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

It's a Jungle Out There...

Water
CERCLA
Sediment
RI/FS
Risk Assessment
???
Fish
Remediation
NRDA
Natural Recovery

- 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)

- **Defined endpoints increase model utility.**
- **Best use is relative difference in time to reach goal.**

Data are Everything!

- 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 it's 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

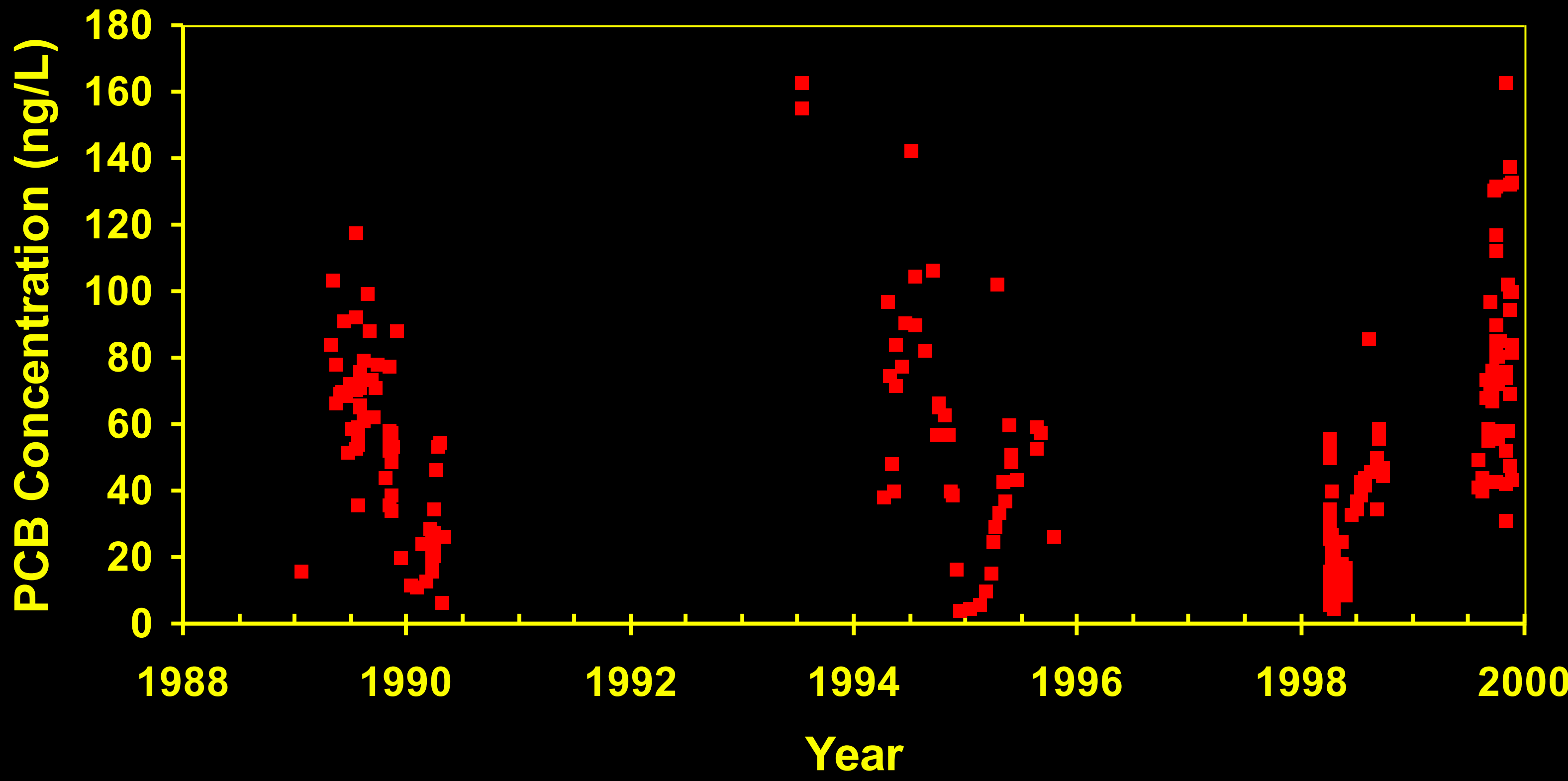
Data Behind the Model (1)

- 1988 - 1990 Green Bay Mass Balance Study
- 1991 - 1994 Deposit A RI / FS
- 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

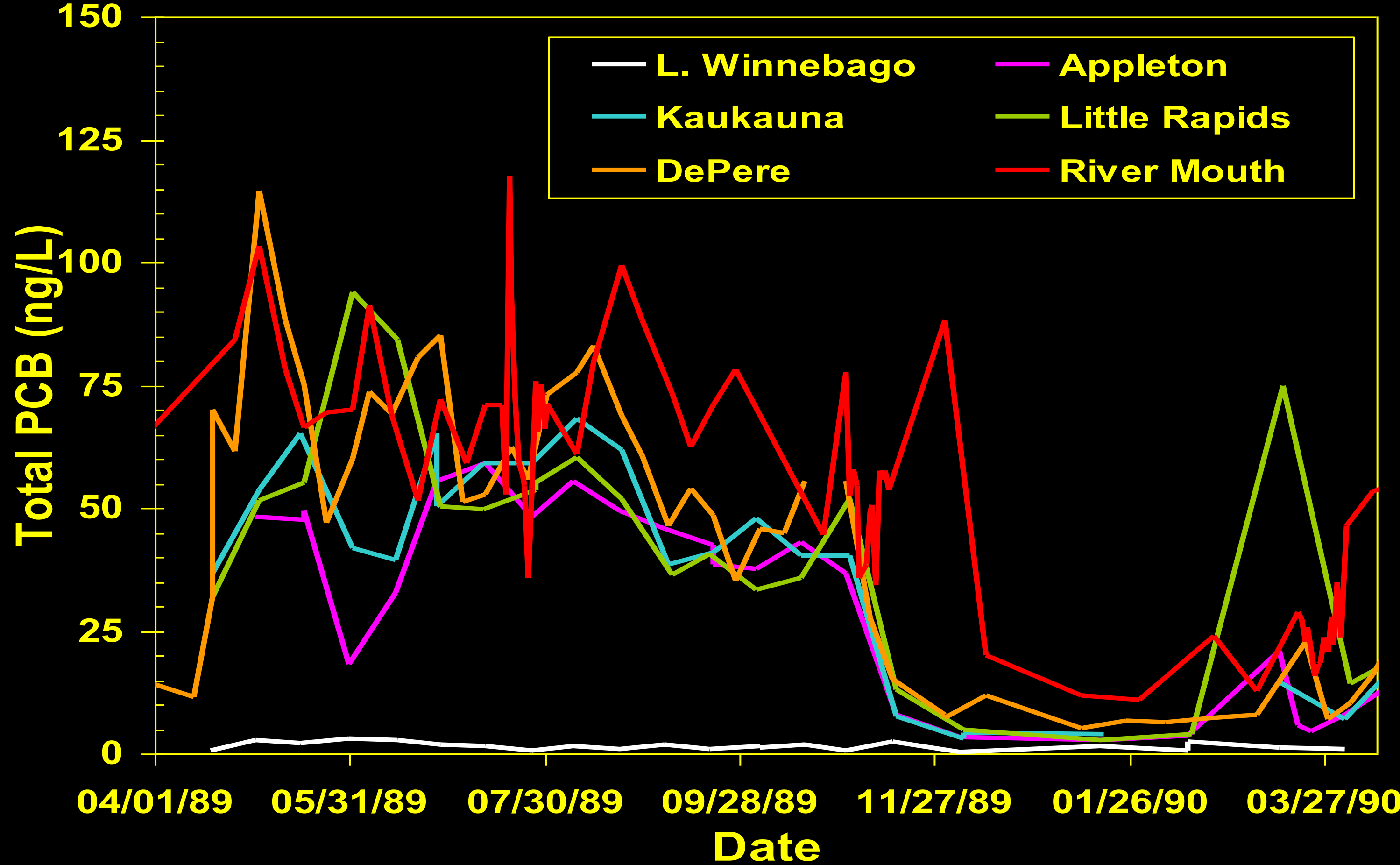
Data Behind the Model (2)

