Lower Fox River Water Quality Models for Sediment Remediation Planning

presented by

Wisconsin Department of Natural Resources
Presentation Overview

Part 1: Model Use for Remediation Planning

Part 2: Lower Fox River Field Data Summary

Part 3: Development of a Water Quality Model for the Lower Fox River RI/FS
Part 1: Model Use for Remediation Planning
• Water (and Fish) Quality Models are one tool that can help … if you know the pitfalls!
Key Points to Consider at the Outset

• **Water Quality Models** are one of many possible tools that can be used to estimate how fast contaminant levels change in the environment.

• Only as good as the data used for development.

• The more variable the data, the wider the range of results.

• The Devil is in the Details: subtle changes in assumptions can lead to mutually exclusive results!
Modeling 101: What is a Model?

Model  =  Framework + Site Data for Parameters

Framework  =  Computer program to solve equations that describe movement of particles and chemicals in environment. Equation terms represent mechanisms that affect chemical fate (site data for parameters).

Site Data  =  Observations of water and sediment conditions at various points in time and space (flow, temperature, concentration, etc.) used to assign model parameter values (calibration).
Know the Goal!

- Models help you organize data and are useful to estimate the time to reach identified quality thresholds in water, sediment (and fish) but...
- Water quality models are only a means to an end.
- Decision-makers must identify remediation goals first! The environmental endpoint selected is target against which model results are compared. Models cannot help you choose an endpoint.
- Define “How good is good enough?” for model: absolute versus relative performance.
### Example Lower Fox River Model Forecast Summary (from January 1997 report)

<table>
<thead>
<tr>
<th>Endpoint</th>
<th>Condition</th>
<th>No Action</th>
<th>Up</th>
<th>Down</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>17</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>50</td>
<td>100</td>
</tr>
</tbody>
</table>

- **Wild & Domestic Animal PCB**
  - Water quality Criteria: 3 ng/L
  - Years to attain: 220

- **PCB Fish Consumption**
  - Advice: 1 meal / week
  - Years to attain: 142

- **PCB Export to Green Bay**
  - % Reduction: 0%, 46%, 75%

- Defined endpoints increase model utility.
- Best use is relative difference in time to reach goal.
Field data are the cornerstone of any model.

Ideally, you need to have observations for a wide range of factors at all points in space and time:

- Hydrodynamics (water velocities and flows).
- Source, type, and magnitude of suspended solids delivered to the waterway.
- Magnitude of solids transported through the waterway (bed load, suspended load, growth of algae).
- Transport properties of sediment (erosion/deposition).
- Chemical concentrations in water, sediment, and fish.
What You Don’t Know Can Hurt You!

• Every transport pathway needs to be quantified.
• Everything you don’t measure ends up as an assumption in a model!
• It is generally not possible to actually measure all the factors that affect chemical fate!
• Consequence: there will always be assumptions.
• To really interpret model results, you need to identify all assumptions made and know how these assumptions affect (bias) the results.
Model Performance and Evaluation

• If you have a model or are going to develop one, you will need to assess its performance.

• You need to decide what level of performance is good enough to make decisions.

• Sample comparisons to evaluate performance:
  – time series to examine trends and magnitudes
  – frequency distribution to examine statistical properties
  – point-in-time to examine relative differences
One Opinion Regarding Model Use

• The best use of models is to help organize data and think about the waterway in a holistic way.
• However, water quality model development is often as much “art” as science.
• Without data (and sometimes regardless of data), models results only reflect the assumptions of development …
• Don’t rely on any single tool to assess chemical trends … use a range of approaches.
• Don’t discount the value of common sense…
Part 2: Field Data Summary
Data Behind the Model (1)

- 1988 - 1990 Green Bay Mass Balance Study
- 1991 - 1993 Water sampling
- 1992 Fish sampling
- 1994 - 1996 RI / FS for select deposits
- 1994 - 1996 Water sampling (LMMBS)
- 1995 Detailed sediment characterization
- 1996 Fish sampling
Data Behind the Model (2)

