PCBs in the Upper Hudson River

Executive Summary

Prepared for:

General Electric
Albany, New York

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Section 1

Introduction

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SECTION 1
INTRODUCTION

In 1989, Region II of the U.S. Environmental Protection Agency (USEPA) announced it was reassessing its 1984 decision, under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), that no action should be taken for PCBs within Upper Hudson River sediments. Since that time, USEPA has been involved in a multi-phased reassessment project, which has included a review of site data, collection and analysis of new data, and evaluation of different remedial action strategies for Upper Hudson River sediments with particular emphasis on the Thompson Island Pool (Figure 1-1). The General Electric Company (GE) has been extensively involved in the reassessment process, providing comments on USEPA work products, performing independent data collection and analysis, and conducting field and laboratory research. USEPA and GE reassessment efforts are focused on answering three central questions:

1) When will PCB levels in fish populations recover to levels meeting human health and ecological risk criteria under continued No Action?

2) Can remedies other than no action significantly shorten the time required to achieve acceptable risk criteria?

3) Are there contaminated sediments now buried and effectively sequestered from the food chain that are likely to become biologically available following a major flood, possibly resulting in an increase in contamination of the fish population?

An integral part of GE's work during the reassessment has been the development of a quantitative model. This model mathematically describes the fundamental processes governing the behavior of PCBs within the Upper Hudson River and represents the principal means by which the above questions can be answered. The complex and dynamic nature of the links among PCB levels in the sediment, water column, and biota is described within the modeling framework to provide scientifically valid and reliable estimates of future PCB levels in the Upper

Hudson River. The model integrates site data and scientific knowledge of the physical, chemical and biological processes that govern PCB fate within the river.

This report, developed by Quantitative Environmental Analysis, LLC (QEA), on behalf of GE, documents a nine year effort to: 1) quantitatively understand PCB dynamics in the Upper Hudson River, and 2) develop, calibrate, validate, and apply a state-of-the-science PCB fate, transport, and food web bioaccumulation model to the Upper Hudson River. Specifically, the model predicts future PCB concentrations in water, sediment, and fish under continued "no action" (natural recovery), taking into account source control to date upstream of Roger Island as well as under various assumed remedial scenarios. As such, it is the most powerful quantitative tool available to answer the central reassessment questions. There are no other means to perform such assessments at a comparable level of confidence. Therefore, the model is an essential element of the decision-making process.

The development and application of the model have produced the following key findings:

- The fish and other biota in the river are exposed only to those PCBs that are in the water column or in the top inch or two of bottom sediment.

- Sediment burial has been, and continues to be, an important natural mechanism for the recovery of the river.

- The Upper Hudson River is undergoing a natural recovery that will result in average largemouth bass PCB concentrations in all reaches of the river declining below 2 ppm within about 10 years, based upon the most likely estimate of the model.

- Additional reductions in the PCB loading to the river from the vicinity of the GE Hudson Falls site would accelerate the recovery throughout the river, reducing the time needed to reach 2 ppm by as much as 4 years, based upon the most likely estimate of the model.

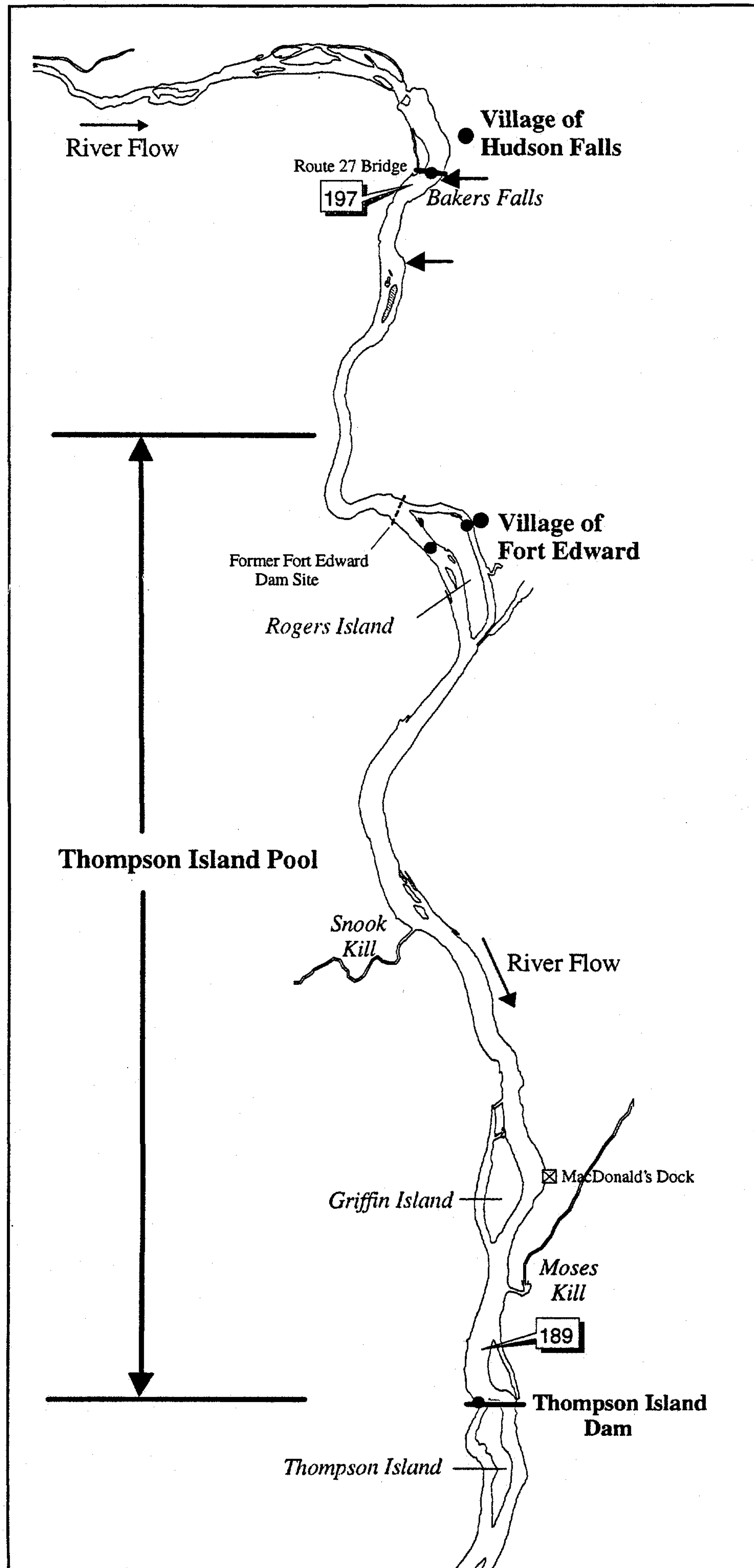
- Bounding calculations indicate that, although less likely, the time for largemouth bass in all reaches of the river to decline below 2 ppm could be as long as 24 years. If this were the case, additional reductions in the PCB loading to the river would accelerate the recovery by as much as 12 years.

- Remediation of sediments by dredging, even at optimistic rates and efficiencies, would provide only a minor and temporary reduction in PCB levels that would be limited to the reaches in which remediation occurred.

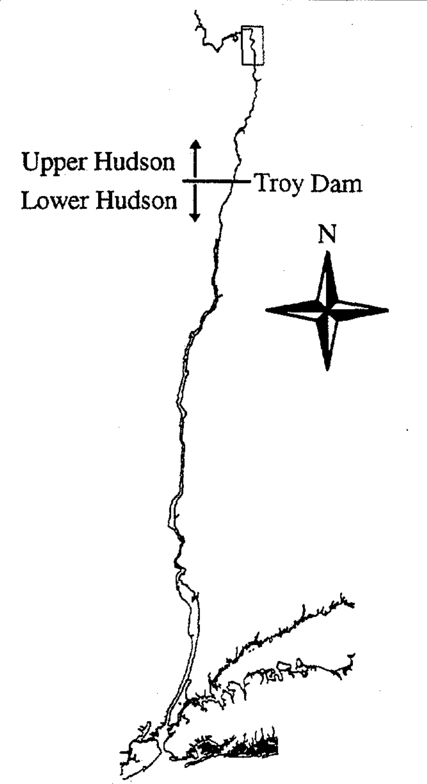
- Dredging would be ineffectual, even if optimistic goals were attained, because it would achieve only small reductions in surface sediment PCB concentrations. Natural recovery will effectively reduce these concentrations prior to the commencement of remediation and during the decade time scale it takes to complete the remediation.

- PCBs associated with buried sediments would not become exposed even if a rare high flow event such a 100-year flood were to occur. Ninety percent of the river bottom would experience less than one-half inch of sediment erosion in this event.

- A 100-year flood would not significantly alter natural recovery. It would cause a temporary increase in PCB levels in fish within the Thompson Island Pool that could extend the time needed for largemouth bass to reach 2 ppm by a few years if the flood occurred in the near future. It would have almost no impact on fish within other reaches of the river.



LOCATION MAP OF THE HUDSON RIVER



GRAPHIC SCALE

0.5 0 0.5 1 Miles

LEGEND

- GE Plant Sites
- Approximate Location of Remnant Deposits
- Approximate Mile Point from Battery in NYC
- Routine Water Column Monitoring Locations

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Figure 1-1.

Portion of the Upper Hudson River including GE plant sites and Thompson Island Pool (Reach 8).

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Section 2

Historical Perspective

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SECTION 2
HISTORICAL PERSPECTIVE

2.1 RIVER SETTING

The Hudson River is located in eastern New York State and flows south for more than 300 miles from the Adirondack Mountains to the Atlantic Ocean (Figure 2-1). The Upper Hudson River is defined as the stretch of river between Hudson Falls and Troy, New York that contains a series of locks and dams that serve as navigational controls for the Champlain Canal system. The Upper Hudson River is divided into eight reaches, or pools, which terminate at a lock or dam at their downstream ends (Figure 2-2). A focus of this report is the farthest upstream reach, Thompson Island Pool (TIP) or Reach 8. The watershed for the Upper Hudson River and its tributaries between Corinth and Troy, New York covers an area of approximately 1860 square miles. Terrain in this area consists of river valley lowlands, with rolling and hilly areas extending to the west and east, and the Adirondack Mountains to the north. The Upper Hudson River watershed is primarily forest land, while cropland and pastures predominate within the river valley and adjacent areas (Figure 2-3).

2.2 HUDSON RIVER PCB HISTORY

Over approximately 30 years, ending in 1977, GE discharged wastewater containing polychlorinated biphenyl (PCB) into the Upper Hudson River from two capacitor manufacturing facilities in Hudson Falls and Fort Edward, New York. Much of the PCBs accumulated in sediments upstream of the former Fort Edward Dam (former Reach 9, Figure 2-2) located approximately 2 miles downstream of the Hudson Falls capacitor plant (Figure 2-4). Removal of this dam in 1973 by the owner lowered the water level in this reach and exposed PCB containing sediment and wood wastes that had accumulated in the pool created by the dam. Subsequent high flow events in the mid-1970's resulted in the movement of PCB-containing sediments downstream. A significant proportion of these sediments and associated PCBs settled within depositional zones of the river. These areas were extensively sampled and analyzed for PCBs by the New York State Department of Environmental Conservation (NYSDEC) between 1976 and

1978. From these data, 40 sediment PCB hot spots (i.e., locations where PCB concentration exceeded 50 ppm) were identified between Fort Edward and Troy (Figure 2-5), half of which are in the Thompson Island Pool. The exposed sediments remaining upstream of the Fort Edward Dam site following the dam removal and subsequent scour events are referred to as the Remnant Deposits (Figure 2-4).

Following the large scour events and elimination of direct PCB discharges in the late 1970's, PCB levels in the Upper Hudson River generally declined. However, in mid-September 1991, a large increase in water column PCB levels at Fort Edward was detected. The source of this loading was attributed to PCB oil releases associated with the collapse of a wooden gate structure within an abandoned mill located adjacent to the Hudson Falls capacitor plant (Allen Mill, Figure 2-6). Additional PCB loadings from the area of the plant site were discovered in the mid-1990's from bedrock oil seeps at the base of Bakers Falls (Figure 2-6).

2.3 REMEDIAL AND REGULATORY HISTORY

Remedial efforts directed to PCBs in the Hudson River have been ongoing since the early 1970's. Between 1974 and 1978, NYSDEC performed work consisting of stabilization and limited excavation of the Remnant Deposits. In the mid to late 1970's, New York State removed large quantities of sediment and associated PCBs from the TIP as part of the maintenance of the Champlain Canal channel. In 1990, GE completed remedial work under a federal consent degree for the in-place containment of the Remnant Deposits. In the early to mid-1990's, under plans approved by New York State, GE removed approximately 3,400 tons of sediment containing PCBs from the Allen Mill. Throughout the 1990's, GE conducted extensive remedial efforts in the area of the Hudson Falls plant site to prevent PCB oil and groundwater from reaching the river.

Regulatory action by both Federal and State agencies dates back to the early 1970s. Under the auspices of New York State, the sediment PCB hot spots and Remnant Deposits were identified, and PCBs were also detected in Hudson River fish, resulting in a 1976 state-mandated ban on fishing in the Upper Hudson River. During the 1980s, New York State designed and attempted to implement dredging projects in the Upper Hudson River. These attempts failed when NYSDEC was unable to obtain approvals for a landfill site. In 1983, USEPA listed the Hudson River PCB site on the Superfund National Priorities List and conducted an investigation to assess site conditions and evaluate remedial alternatives for the site. In September 1984, USEPA issued a Record of Decision for the Hudson River PCB site consisting of a no-action ruling for the river sediments and in-place containment of the Remnant Deposits. In 1989, USEPA began the Reassessment Remedial Investigation/Feasibility Study (RRI/FS) of its 1984 no-action decision for Upper Hudson River sediments.

2.4 HISTORICAL TRENDS IN PCB LEVELS

Since the 1970's, GE and state and federal agencies conducted numerous sampling and analysis programs to evaluate PCB levels in the Upper Hudson River water, sediment, and biota. In response to decreases in PCB discharge to the river and natural recovery processes, water column PCB levels at Fort Edward and Schuylerville declined between the late 1970's and late 1980's (Figure 2-7). In late 1991, PCB levels at Fort Edward and Thompson Island Dam suddenly increased due to the Allen Mill gate collapse. Remediation of the Allen Mill source began in 1993 and reduced average PCB concentrations at Fort Edward to levels similar to those in the late 1980s (Figure 2-7). PCB levels have continued to decline through the late 1990's as a result of remedial efforts to eliminate bedrock PCB oil seeps in the Bakers Falls area. PCB levels at Thompson Island Dam in the mid- to late-1990's exceed those at Fort Edward (Figure 2-7), indicating that sediment sources within TIP are contributing PCB to the water column.

Thirty years of PCB loadings from the two GE plant sites and the subsequent Fort Edward Dam removal resulted in high PCB concentrations in sediment downstream of Fort Edward. Decreases in PCB loadings since the mid-1970's, coupled with the influx and deposition of sediment from Upper Hudson River tributaries have resulted in a decline in Upper Hudson River surface sediment PCB concentrations over time (Figure 2-8).

PCB concentrations in fish from the Upper Hudson River have also declined since the late 1970's in response to reductions in water column and surface sediment PCB concentrations

(Figure 2-9). The decline in PCB levels in fish was rapid in the late 1970's as sediments with high PCB concentrations were buried by cleaner sediments. Decline rates slowed from the early 1980's through the mid-1990's largely due to what is now recognized as PCB flux to the river from the area of GE plant sites (Figure 2-9). The decline rates accelerated in the mid-1990's in response to GE's efforts to eliminate the PCB sources at the Allen Mill and GE plant site area (Figure 2-9).

