Re-Visiting Model Projections of Lower Hudson River Fish PCBs

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EPA Contaminated Sediment Forum

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Introduction

- Mechanistic model projections of PCBs in fish played an important role in the comparison of remedial alternatives in the 2002 Record of Decision (ROD) for the Hudson River PCBs Superfund Site
- Post-ROD findings showed that the mechanistic models overestimated the rate of natural recovery in surface sediment
- Model emulation provides a way to update the original mechanistic models with new information

Why Revisit Model Projections?

- Need models to predict the future impact of decisions
- Decisions often difficult, expensive, and controversial
- Similar mechanistic models used to inform decision-making at other Superfund sites
- Rare opportunity to revisit model predictions

Important Questions

- What is the impact of post-ROD data on mechanistic model projections for recovery of fish concentrations in the Lower Hudson River?
- What are the implications for the use of similar models in comparing remedial alternatives?

Overview

- Background (Hudson River, selected remedy)
- Post-ROD findings
- Mechanistic modeling for the Upper Hudson River (UHR) and Lower Hudson River (LHR)
- Emulation of mechanistic model
- Impact of post-ROD findings on mechanistic model projections of recovery of LHR Fish
- Issues and recommendations for estimating temporal trends in sediment

Hudson River PCBs Superfund Site

Hudson Falls/Ft Edward GE Plant Sites

Former Ft Edward Dam

River Section 1

River Section 2

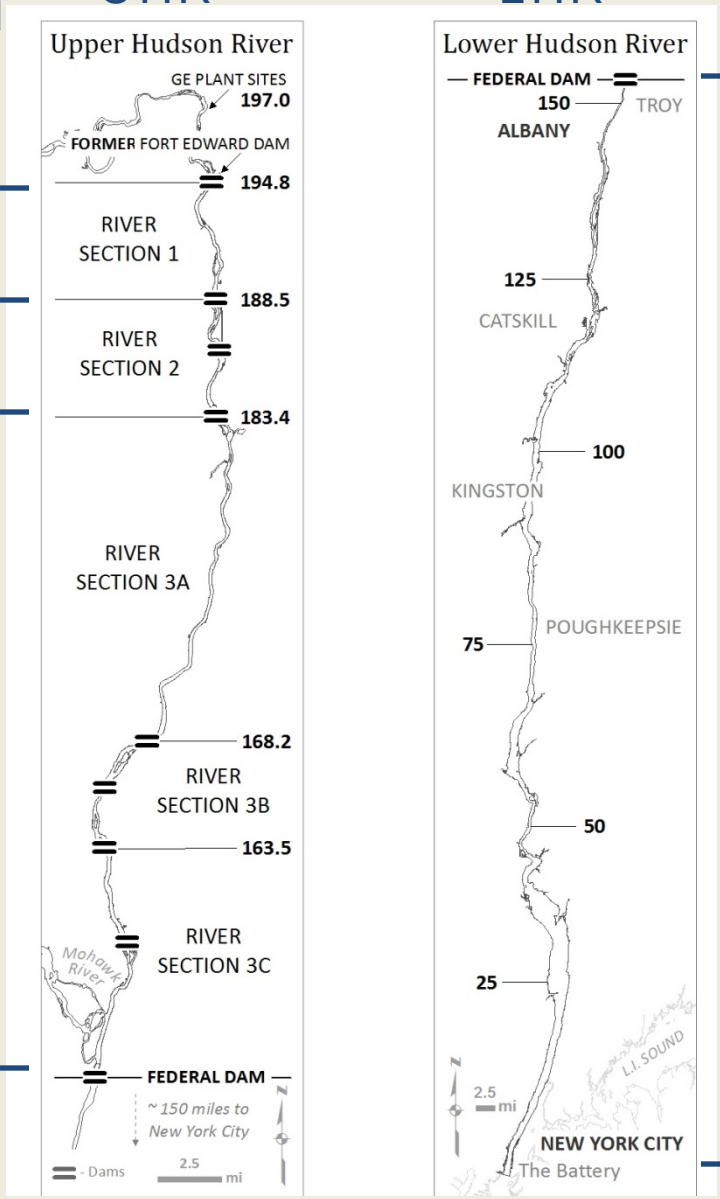
EPA Remedy

River Section 3

Federal Dam

UHR

LHR



Federal Dam

~ 150 miles

The Battery/NYC

Selected Remedy for the Upper Hudson River (UHR)

- REM 3/10/Select: Dredging and Monitored Natural Recovery
  - Upstream source control (NY State remedial process)
  - Target Cleanup Levels
    - River Section 1 (Thompson Island Pool) ~ 6 miles
      - **3 g/m^2 Tri+ PCBs mass per unit area (MPA)**
      - **10 mg/kg Tri+ PCBs in surface sediment** (~ 25-30 mg/kg total PCBs in top 12 inches)
    - River Sections 2 & 3 (multiple reaches/pools) ~ 35 miles
      - **10 g/m^2 Tri+ PCBs MPA**
      - **30 mg/kg Tri+ PCBs in surface sediment** (~ 60-90 mg/kg total PCBs in top 12 inches)

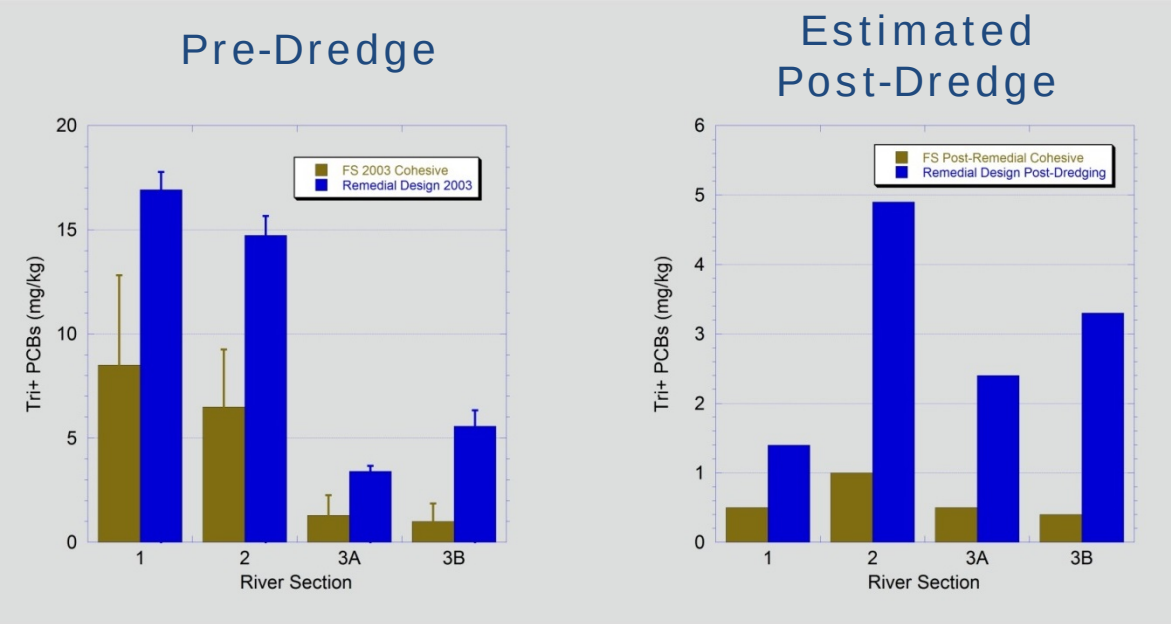
Tri+ PCBs: Trichloro-biphenyl and higher chlorinated PCBs

- Consistent with historical analytical data
- PCBs in HR fish 98-100% Tri+ (USEPA 2002)

Post-ROD Data

- Sediment Data collected for Remedial Design
  - Systematic (unbiased) sampling for UHR (2002-5)
    - RS1: all sediment (cohesive and non-cohesive)
    - RS2 & RS3: cohesive sediment only
  - >8000 cores collected from UHR with PCBs measured in the top 2 inches (5 cm)
  - Mean PCBs assumed to represent 2003 and comparable to 4 cm surface PCBs in mechanistic model output

Surface Sediment PCBs: Mechanistic Model Predicted vs Measured Post-ROD



Tri+ PCBs in surface sediments exceeded the mean by a factor of 2-3 and the upper bound of model predictions

Estimated post-remediation PCBs for the selected remedy were 3-5X higher than model predictions

Surface sediment represents top 4 cm for model and top 2 inches (5 cm) for remedial design data

Empirical Estimate of Natural Recovery Rate

	Average Tri+PCB (mg/kg) in Surface Sediment		
Model Subsection	GE 1991 UHR Survey[1] (Cohesive Sediment)	Remedial Design Data 2002-2005[2]	Exponential Decay Rate
1	20	16.9 (3414)	1.4%
2	18	14.7 (1540)	1.7%
3A	4.3	3.4 (2129)	2.0%
3B	5.7	5.6 (685)	0.1%
Mean			1.3%
95% CI			-0.1% - 2.6%

< 3%

[1] O'Brien & Gere Engineers, Inc. 1991 Data Summary Report, Hudson River Project

[2] Includes cohesive and non-cohesive sediments from top 2 inches in River Section 1 and cohesive only in Sections 2 and 3. Data collected 2002-2005, considered to represent concentrations in 2003.

