Lake I model (Lake Ontario and Lake Huron)**
  - Process model
  - Dynamic MB of P, N, chlorophyll, zooplankton

- **DiToro Lake Erie model**
  - Process model
  - Dynamic MB of P, N, Si, DO, diatom and non-diatom chlorophyll, zooplankton

- **Bierman Saginaw Bay model**
  - Process model
  - Dynamic MB of P, N, Si, five phytoplankton groups, zooplankton
Original Saginaw Bay Eutrophication Model - used for establishing target TP Load
<table>
<thead>
<tr>
<th>Basin</th>
<th>1976 TP Load (mta)</th>
<th>Target TP Load (mta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lake Superior</td>
<td>3600</td>
<td>3400</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>6700</td>
<td>5600</td>
</tr>
<tr>
<td>Main Lake Huron</td>
<td>3000</td>
<td>2800</td>
</tr>
<tr>
<td>Georgian Bay (LH)</td>
<td>630</td>
<td>600</td>
</tr>
<tr>
<td>North Channel (LH)</td>
<td>550</td>
<td>520</td>
</tr>
<tr>
<td>Saginaw Bay (LH)</td>
<td>870</td>
<td>440</td>
</tr>
<tr>
<td>Lake Erie</td>
<td>20000</td>
<td>11000*</td>
</tr>
<tr>
<td>Lake Ontario</td>
<td>11000</td>
<td>7000*</td>
</tr>
</tbody>
</table>

* Require 1 mg/L PS effluent + 50% diffuse source reduction or 0.5 mg/L PS effluent + 30% diffuse source reduction
Saginaw Bay Phytoplankton Model Post-audit
(from Bierman and Dolan 1986)
1990’s - present:
Reoccurrence of water quality problems
Return of *Microcystis* Blooms to Great Lakes embayments, including Saginaw Bay

- Colonial harmful algal bloom species (HAB)
- Forms blooms and scums
  - Taste/odor issues
  - Loss of recreational and fishing value to affected waters
  - Hypoxia/anoxia, may lead to mortality in benthic invertebrate community and fish kills
  - Potential production of hepatotoxin - microcystin
NOAA-GLERL Conducted Bay Sampling from 1991 - 1996
Temporal Variations in Monthly Avg. Phytoplankton Cell Densities

Blue-Greens

Greens

Cells/mL

Date
Temporal Variations in Monthly Avg. Phytoplankton Cell Densities

**Diatoms**

- Cells/mL
- Date:
  - 10/1990
  - 5/1991
  - 7/1991
  - 8/1991
  - 9/1991
  - 11/1991
  - 9/1992
  - 7/1992
  - 10/1992
  - 8/1992
  - 9/1993
  - 10/1993
  - 8/1994
  - 8/1995
  - 10/1995
  - 7/1996
  - 8/1996
  - 9/1996
  - 10/1996

**Dinoflagellates**

- Cells/mL
- Date:
  - 10/1990
  - 5/1991
  - 7/1991
  - 8/1991
  - 9/1991
  - 11/1991
  - 9/1992
  - 7/1992
  - 10/1992
  - 8/1992
  - 9/1993
  - 10/1993
  - 8/1994
  - 8/1995
  - 10/1995
  - 7/1996
  - 8/1996
  - 9/1996
  - 10/1996
  - 8/1997
Return of “Muck” to the Bay Shoreline

“Muck” along shoreline at Bay City State Park
Return of Benthic Algae Blamed for “Muck”

Photo by B. Lafrancois, Sleeping Bear Dunes
1990’s - present: Has the phosphorus loading caused the problems?

- **1991-1992**
  26 sites (18 inner, 8 outer)

- **1991-1996**
  13 sites (8 inner, 5 outer)

- **1974 - 1980**
  sampled by EPA & others
  (Smith et al. 1977)
  (Bierman et al. 1984)
Figure 3. Box and Whisker Plot of Total Phosphorus Data by Year. Boxes show upper and lower data quartiles; the central solid line represents the median. Whiskers represent 1.5 times the interquartile range, up to the maximum and minimum data values.