- 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)

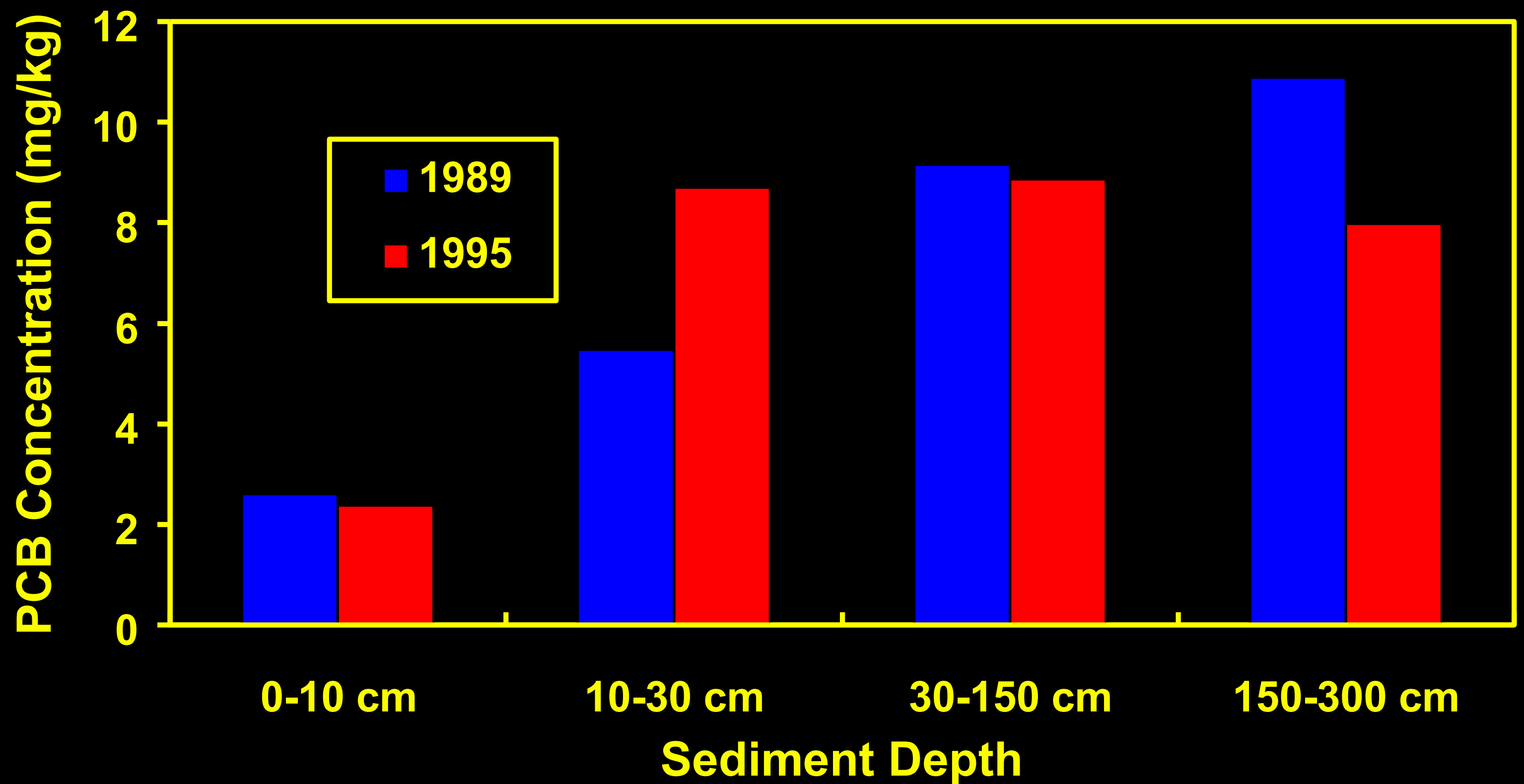
Observed Water Column PCB Concentrations at the Fox River Mouth: 1989 - 1995



Observed Water Column PCB Concentrations at Lower Fox River Monitoring Stations: 1989-1990