Summary of Post-ROD Findings

- Measured surface sediment PCBs higher than predicted by the mechanistic model throughout UHR
- Rate of sediment recovery slower than mechanistic models predicted
- PCB loads from the UHR to the LHR prior to 2009 greater than predicted by EPA's mechanistic models and showed little evidence of decline[1]

[1] USEPA 2010. Hudson River PCBs Site EPA Phase 1 Evaluation Report

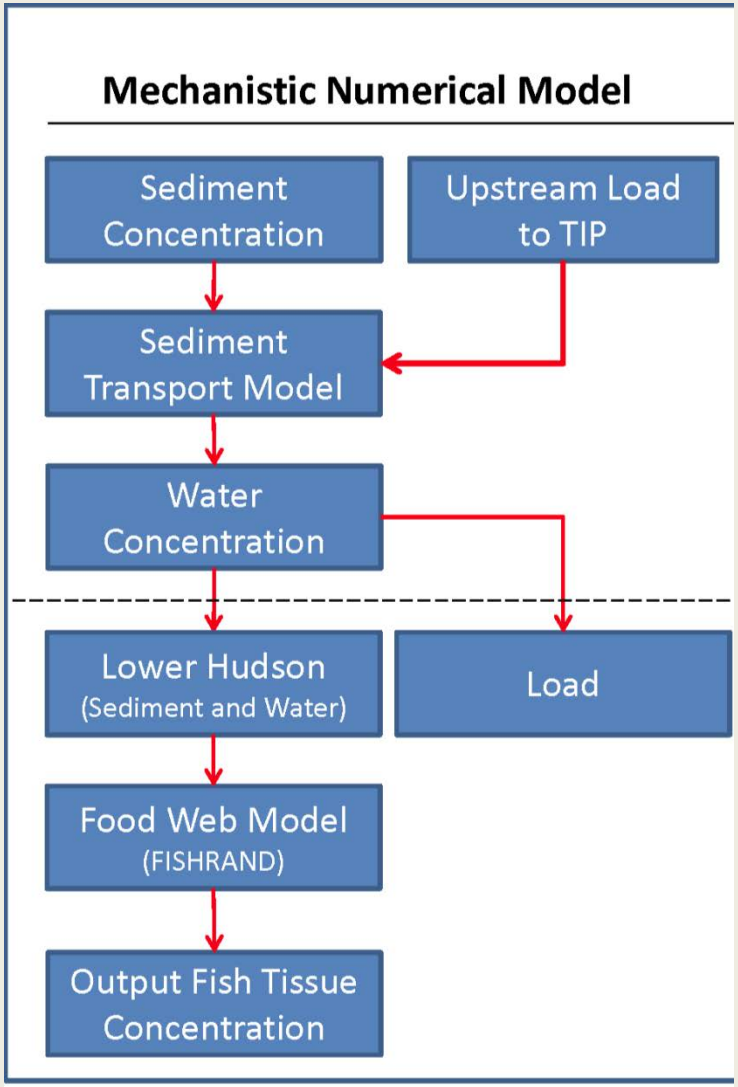
Importance of Incorporating New Data into Mechanistic Model Framework

- Post-ROD findings in UHR sediment and estimates of load to LHR likely impact projected declines in LHR fish PCBs
- Re-running the original mechanistic models with new data was not an option because of the cost and effort involved

Why Use Model Emulation?

- Provides alternative approach to efficiently condense complex integrated models into a simple, easy-to-use model
- Maintains the underlying relationships within the mechanistic model
- Enables use of updated data and evaluation of alternative scenarios
- Used effectively for large numerical ocean and climate change models

Mechanistic Model Schematic



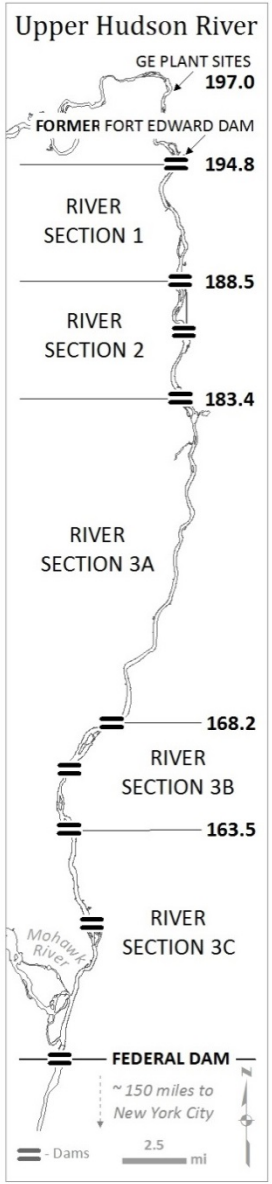
Model boundary conditions: Upstream PCB input into RS1 (Thompson Island Pool)

Surface sediment PCBs projected for UHR model subsections

PCBs in water projected for UHR model subsections

Output from UHR models used to predict fish PCBs at 4 LHR locations between RM152 and RM50 for 4 species of fish

Upper Hudson River (UHR)



Boundary Condition

RS1

RS2

RS3A

RS3B

RS3C

Surface sediment & water PCBs projected for UHR

PCB Load from Waterford (RS3B) used as input to LHR models

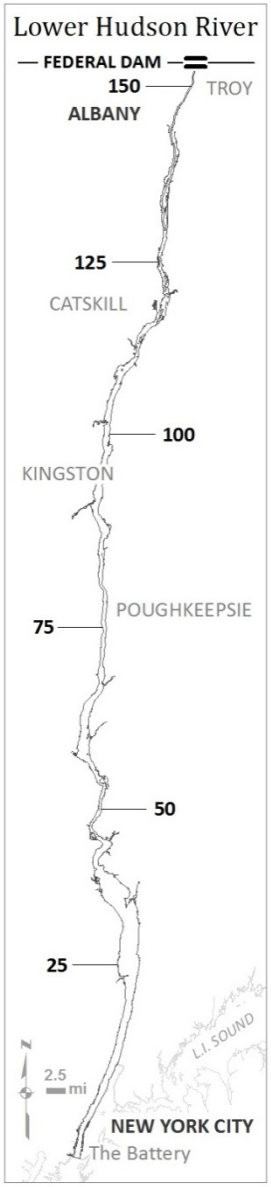
Lower Hudson River (LHR)

Output from mechanistic model PCB Load from Waterford (RS3B) used as input to LHR models

Farley[1] model used to project LHR water and sediment PCBs

FISHRAND Food Web model used Farley model output to project PCBs in 4 species of fish at 4 LHR locations

- White Perch
- Largemouth Bass
- Brown Bullhead
- Yellow Perch



RM152

RM113

RM90

RM50

[1]Farley KJ 1999. An integrated model of organic chemical fate and bioaccumulation in the Hudson River Estuary

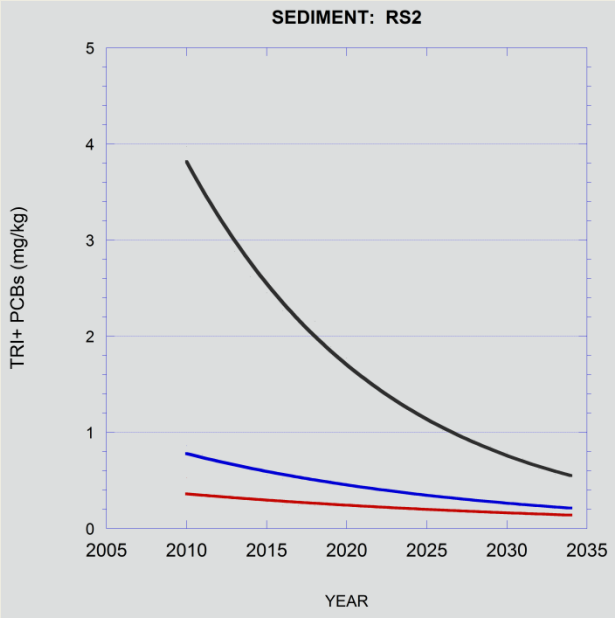
Mechanistic Model Remedial Scenarios

- MNA: Monitored Natural Attenuation with source control (assumes upstream boundary conditions of 2 ng/L PCBs by 2005)
- REM-3/10/Select: Selected Remedy
- REM-0/0/3: Full section removal in RS1 & RS2

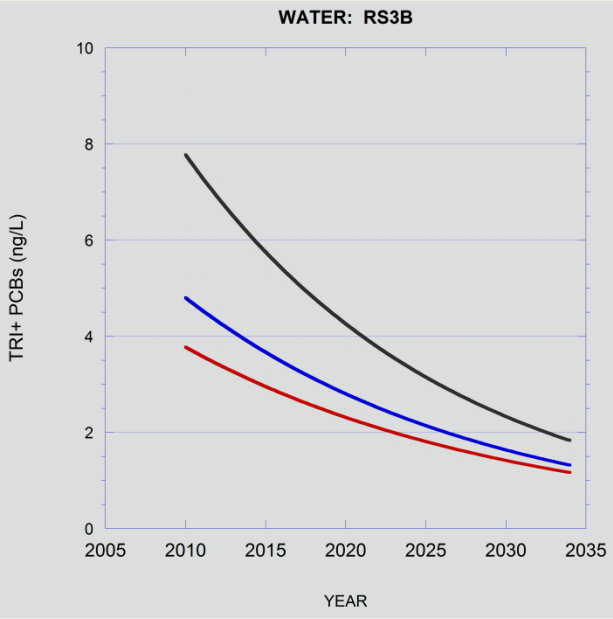
Models assumed active remediation began in 2003 and completed by 2010