- 1997-1999 Deposit N Removal
- 1998-2000 SMU 56/57 Removal
- 1998 Supplemental RI/FS sampling (WDNR)
  - Water and Sediment
- 1998 Select areas, River/Bay (Fox River Group)
  - Water, sediment, geochemistry, and fish
- 1998 River bottom characterization (acoustic)
Observed Water Column PCB Concentrations at the Fox River Mouth: 1989 - 1995
Observed Water Column PCB Concentrations at Lower Fox River Monitoring Stations: 1989-1990

<table>
<thead>
<tr>
<th>Date</th>
<th>Total PCB (ng/L)</th>
<th>L. Winnebago</th>
<th>Appleton</th>
<th>Kaukauna</th>
<th>Little Rapids</th>
<th>DePere</th>
<th>River Mouth</th>
</tr>
</thead>
<tbody>
<tr>
<td>04/01/89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>05/31/89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>07/30/89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>09/28/89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>11/27/89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>01/26/90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>03/27/90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
Observed Sediment PCB Concentrations Downstream of DePere: 1989 and 1995

Based on temporal segregation of 1989 and 1995 data.

- PCB Concentration (mg/kg)
- Year

- Do Not Eat
- Unlimited Consumption
Field Observation Summary

• Water Column PCB concentrations have not changed from 1989 to 1999 and exceed water quality standards.

• Sediment PCB concentrations have not changed from 1989 to 1996.

• PCB concentrations in large walleye and other fish show little change since 1979 and pose a significant human health and ecological risk.
Some Issues for the Lower Fox River

• What effect do sediment bed elevations changes have on exposures and potential health risks?
  – Do bed elevations change over time?
  – Do bed elevations ever decrease?

• The only significant source of PCBs is the river sediments. If the river is a largely depositional environment, what processes can explain why PCB levels increase from zero at the upstream boundary to 50-100+ ng/L at the river mouth?

• Will falling lake levels affect sediment transport?
Lower Fox River Sediment Bed Elevation: Long-Term Longitudinal Profile

Distance from mouth (meters) vs. Elevation (IGLD 1955, meters)

- 1977
- 1982
- 1990
- 1993
- 1997
- 1998

(frequent dredging)
USCOE Survey at Fort James West (205+00)

Average elevation change:
1977 to 1982: -9 cm
1982 to 1990: +24 cm
1990 to 1993: -7 cm
1993 to 1997: -26 cm
1997 to 1998: -3 cm
Cross-Channel Elevation Changes (Ft. James West)
Part 3: Development of a Water Quality Model for the Lower Fox River RI/FS

One component was to “evaluate models for the Lower Fox River and Green Bay.”

Intent was to establish performance goals to evaluate the quality of model results.

Development of a series of technical reports followed.

Tech Memo 1 presents model performance goals.
Model Development History (1)

- 1989: Initial development (calibration) for USEPA Green Bay Mass Balance Study [USEPA Large Lakes Research Station (LLRS)].
- 1994: Development for use as long-term prognostic tool (forecasts) [USEPA-LLRS].
- 1997: Post-audit assessment of performance (verification) [Wisconsin DNR].
- 2000: Extension of features to address review comments ("enhancement") [Wisconsin DNR].
Model Development History (2)

- Through each stage of development the model has been extensively reviewed. A series of publications, including three peer-reviewed journal articles, document model performance:
The Calibration Process

• **Calibrations are a diagnostic tool to interpolate observations.** Day-by-day and site-by-site judgments are often used to assign parameter values. Observed effects are used to infer causes.

• **Model performance goals and many parameter values are defined in Tech Memos developed as part of the January 31, 1997 Agreement:**

  TM1: Model Evaluation Metrics, TM2a: Watershed Flows and Loads, TM2c: Autochthonous Production; TM2d: Point Source loads, TM2e: Sediment Bed Properties; TM5b: Hydrodynamics and Sediment Transport; etc...
Model Performance Goals