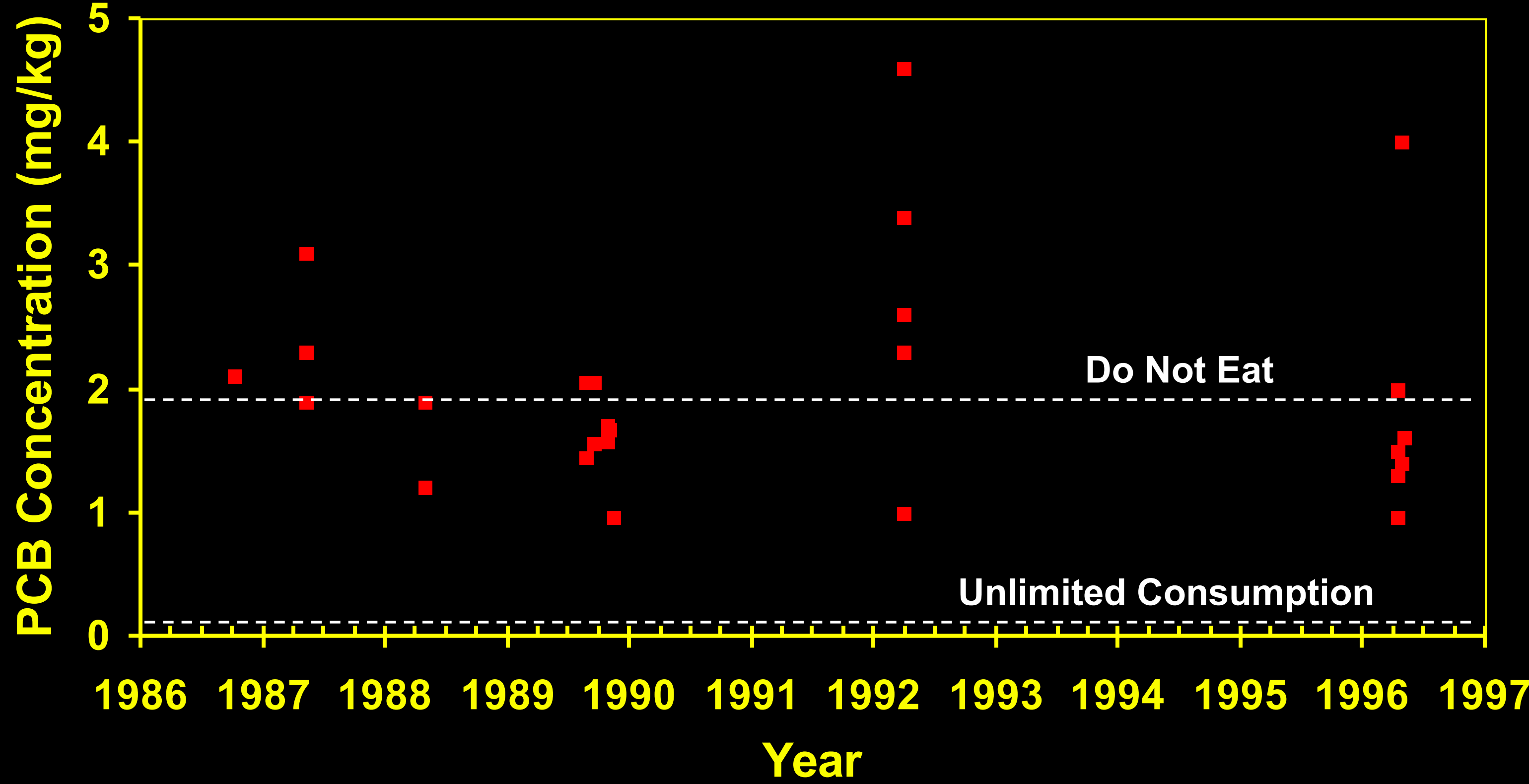


Observed Sediment PCB Concentrations Downstream of DePere: 1989 and 1995



Based on temporal segregation of 1989 and 1995 data.