EPA Mechanistic Model Projections for 3 Remedial Alternatives

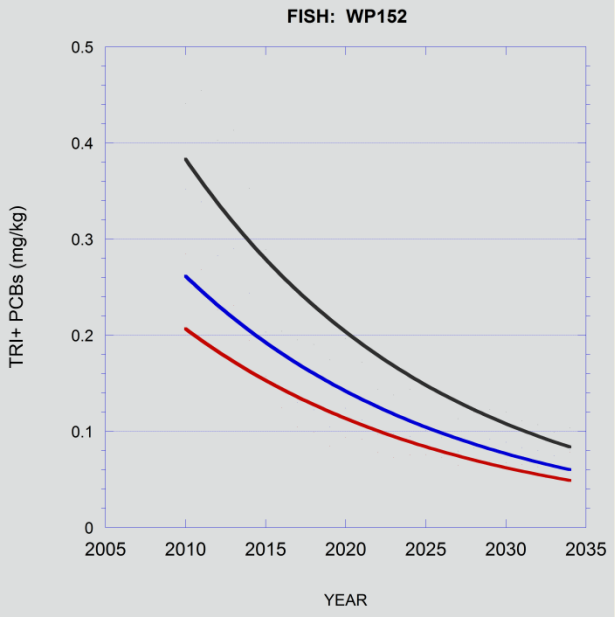
SEDIMENT (RS2)[1]

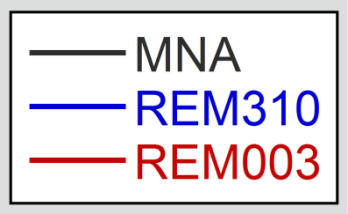


WATER (RS3B)[1]



FISH (LHR)[2]





[1] USEPA 2000. Hudson River PCBs Reassessment RI/FS Phase 3 Report. Feasibility Study.
[2] USEPA. 2002. Hudson River PCBs Site Record of Decision and Responsiveness Summary.

Model Emulation Approach

- Develop statistical models to reproduce mechanistic model projections for PCBs in UHR surface sediment and water and LHR fish for Monitored Natural Attenuation (MNA) and the selected remedy (REM)

- Use updated surface sediment PCBs and rate of decrease in sediment PCBs to assess the impact of the post-ROD findings on predictions of LHR fish PCBs

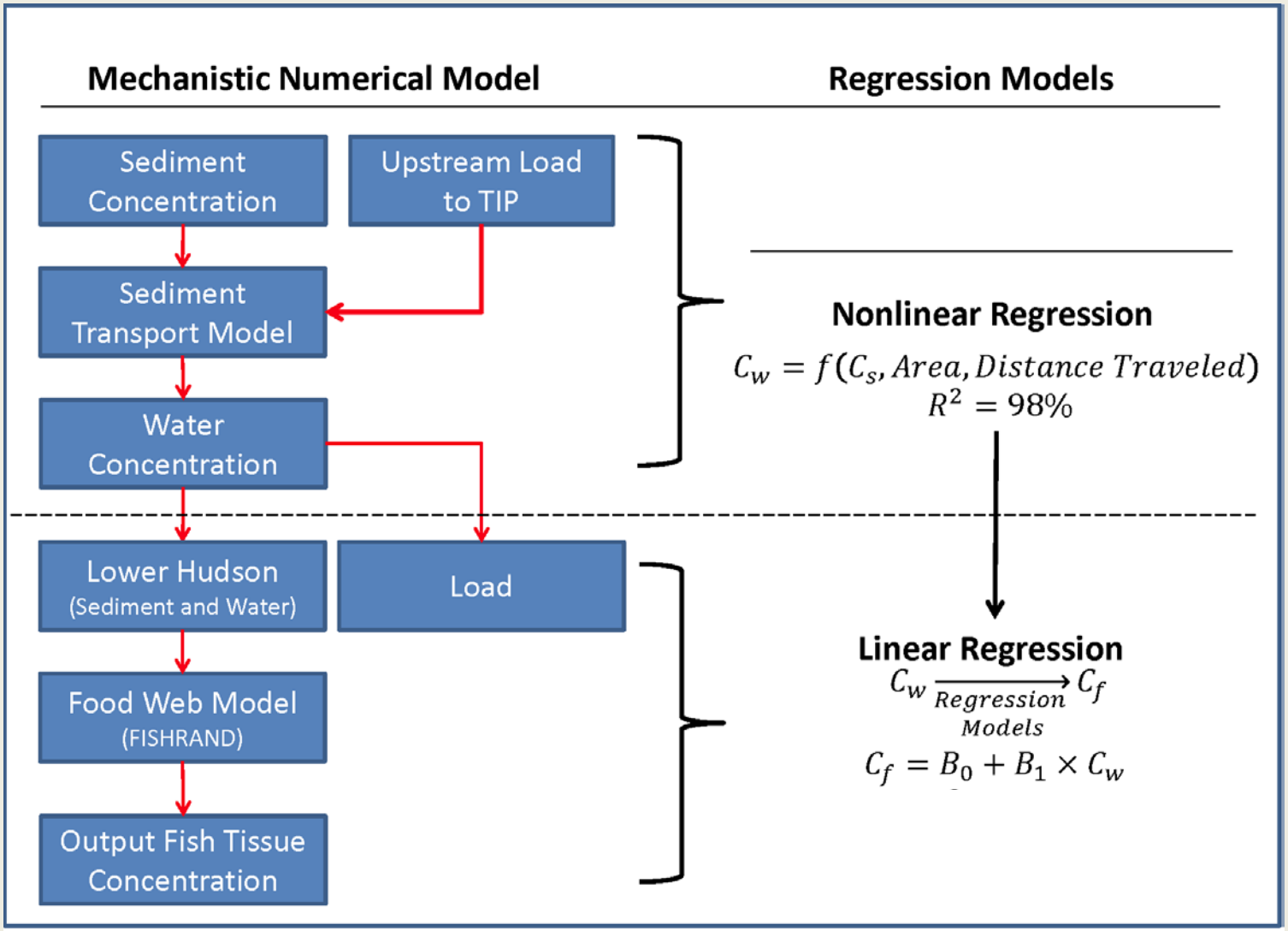
Overview of Model Emulation

- UHR Sediment: Reproduce mechanistic model projections for cohesive sediment PCBs in 4 UHR subsections for MNA and the selected remedy

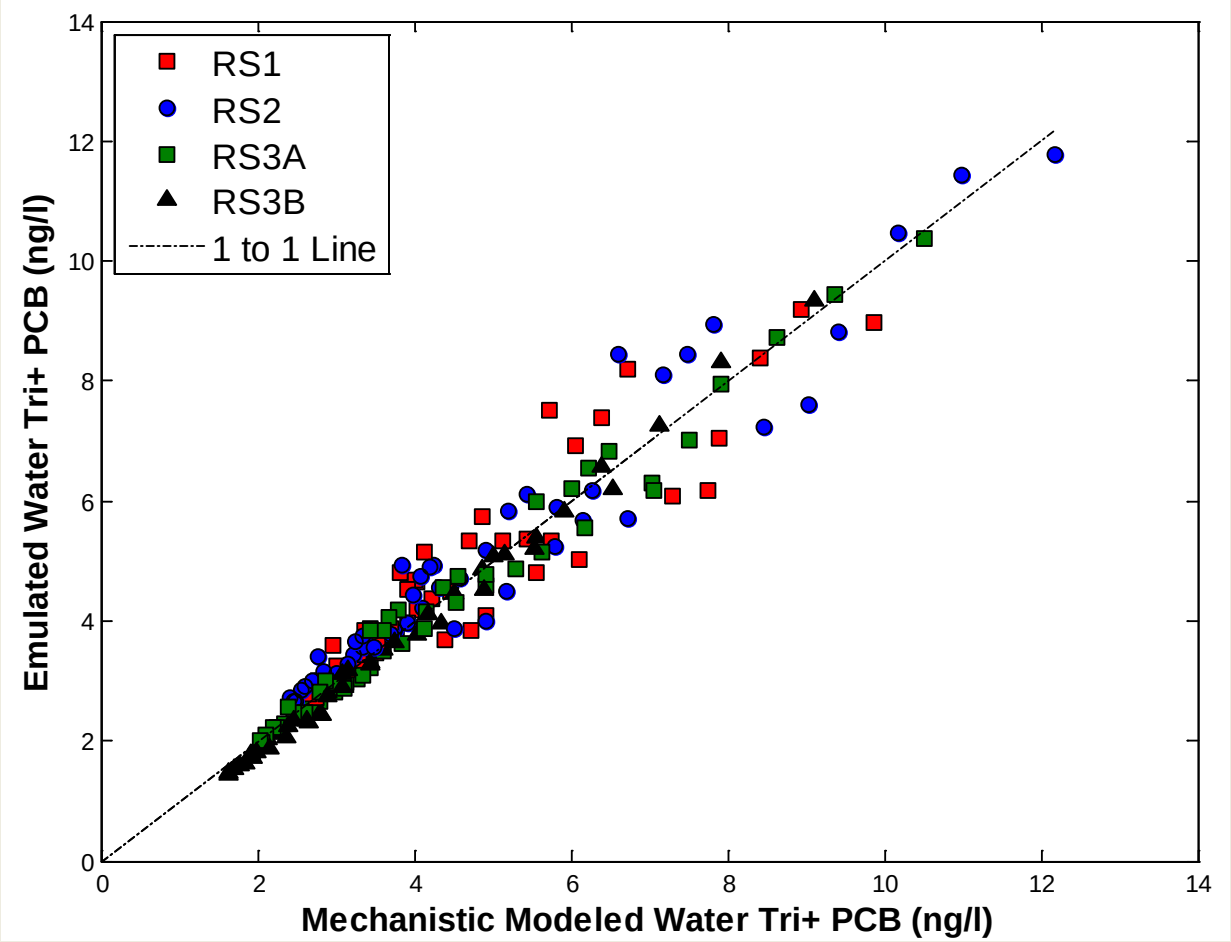
- UHR Water: Use non-linear regression to predict water PCBs in 4 UHR subsections from sediment PCBs