Environment Canada

Michigan Department of Environmental Quality

Target concentration 0.015 mg/L
Long Term Data Set for Saginaw River Total Phosphorus

Total Phosphorus - Saginaw River

- Essexville
- Saginaw-Center
- Saginaw-Rust
- Bay City

Concentration (mg/L)

Year:
- 1970
- 1975
- 1980
- 1985
- 1990
- 1995
- 2000
- 2005
Long Term Data Set for Saginaw River Orthophosphate

Total Orthophosphate

- Essexville
- Saginaw-Center
- Saginaw-Rust

Concentration (mg/L)

- 0.8
- 0.7
- 0.6
- 0.5
- 0.4
- 0.3
- 0.2
- 0.1
- 0

Year:
- 1970
- 1975
- 1980
- 1985
- 1990
- 1995
- 2000
- 2005
TP Concentration and Load Relationship to Flow
(All data from 1990 to 2005)
Saginaw River Load Estimates

- **MDEQ: Stratified Beale Ratio**, using single year data

- Regression approach using all 1998-2005 data:
  - Concentration as linear function of Q and season
  - Concentration as linear function of Q and antecedent 5-day average flow

\[
L_{Beale} = \overline{Q} \left( \frac{\overline{L}}{\overline{Q_L}} \right) \left[ 1 + \frac{S_{LQ}}{N\overline{LQ}_L} \right] \left[ 1 + \frac{S_{QQ}}{N\overline{Q}^2} \right]
\]
1997-2006 Saginaw River Load

Saginaw River Annual TP Load Estimates

GLWQA Saginaw Bay phosphorus target load

Annual Load (Metric Tons)

Annual Discharge (Mcm)

4 Seasons
3 Seasons
Annual+PF
MDEQ
Discharge
## Saginaw Bay TP Annual Load (2004-06)?

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Saginaw</td>
<td>16,680</td>
<td>71.6</td>
<td>110-127</td>
<td>15.3 – 38.2</td>
<td>673-758</td>
<td>288-459</td>
<td>746-829</td>
</tr>
<tr>
<td>AuGres/Rifle</td>
<td>2,777</td>
<td>11.9</td>
<td>3.7-4.6</td>
<td>2.6-3.5</td>
<td>112-126</td>
<td>47-76</td>
<td>124-138</td>
</tr>
<tr>
<td>KawKawlin/Pine</td>
<td>1,409</td>
<td>6.0</td>
<td>5.1-6.4</td>
<td>3.7-4.3</td>
<td>57-64</td>
<td>24-38</td>
<td>63-70</td>
</tr>
<tr>
<td>Pigeon/Wiscoggin</td>
<td>2,425</td>
<td>10.5</td>
<td>9.8-10.8</td>
<td>6.7-8.0</td>
<td>97-110</td>
<td>42-67</td>
<td>108-121</td>
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<tr>
<td>Total</td>
<td>23,291</td>
<td>130-147</td>
<td></td>
<td></td>
<td>939-1058</td>
<td>402-640</td>
<td>1041-1157</td>
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Saginaw Bay Watershed Annual TP Load
Assuming rest of watershed behaves as Saginaw River (same areal load)
### CSO and WWTP Fraction of Saginaw River TP Annual Load

<table>
<thead>
<tr>
<th>Year</th>
<th>CSO/SSO Est. (Met. Ton)</th>
<th>WWTP Effluent (Met. Ton)</th>
<th>Total Load MDEQ (Met. Ton)</th>
<th>Total Load Regr. (Met. Ton)</th>
<th>CSO’s Fraction of load (%)</th>
<th>WWTP Fraction of load (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>1.78</td>
<td>--</td>
<td>--</td>
<td>316-346</td>
<td>0.50 / 0.56</td>
<td>-- / --</td>
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<tr>
<td>2001</td>
<td>2.43</td>
<td>--</td>
<td>642</td>
<td>467-480</td>
<td>0.38 / 0.52</td>
<td>-- / --</td>
</tr>
<tr>
<td>2002</td>
<td>3.02</td>
<td>--</td>
<td>513</td>
<td>485-507</td>
<td>0.59 / 0.62</td>
<td>-- / --</td>
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<tr>
<td>2003</td>
<td>0.59</td>
<td>--</td>
<td>228</td>
<td>196-228</td>
<td>0.17 / 0.30</td>
<td>-- / --</td>
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<tr>
<td>2004</td>
<td>2.98</td>
<td>116</td>
<td>724</td>
<td>673-758</td>
<td>0.40 / 0.44</td>
<td>15.3 / 17.2</td>
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<tr>
<td>2005</td>
<td>--</td>
<td>110</td>
<td>288</td>
<td>449-459</td>
<td>-- / --</td>
<td>24.0/38.2</td>
</tr>
<tr>
<td>2006</td>
<td>--</td>
<td>128</td>
<td>--</td>
<td>746-829</td>
<td>-- / --</td>
<td>15.4/17.2</td>
</tr>
</tbody>
</table>
Modeling Approach to Saginaw Bay Watershed (DLBRM)