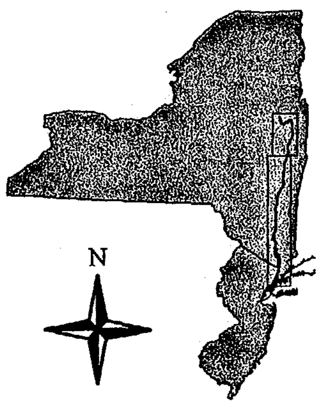
2.5 FACTORS CONTROLLING PCBs IN THE UPPER HUDSON RIVER

A number of processes affect the fate of PCBs within the Upper Hudson River (Figure 2-10). River hydrodynamics affect the movement of particulate and dissolved phase PCBs within the water column. PCB exchange between the sediments and overlying water is accomplished by a number of mechanisms including diffusion, groundwater inflow, sediment scour, and settling of water column particulates. PCBs also move to the atmosphere by volatilization. PCBs can also be removed from the biologically active part of the system via burial into the deep sediment bed layers. Uptake of PCBs by fish is from the water column and surficial sediments and PCBs are transferred up through the food chain *via* predation.

The hydrology of the Upper Hudson River watershed and its tributaries directly affects river hydrodynamics. Tributaries in the study area contribute more than 1/3 of the river flow at Troy, resulting in downstream dilution of PCBs from Fort Edward and TIP. Spring snowmelt causes high flow periods, but hydraulic controls regulate river flow during flood periods.

The Upper Hudson River is a conveyance for particulates that erode from the surrounding watershed and upstream areas within the river. Depending on the velocities in the river and the nature of the particulate matter, sediments are deposited to or eroded from the bed. In the near shore quiescent zones of the Upper Hudson River, deposition is the greatest, and soft sediments have accumulated over many years. It is in these areas where the sediments with the highest PCB concentrations were also deposited (i.e., the hot spots). Data from the many sampling programs have shown that most of the historically deposited sediment and associated PCBs are now sequestered below the sediment surface, a consequence of the continual accumulation of watershed derived particulate matter. However, in some areas of the river, sediment containing PCBs may become resuspended during elevated flows and cause water column PCB levels to increase.

LOCATION MAP OF THE
HUDSON RIVER



Upper Hudson Scale

3 0 3 6 Miles

Lower Hudson Scale

7 0 7 14 21 28 Miles

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Figure 2-1.
Hudson River location map.

Note: Numbers along river indicate river miles measured from the Battery

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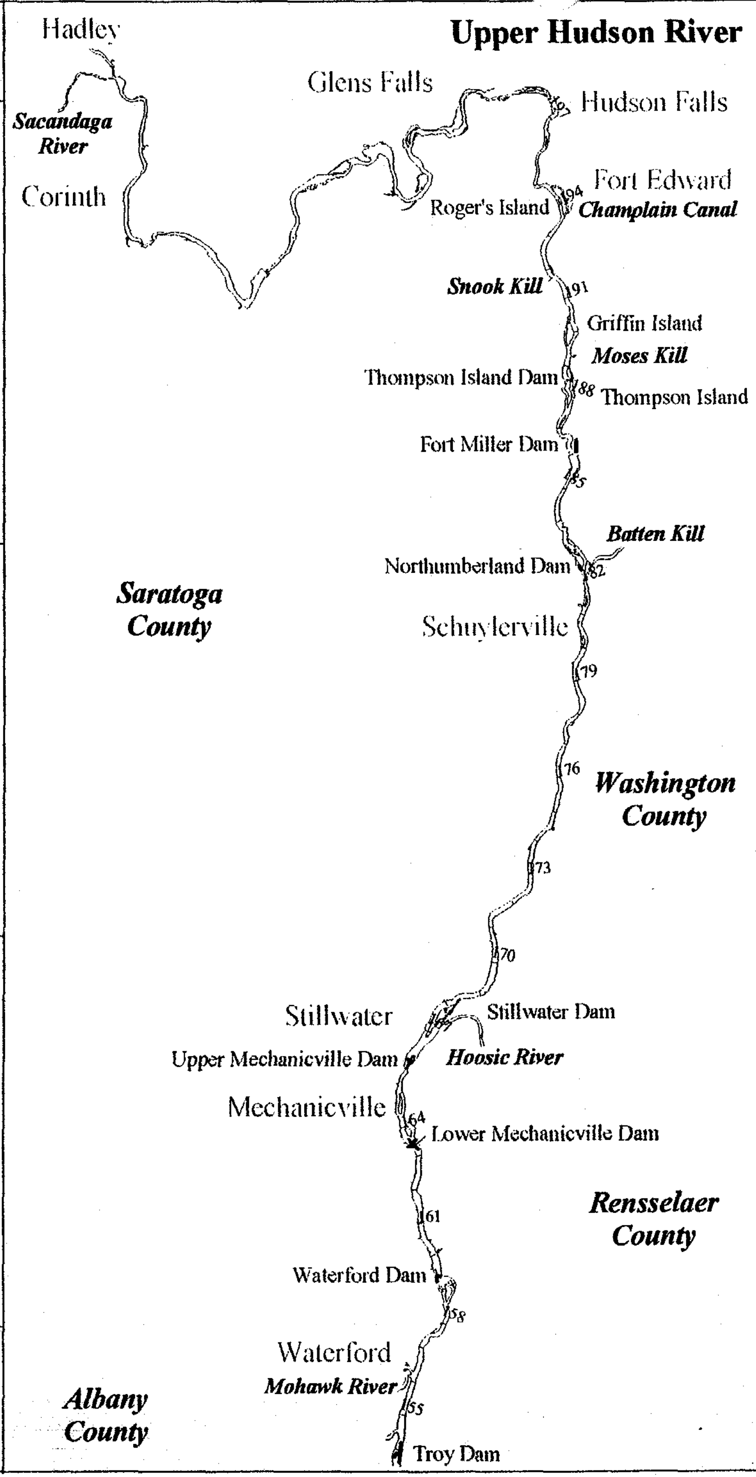

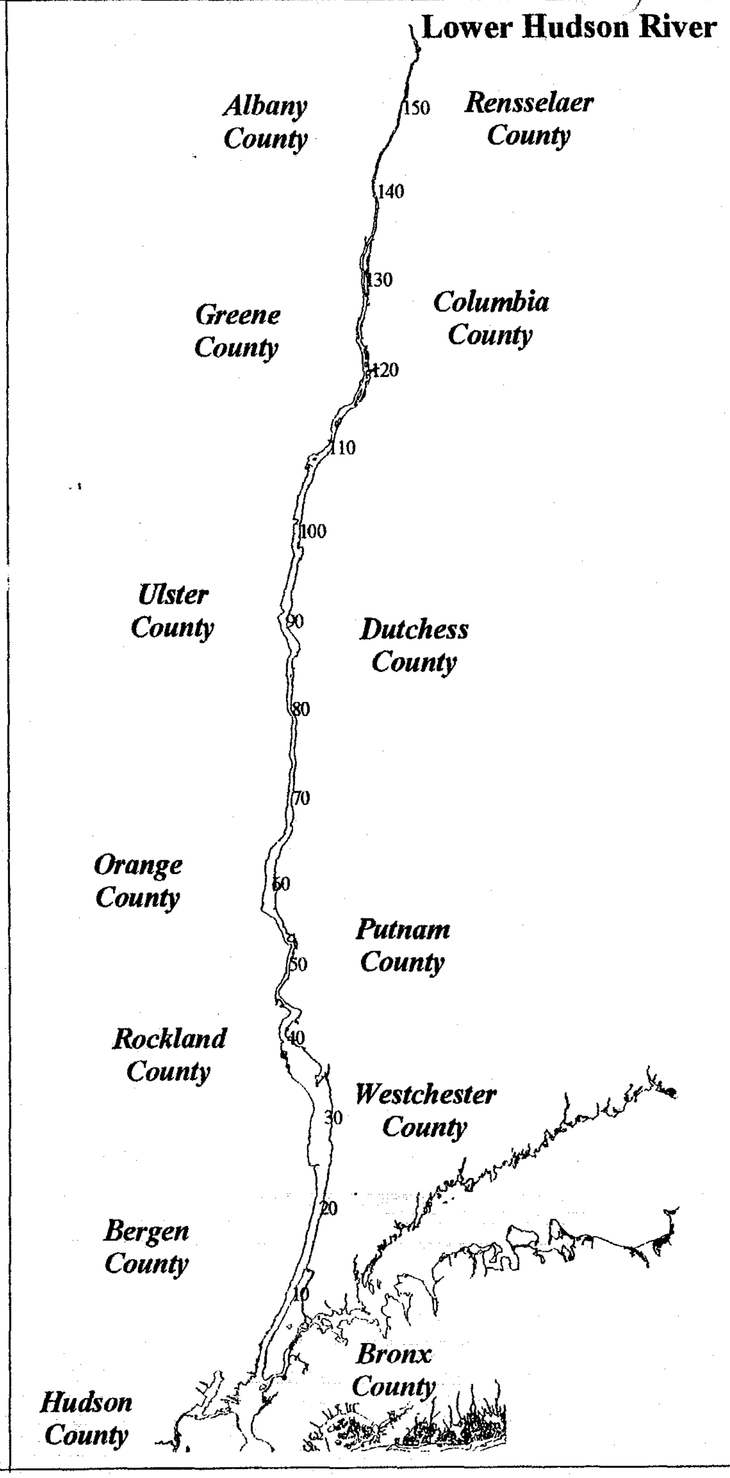

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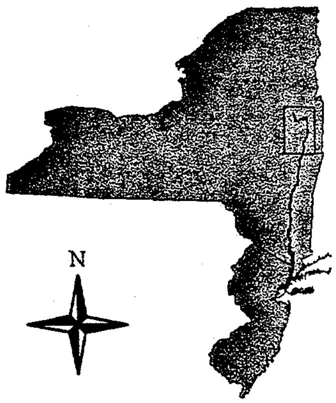
LOCATION MAP OF THE
UPPER HUDSON RIVER



Graphic Scale

2 0 2 4 Miles

Legend

Mile Points

Shoreline

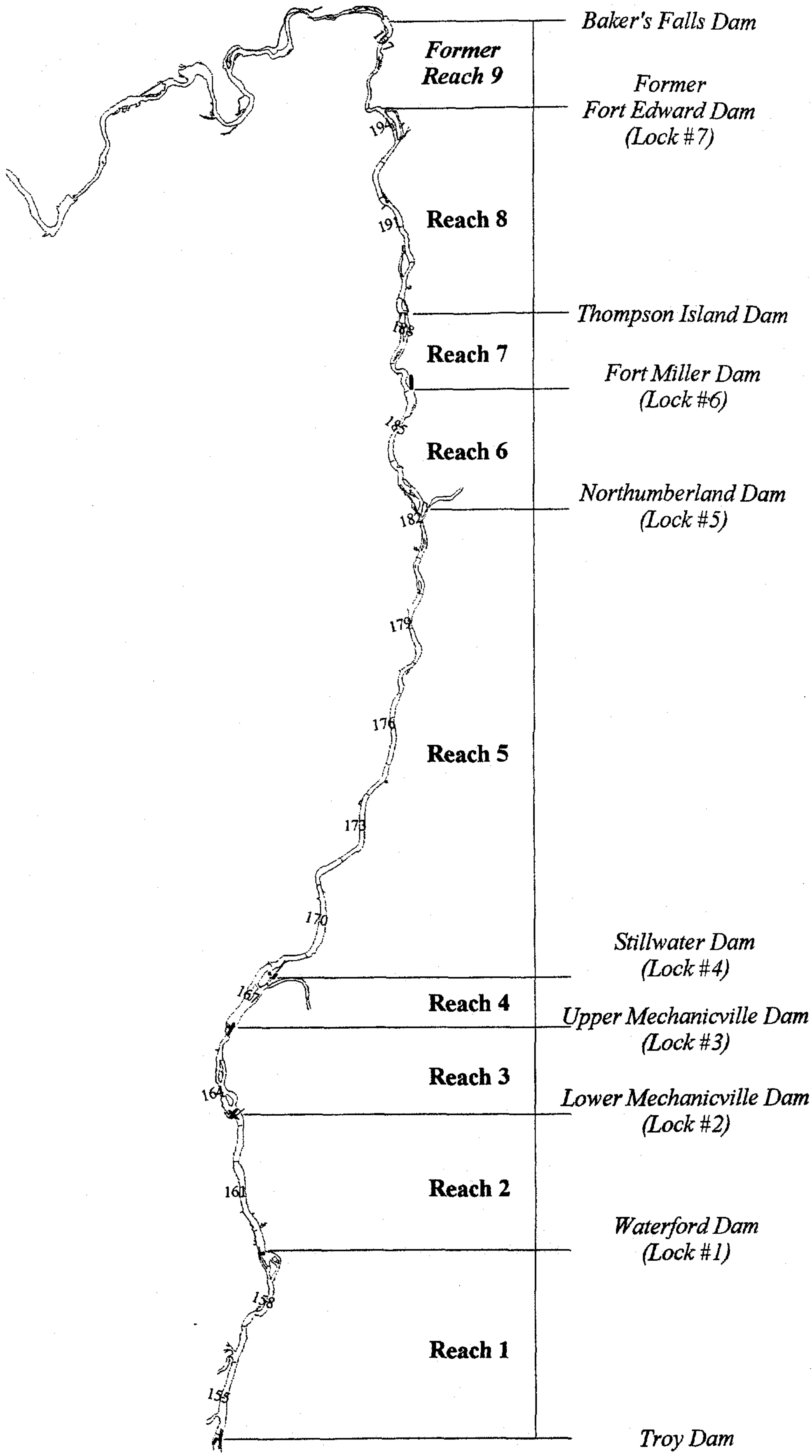


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Figure 2-2.
Upper Hudson River reaches.

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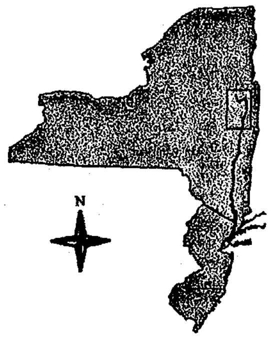
LOCATION MAP OF THE
UPPER HUDSON RIVER



LEGEND
Land Use Types

- Residential or Developed
- Agricultural
- Forest
- Streams, Lakes, or Rivers

Data Source: USEPA Basins

Graphic Scale

3 0 3 6 9 Miles

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Figure 2-3.
Land use patterns in the Upper Hudson River drainage basin between Corinth and Troy, NY.