- Defined in Technical Memorandum 1.
- Express the idealized level of correspondence between model results and field conditions.
- Water Column: match concentration time series (trend and magnitude) and frequency distributions (mean values to ~30% relative error).
- Sediments: match net burial rate (mean value to ~30% relative error), bed elevation changes (trend and magnitude) and PCB concentration trends (trend and magnitude).
## Lower Fox River Model Features (1)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spatial Domain</strong></td>
<td>39 Miles (Whole River)</td>
<td>Prior model development for GBMBS; AGI recommendation; upstream PCB boundary condition is zero</td>
</tr>
<tr>
<td><strong>Temporal Domain</strong></td>
<td>1989-1995</td>
<td>Tech Memo 1; period of greatest data availability</td>
</tr>
<tr>
<td><strong>State Variables</strong></td>
<td>3 solids types, Total PCBs</td>
<td>Multiple particle types needed to represent transport of different particles; Tech Memo 2d; AGI recommendation</td>
</tr>
</tbody>
</table>
### Lower Fox River Model Features (2)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Segments</td>
<td>535</td>
<td>Prior model development for GBMBS</td>
</tr>
<tr>
<td>Water Segments</td>
<td>40</td>
<td>Prior model development for GBMBS</td>
</tr>
<tr>
<td>Surface Sediment Segments</td>
<td>165 (deposits, interdeposits, SMUs)</td>
<td>Sediment areas defined in draft RI/FS; Tech Memo 2e; prior model development</td>
</tr>
<tr>
<td>Subsurface Sediment Segments</td>
<td>330 (remaining sediment in “ghost stack”)</td>
<td>Two layers under each surface segment permits description of sediment mixing</td>
</tr>
<tr>
<td>Feature</td>
<td>Value</td>
<td>Basis</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------------</td>
<td>--------------------------------------------------------------</td>
</tr>
<tr>
<td>Framework</td>
<td>Semi-Lagrangian</td>
<td>Avoid mixing in deep sediments; AGI recommendation</td>
</tr>
<tr>
<td>Sediment Layers (nominal thickness)</td>
<td>0-5 cm 5-10 cm 10-30 cm 30-50 cm 50-100 cm 100-150 cm 150-200 cm 200-250 cm 250-300 cm 300+ cm</td>
<td>Tech Memo 2e; consistency with other aspects of RI/FS</td>
</tr>
</tbody>
</table>
## Lower Fox River Model Features (4)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PCBs: 0</td>
<td></td>
</tr>
<tr>
<td>Watershed Loads</td>
<td>Solids: 54,000 MT/yr</td>
<td>Tech Memo 2a</td>
</tr>
<tr>
<td></td>
<td>PCBs: 7.5 kg/yr</td>
<td>Tech Memos 2b/2a/3a</td>
</tr>
<tr>
<td>Internal Loads</td>
<td>Solids: 20,000 MT/yr</td>
<td>Tech Memo 2c</td>
</tr>
<tr>
<td></td>
<td>PCBs: not applicable</td>
<td></td>
</tr>
<tr>
<td>Point Source Loads</td>
<td>Solids: 3,400 MT/yr</td>
<td>Tech Memo 2d</td>
</tr>
<tr>
<td></td>
<td>PCBs: 12.25 kg/yr</td>
<td></td>
</tr>
</tbody>
</table>
### Lower Fox River Model Features (5)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Initial Conditions</strong></td>
<td>sand, silt, clay, bulk density, organic carbon, PCBs</td>
<td>Tech Memo 2e</td>
</tr>
<tr>
<td>“Sand” Settling</td>
<td>$V_s = 470$ m/day, $\tau_{cd} = 0.80$ dynes/cm$^2$</td>
<td>Gessler (1967); Cheng (1997)</td>
</tr>
<tr>
<td>“Silt” Settling</td>
<td>$V_s = 3.5$-4.3 m/day, $\tau_{cd} = 0.15$ dynes/cm$^2$</td>
<td>Partheniades (1992); Burban (1990)</td>
</tr>
<tr>
<td>“Clay” Settling</td>
<td>$V_s = 0.1$ m/day, $\tau_{cd} = 0.10$ dynes/cm$^2$</td>
<td>Partheniades (1992); Chapra (1997)</td>
</tr>
</tbody>
</table>
### Lower Fox River Model Features (6)