Watershed divided into four sub-basins
- Saginaw River
- AuGres/Rifle
- Kawkawlin/Pine
- Pigeon/Wiscoggin

Subwatersheds are subdivided into a grid of square pixels (1 km x 1 km)

Water and pollutants move horizontally according to the difference in elevation between neighboring pixels
Zipcode Areas within the Saginaw Bay Watershed: 2000

Manure and fertilizer application data compiled by Chansheng He, Western Michigan University
Saginaw River Watershed

Manure and Fertilizer P2O5 Loading in the Saginaw River Watersheds: 1987

Manure and Fertilizer P2O5 Loading in the Saginaw River Watersheds: 2002

P2O5/KG/Ha

- 0 - 8
- 9 - 18
- 19 - 34
- 35 - 100
- 101 - 214

P2O5/KG/Ha

- 0 - 8
- 9 - 18
- 19 - 27
- 28 - 100
- 101 - 182

Map of Saginaw River Watershed showing P2O5 loading in 1987 and 2002.
Heidelberg WQL Data for SRP, 1975-2007

Ave. Daily Conc., mg/L

Maumee

Sandusky

Ave. Daily Load, metric tons/day

Maumee

Sandusky
Development of Saginaw Bay Aquatic Ecosystem Model

Will phosphorus load reduction solve the recent problems? Is there a new load - ecosystem response relationship in Saginaw Bay?
Dreissenids are Effective Ecosystem Engineers

Interactions of dreissenid mussels with other ecosystem components in shallow systems via mussel feeding, nutrient excretion (blue), and physical ecosystem engineering (habitat modification: yellow & red). Solid lines indicate material flow (C, nutrients, sediment), and broken lines indicate physical engineering effects.
Model Development Concept

- Saginaw Bay Multi-Class Phytoplankton Model
- Zebra Mussel Bioenergetics Sub-Model
- Coupled Phytoplankton/Zebra Mussel Model
- Benthic Algal Sub-Model
- PCB Dynamics Model
- Bioaccumulation Sub-Model
- Saginaw Bay Ecosystem Model
Coupled Phytoplankton-Zebra Mussel-Benthic Algal Model

Higher Predators

Carnivorous Zooplankton

Herbivorous Zooplankton

Diatoms, Greens, Others

Available Nutrients (P, N, Si)

Blue-Greens (N-fixers and Non N-fixers)

Atmospheric Nitrogen

Benthic Algae

Unavailable Nutrients (P, N, Si)

Particulate Detritus

Abiotic Solids

Total Nutrients (P, N, Si)

Particulate Detritus

Abiotic Solids

Zebra mussels
Zebra Mussel Input Conditions
(data from NOAA-GLERL)

Numbers/meter**2
(Thousands)

- 1991
- 1992
- 1993
- 1994
- 1995

2 Year Olds
1 Year Olds
YOY

20
15
10
5
0
Phosphorus Cycling in New Saginaw Bay Ecosystem

Solar Radiation

External P Loads

Uptake of $\text{PO}_4$

Grazing

Predation

Release of $\text{PO}_4$

Decay and Mineralization - release of $\text{PO}_4$

Phytoplankton

Zooplankton

Upper Trophic Levels

Release of $\text{PO}_4$

Filtering

Fecal Pellet Settling

Detrital P Settling

Resuspension

Diffusive Exchange

Feces/Pseudofeces Deposition

Cladophora, Other Benthic Algae

Exchange with Offshore

Decay and Mineralization - release of $\text{PO}_4$
Chladophora Respond to Nearshore SRP and Light Availability (Auer, Higgins, et al.)