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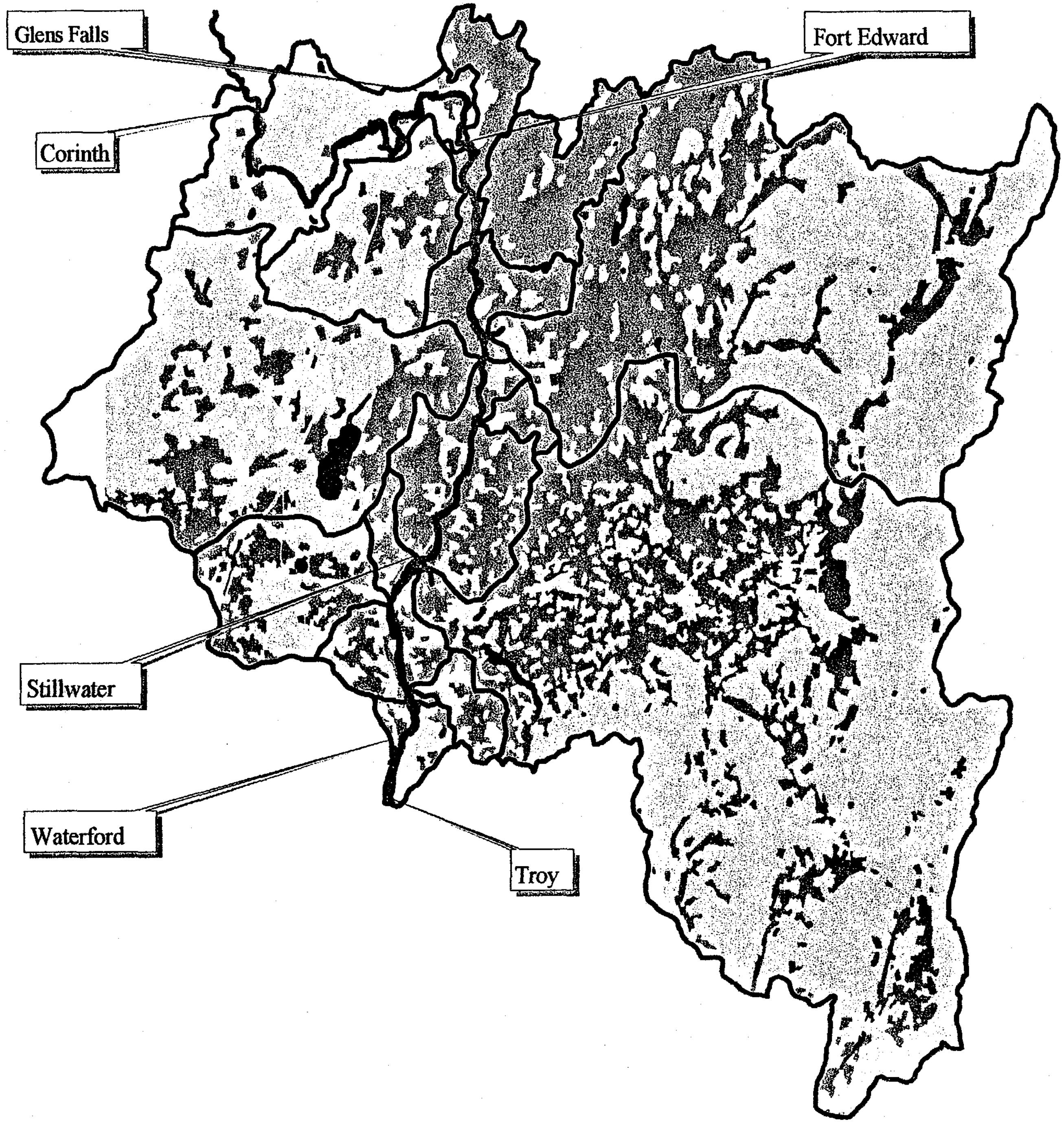

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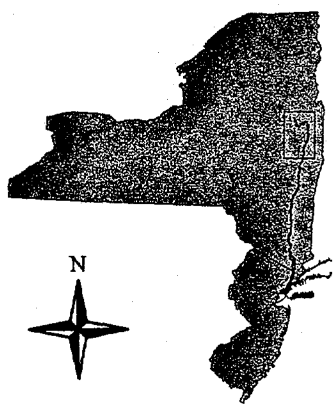
LOCATION MAP OF THE
UPPER HUDSON RIVER



Graphic Scale

500 0 500 1000 1500 Feet

Legend

- Remnant Deposits
- Routine Water Monitoring Stations
- Mile Points
- Shoreline

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Figure 2-4.
Remnant Deposits in former Reach 9 of the Upper Hudson River.

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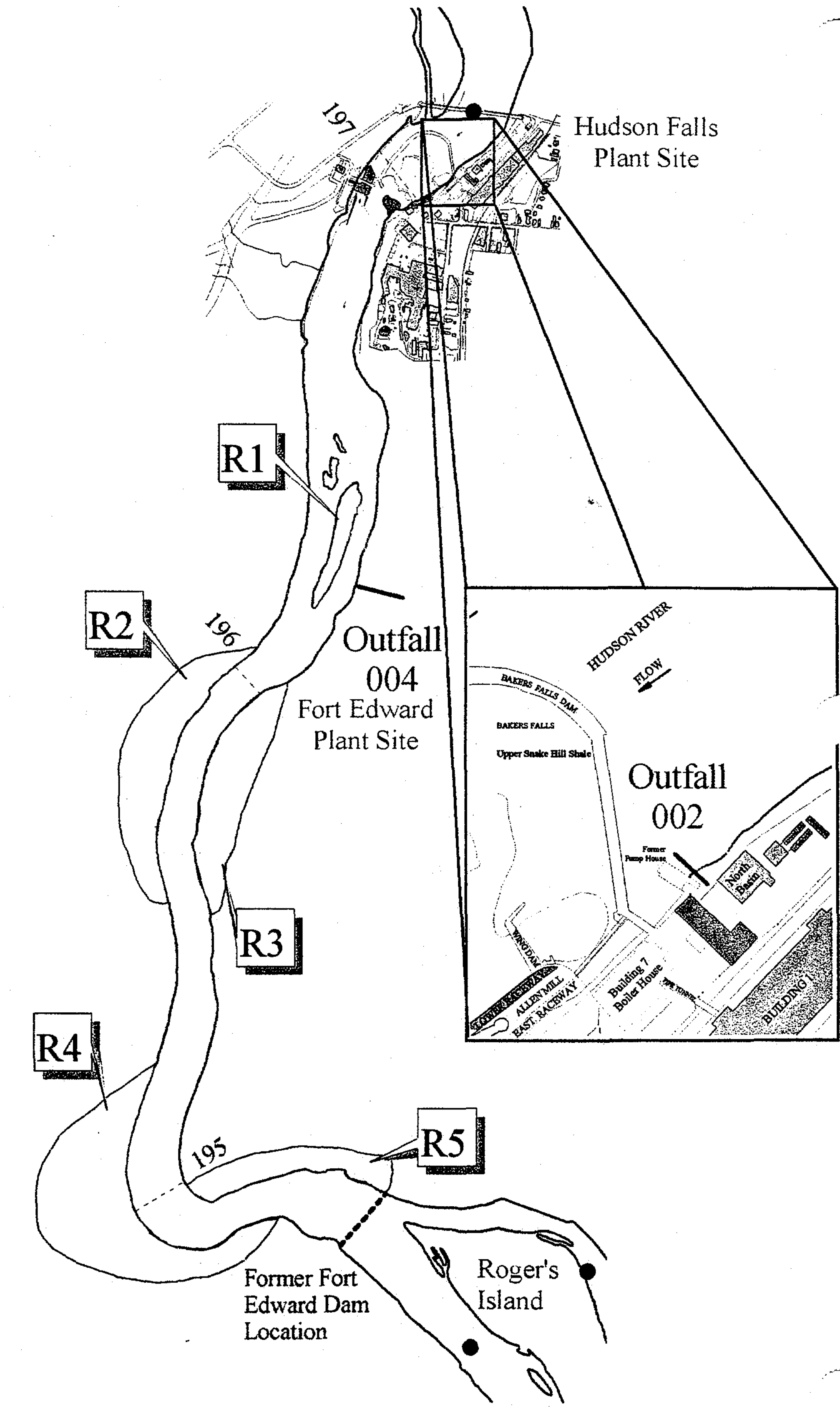

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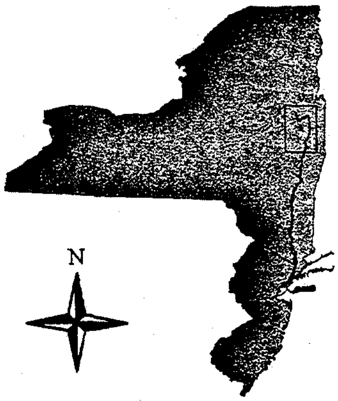
LOCATION MAP OF THE UPPER HUDSON RIVER



Graphic Scale

2 0 2 4 Miles

Legend

Shoreline

1976 NYSDEC hot spots

Data Source: Tofflemire et al., 1979

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Figure 2-5.

NYSDEC designated PCB hot spot locations.

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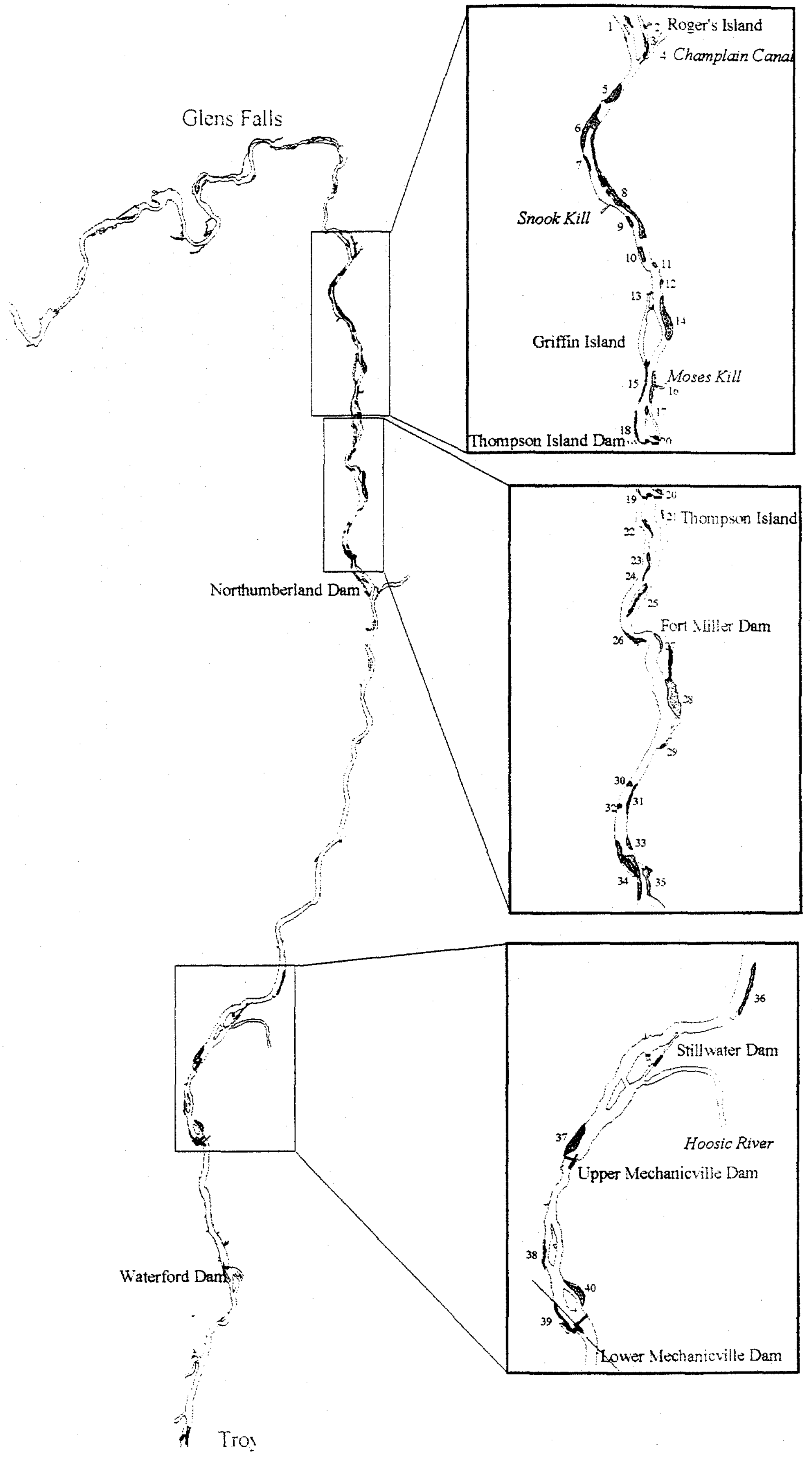

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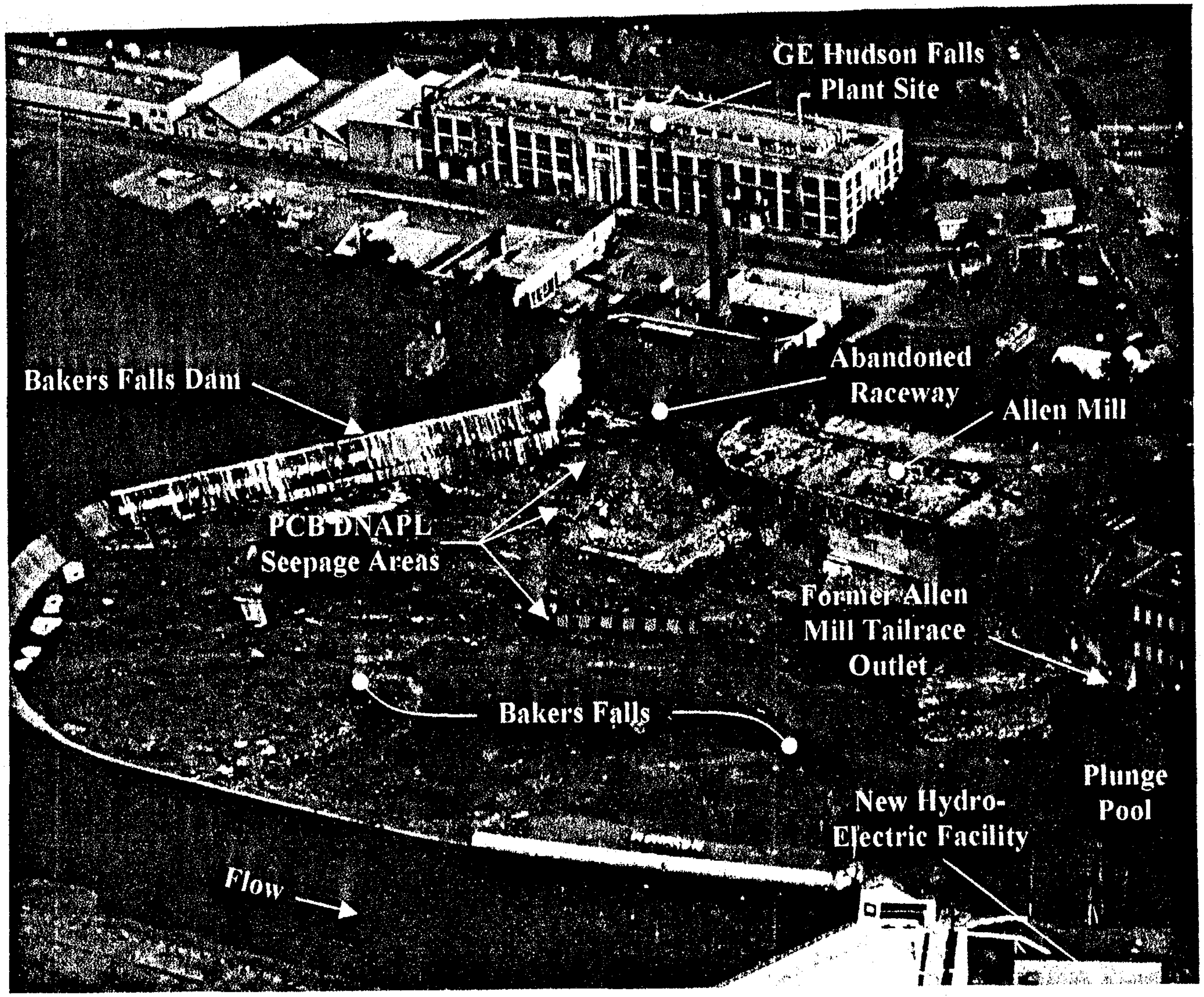

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Allen Mill and GE Hudson Falls facility (ca. 1996)

FIGURE 2-6.