Observed PCB Concentrations in Walleye >20" Downstream of DePere: 1989 - 1995



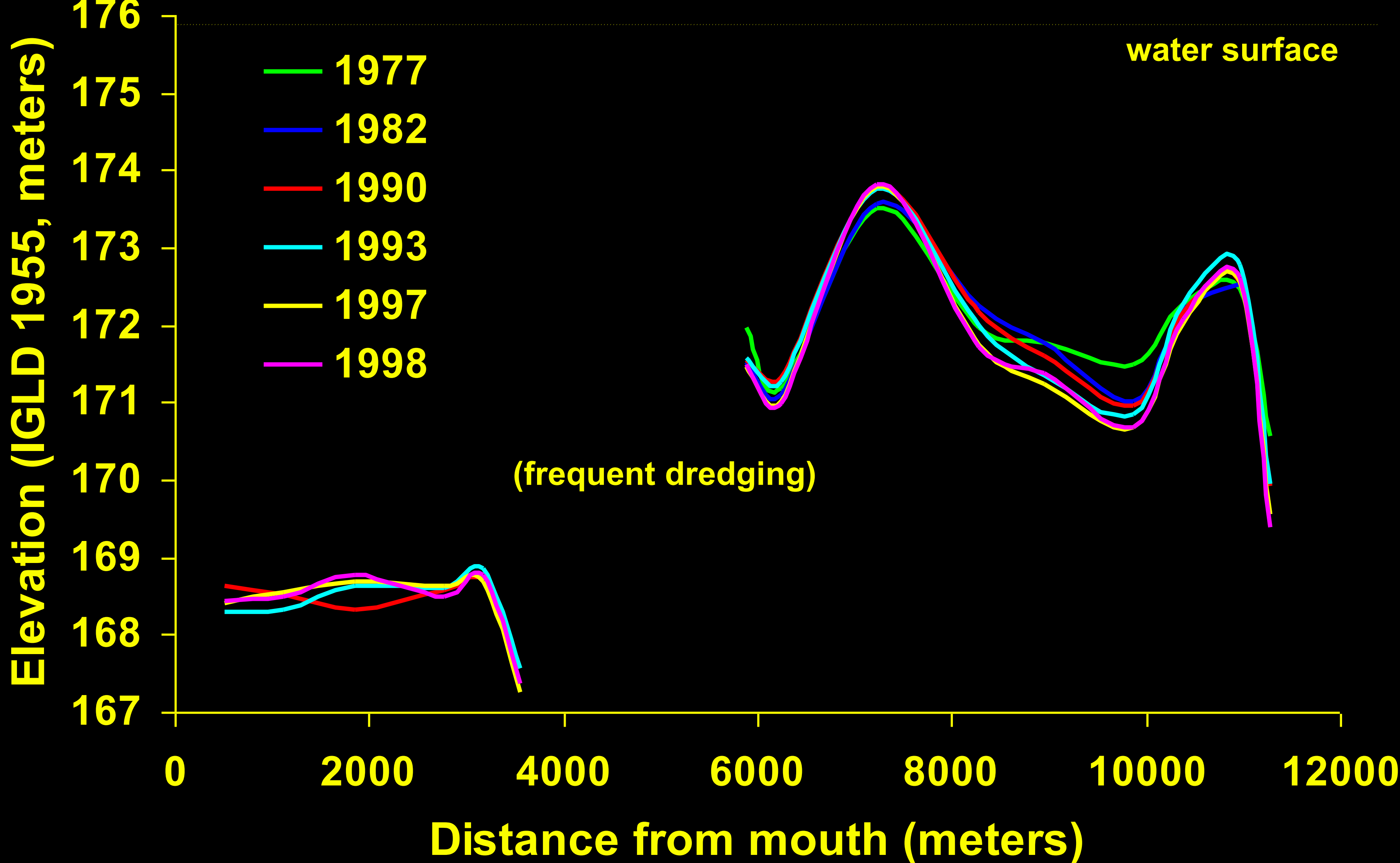
Field Observation Summary

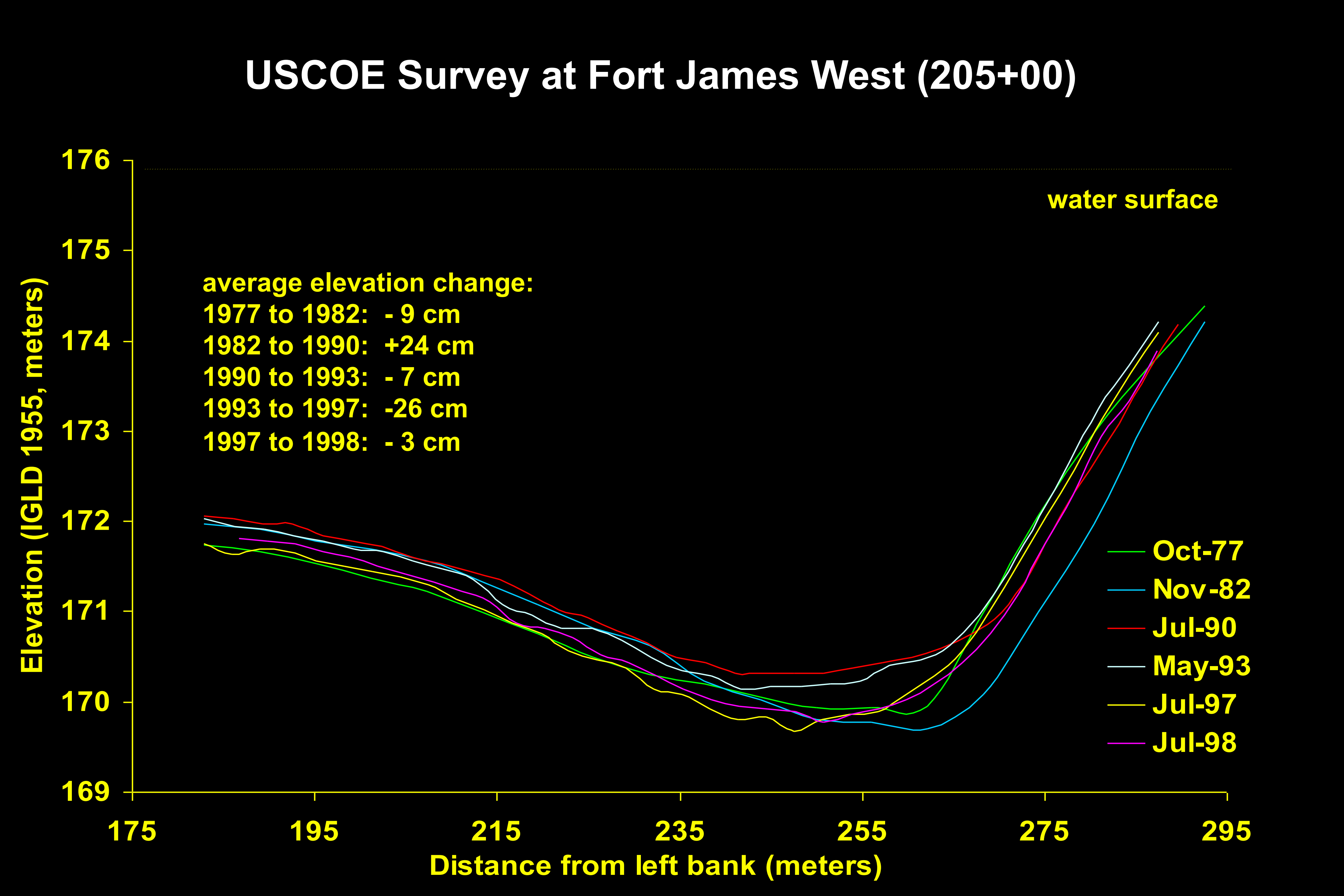
- Water Column PCB concentrations have not changed from 1989 to 1999 and exceed water quality standards.
- Sediment PCB concentrations have not changed from 1989 to 1996.
- PCB concentrations in large walleye and other fish show little change since 1979 and pose a significant human health and ecological 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?

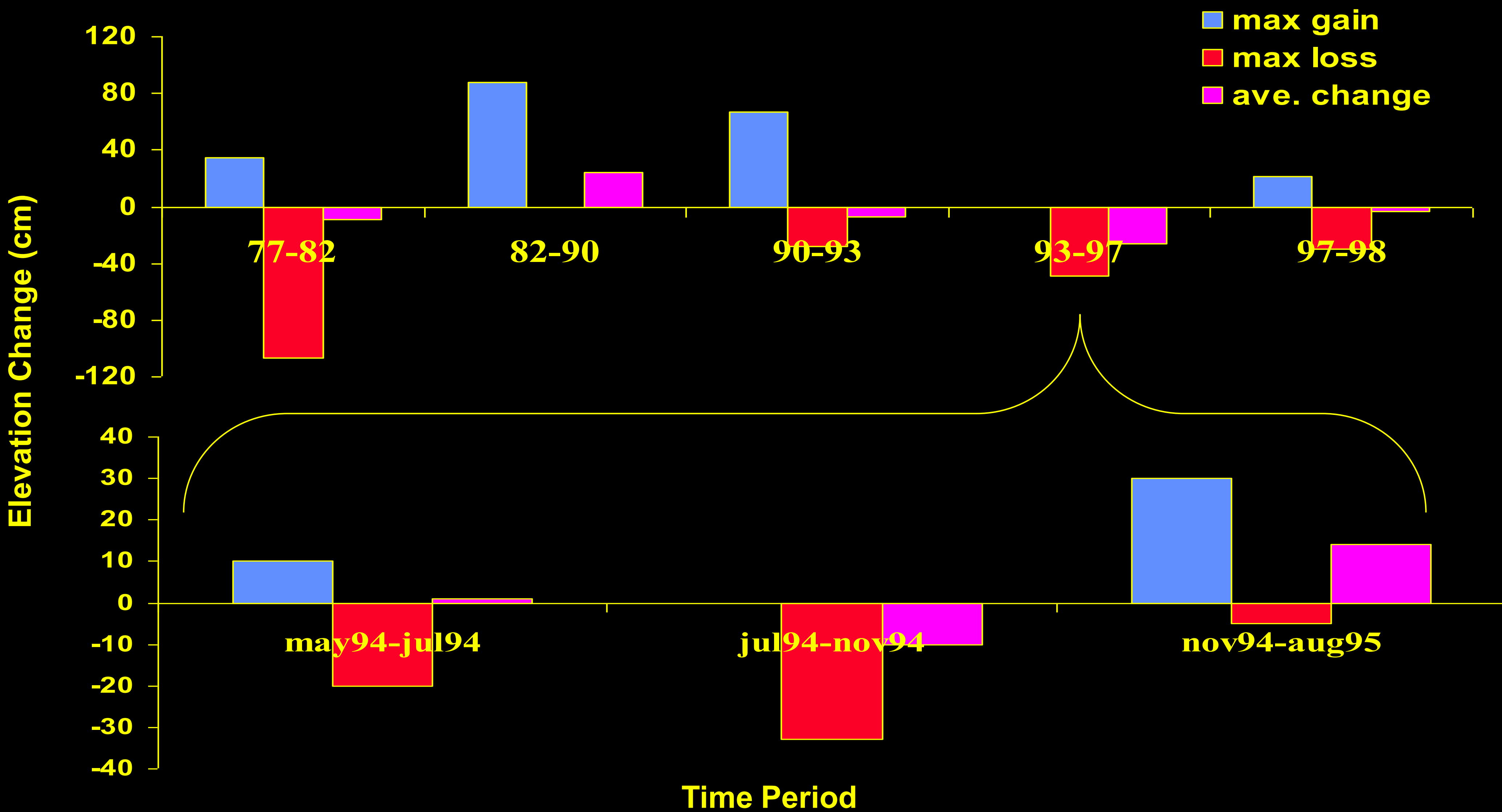
Lower Fox River Sediment Bed Elevation: Long-Term Longitudinal Profile





USCOE Survey at Fort James West (205+00)
water surface
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
Oct-77
Nov-82
Jul-90
May-93
Jul-97
Jul-98
Elevation (IGLD 1955, meters)
176
175
174
173
172
171
170
169
175
195
215
235
255
275
295
Distance from left bank (meters)

Cross-Channel Elevation Changes (Ft. James West)



Part 3: Development of a Water Quality Model for the Lower Fox River RI/FS

Context: The State-PRP Agreement

- The State of Wisconsin signed an Agreement with seven PRPs on January 31, 1997.
- 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:
  - Velleux and Endicott (1994). JGLR 20(4):416-434 (Calibration).
  - Velleux et al. (1995). JGLR 21(3):359-372 (Forecasts).
  - Velleux et al. (1996). ASCE JEE 122(6): 503-514 (Simulation Method).
  - WDNR (1997). WDNR Technical Publication PUBL-WT-482-97 (Verification).
  - AGI Model Review of 1997 Model [FRG sponsored] (2000).