(photo by Scott Higgins–June 2006)
Use of SAGEM to Understand Nutrient - Trophic Changes
Start with phytoplankton-zebra mussel model confirmed with 1991 field data
Incorporate zebra mussel and benthic algae sub-models
Run diagnostic comparisons with, in general:
- No zebra mussels
- Zebra mussels at 1991-1995 average densities
- Adjustments by:
  - inclusion/exclusion of P cycling processes
  - Allowing mussels to filter blue-greens
Segment 3 (Open Water):
- 8 m deep (Depositional)
- Chemical-biological processes
- Less ZMs

Segment 4 (Near Shore):
- 3.8 m deep
- Influenced by Saginaw River inflow
- More ZMs
Time Series for Total Blue-Greens
(Adding zebra mussels to base run)

Open Water

- Base Run
- With zebra mussels
- Data 1991

Near Shore
Model Diagnostic Results

Open Water Responses

Annual Total Production (mg/l)

Total Phosphorus Load Factor

Zebra Mussel Density Factor

Near Shore Responses

Annual Total Production (mg/l)

Total Phosphorus Load Factor

Zebra Mussel Density Factor
Model Diagnostic Results

Open Water Responses

Near Shore Responses

Annual BG Prod., mg/l

ZM Density Factor

TP Load Factor
Effect of Mussels on Light Penetration

![Bar chart showing the effect of mussels on light penetration. The x-axis represents Segment Number (1 to 7), and the y-axis represents Light Extinction Coefficient (1/m). The chart compares light penetration without Zebra Mussels (blue) and with Zebra Mussels (red). The data shows a decrease in light penetration with the presence of Zebra Mussels in all segments.](image-url)
Model Data Comparison

Data from Lowe & Pillsbury - JGLR 21(4):1995

Benthic Algal Biomass (mg/m²)

Julian Date

- Model
- 1992
- 1993
Increased Water Clarity Promotes Benthic Primary Production

Scenario 1 - No Zebra Mussels

Scenario 2 - Zebra Mussels
Bay-wide Primary Production

**without Zebra Mussels**
- Pelagic: 199
- Benthic: 10

**Gross Production Remained Same**

**with Zebra Mussels**
- Pelagic: 65
- Benthic: 155
Blue-Greens and Benthic Algae Response

Without Zebra Mussels

With Zebra Mussels
Summary of Trophic Impacts

- Total phytoplankton production is **directly proportional** to external phosphorus load and **inversely proportional** to zebra mussel density.
- Blue-green production is **directly proportional** to external phosphorus load **and** zebra mussel density.
- Selective rejection of blue-greens by zebra mussels appears to be a **necessary** factor in enhancement of blue-green production in the presence of zebra mussels, but late summer P recycle is also **necessary**.
- Zebra mussel invasion of Saginaw Bay did not appear to significantly alter total system primary production, but **shifted** a substantial portion of system primary production from the pelagic to the benthic compartment due to increase in water clarity.
Phosphorus is the limiting nutrient in Saginaw Bay, and P recycle is important to maintaining late-summer phytoplankton production even in the absence of zebra mussels.

The presence of zebra mussels alters P recycle by introducing a benthic recycle pathway (zebra mussel P recycle) that accounts for approximately half of the internal P recycle in the system.

Summary of Impacts
- Alteration of phosphorus cycling - new recycle process
- Alteration of phytoplankton speciation - enhanced blue-green production
- Alteration of primary production - benthification
Next Steps - Saginaw Bay Multi-stressor Project

- Upgrades of Saginaw Bay Ecosystem Model (SAGEM)
  - Link SAGEM to fine-scale hydrodynamic model
  - Add *Cladophora* sub-model to SAGEM
  - Add upper food web (fish) to SAGEM
- Run revised SAGEM for entire 1991-97 to confirm model and evaluate full impact of zebra mussels on nutrient-trophic relationships
- Apply model to help design and interpret Project field monitoring/experimental program
- Apply watershed and bay models to evaluate alternative management scenarios for Saginaw Bay
Questions/Discussion

KEEP ‘EM GREAT

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