SCALE: NONE

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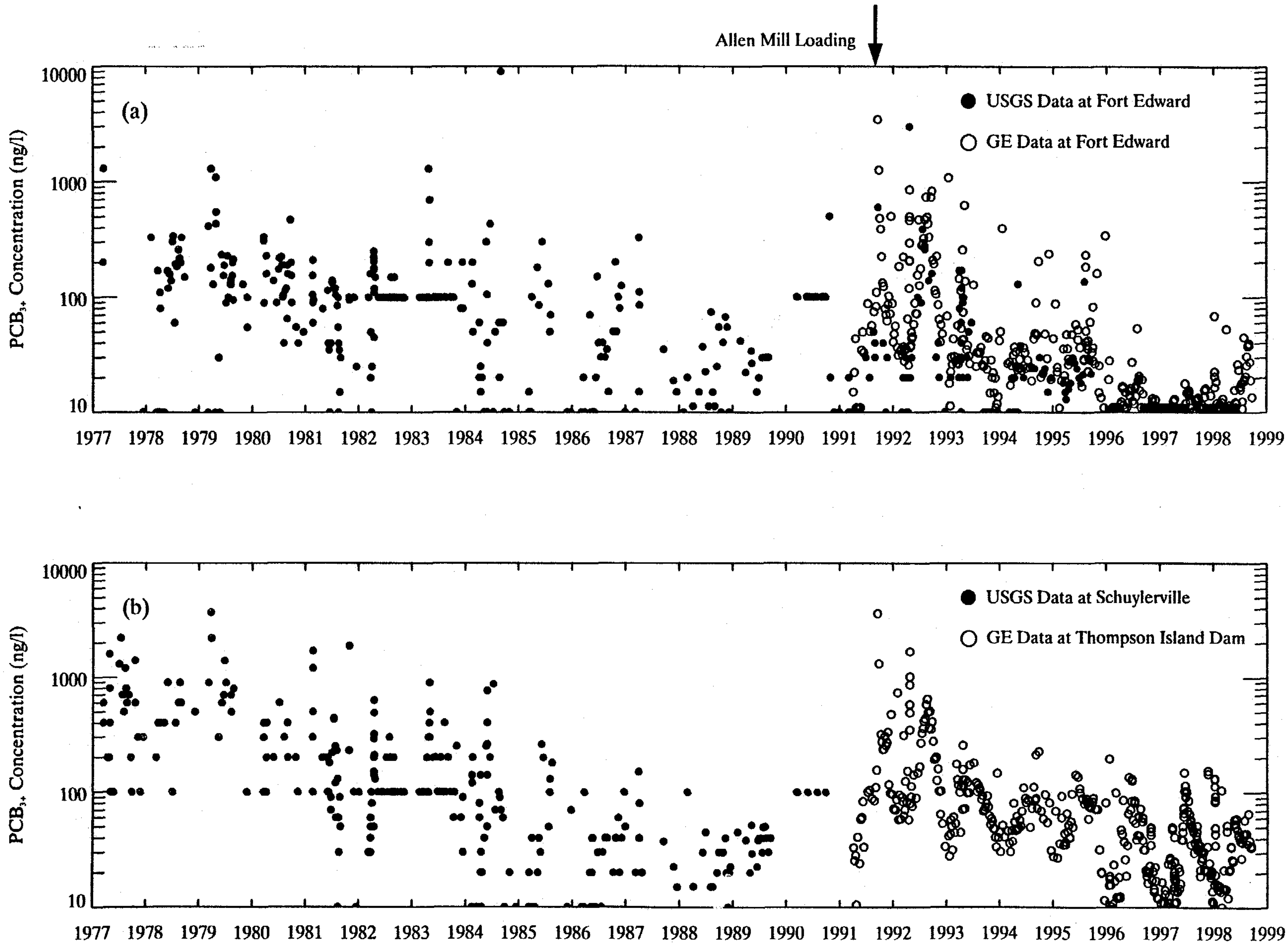

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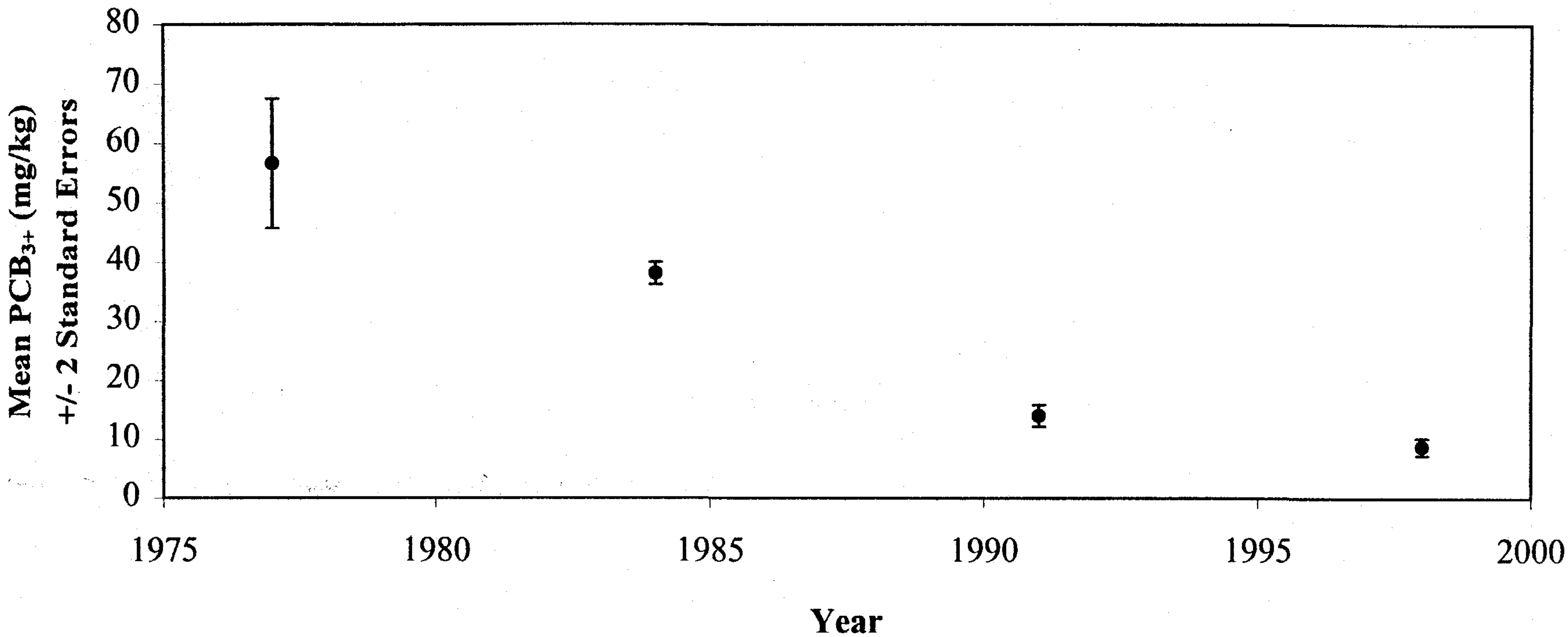
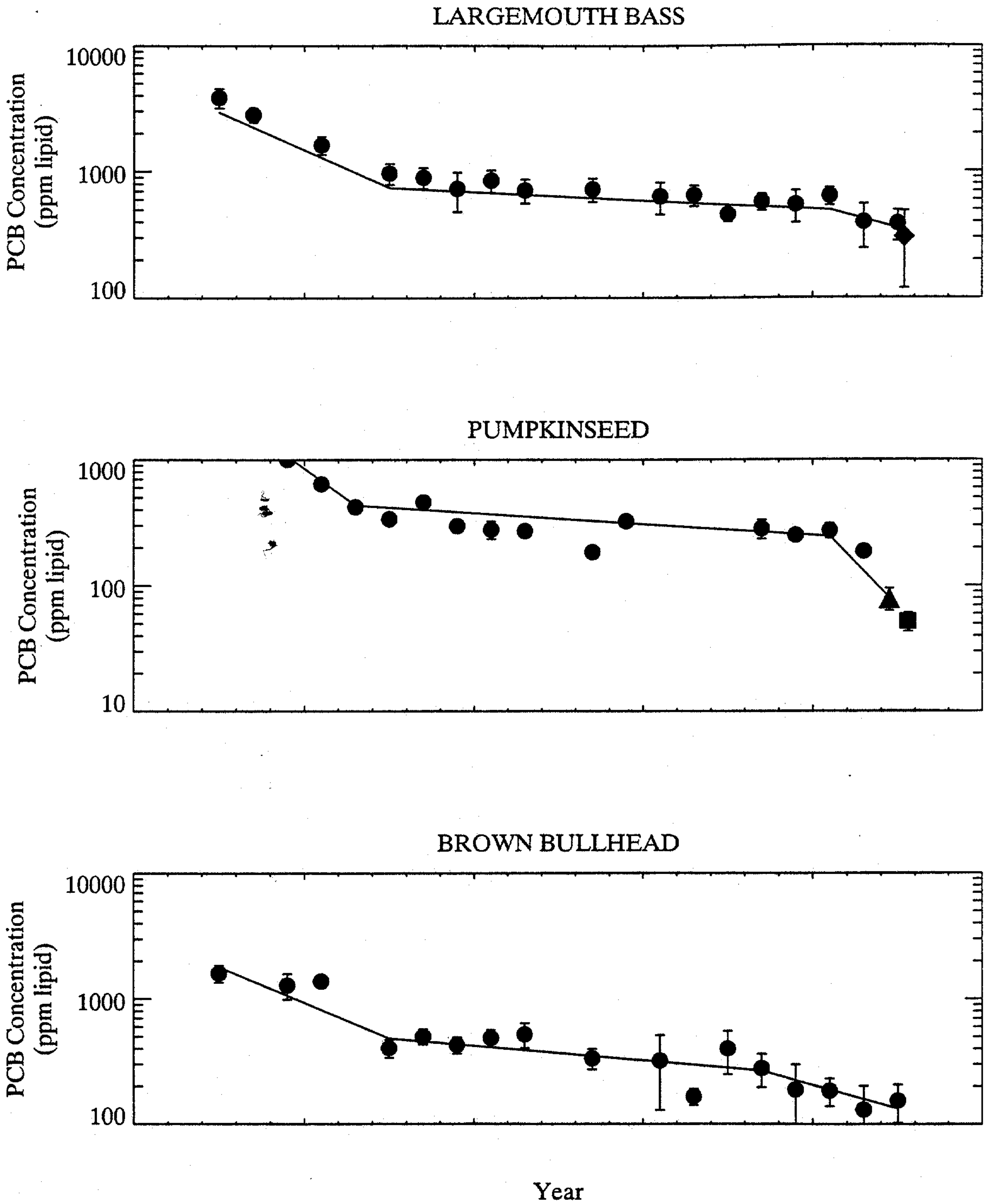
Notes: Total PCB detection limit was used for plotting and load calculations for non-detects. Tick marks on date axis correspond to January 1st. Outlier in 1983 removed from Fort Edward.

Figure 2-7. Temporal trends in PCB$_{3+}$ concentration at (a) Fort Edward and (b) Thompson Island Dam and Schuylerville.



Note: Data averages were developed to represent 0-5 cm layer. However, 1984 average includes surface samples with depths up to 20 cm.

Figure 2-8. Temporal profile of PCB_{3+} concentration in area weighted average, cohesive and non-cohesive surface sediments within Thompson Island Pool.



Solid lines represent logarithmic regressions of data.
Data are arithmetic means +/- 2 standard errors.
Circles = NYSDEC, Squares = NYSDOH, Triangles = Exponent, Diamonds = GE.
Crosses indicate values excluded from the annual averages.

Figure 2-9. Annual average PCB concentrations in resident fish of the Upper Hudson River. Lipid normalized, Stillwater Pool.

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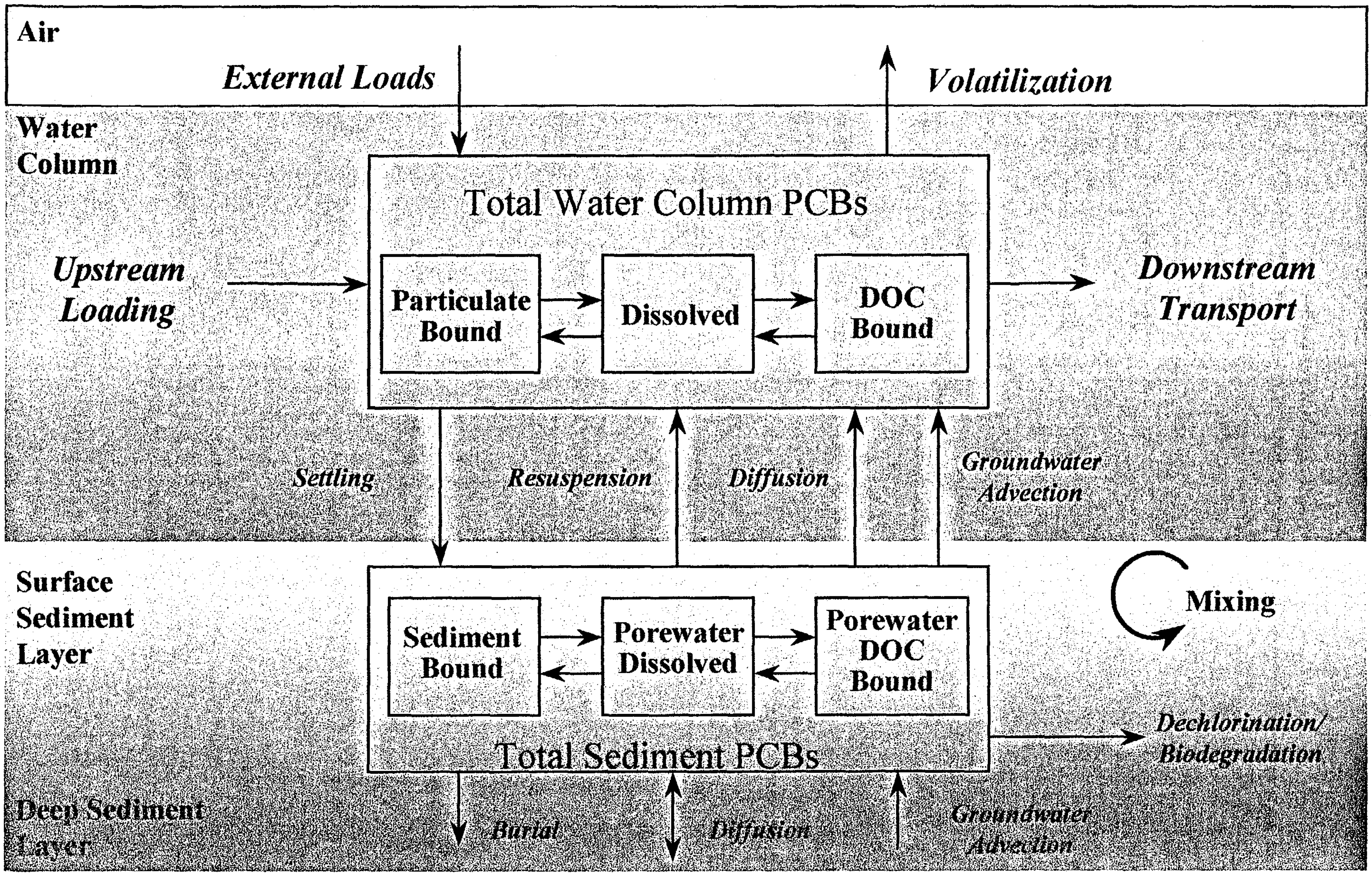

Figure 2-10. Processes affecting PCB fate and transport in the Upper Hudson River.