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)

Feature	Value	Basis
Spatial Domain	39 Miles (Whole River)	Prior model development for GBMBS; AGI recommendation; upstream PCB boundary condition is zero
Temporal Domain	1989-1995	Tech Memo 1; period of greatest data availability
State Variables	3 solids types, Total PCBs	Multiple particle types needed to represent transport of different particles; Tech Memo 2d; AGI recommendation

Lower Fox River Model Features (2)

Feature	Value	Basis
Total Segments	535	Prior model development for GBMBS
Water Segments	40	Prior model development for GBMBS
Surface Sediment Segments	165 (deposits, interdeposits, SMUs)	Sediment areas defined in draft RI/FS; Tech Memo 2e; prior model development
Subsurface Sediment Segments	330 (remaining sediment in "ghost stack")	Two layers under each surface segment permits description of sediment mixing

Lower Fox River Model Features (3)

Feature	Value	Basis
Framework	Semi-Lagrangian	Avoid mixing in deep sediments; AGI recommendation
Sediment Layers (nominal thickness)	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	Tech Memo 2e; consistency with other aspects of RI/FS

Lower Fox River Model Features (4)

Feature	Value	Basis
Upstream Boundary Loads	Solids: 68,000 MT/yr PCBs: 0	Measurements at Lake Winnebago (1986-90); Gustin (1995)
Watershed Loads	Solids: 54,000 MT/yr PCBs: 7.5 kg/yr	Tech Memo 2a Tech Memos 2b/2a/3a
Internal Loads	Solids: 20,000 MT/yr PCBs: not applicable	Tech Memo 2c
Point Source Loads	Solids: 3,400 MT/yr PCBs: 12.25 kg/yr	Tech Memo 2d

Lower Fox River Model Features (5)

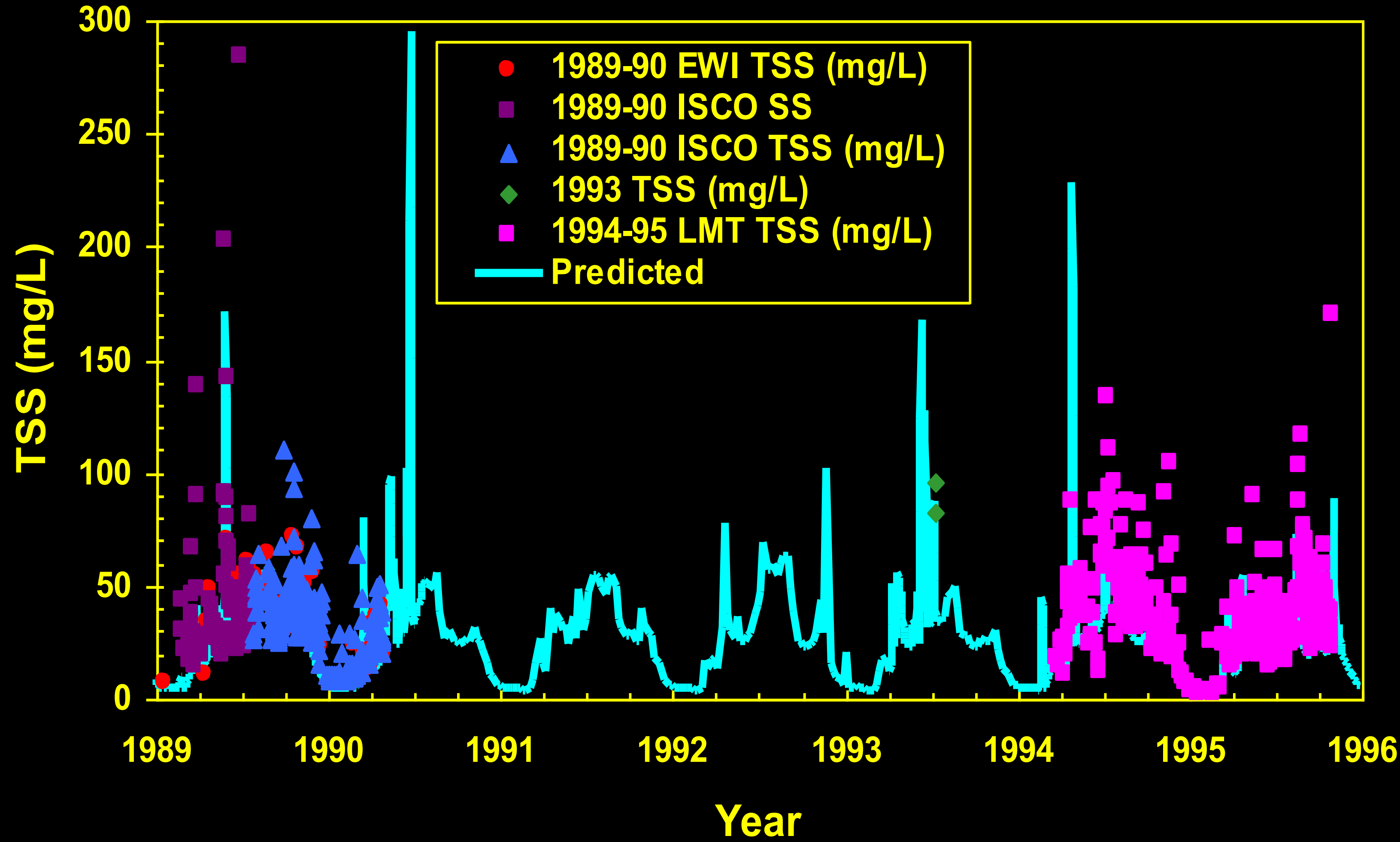
Feature	Value	Basis
Initial Conditions	sand, silt, clay, bulk density, organic carbon, PCBs	Tech Memo 2e
"Sand" Settling	V_s = 470 m/day τ_{cd} = 0.80 dynes/cm^2	Gessler (1967); Cheng (1997)
"Silt" Settling	V_s = 3.5-4.3 m/day τ_{cd} = 0.15 dynes/cm^2	Partheniades (1992); Burban (1990)
"Clay" Settling	V_s 0.1 m/day τ_{cd} = 0.10 dynes/cm^2	Partheniades (1992); Chapra (1997)

Lower Fox River Model Features (6)