- LHR Fish: Use linear regression to predict fish PCBs in 4 species of fish at 4 locations in the LHR from water PCBs at Waterford (RS3B)

Model Emulation Schematic



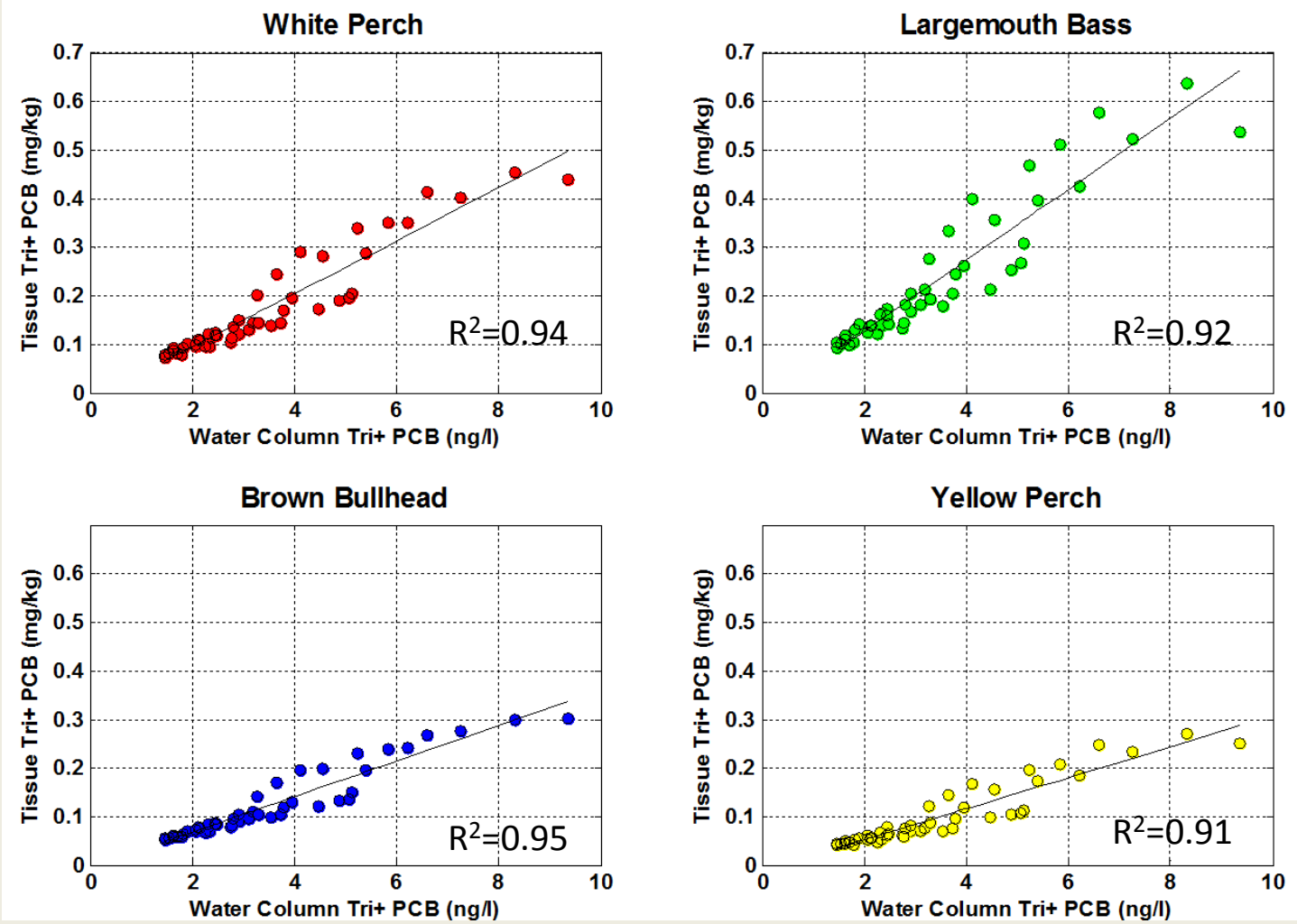
Emulated vs Mechanistic Model Water Concentrations (Tri+ PCB, ng/L)



Data Source: USEPA. 2002. Hudson River PCBs Site Record of Decision and Responsiveness Summary.

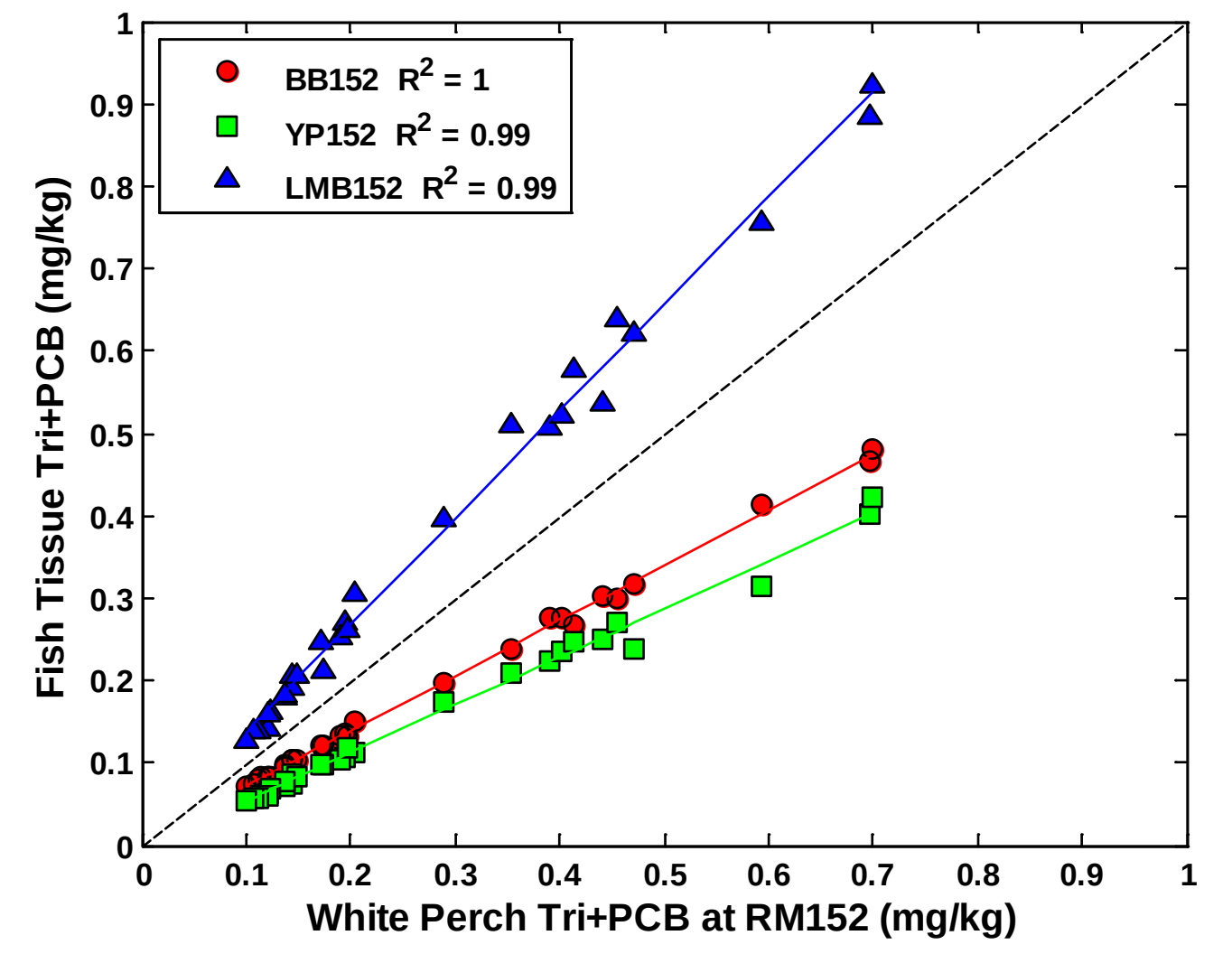
Emulation of LHR Fish PCBs Mechanistic Model Output