<table>
<thead>
<tr>
<th>Feature</th>
<th>Value</th>
<th>Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event Resuspension</td>
<td>$V_r$ varies with $\tau$</td>
<td>McNeil et al. (1996); Tech Memo 5b; UFRHydro Report</td>
</tr>
<tr>
<td></td>
<td>Epsilon ($\varepsilon$) Equation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\tau &gt; 1$ dyne/cm$^2$</td>
<td></td>
</tr>
<tr>
<td>&quot;Background&quot; Resuspension</td>
<td>$V_{rb}$ varies with $\tau$</td>
<td>Calibration; fit to observed PCBs in water column</td>
</tr>
<tr>
<td></td>
<td>On annualized basis, $V_{rb} \approx 0.6$ cm/yr</td>
<td></td>
</tr>
<tr>
<td>Porewater Dispersion</td>
<td>$K_f = 2 \times 10^{-8}$ cm/day</td>
<td>After Upper Hudson River Report (1999)</td>
</tr>
<tr>
<td>Sediment Mixing</td>
<td>$1 \times 10^{-10}$ m$^2$/s</td>
<td>Interpretation of field data; Tech Memo 2g</td>
</tr>
</tbody>
</table>
Model Results
Predicted and Observed Water Column Solids Concentrations at the Fox River Mouth: 1989 - 1995

![Graph showing predicted and observed TSS concentrations from 1989 to 1995.](image-url)
Predicted and Observed Solids Frequency Distributions at the Fox River Mouth: 1989-1995

![Graph showing predicted and observed solids frequency distributions.](image-url)
Predicted and Observed Water Column PCB Concentrations at the Fox River Mouth: 1989 - 1995

- 1989-90 PCB (ng/L)
- 1993 PCB (ng/L)
- 1994-95 PCB (ng/L)
- Predicted
Predicted and Observed PCB Frequency Distributions at the Fox River Mouth: 1989-1995
Predicted and Observed Particulate PCB Concentrations at the Fox River Mouth: 1989-1995

Flow estimates from Technical Memorandum 2a

- Observed
- Predicted
Predicted and Observed Particulate PCB: 1989-1995
(from January 1997 report)

Flow estimates from Technical Memorandum 2a

Observed
Predicted

Flow (m³/s)
Particulate PCB (mg/kg)
Sediment Results (1)

• **Sediment Bed Elevation Change, Average (Max):**

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>Predicted</th>
<th>Observed*</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMU 86-91</td>
<td>1990-93</td>
<td>+1.37 cm</td>
<td>+5 cm (+28 cm)</td>
</tr>
<tr>
<td>SMU 86-91</td>
<td>1993-97</td>
<td>+0.59 cm</td>
<td>+2 cm (-110 cm)</td>
</tr>
</tbody>
</table>

* Results for Location 91+00 (1990-1997) from Tech Memo 2g.

• **Net Burial Rate**

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>Predicted</th>
<th>Inferred*</th>
</tr>
</thead>
<tbody>
<tr>
<td>DP-FRM</td>
<td>1989-1995</td>
<td>0.3 cm/yr</td>
<td>0.2-1.4 cm/yr</td>
</tr>
</tbody>
</table>

* 1989-1995 rate based on analysis of PCBs in 1995 cores assuming 1969 was peak discharge with loads from Tech Memos 2a-2d.
### Sediment PCB Time Trends:

<table>
<thead>
<tr>
<th>Reach</th>
<th>Predicted</th>
<th>Inferred</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLBdM</td>
<td>-6%/yr</td>
<td>See TTA Report</td>
</tr>
<tr>
<td>AP-LR</td>
<td>-3%/yr</td>
<td>See TTA Report</td>
</tr>
<tr>
<td>LR-DP</td>
<td>-1%/yr</td>
<td>See TTA Report</td>
</tr>
<tr>
<td>DP-FRM</td>
<td>+10%/yr</td>
<td>See TTA Report</td>
</tr>
<tr>
<td>Whole River</td>
<td>~0%/yr</td>
<td>See TTA Report</td>
</tr>
</tbody>
</table>

* Qualitative comparison based on assuming equal weight for results of each reach.
Model Result Caveats

• Assessment of water column results is based on comparison to direct observations.
• Assessment of sediment results is complex because most comparisons are based on inferences rather than direct observations.
• Inferences may have imbedded assumptions. If you change the underlying assumptions you can completely change the outcome of an analysis.
• Strongest use of river model is to estimate loads to Green Bay.
Model Performance Summary

- **Water Column**: mean predicted concentrations are within ~30% of observations for solids and ~15% for PCBs.