A Model of PCB Fate, Transport and Bioaccumulation

Section 3

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SECTION 3
A MODEL OF PCB FATE, TRANSPORT AND BIOACCUMULATION

3.1 BRIEF OVERVIEW OF THE MODEL

The development of a comprehensive mathematical model for determining the fate and transport of PCBs in the Upper Hudson River involved three steps: (1) collection and analysis of relevant environmental data, (2) selection and development of a model framework, and (3) calibration and validation of the model by comparing its results with historical data from the Upper Hudson River. The model consists of four sub-models that describe hydrodynamics, sediment transport, PCB fate, and PCB bioaccumulation.

The sub-models are equations developed from the basic scientific principles of conservation of mass, energy, and momentum and from laboratory and field studies of individual processes. The equations are general and can be applied to any river system. The application of the equations to the Upper Hudson River involved the determination of appropriate values for each of the parameters in the equations. Site-specific data were the basis for assigning values, either directly or by the process of model calibration. Each of the sub-models was calibrated and validated using a data record that extends from 1977 to the present. The extensive database makes the Hudson River uniquely suited for the application of these models.

3.1.1 Hydrodynamic Models

Hydrodynamics refers to the movement of water through the river and the friction or shear stress that this movement causes at the interface between the water and the sediment bed. The hydrodynamic model computes the velocity and water surface elevation, as well as the shear stress at the sediment-water interface, in response to upstream flows and flows entering the river from tributaries.

Two hydrodynamic models were developed, calibrated, and validated in order to provide the necessary hydrodynamic input for the sediment transport and PCB fate sub-models. A two-dimensional, vertically-integrated hydrodynamic model defines the distribution of shear stresses at the sediment-water interface that controls sediment transport. By contrast, a one-dimensional hydrodynamic model defines the average transport of PCBs within the water column.

3.1.2 Sediment Transport Model

Sediment transport includes the movement of suspended solids within the river and the settling and resuspension of solids that occur at the sediment-water interface as a result of the shear caused by the moving water. The sediment transport model computes the concentration of solids in the water column and the rate at which sediment accumulates in the bed.

Results of laboratory and field studies were used to describe the resuspension and deposition processes of fine-grain (cohesive) and coarse grain (non-cohesive) sediments. Resuspension and deposition fluxes calculated by the sediment transport model were used directly by the PCB fate model.

3.1.3 PCB Fate Model

PCB fate includes the transport of PCBs dissolved in the water or sorbed to solids, transfer between the dissolved and sorbed phases, transfer between the water and atmosphere, and degradation that occurs chemically or biochemically. The PCB fate model computes the concentrations of PCBs in the water column and sediment and includes mechanistic descriptions of the transport, transfer and reaction processes. PCBs partition between dissolved and particulate (sorbed) phases, with partitioning assumed to be rapid, such that PCBs in the two phases are generally near equilibrium. The dissolved phase is composed of freely dissolved PCBs and PCBs sorbed to dissolved and colloidal organic matter. Freely dissolved PCBs are transferred from the water column to the atmosphere by volatilization across the air-water interface. Particulate-phase PCBs settle from the water column to the sediment bed, and are resuspended from the sediment bed into the water column. Dissolved PCBs are exchanged between the water column and sediment bed and within the sediment in accordance with the laws of diffusion, that is, from a region of higher concentration to one of lower concentration, with the rate of transfer controlled by a mass transfer coefficient.

3.1.4 PCB Bioaccumulation

PCB bioaccumulation involves the uptake of water- and sediment-borne PCBs by invertebrates and the sequential transfer of those PCBs through the food web *via* predation. The bioaccumulation model consists of a food web representative of the Upper Hudson River, empirically defined trophic transfer factors for calculating PCB levels in invertebrates, and a mechanistic, dynamic simulation framework for computing PCB levels in fish.

The model food web structure and the diet of each of the model species were developed based on site-specific information. The model food web contains four trophic levels: particulate matter (trophic level 1, or TL1), invertebrates (TL2), forage fish (TL3) and predators (TL4). TL1 includes water column and surface sediment particulate matter. TL2 is represented by two functional groups, benthic macroinvertebrates (BMI) associated with the sediment bed and phytophilous macroinvertebrates (PMI) associated with particulate matter and periphyton in contact with the water column. Two species, pumpkinseed and brown bullhead, represent TL3. TL4 is represented by largemouth bass.

The dynamic PCB bioaccumulation model is based on the scientific principles of conservation of mass and energy and mechanistically describes the uptake and loss of PCBs by forage and predatory fish. PCBs are taken up during respiration and ingestion and are lost by diffusion across the respiratory surfaces. Rates of PCB uptake and loss are calculated from computed rates of feeding and respiration and empirically defined transfer efficiencies of PCBs.

3.1.5 Model Calibration and Validation

The essential test of each sub-model is its ability to generate results that are consistent with observed data. Calibration involves the adjustment of select model parameter values, within the limits of the range of prior measurements, to obtain improved agreement between calculated model results and observed data. Validation entails the independent comparison of calculated model results with observed data. Confidence in the model derives from the realism of the model equations, the accuracy and precision of the underlying data, previous successful experience in using the model, the accuracy of the parameter estimates based on site-specific data as well as more general information, and the ability of the model to reproduce (or "predict") observed data.

The model presented in this report has been calibrated and validated with numerous independent data sets. These data include hydrodynamic data (e.g., water flow rates, surface elevations, and velocities); sediment transport data (e.g., suspended solids concentrations, sediment loadings and sediment accumulation rates); ecological data (e.g. fish feeding preferences); and PCB data (e.g., water, sediment and fish PCB concentrations). Many of these data sets were collected specifically to facilitate model development and calibration.

3.2 SUMMARY OF MODEL CALIBRATION AND VALIDATION

3.2.1 Hydrodynamics

Both hydrodynamic models were calibrated by adjusting friction coefficients to achieve agreement between predicted and observed water surface elevation data collected in each of the reaches of the river.[1] The hydrodynamic models were validated using water surface elevation data obtained in the TIP during the 1983 spring high flow period. Bottom friction coefficients were not adjusted during model validation, only model boundary conditions were changed, i.e., upstream and tributary flow rates and stage height at the Thompson Island Dam (TID).

Results of the one-dimensional model validation are presented in Figure 3-1 (panel a). Predicted stage heights (or elevations of the water surface) at Champlain Canal gauge 119 (TIP) are in agreement with observed stage heights during the 1983 spring high flow period (April 24 to May 16). However, the model under-predicts stage height (or elevation of the water surface) during the peak of the high flow period. The two-dimensional model validation results are

[1] Because calibration of the reach between the Thompson Island Dam and the Fort Miller Dam was not possible due to a lack of data, the assumption was made that friction coefficients determined for the TIP would be used in this reach.

shown in Figure 3-1 (panel b). The agreement between predicted and measured stage heights during this high flow period indicates that the models accurately represent the major hydrodynamic features of the system. Further validation of the two-dimensional model was accomplished using current velocity data collected during August 1997 in the TIP. Additional validation of both models was performed through comparison of measured and predicted flow rates at Stillwater and Waterford between 1977 and 1992.

3.2.2 Sediment Transport

Sediment transport processes are controlling factors in the fate and transport of PCBs in the Upper Hudson River. The rate of natural recovery in the river is primarily determined by the long term sedimentation rate, which is affected by resuspension and deposition processes, as well as sediment loading to the Upper Hudson River. Bed erosion during a rare flood event (100-year flood), which could possibly cause elevated bed PCB concentrations buried at depth to be introduced back into the bioavailable zone, is determined by hydrodynamic processes (generation of bottom shear stress) and site-specific erosion properties of the sediment bed. Thus, understanding and quantifying sediment transport processes in the Upper Hudson River is of critical importance when evaluating PCB fate in the river and the effectiveness of various remedial alternatives.

The TIP sediment transport model was calibrated using total suspended solids (TSS) concentration data collected during the 1994 spring high flow between March 31 to April 29, 1994. The calibration process involved comparing predicted and observed TSS concentrations at three locations in the TIP: (1) upstream of Snook Kill, (2) McDonald's dock, and (3) TID. Results of the final calibration are presented in Figure 3-2. The model computes net erosion from the non-cohesive sediment bed and net deposition in the cohesive sediment bed. Overall, the model computes net erosion of sediment during the period of a magnitude that compares well with the estimate derived from a mass balance analysis of TSS data.

The model was calibrated for Reaches 1 to 7 for the 1994 spring high flow period. Comparisons between predicted and measured TSS concentrations at six locations during the 1994 spring flood are shown in Figure 3-3. Model predictions are in agreement with observed

TSS at each of the stations. Comparison between model predicted and data-based derived mass balances for the 30-day period from March 31 to April 29 was used as an additional means of model evaluation. Net erosion occurred between the TID and Stillwater during this flood, with the model predicting 18% more erosion than indicated by the data. Both model and data showed that net deposition occurred between Stillwater and Waterford, but the model predicted 41% less deposition.

Three simulations were conducted to validate the Upper Hudson River sediment transport model: (1) 1997 spring flood; (2) 1993 spring flood; and (3) 21-year (1977 to 1998) period. No adjustments of model parameter values were made during the validation simulations. Only model boundary conditions, e.g., flow rates and sediment loadings, were changed to reflect the time-varying conditions during each validation period.

Comparisons of predicted and observed TSS concentrations at TID in the spring 1997 and spring 1993 high flow periods are shown in Figure 3-4. Model results agree well with measured TSS. Similar to the 1994 simulation, a mass balance approach was applied to the 1997 spring high flow period to evaluate model performance. The data mass balance indicated that net erosion occurred in the TIP between April 28 and May 4. This data-based estimate is reproduced almost identically by the model (a difference of 4%). Net erosion was predicted only in the non-cohesive bed areas. Net deposition occurred in the cohesive bed areas.

A long-term simulation was conducted for the period from January 1, 1977 to December 9, 1998. Over this period, net deposition occurred in both the non-cohesive (0.02 cm/yr) and cohesive (0.8 cm/yr) sediment bed areas of the TIP. Calculated sediment deposition rates were compared to rates estimated from high-resolution sediment cores collected in 1992 by USEPA at three locations in the TIP. The model to data comparisons are 0.5 to 0.9 cm/yr, 1.1 to 1.2 cm/yr and 1.7 to 0.9 cm/yr.

Predicted and observed TSS concentrations at Stillwater and Waterford during the 1993 spring high flow period are shown in Figure 3-5. Similar to the 1994 results, agreement between predicted and observed measurements was generally achieved. These results also indicate that the tributary solids loading estimation method performed reasonably well as no tributary TSS data were available during the 1993 flood (all tributary loading was estimated using rating curves). Consistent with the 1994 spring flood results, the model under-predicted deposition between Stillwater and Waterford by 52% during the 1993 flood. Between Stillwater and Waterford, model resolution was lower and data available for model input were sparser. These factors contribute to uncertainty in model results in Reaches 1 to 4.

In summary, the TIP sediment transport model was calibrated and validated using a combination of short- and long-term data. The model was capable of accurately simulating solids dynamics during high flow events when most of the sediment transport in the river occurs. The model was also capable of simulating long-term deposition rates, which are important determinants of the long-term fate of PCBs in the river.

3.2.3 PCB Fate Model

The PCB fate model was calibrated and validated using the sediment and water column PCB data sets collected at the site since the late 1970's. The calibration period extended from the time of the first extensive sediment sampling study in 1977 to the 1991 sediment survey. Validation was accomplished by extending the simulation to 1998 and comparing results to extensive water column and sediment data collected in the TIP in 1998.

The long-term trends in the average surface sediment (0-5 cm) concentration of PCBs with three or more chlorine atoms (PCB_{3+})[2] in the TIP indicated by data and by the model are shown in Figure 3-6. Cohesive sediment PCB_{3+} levels declined from about 105 ppm in 1977 to about 20 ppm in 1991 and to about 14 ppm in 1998, declines of about 80% and 87%, respectively. The model closely reproduces this trend, predicting about 18 ppm in 1991 and about 10 ppm in 1998, declines of about 83% and 90%, respectively. The concentrations computed by the model lie within the uncertainty bars shown on the plot, which indicate ± two standard errors of the mean. Thus, there is no statistically significant difference between the model and the data.

[2] PCB_{3+} was modeled due to limitation in the analytical methods employed in the historical sampling and analysis programs. As this PCB fraction constitutes the majority of the PCBs in fish tissue, this does not adversely impact the predictive capability of the model.

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The non-cohesive sediment PCB_{3+} levels declined from about 40 ppm in 1977 to about 12 ppm in 1991 and 7 ppm in 1998, declines of about 70% and 83%, respectively. This downward trend is slightly slower than that of the cohesive sediments. The model accurately reproduces the trend, computing concentrations of about 11 ppm in 1991 and 8 ppm in 1998. Thus, the model accounts for the difference in the trend between the cohesive and non-cohesive sediments, as well as the absolute concentration drops between 1977 and 1998.

Closer examination of the model predictions in the TIP was conducted by comparing concentrations computed for each model segment with average concentrations calculated from the 1991 and 1998 measurements for each river segment. Comparisons for cohesive sediments in nine segments are shown in Figure 3-7. The model reproduces the trends in most segments, including substantial differences in trends among the segments. For example, concentrations drop in Segment 10 (north of Griffin Island) from about 140 ppm in 1977 to about 35 ppm in 1998, whereas concentrations in Segment 13 (at Moses Kill) decline from about 240 ppm in 1977 to about 5 ppm in 1998. The model predicts this difference almost exactly. In other segments, the model sometimes over-predicts or under-predicts the trend, but the deviations are never large. In some cases the 1998 data point represents a single sample (indicated by symbols without error bars) and the deviations between model and data may reflect uncertainty in the actual average sediment concentrations.

The results for the non-cohesive sediments are similar to those for the cohesive sediments (Figure 3-8). Again the model predicts the differences in trends among the segments. For example, in Segment 5 (at Snook Kill) concentrations decline from about 40 ppm in 1977 to about 14 ppm in 1998, whereas in Segment 8 (north of Griffin Island) a smaller decline from about 17 ppm to about 8 ppm occurs over this period. The model predicts this difference as well as most of the other differences among the locations. The only segments in which the predicted 1998 concentrations do not fall within the confidence limits of the data mean are ones in which the data is from a single sample.

The ability of the model to reproduce the average trend in TIP sediments and the major features of the spatial variation of that trend within the TIP provides strong evidence of its predictive capabilities. We are unaware of any other model of a contaminated sediment site that has demonstrated this degree of accuracy.