Water (RS3B) vs Fish PCBs at RM152



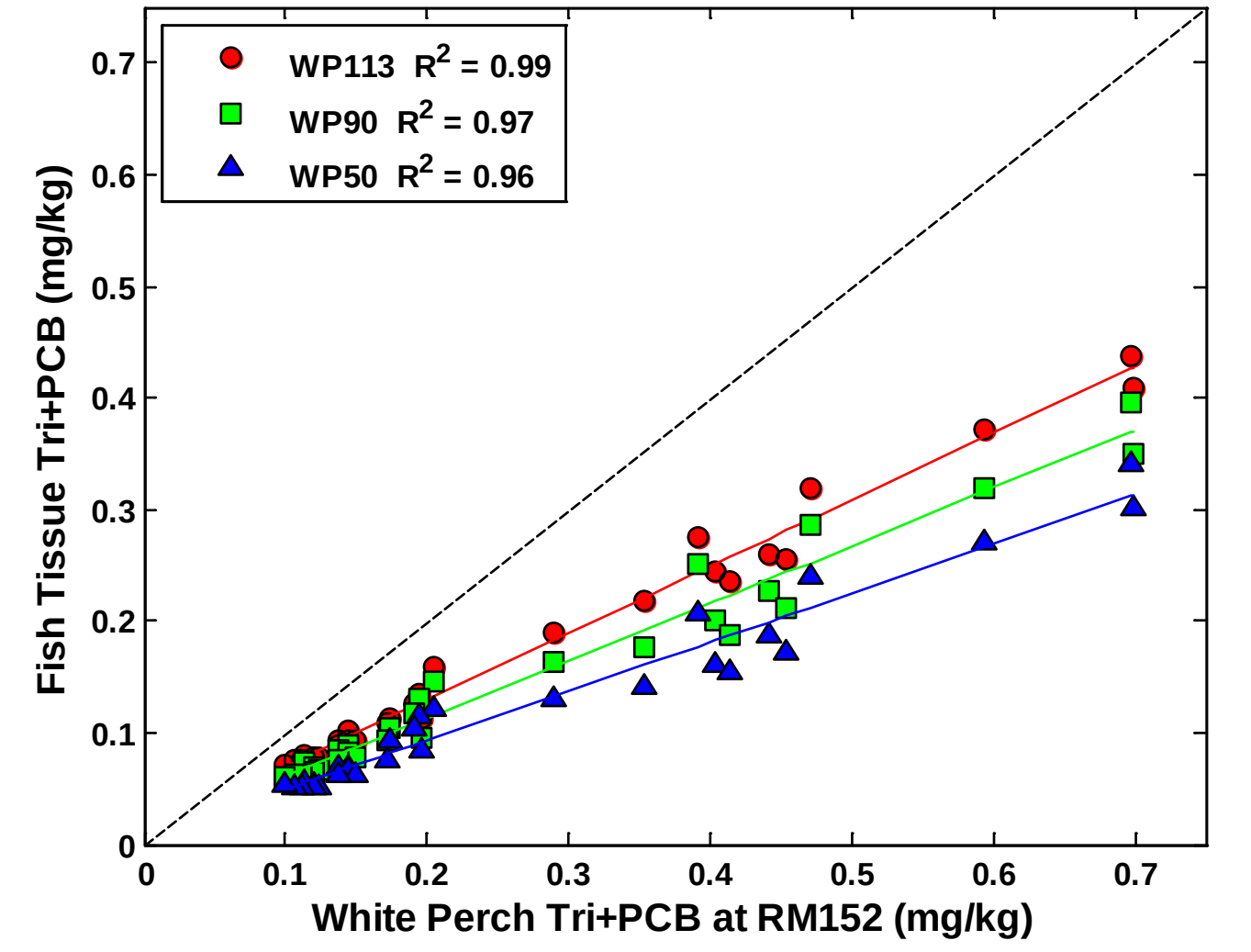
Data Source: USEPA. 2002. Hudson River PCBs Site Record of Decision and Responsiveness Summary.

Mechanistic Model Output
Fish Species Comparison



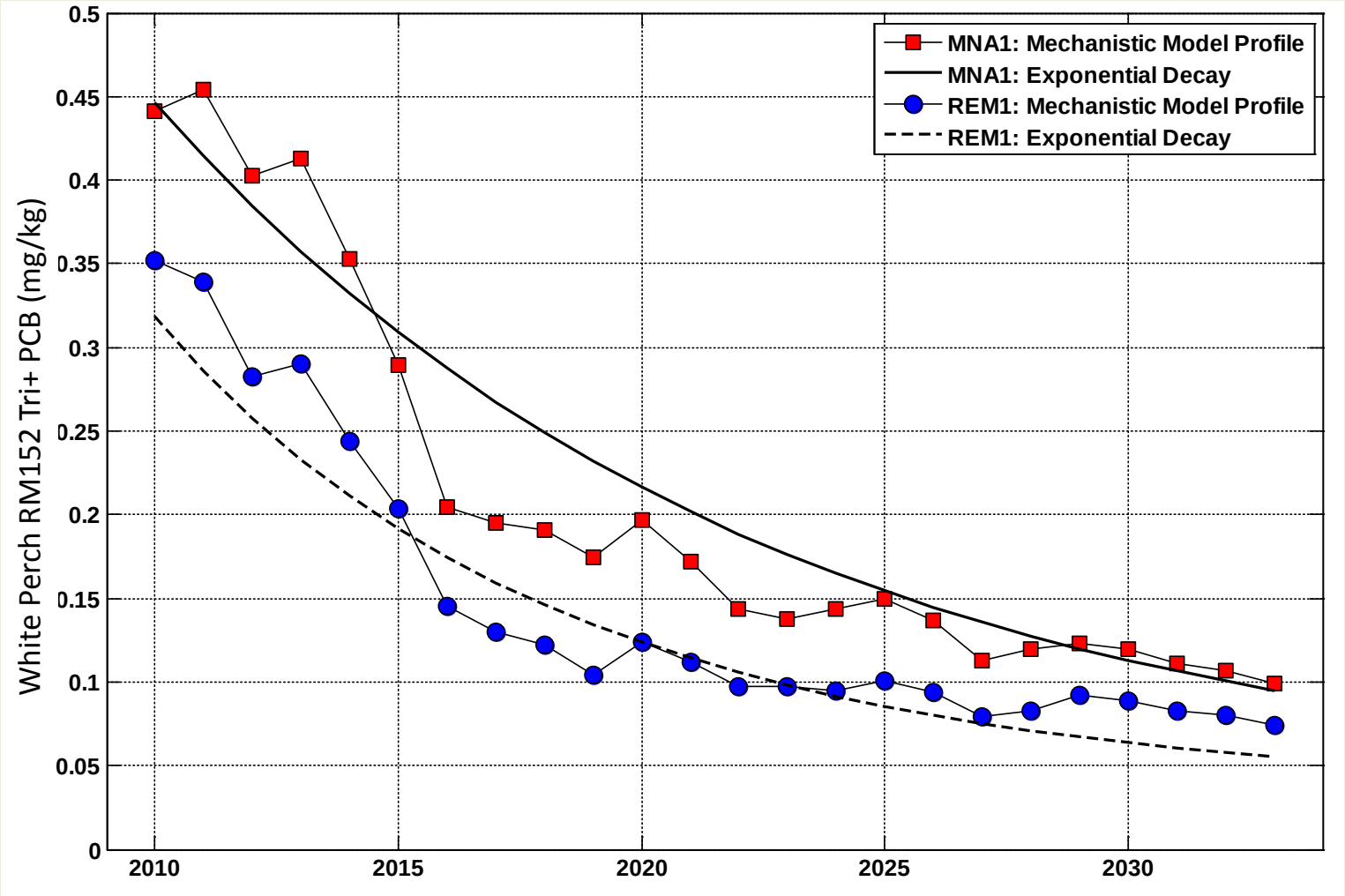
Data Source: USEPA. 2002. Hudson River PCBs Site Record of Decision and Responsiveness Summary.

Mechanistic Model Output
Fish Location Comparison



Data Source: USEPA. 2002. Hudson River PCBs Site Record of Decision and Responsiveness Summary.