- **Sediments**: predicted bed elevation changes differ from observations; however, predicted net solids burial rate and PCB time trends are within the uncertainty of inferred values.

- **Conclusion**: To the extent that valid comparisons can be made, model performance meets the goals identified in Tech Memo 1.
Model Performance Assessment

- Is it “good enough”?
- What is the best use?
- What are the limitations?
Some Final Thoughts for the Lower Fox River...

• The long-term fate of PCB contaminated sediments is the key issue to quantify.

• Nearly 30 years of “natural recovery” have failed to reduce risks to acceptable levels (water, fish).

• Advocacy is no substitute for science...
  – PRP position: a 1-in-100 year flow event would cause no more than 0.2 cm of gross erosion.
  – Observations: sediment bed elevation changes are dynamic and vary by +/- 10-40 cm or more from year to year with a maximum observed loss: 200 cm.
Any Questions?
Forecasts

- Forecasts are a prognostic tool to extrapolate beyond observations. Generalized calibration results are used to assign parameter values. Inferred causes are used to estimate future effects.

- Future conditions are a replay of past conditions: historical flow record assumed to repeat; need to make assumptions regarding time trends of loads and boundary conditions.

- Result express general trends because the future conditions may not occur as assumed...
Pitfalls and Advocacy (1)

• Model Evaluation:
  – PRP focus will be to make models more favorable to them ... alter/“enhance” models not to evaluate.
  – Use “evaluation” as an opportunity for delay.

• Model Performance Standards:
  – Design standards to assess performance with available data ... or there will be delay for data collection.
  – There will be resistance to setting performance standards. Typical approach is to claim absolute performance standards are “too restrictive” ... the “we’ll know a good model when we see one” approach.
Pitfalls and Advocacy (2)

• Biased and Redundant Data Collection Efforts:
  – Beware data collection efforts that tend to focus on data types already collected instead of filling data gaps. Data are then used to confound analysis.
  – Example: collect a few sediment samples at a site already characterized ... then conclude that any difference in results show rapid natural recovery...

• Upstream Sources (Boundary Conditions):
  – If there are chemical inputs from an upstream source, the conclusion will be that the most important source of chemical transport is from upstream...
Pitfalls and Advocacy (3)

- **Apples-to-Oranges Comparisons:**
  - Observations only applicable to one site or condition will be generalized and presented as if applicable to all sites and all conditions.
  - Inappropriate data use (e.g. geochronology).

- **Data Use and Censoring:**
  - Need to catalog and assess all available data.
  - **Beware:** evaluations will often hinge on excluding key data from the analysis.
Pitfalls and Advocacy (4)

• Rate of Natural Recovery:
  – For PCBs in rivers systems, typical conclusion is that concentrations will drop by 50% in 4-12 years.
  – Analysis is based on an assumption that erosion does not occur and that dilution of chemicals in sediments is the only process and that recovery is only one-way.
  – Such analyses will differ from site to site as needed to “conclude” natural recover is rapid even though the work may be performed by the same contractor...
  – Example: Fish tissue PCB trends for the Lower Fox (OC normalized) and Kalamazoo Rivers (not OC normalized).
• **Open-Ended Research and Delay:**
  
  – If PRPs undertake a model development effort, the likely position will be that only a model can assess complex remedial options and that clean-up decisions should be delayed until models can be developed.
  
  – Massive data collection efforts are needed to support system-wide mass balances of chemicals and take years to plan and complete (7 years for the GBMBS).
  
  – **Unresolvable Limitations:** Present models do not describe the dynamic link between river channel evolution and sediment transport. It’s unlikely that this limitation will be addressed in the next few years.