The capability of the model to capture the PCB trends throughout the Upper Hudson River was examined using the 1991 individual composite core data and model segment concentrations (Figure 3-9). As with the 1984 model-data comparison, the segment mean calculated concentrations are indicated by a solid horizontal line and the concentration range is indicated by the shaded region. The horizontal dashed lines show the 1977 initial conditions. The model reproduces the large-scale spatial trend evident in the cohesive surface sediment (0-5 cm) data (Figure 3-9a), capturing both the decline from levels of tens of ppm above mile point 185 to a few ppm below mile point 180 and the lack of trend from mile point 180 to mile point 155. The model over-predicts concentration in the most-downstream segment between mile points 154 and 156. The single composite core in this region yielded a concentration of about 2 ppm, whereas the model computes a concentration of about 4 ppm. This difference may be partially due to an uncertain initial condition. No 1977 data were available for this region of the river, and the value from the closest upstream segment was used. It may also reflect an under-prediction of burial in this region. The model under-predicts concentrations in the two segments between mile points 164 and 168. The data in this region range from about 1.8 to 6 ppm, whereas the model computes concentrations of about 1.5 ppm. This difference appears to be due to an over-estimation of burial in this region. The inaccuracies in burial rate in the lower reaches of the river are the result of partial knowledge of sediment bed conditions and bathymetry and the crude resolution of the model in the lower reaches.

The model is in general agreement with the data in the subsurface sediments (Figure 3-9b and c). Significant declines are predicted between 1977 (dashed lines) and 1991 in the 5-10 cm layer (Figure 3-9b). These declines yield concentrations that fall within the measurements in this depth range. As in the top 5 cm of sediment, the model over-predicts the decline in the segments between mile points 164 and 168 and under-predicts the decline in the farthest downstream segment. Again, these differences likely are due to a combination of inaccuracies in predicted burial rates and the estimated 1977 concentrations.

In contrast to the 0-5 and 5-10 cm layers, the model predicts little change in concentration in the 10-25 cm layer (Figure 3-9c). In some segments a small decline is predicted, in others a small increase is predicted. The lack of substantial change is in general agreement with the observations, which fall around the predicted concentrations. The lack of large changes in this layer, which contains the largest portion of the sediment PCB mass included in the model, indicates that most of the PCB inventory has remained in the sediment.

Comparison of the 1991 model results and data in the non-cohesive sediments is presented in Figure 3-10. The model reproduces the general features of the data; however, the model tends to over-predict concentrations downstream of mile point 173. The model computes concentrations of about 1 to 3 ppm, whereas the data indicate concentrations in the range of 0.2 to 2 ppm. The cause of this bias is unclear but could be due to over-estimation of the 1977 concentrations or an over-estimation of the depth of contamination in the non-cohesive sediments in this area of the river. From a practical standpoint, the over-estimation is not significant to the overall modeling because of the relatively low PCB concentrations in this area of the river.

The comparison of predicted and GE measured water column PCB_{3+} concentrations at Schuylerville, Stillwater and Waterford in 1991 is presented in Figure 3-11. From April to September 1991, the model predicts concentrations that closely match the measured values at each of the stations. The large concentration increase in September is associated with the Allen Mill event. Following this event, the model under-predicts water column concentrations for a period of about 1 month. Apparently the event had a residual effect that the model did not capture. However, the bias disappears after a month and the predicted concentrations are similar to the measured values.

The comparison of predicted and GE measured water column PCB_{3+} concentrations at the TID and Schuylerville in 1997 and 1998 is presented in Figure 3-12. A seasonal cycle in

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concentration, interrupted by occasional spikes associated with high flow events or inputs from above Fort Edward, is evident at both stations. Concentrations are minimum in winter and maximum in early summer. The model generally reproduces the seasonal trend and the absolute concentrations at both stations. The large concentration spike in January 1998 that the model accurately predicts is associated with a high flow event with a peak flow of about 34,000 cfs at Fort Edward. This event equates to about a 1-in-10 year flood in the river. The data were collected at and after the peak of the flood. The ability of the model to reproduce the concentration increase is evidence that it has accurately represented the resuspension processes occurring during such a rare event.

The ability of the model to accurately predict water column PCB concentrations in 1991, 1997 and 1998, coupled with the accurate prediction of the surface sediment concentration change between 1977 and 1991, indicates that it properly represents the movement of PCBs between the sediment and the water column. These results provide evidence that the model has accurately described the principal processes affecting PCB fate in the Upper Hudson River. They support the use of the model to predict the potential impacts of remedial scenarios on downstream PCB transport and concentrations of PCBs in the sediment and water column. The model's ability to predict increases in water column PCBs associated with a substantial high flow event supports the use of the model to predict sediment processes during rare events.

Further evaluation of the model was conducted using the USGS measured water column PCB_{3+} concentrations at Schuylerville, Stillwater and Waterford. Because of the lower reliability of these data due to limitations of the PCB measurement method, evaluations conducted with them are viewed as supplementary to those discussed earlier. Comparisons of the long-term temporal pattern of water column PCB concentrations computed by the model at Schuylerville, Stillwater and Waterford with the USGS data are presented in Figure 3-13. The data indicate a decline in concentration from the late-1970s to the mid-1990s by about a factor of ten. In any year, considerable variability is evident with some suggestion of a seasonal cycle. The decline in concentrations computed by the model is shallower than the decline indicated by the data. In the late-1970s the computed concentrations tend to be lower than the measured values. This difference appears to be greatest at Schuylerville, where the model computed concentrations ranging from about 50 ng/L to about 800 ng/L, whereas the data range from non-detect at 100 ng/L to more than 2,000 ng/L. The bias disappears by the early 1980s. From about 1981 to 1983, the model and data indicate similar concentrations. After this time, a bias is again evident. From about 1984 to 1990, the model computes concentrations that tend to be higher than the measured values by about a factor of two. This bias continues into the 1990s, although the magnitude appears to be lower.

The cause for the differences between the model and the USGS data set are not known. Because the model accurately predicts the changes in PCB_{3+} concentrations in the sediments and the water column concentrations measured by GE between 1991 and 1998, the model has not misrepresented any major fate process. It is possible that the low bias in the late-1970s is due to the presence of undocumented PCB sources. Sediment and debris dredged from the river after the removal of the Fort Edward Dam and the 1976 flood were placed in close proximity to the river (i.e., on Rogers Island and in landfills along the shore) and could have been a continuing source of PCBs to the river. It is also possible that some of the material left in the river channel after dredging was unconsolidated and easily mobilized into the water column, providing a temporary additional in-river source. The apparent high bias of the model in the later years likely is due to errors in the USGS measurements. Comparison between the GE and USGS data suggest that the USGS data may under quantify PCB concentrations.

3.2.4 Bioaccumulation

Model simulations were performed for pumpkinseed, brown bullhead and largemouth bass at Stillwater and TIP for the period from May 1, 1977 to December 8, 1998. Sediment and water column PCB concentrations that were computed by the PCB fate model were used as exposure levels for the invertebrates. The food web was exposed to PCBs in the cohesive sediment bed, based upon the observation that fish are found primarily in vegetated areas, and vegetation is found primarily in soft sediments.

The BMI were exposed to the PCBs in the top two cm of the sediment bed, based upon two lines of evidence. An analysis of PCB composition in the sediments and fish indicated that

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the food web was exposed to PCBs within the top 5 cm of the surface of the sediment bed. In addition, a homolog-specific bioaccumulation model was developed and used in a diagnostic fashion to further refine the estimated bioavailable depth. This model was parameterized identically to the dynamic total PCB model, except for the addition of homolog-specific values for selected parameters. The model food web was exposed to three different sediment homolog distributions, representative of 0-2 cm, 0-5 cm, and deeply buried TIP sediments containing PCBs that have undergone extensive dechlorination. The computed fish homolog distributions are most similar to the measured distributions if the fish are exposed to sediments characteristic of the 0-2 cm layer of the high-resolution cores, indicating that the food web is exposed predominately to PCBs within approximately the top 2 cm of the sediment bed.

Calibration was achieved by adjusting the PCB elimination rate, which affects all three species. Calibration of the pumpkinseed and brown bullhead models also involved adjusting the mix of PMI and BMI in the diet. Calibration of the largemouth bass model involved adjusting the proportions of pumpkinseed and brown bullhead in its diet. The model was calibrated to NYSDEC monitoring data collected between 1980 and 1997.

The model reproduces the observed temporal trends in PCB concentrations in all three species of fish reasonably well (Figure 3-14 for Stillwater and 3-15 for the TIP). For example, the model captures the decline in the largemouth bass at Stillwater, as well as the various rises and falls observed in the data throughout the entire 18-year period. The model also captures the trends in the Stillwater pumpkinseed and brown bullhead. It under-estimates the average brown bullhead levels in the mid- to late 1980s and over-estimates levels observed in the 1990s, but remains within two standard errors of the means throughout both periods.

Both model and data exhibit little or no trend in the Thompson Island Pool pumpkinseed during the late 1980s (Figures 3-15). Following a rise due to the Allen Mill event, the computed levels decline through the mid-1990s. No yearling pumpkinseeds were collected in 1991 and 1992, so the immediate response to the Allen Mill event was not observed. Both observed and computed levels declined from 1993 to 1997, although the rate of decline appears to be somewhat slower in the model. Both computed and observed brown bullhead concentrations decline during the late 1980s, rise in the early 1990s and then resume their decline. The computed values lie generally within the error bars of the data.

Computed PCB concentrations in the Thompson Island Pool largemouth bass reproduce the gradual downward trend observed in the 1980s, with differences ranging from 1 to 55% (Figure 3-15). The model under-estimates the largemouth bass means in 1990 and in 1992 through 1995. By 1996 the computed and observed values are again similar, exhibiting similar declines between 1996 and 1997.

The under-estimation of the TIP largemouth bass levels in the early 1990s by the model is not likely due to the under-estimation of the average overall exposure of the largemouth bass population. This conclusion is based on the observation that the model results for the brown bullhead and pumpkinseed are similar to the data during this period.

On the other hand, changes in the distribution of exposure levels among the individual sampled largemouth bass may account for both the patterns in the data and the differences between the model and the data. Usually, wet weight-based PCB concentrations in fish are positively correlated with percent lipid, with individual values scattered randomly about a central relationship. However, in some years, the Hudson River largemouth bass data appear to cluster into distinct relationships. For example, most of the data collected in 1990 and 1993 appear to cluster about two relationships (Figure 3-16; lines drawn by eye).

The observation of more than one cluster of individual values within a single year suggests that the largemouth bass population may be segregated into sub-populations with differing exposure levels. Such segregation could be caused by limited movement and heterogeneous surface sediment concentrations. Between 1990 and 1995, the inclusion in the data averages of sub-populations exposed to higher sediment PCB concentrations would explain the observed wide swings in the average measured levels, the observed increases in variability during this period (larger error bars on Figure 3-15), as well as the under-estimation by the model. It should be recognized that while this hypothesis provides a plausible explanation of the patterns in the data and the model results, the field data necessary to test it directly are not available.

Overall, the model exhibits no bias with respect to the data. On a graph of average computed *vs*. measured concentrations, values line up along the 1 to 1 line (Figure 3-17). In addition, 90% of the computed wet weight-based PCB concentrations are within a factor of two of the data (92% on a lipid basis). Because some of the year-to-year variation in the model/data relationship is due to uncertainty in the data, the uncertainty due to the model itself is likely to be considerably less than a factor of two.

In summary, the model represents average PCB levels in the population as a whole both at Stillwater and Thompson Island Pool generally without bias and within a factor of two. Temporal trends as well as the spatial gradient between Thompson Island Pool and Stillwater are reproduced. While there may be some subpopulations exposed to lower or higher local sediment concentrations, the model can provide realistic projections of PCB concentrations for the population as a whole under natural recovery and alternative remediation scenarios. The trends in the data and model suggest that the mechanisms controlling PCB fate and bioaccumulation have changed over time. One possible interpretation is that the rates of change observed in the late 1970s and mid-1990s characterize the natural rate of decline in the Upper Hudson River. During the 1980s/early 1990s, the decline was slowed due to on-shore sources of PCBs to the river.

3.3 PCB MASS BALANCE FOR THE RIVER

The PCB_{3+} fluxes computed by the model were used to assess the relative importance of the various mechanisms affecting PCBs in the Upper Hudson River. This mass balance analysis indicated that sources upstream of Rogers Island accounted for about 60 percent of the PCB entering the water column of the river over the last 20 years. The remainder came from the river sediments. Ninety percent of the PCBs entering the water column were fluxed to the Lower Hudson River and ten percent were transferred to the atmosphere.

The PCB_{3+} flux from the sediments to the water column came mostly from the non-cohesive sediments. Ninety percent of the PCB_{3+} that entered the water from the sediment came from the non-cohesive sediments *via* continuous flux from sediment pore water. The settling and erosion fluxes have been closely balanced, yielding a small net flux from the water column to cohesive sediments and from non-cohesive sediments to the water column.

The surface sediments of the TIP were an important component of the total input to the water from sediment, but the majority of this input came from sediments downstream of the TID. The TIP sediments were responsible for about one-third of the total input from sediment. Most of that input came from non-cohesive surface sediments largely due to the greater surface area represented by these sediments.

The mass balance analysis further indicates that burial was primarily responsible for the decline in PCB_{3+} observed in the cohesive sediments. Over the entire study area, ninety-eight percent of the inventory change in the surface sediments (i.e., top 10 cm) was the result of burial. Within the TIP, the conclusion is the same, although the comparison is not quite as dramatic. Eighty-six percent of the inventory change was due to burial.

In contrast to the cohesive sediments, the mass balance indicates that the declines observed in non-cohesive sediments have been due principally to PCB_{3+} flux to the water column. Within the surface layer, no burial has occurred in non-cohesive sediments over the study area or within the TIP.

3.4 CONCLUSIONS

The hydrodynamic, sediment transport, PCB fate, and PCB bioaccumulation sub-models of the Upper Hudson River developed on behalf of GE and presented herein represent a comprehensive state-of-the-science tool for evaluating different remedial action scenarios for Hudson River PCBs. The models mechanistically describe important PCB transport, fate, and bioaccumulation processes. The parameterization of the various mechanisms represented in the models relied heavily on the vast array of site-specific data. The models have been calibrated and validated against water column, sediment, and biota data sets of greater than 16,000 PCB measurements collected over a 20-year period. The rich and robust data sets available on the Hudson River constrained the calibration process and provide confidence that the model accurately represents the important processes controlling PCB dynamics in the Upper Hudson River. These models represent the single most important tool in the decision-making process and will be invaluable in addressing the important questions regarding Hudson River PCB remediation.