Mechanistic Model Projections vs Exponential Decay (8%) Model

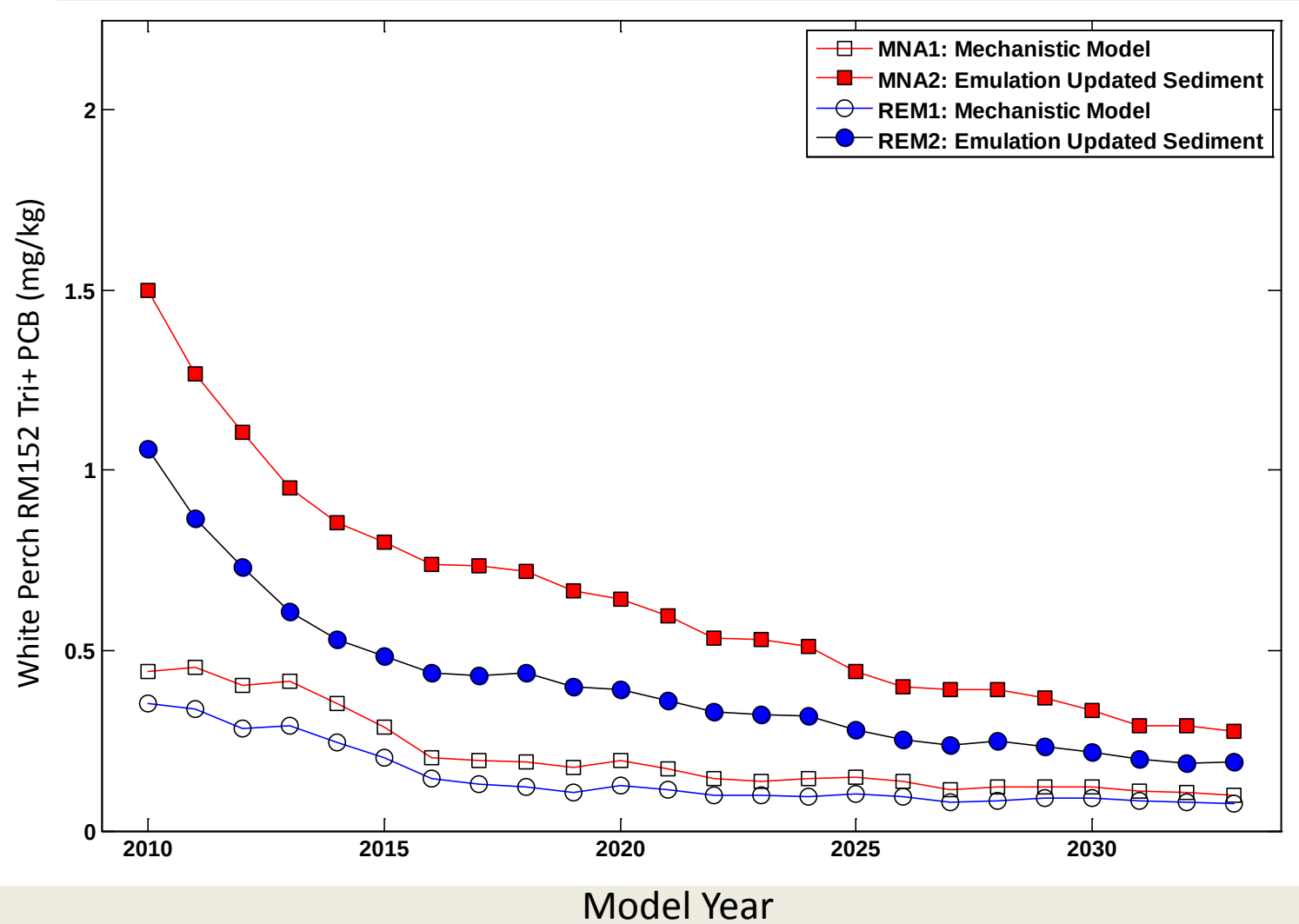


Model Year

Emulated Model Scenarios

Scenario	Emulated Model Projections
MNA1/REM1	Original model projections for Monitored Natural Attenuation (**MNA1**) and the selected remedy (**REM1**)
MNA2/REM2	MNA (**MNA2**) and the selected remedy (**REM2**) with updated sediment PCBs
REM3	Alternative scenario applying RS1 criteria for MPA and surface PCBs to RS2 and RS3 (**REM3**) with updated sediment PCBs
Exponential decrease	Original (8%) and updated (3%) exponential decrease in sediment PCBs applied to all scenarios

Emulated Model Projections of Fish PCBs with Original (MNA1, REM1) and Updated (MNA2, REM2) Sediment PCBs