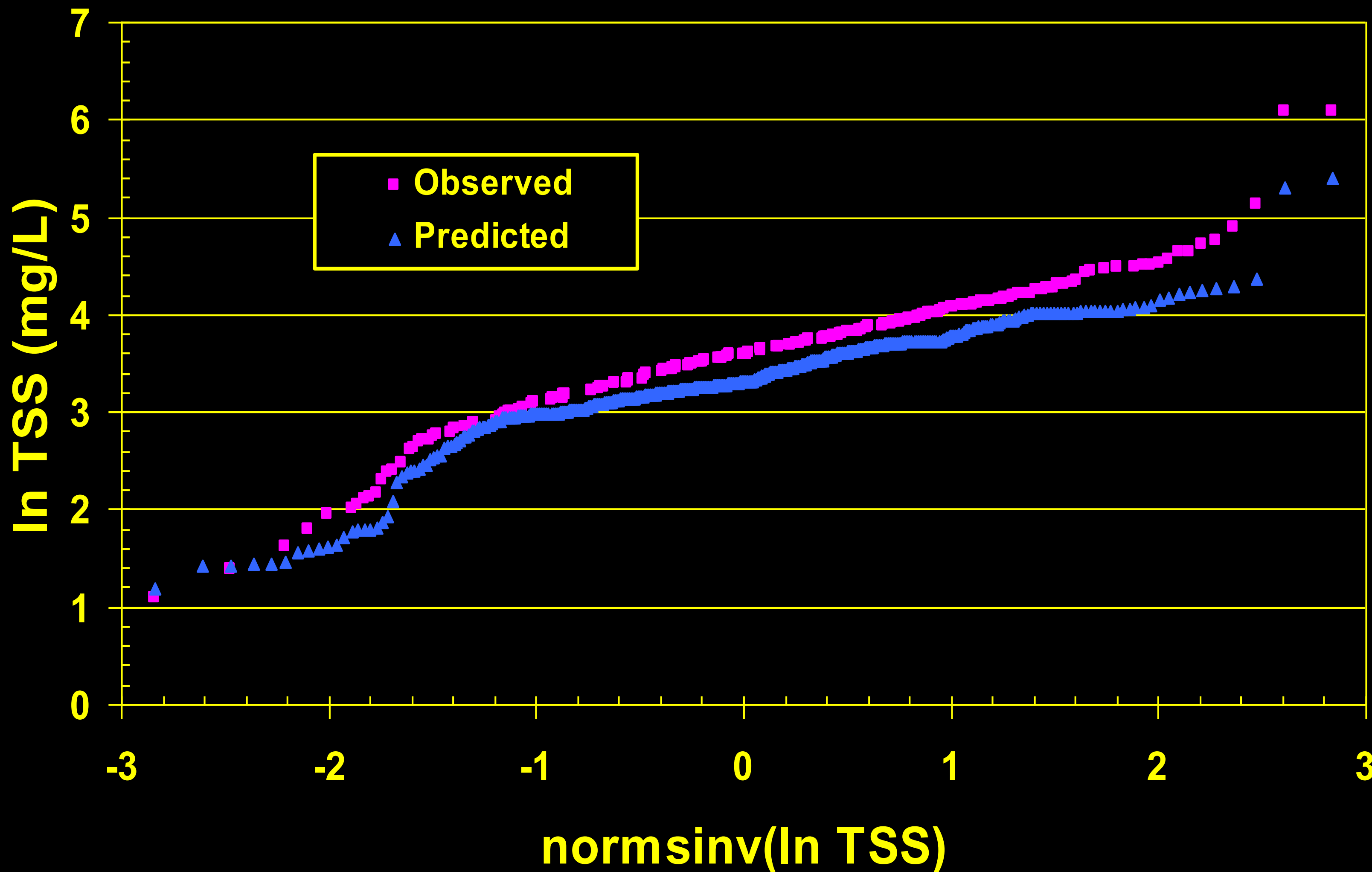
Feature	Value	Basis
Event Resuspension	V_r varies with τ Epsilon (ε) Equation $\tau > 1$ dyne/cm^2	McNeil et al. (1996); Tech Memo 5b; UFRHydro Report
"Background" Resuspension	V_{rb} varies with τ On annualized basis, $V_{rb} \approx 0.6$ cm/yr	Calibration; fit to observed PCBs in water column
Porewater Dispersion	$K_f = 2 \times 10^{-8}$ cm/day	After Upper Hudson River Report (1999)
Sediment Mixing	1×10^{-10} m^2/s	Interpretation of field data; Tech Memo 2g

Model Results

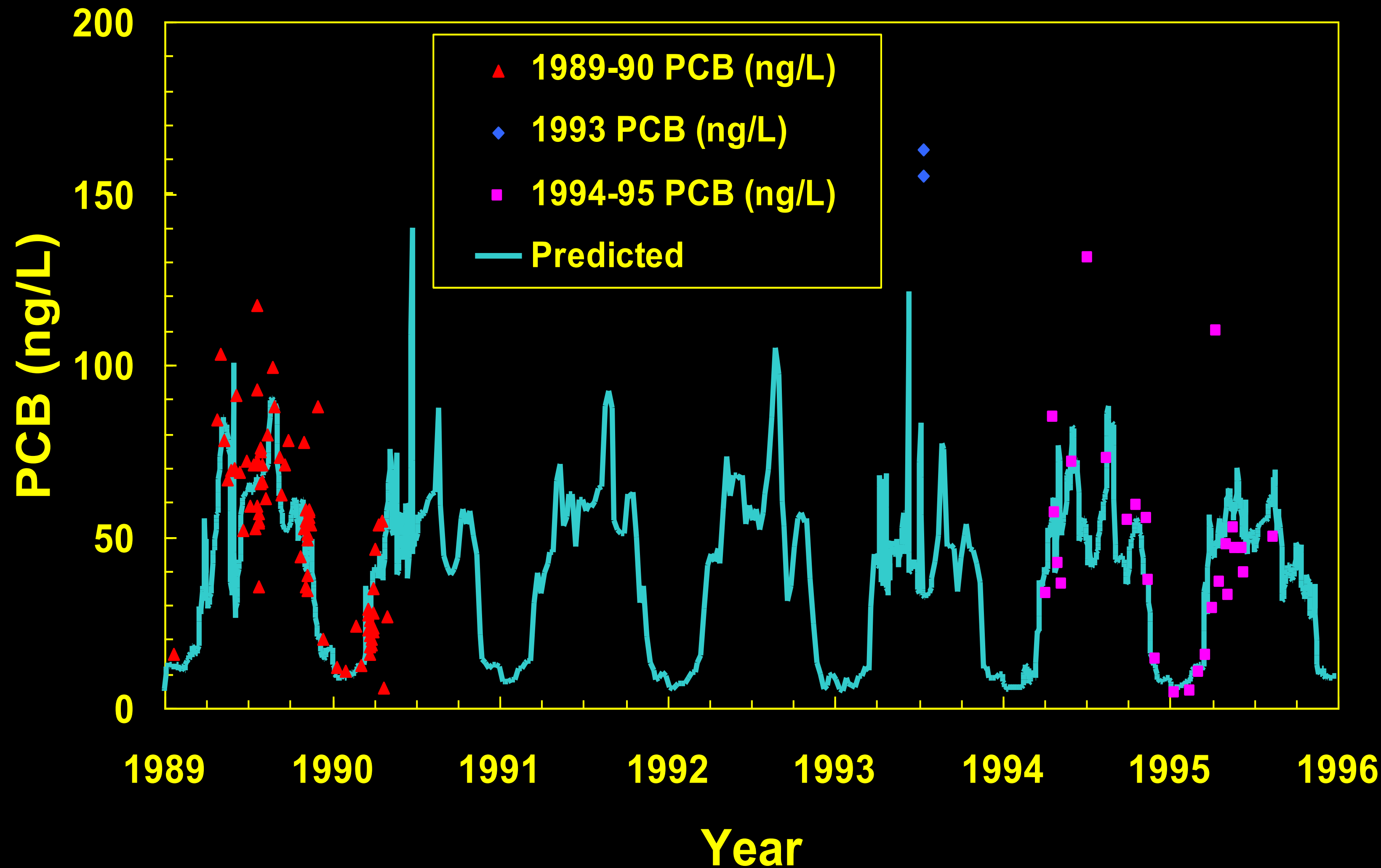
Predicted and Observed Water Column Solids Concentrations at the Fox River Mouth: 1989 - 1995