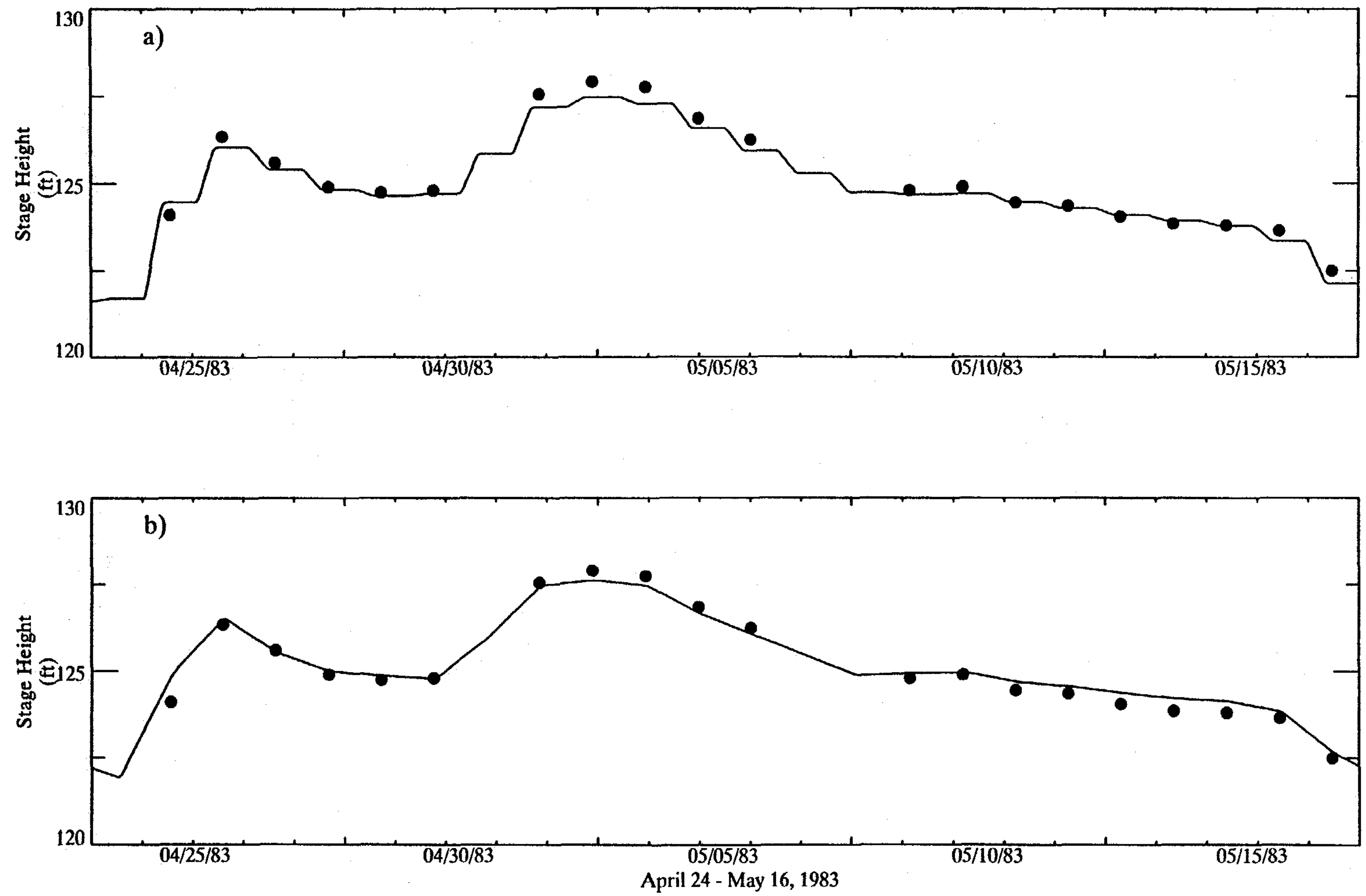

Figure 3-1. Comparison of predicted (line) and measured (symbols) TIP stage heights at gauge 119 during 1983 spring flood for (a) one-dimensional and (b) two-dimensional models.

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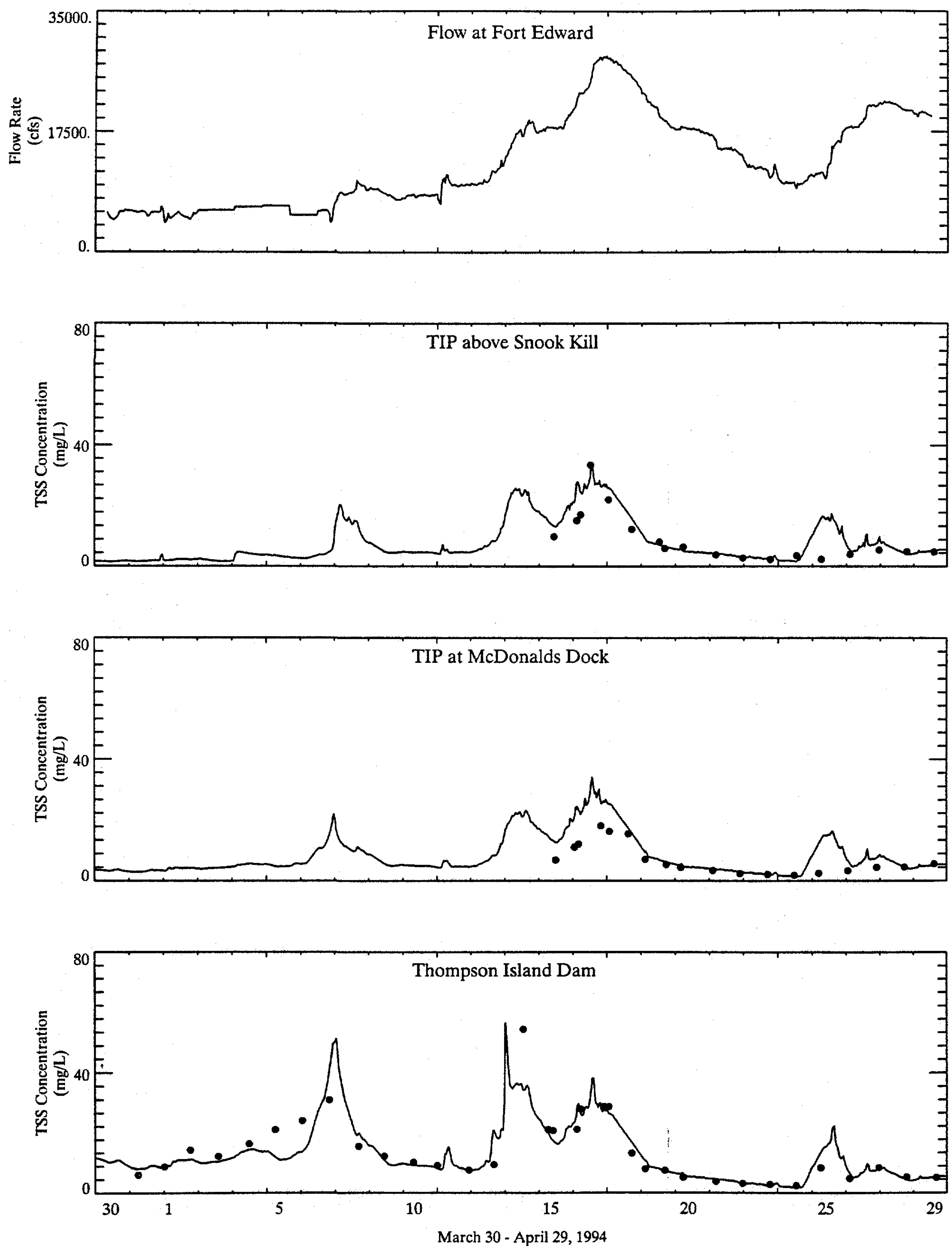

Figure 3-2. Comparison of predicted (line) and measured (symbols) suspended sediment concentrations at three locations in the TIP during the 1994 flood. Top panel shows measured flow at Fort Edward.

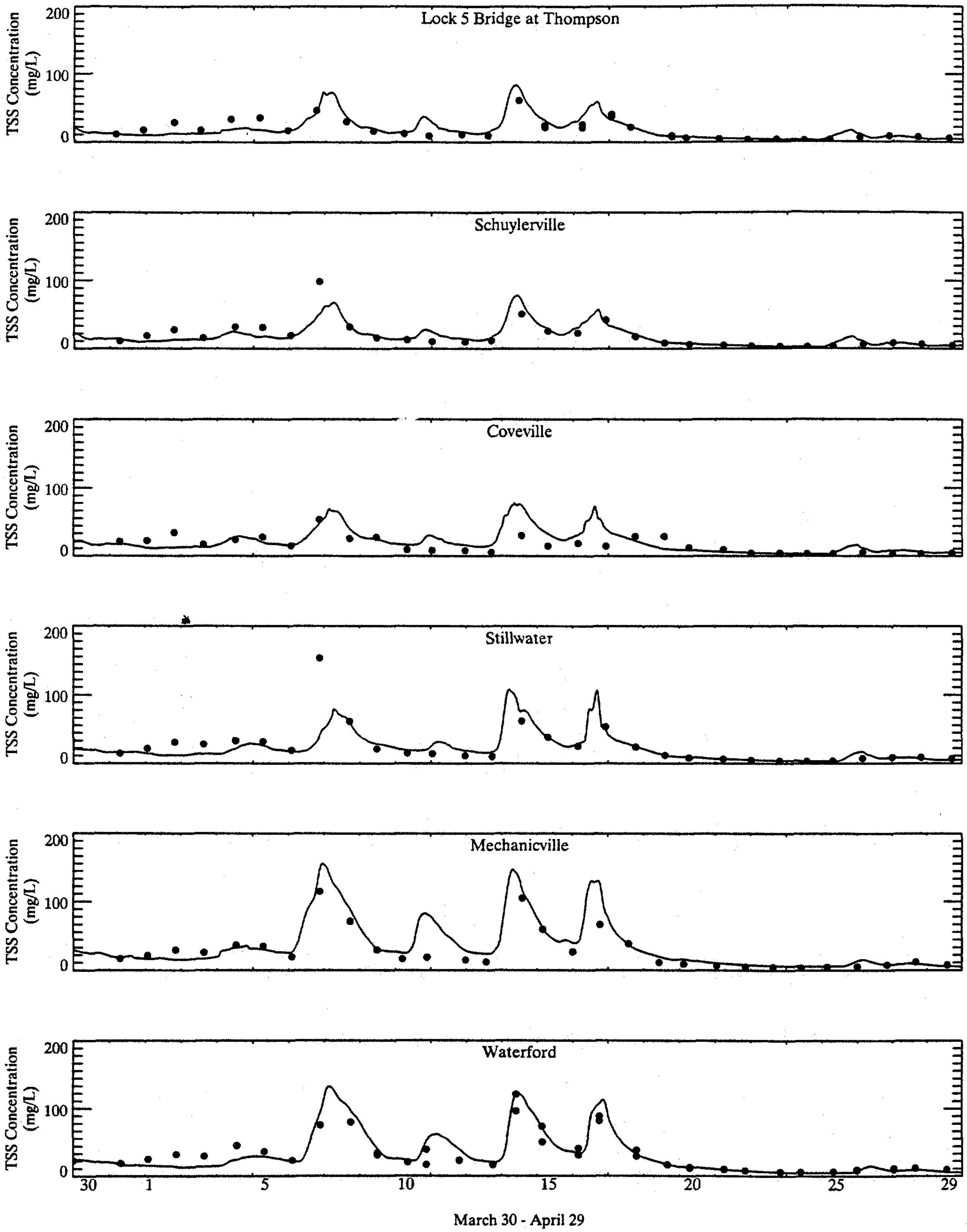

Figure 3-3. Comparison of predicted (line) and measured (symbols) suspended sediment concentrations at six locations in the Upper Hudson River during the 1994 spring flood.

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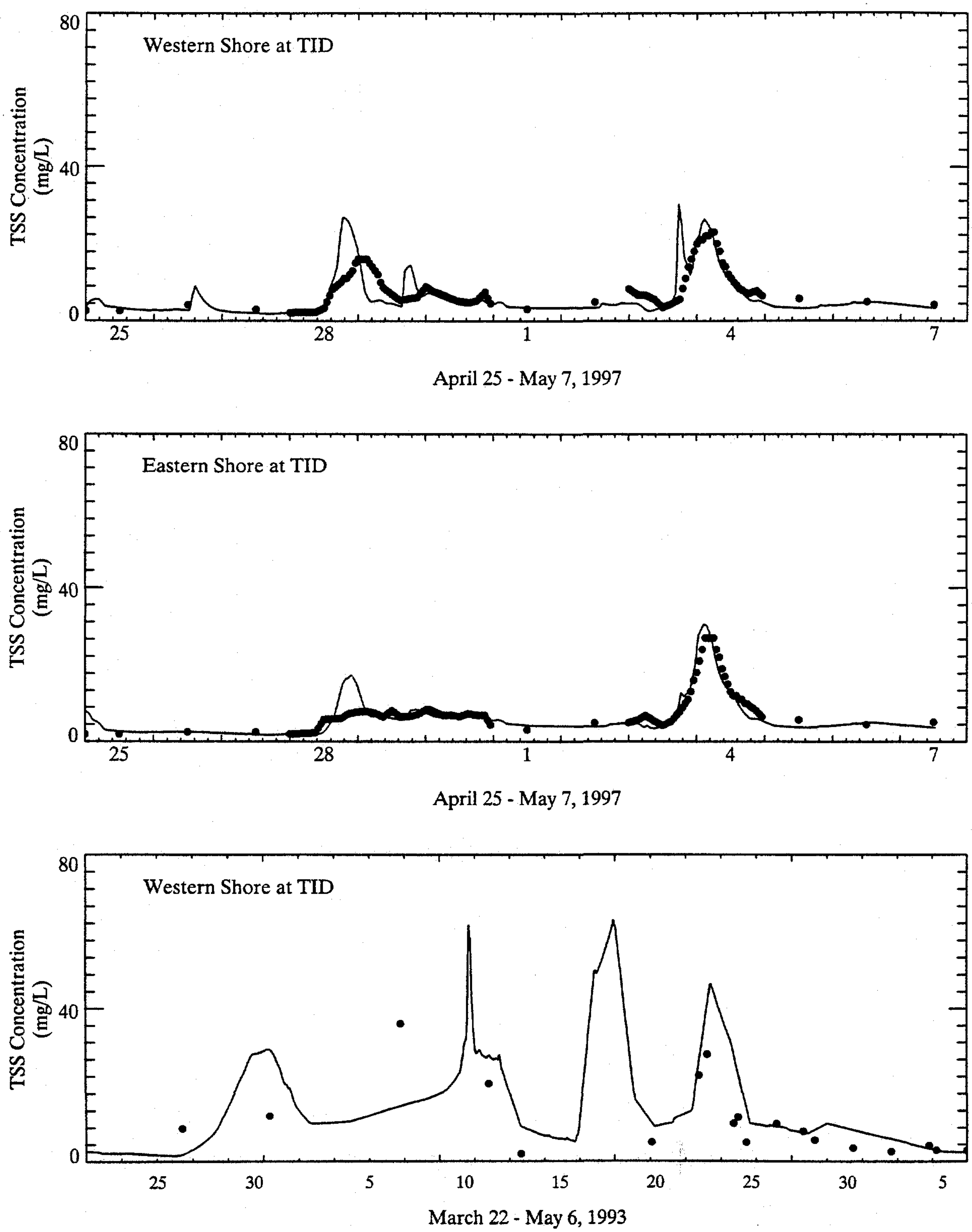

Figure 3-4. Comparison of predicted (line) and measured (symbols) suspended sediment concentrations at the TID during the 1997 spring flood (April 25 to May 7) and the 1993 spring flood (March 22 to May 6).