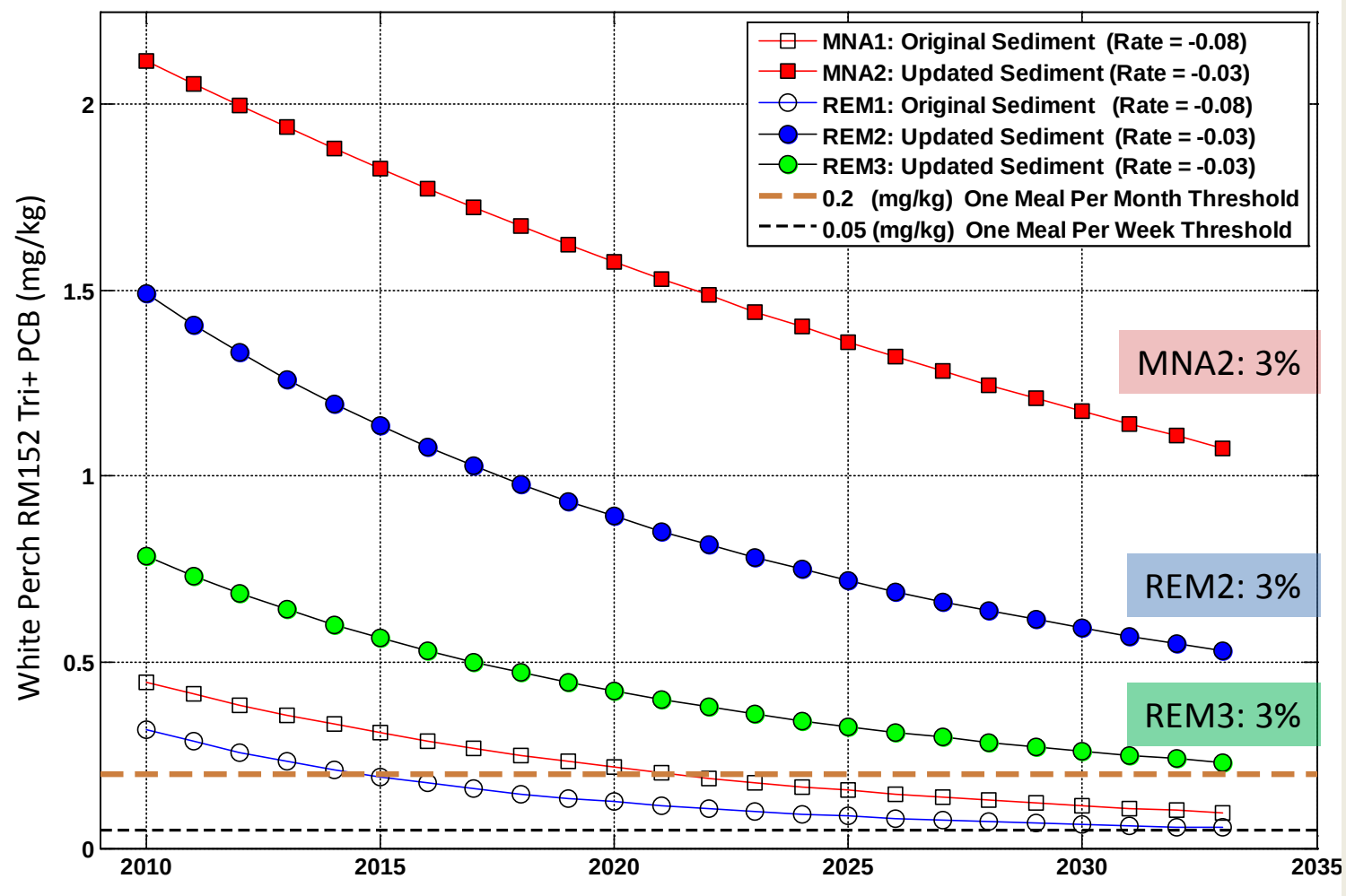


Remedial Action Objectives
Human Health

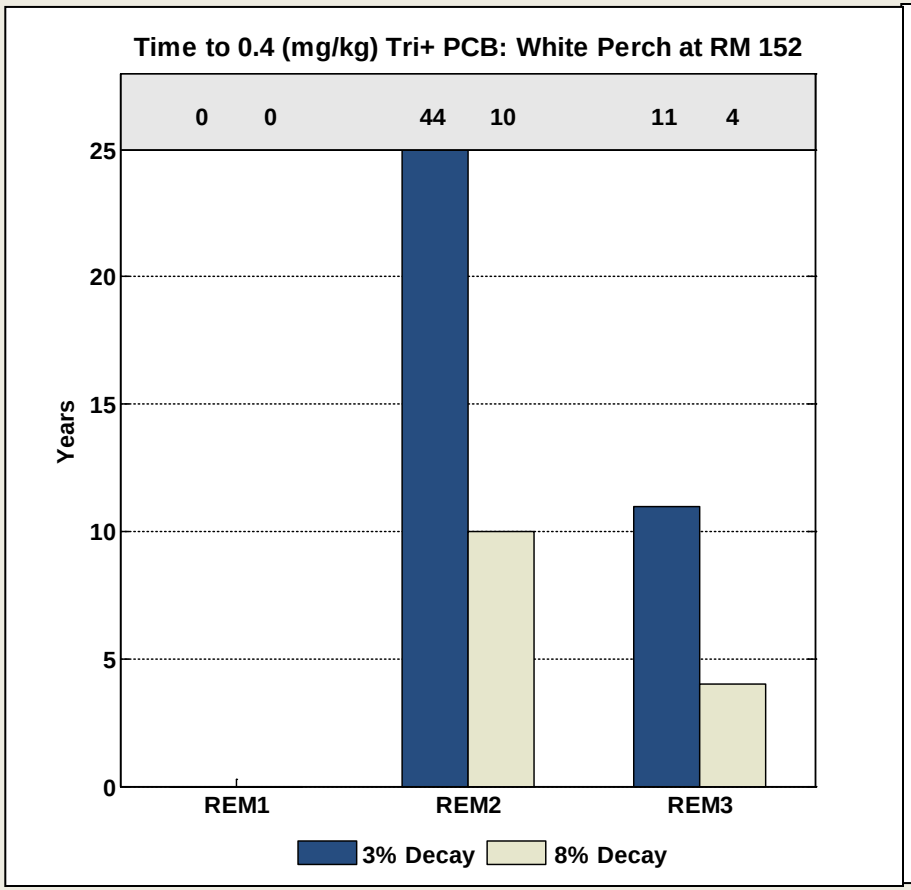
- ***Reduce the cancer risks and non-cancer health hazards for people eating fish from the Hudson River by reducing the concentration of PCBs in fish.***
  - 0.05 mg/kg PCBs in fish fillet, one half-pound meal per week
  - 0.2 mg/kg PCBs in fish fillet, one half-pound meal per month
  - 0.4 mg/kg PCBs in fish fillet, one half-pound meal every 2 months

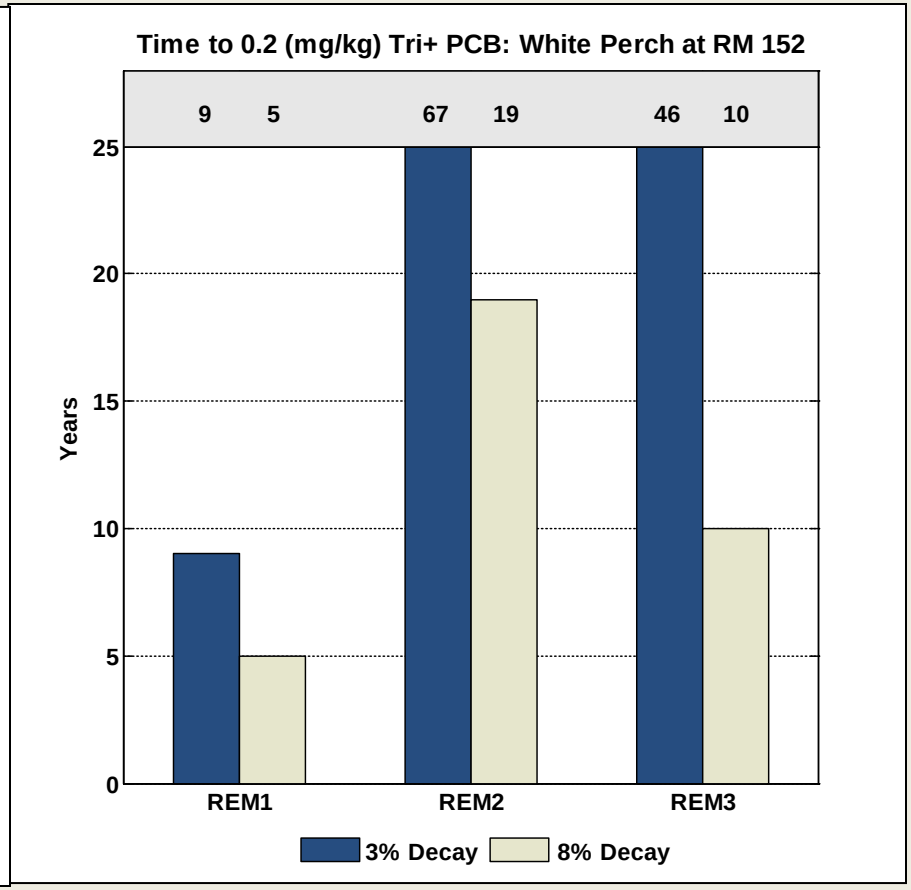
"…the Remediation Goal of 0.05 mg/kg also is expected to be attained in the majority of the Lower Hudson River, due to the lower initial concentration of Site-related PCBs in the Lower Hudson compared to the Upper Hudson." (USEPA 2002)

Emulated Model Projections for MNA and Remedial Scenarios

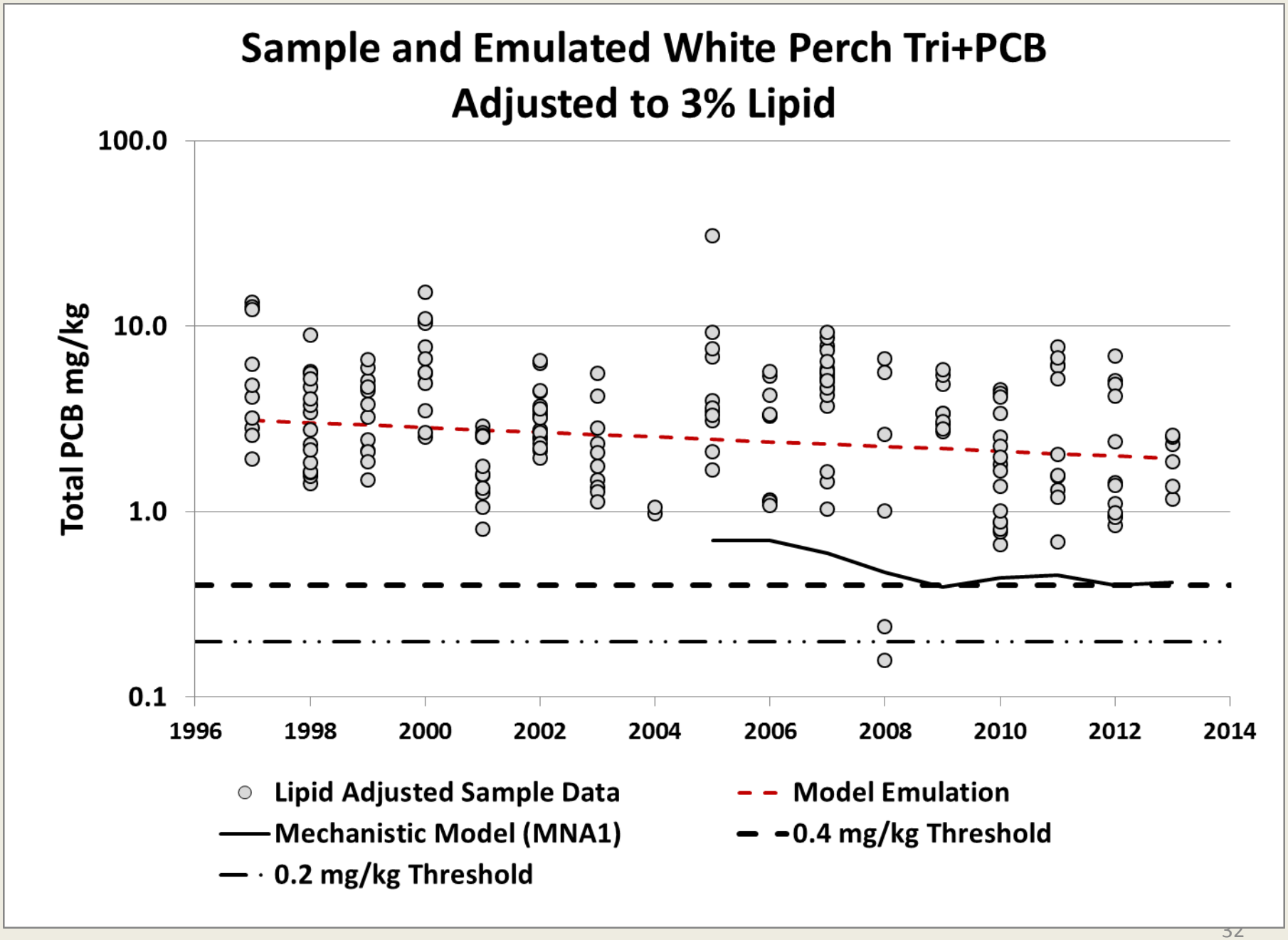


Model Emulation: Post Remediation Years to 0.4 and 0.2 ppm PCB Thresholds





- REM1: Original model initial projected sediment concentrations for selected remedy in 2010
  REM2: Emulated model for selected remedy with updated sediment concentrations
- REM3: Emulated model for revised remedial scenario with updated sediment concentrations


Sample and Emulated White Perch Tri+PCB
Adjusted to 3% Lipid
Total PCB mg/kg
100.0
10.0
1.0
0.1
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
Lipid Adjusted Sample Data
Model Emulation
Mechanistic Model (MNA1)
0.4 mg/kg Threshold
0.2 mg/kg Threshold