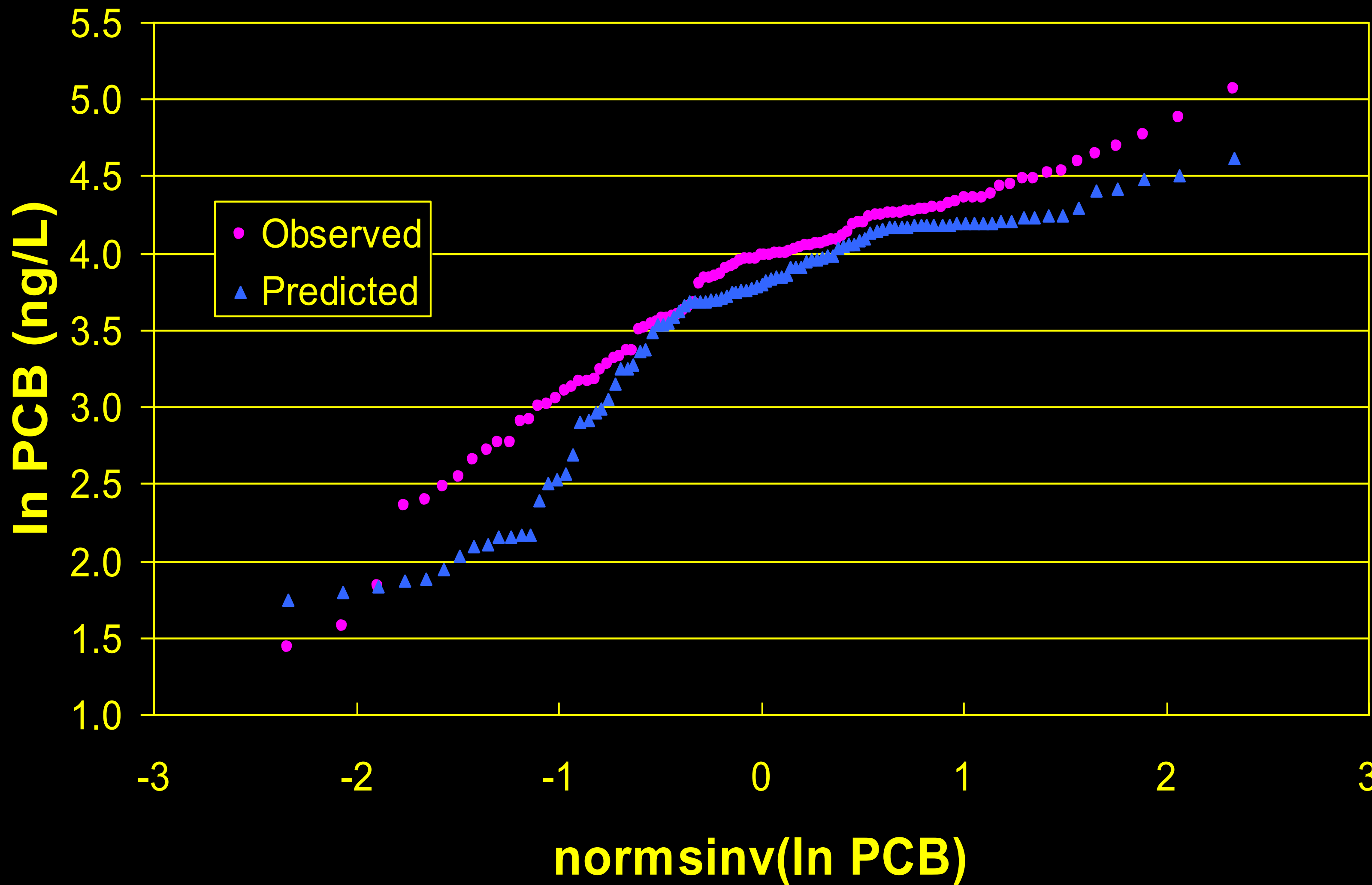
Predicted and Observed Solids Frequency Distributions at the Fox River Mouth: 1989-1995



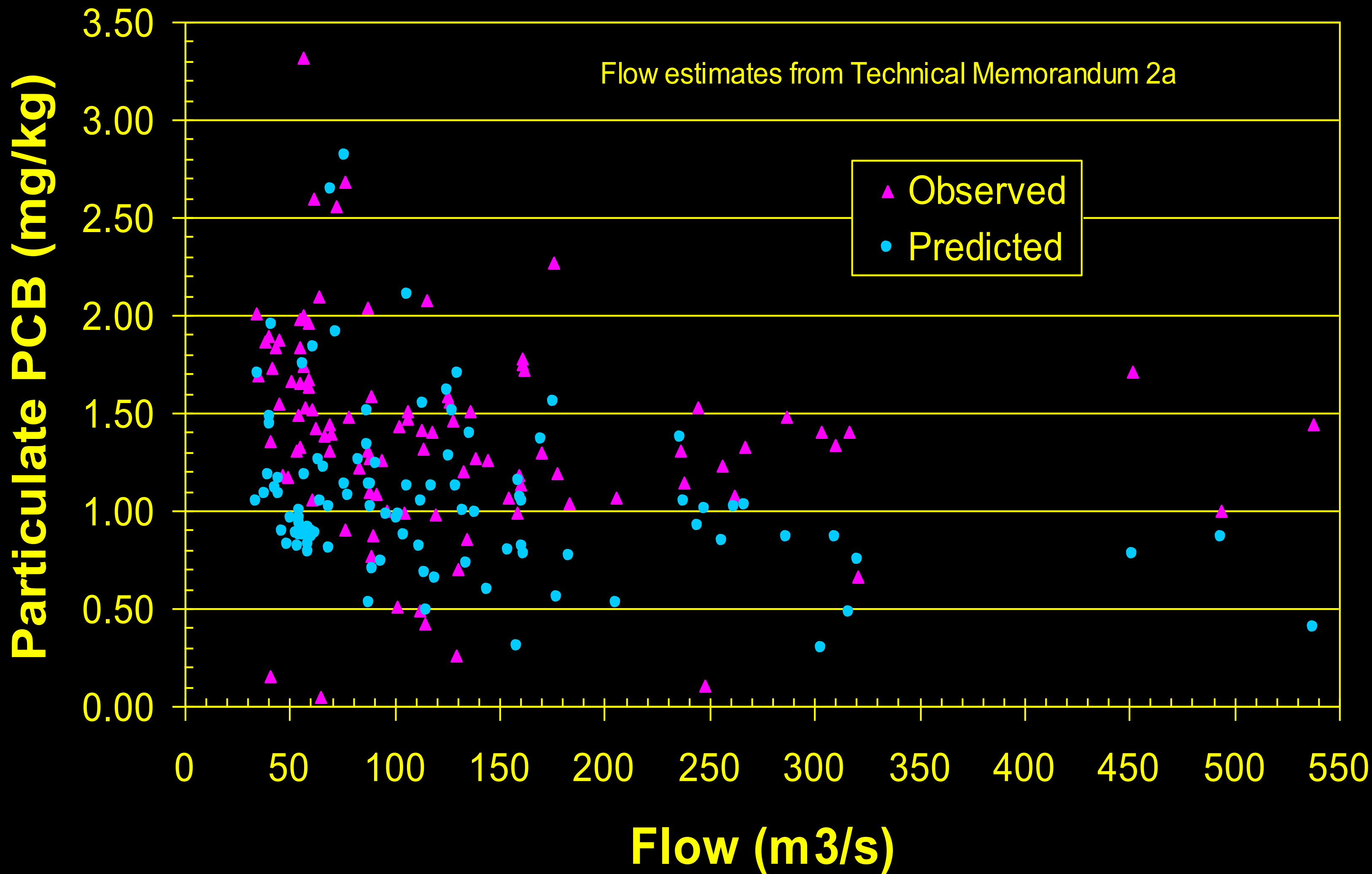
Predicted and Observed Water Column PCB Concentrations at the Fox River Mouth: 1989 - 1995



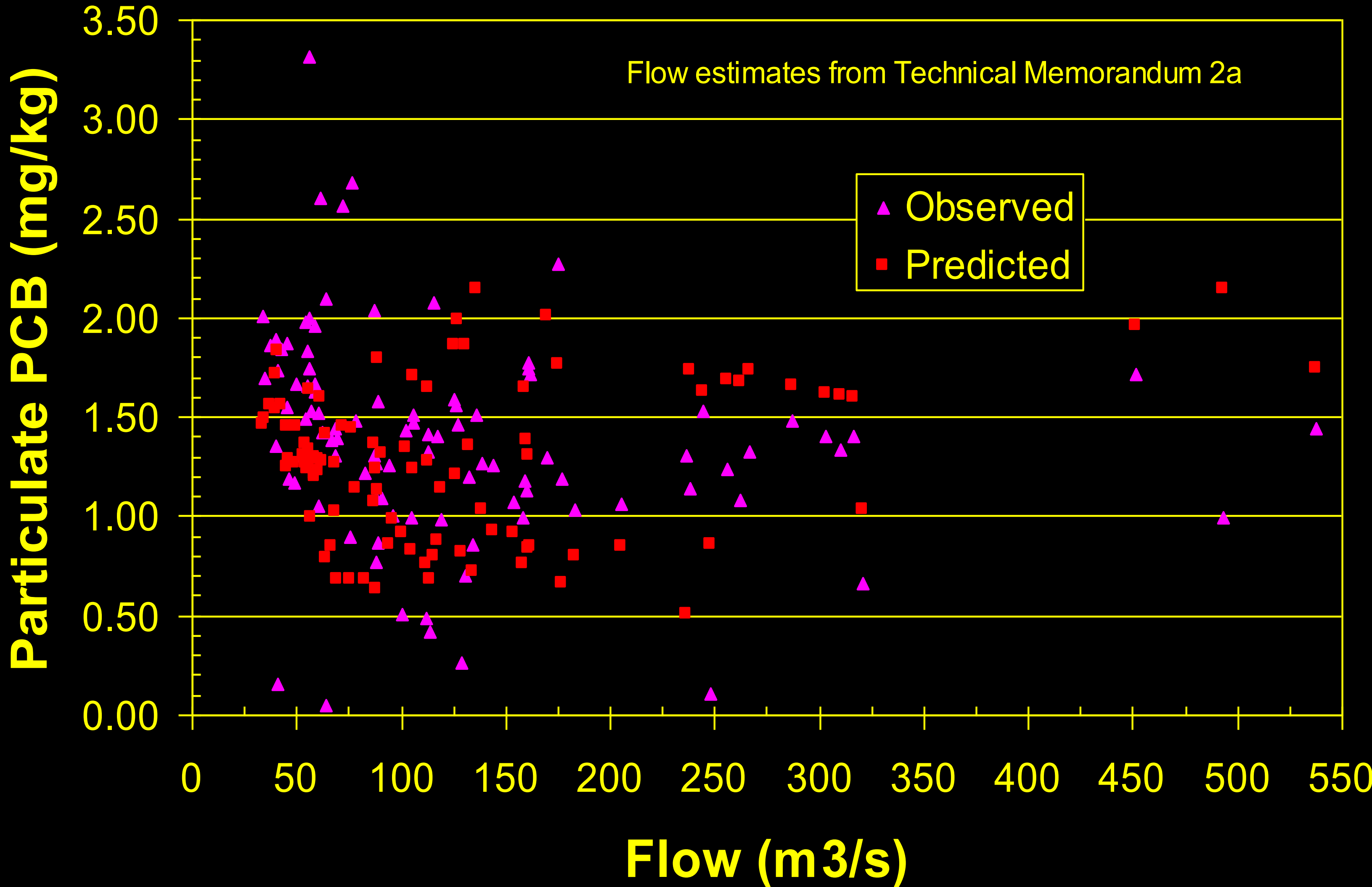
Predicted and Observed PCB Frequency Distributions at the Fox River Mouth: 1989-1995



Predicted and Observed Particulate PCB Concentrations at the Fox River Mouth: 1989-1995



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



Sediment Results (1)

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

Site	Period	Predicted	Observed*
SMU 86-91	1990-93	+1.37 cm	+5 cm (+28 cm)
SMU 86-91	1993-97	+0.59 cm	+2 cm (-110 cm)

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

- **Net Burial Rate**

Site	Period	Predicted	Inferred*
DP-FRM	1989-1995	0.3 cm/yr	0.2-1.4 cm/yr

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

Sediment Results (2)

- **Sediment PCB Time Trends:**

Reach	Predicted	Inferred
LLBdM	-6%/yr	See TTA Report
AP-LR	-3%/yr	See TTA Report
LR-DP	-1%/yr	See TTA Report
DP-FRM	+10%/yr	See TTA Report
Whole River *	~0%/yr	See TTA Report

* 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).

Pitfalls and Advocacy (5)

- **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. Its unlikely that this limitation will be addressed in the next few years.