Summary: Model Emulation

- **Application to Hudson River**
  - Reproduced mechanistic model projections of sediment, water and fish PCBs under MNA and the selected remedy
  - Enabled application of updated sediment concentrations and estimated rate of exponential decrease to re-visit temporal projections of LHR fish tissue concentrations
- **Other Advantages**
  - Statistical uncertainty evaluations
  - More accurate model calibration and validation

Summary: Hudson River Sediment and Fish

- Recovery of UHR sediment surface much slower than predicted
- Recovery of LHR fish much slower than original projections
- Applying an enhanced remedy (eg., REM3) would reduce time to achieve PCB thresholds in fish, but still longer than originally predicted for the selected remedy

Use of Models in Decision-Making

- Overestimation of the rate of natural recovery in sediment minimizes difference between remedial alternatives
- Accurate estimation of the rate of natural recovery during RI/FS is essential for comparisons of alternatives
- Without baseline sediment data, relative comparisons of remedial alternatives may be misleading
- Model emulation can be a useful tool in reducing and understanding uncertainty

Conclusions

- Original mechanistic models used were overly optimistic about the rate of recovery of surface sediment under MNA and the selected remedy
- Attainment of Remedial Action Objectives for fish in the LHR will take much longer than predicted
- Additional removal of PCB-contaminated sediment in the UHR needed to achieve reductions in LHR fish PCBs anticipated in the ROD

Estimating Temporal Trends in Sediment

- Why are temporal decay rates for surface sediment overstated?
- What can we do to more accurately estimate rate of recovery in surface sediment?

Why Were Temporal Decay Rates Overstated?

- What factors contribute to the overestimation of rate of recovery?
- Design recommendations for sediment sampling to determine rate of natural recovery in surface sediment concentrations

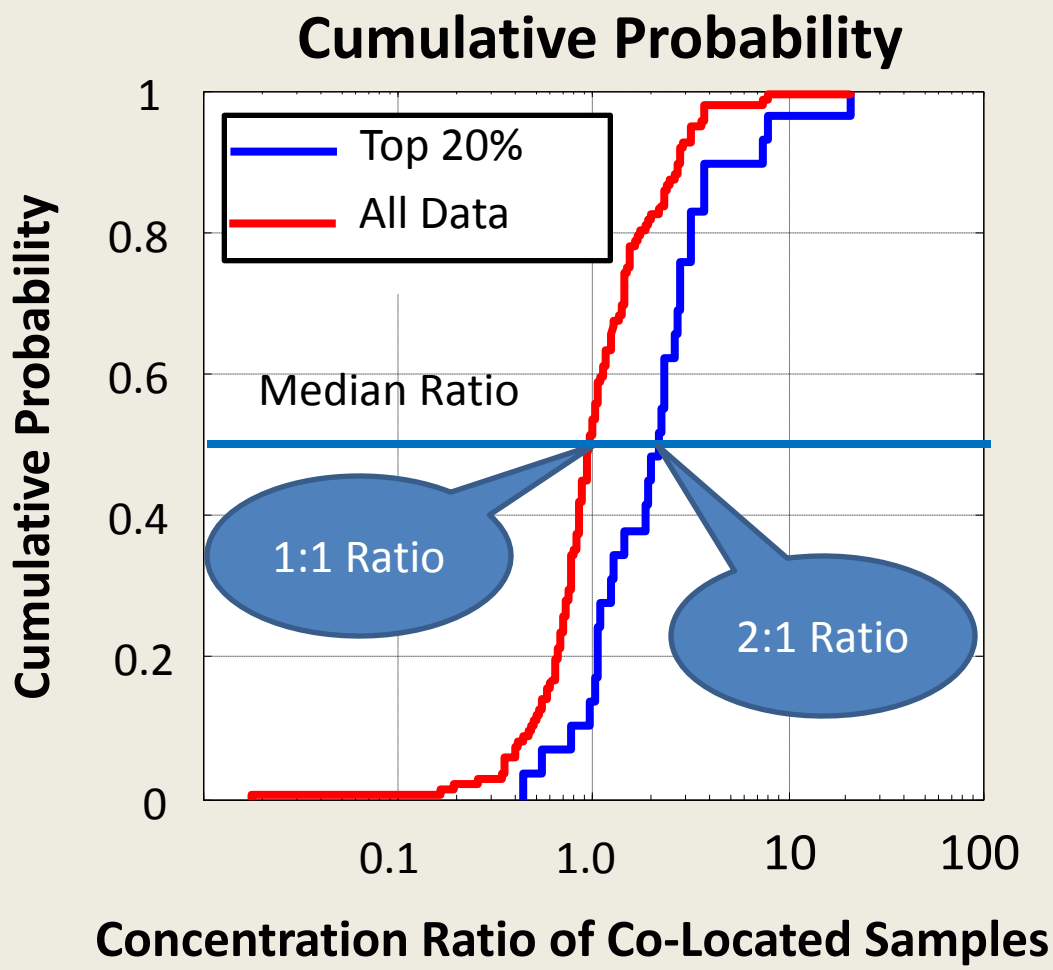
Why Were Temporal Decay Rates Overstated?

- Sedimentation rates in high resolution cores
  - Not all High-Res cores can be dated
  - Those that can be dated are in quiescent areas, not representative of the majority of the study area
  - May bias estimates toward higher sedimentation rates
- Comparison of surface concentrations between time steps
  - RI sampling programs were biased toward higher concentrations
  - Subsequent sampling also biased toward these areas
  - Assumption that trends are easier to detect in high concentration areas

Testing Trend Estimation With Biased Sampling

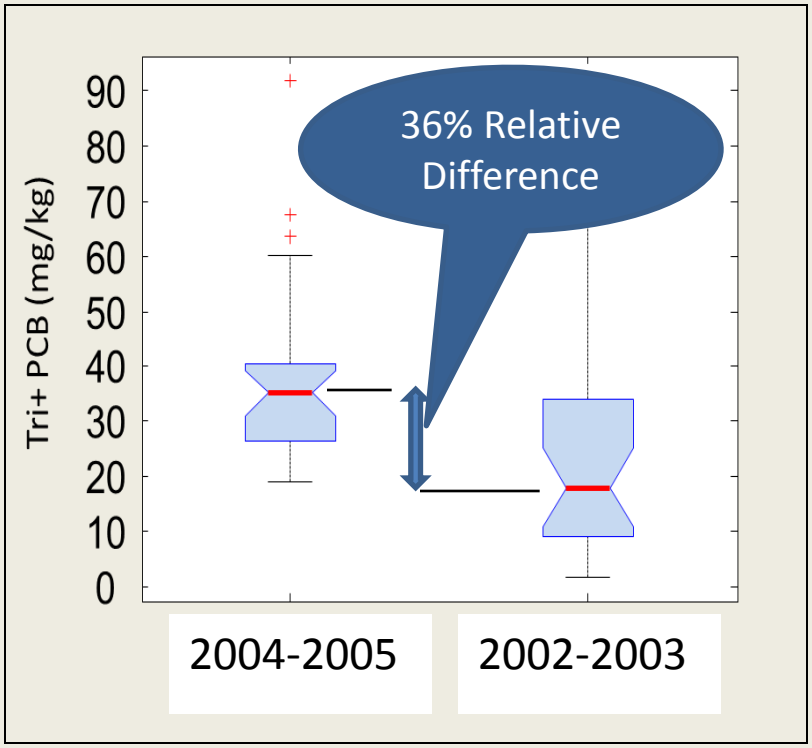
- Used paired co-located surface sediment samples from 136 locations throughout the Upper Hudson collected in 2002-2003 and 2004-2005
- Co-locates within 10 feet of initial sample compared
  - Samples from the upper 20th percentile from 2004-2005
  - Compared with co-located sample from 2002-2003
- Any estimated declines would be artifacts of biased sampling

Distribution of Sample-Pair Ratios



- Median Ratio for all data is 1:1
- Median Ratio for preferentially selected top 20% is ~2:1
- Comparison of secondary sample at locations of top 20% of first sample virtually guarantees apparent decreasing temporal trends

Paired-Sample Comparison Results



- Median concentration for the upper 20th percentile of 2004-2005 sample distribution is 36% higher than the median for paired samples collected 1-3 years earlier.
- Result is an artifact of the biased sampling used to obtain the test set.

“All Models are Wrong, Some are Useful”

- For a decision-maker, useful models provide the ability to discriminate differences in outcome for an array of alternatives
- How do you know if model is useful?
- Need good data, including data for baseline conditions and temporal rate of change in surface sediment concentrations that are representative of the area of concern

Design Recommendations for Sediment Temporal Trend Monitoring Plan

- Incorporate trend monitoring early in site assessment
- Use unbiased sampling procedures
  - Identify important strata boundaries at the outset of the monitoring program
  - Determine sample size using variability of existing data to quantify temporal decay rates with adequate precision for comparisons of remedial alternatives
- Monitor same locations at ~ 5 year intervals
  - Use paired and repeated measures statistical analyses within strata to evaluate local trends
  - Combine results across strata to develop global statements about trend in overall average (SWAC).
  - Interpolation is unnecessary because sampling is unbiased

Questions?