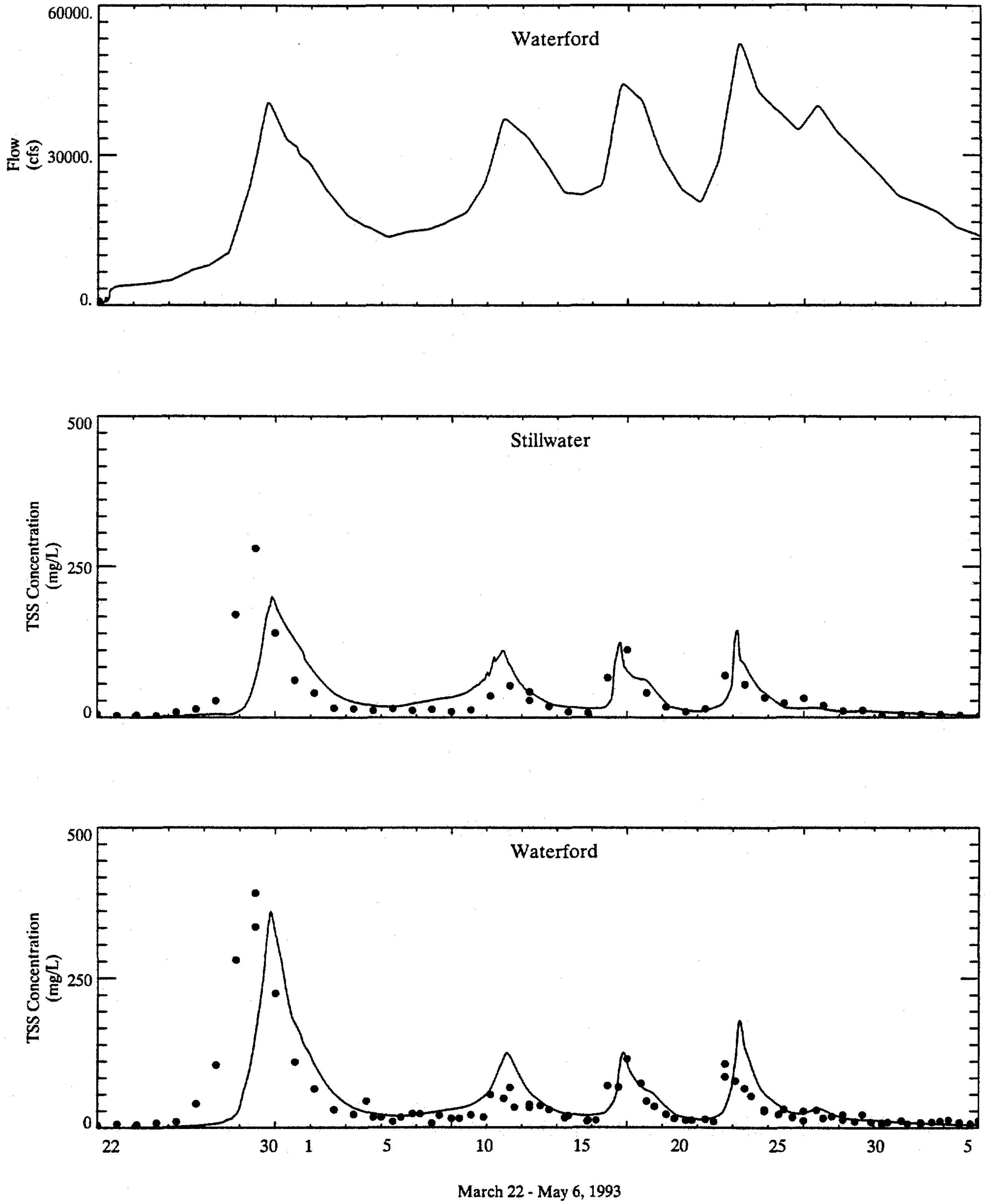

Figure 3-5. Comparison of predicted (line) and measured (symbols) suspended sediment concentration at Stillwater and Waterford during the 1993 spring flood. Top panel shows measured flow at Waterford.

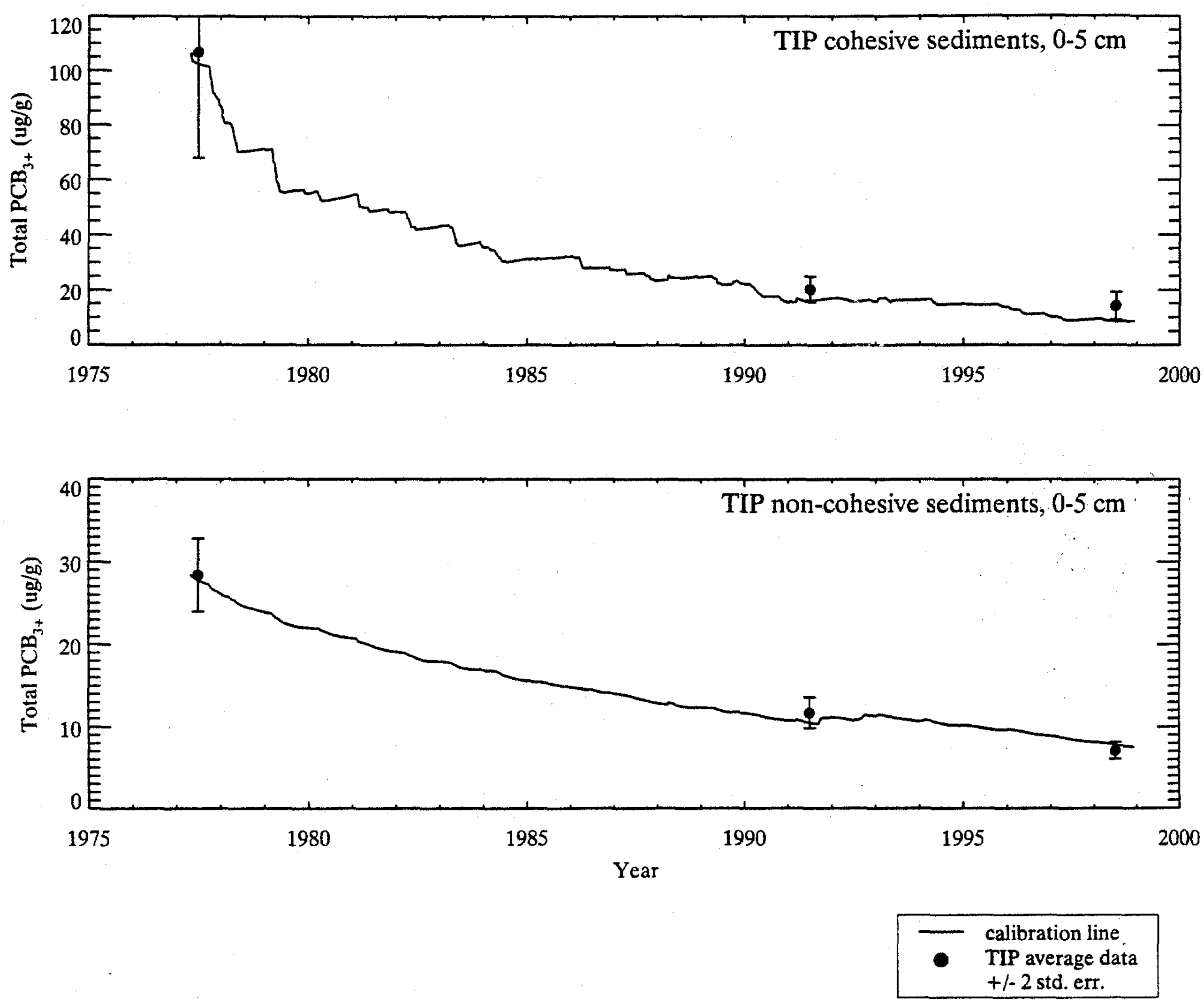

Figure 3-6. Predicted (line) and measured (symbols) average PCB_{3+} concentrations in surface sediments (0-5 cm) of the TIP.

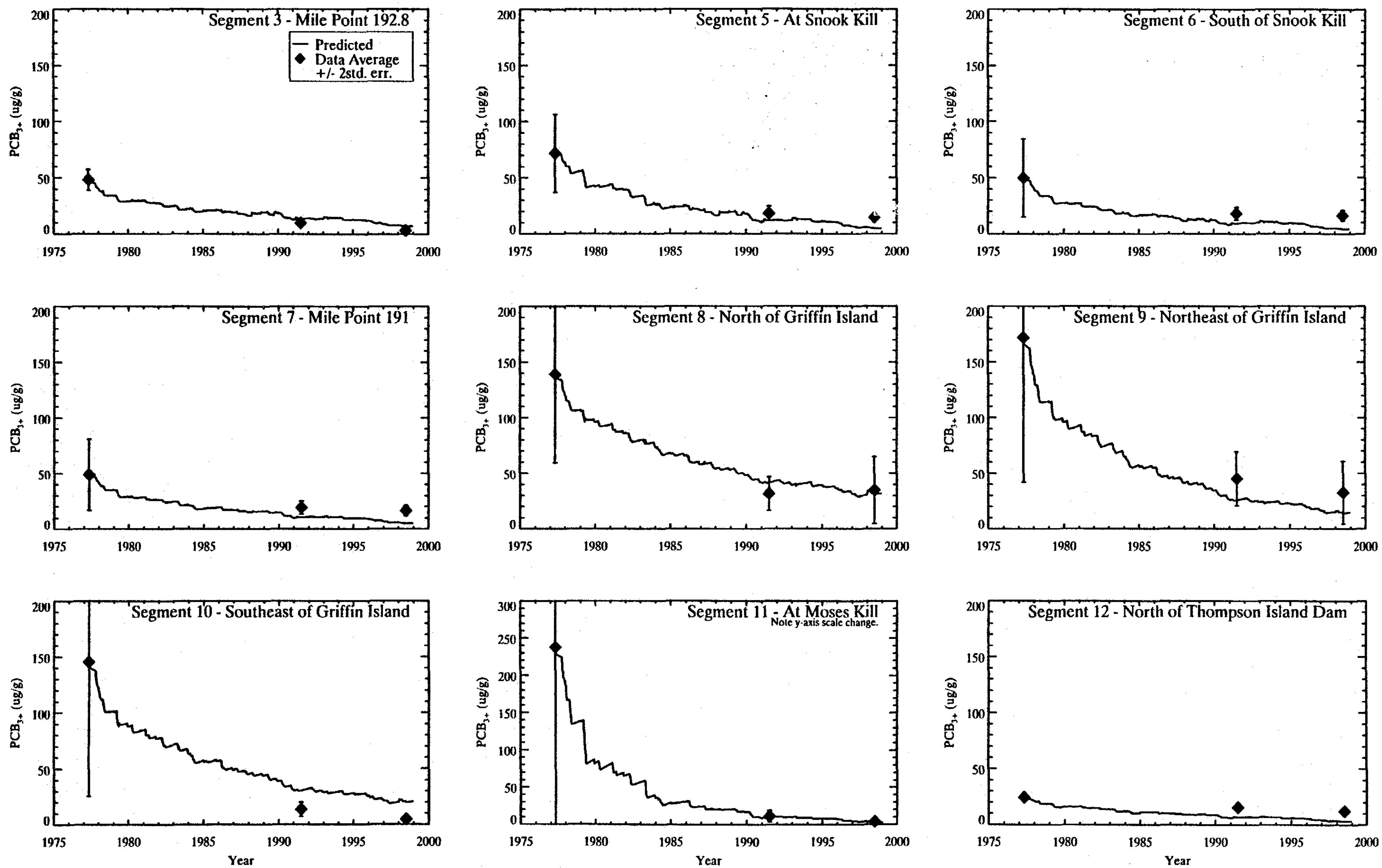

Figure 3-7. Data (symbols) to model (lines) comparison of 0-5 cm cohesive surface PCB_{3+} sediment concentrations at nine select model segments in the TIP.

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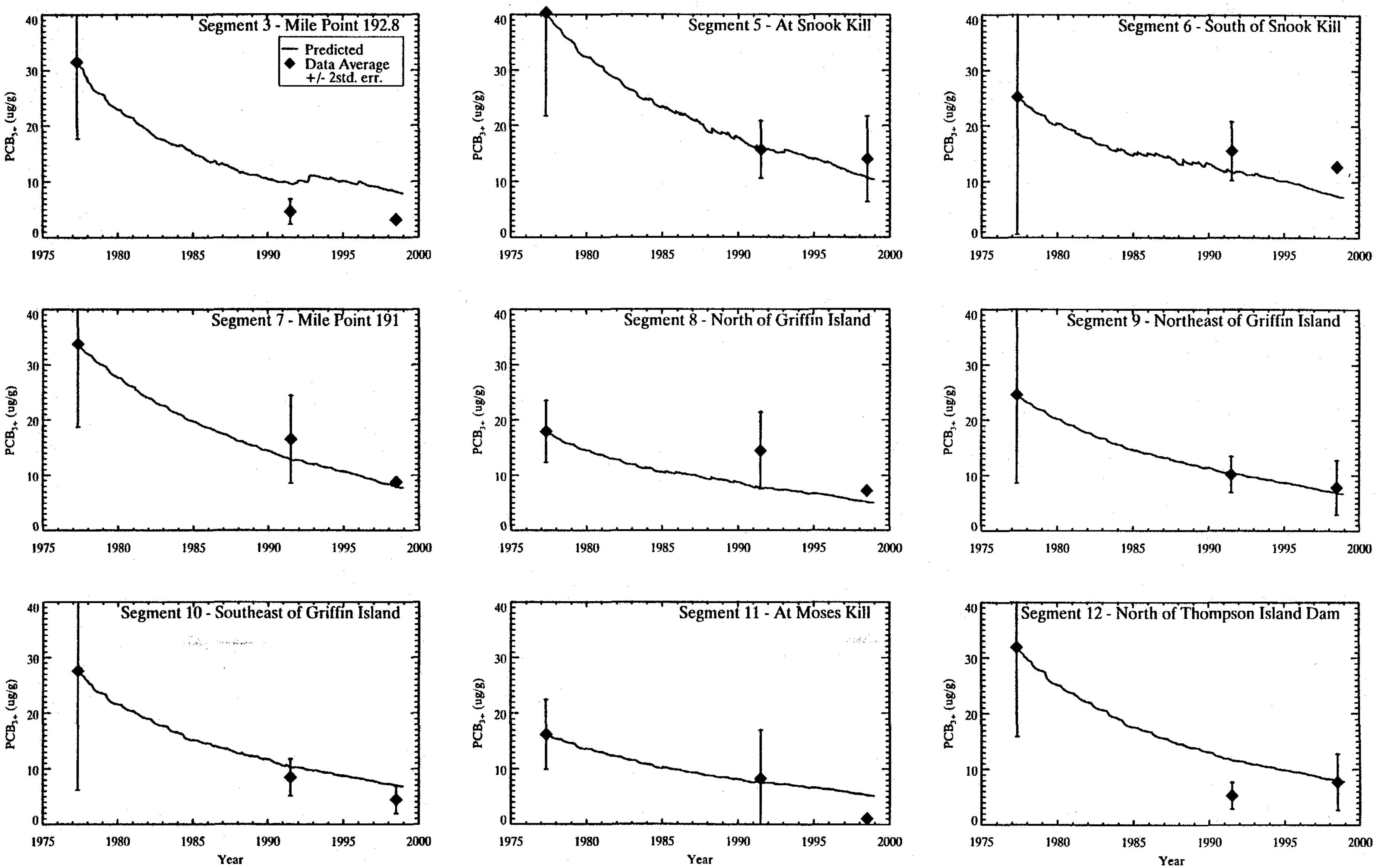
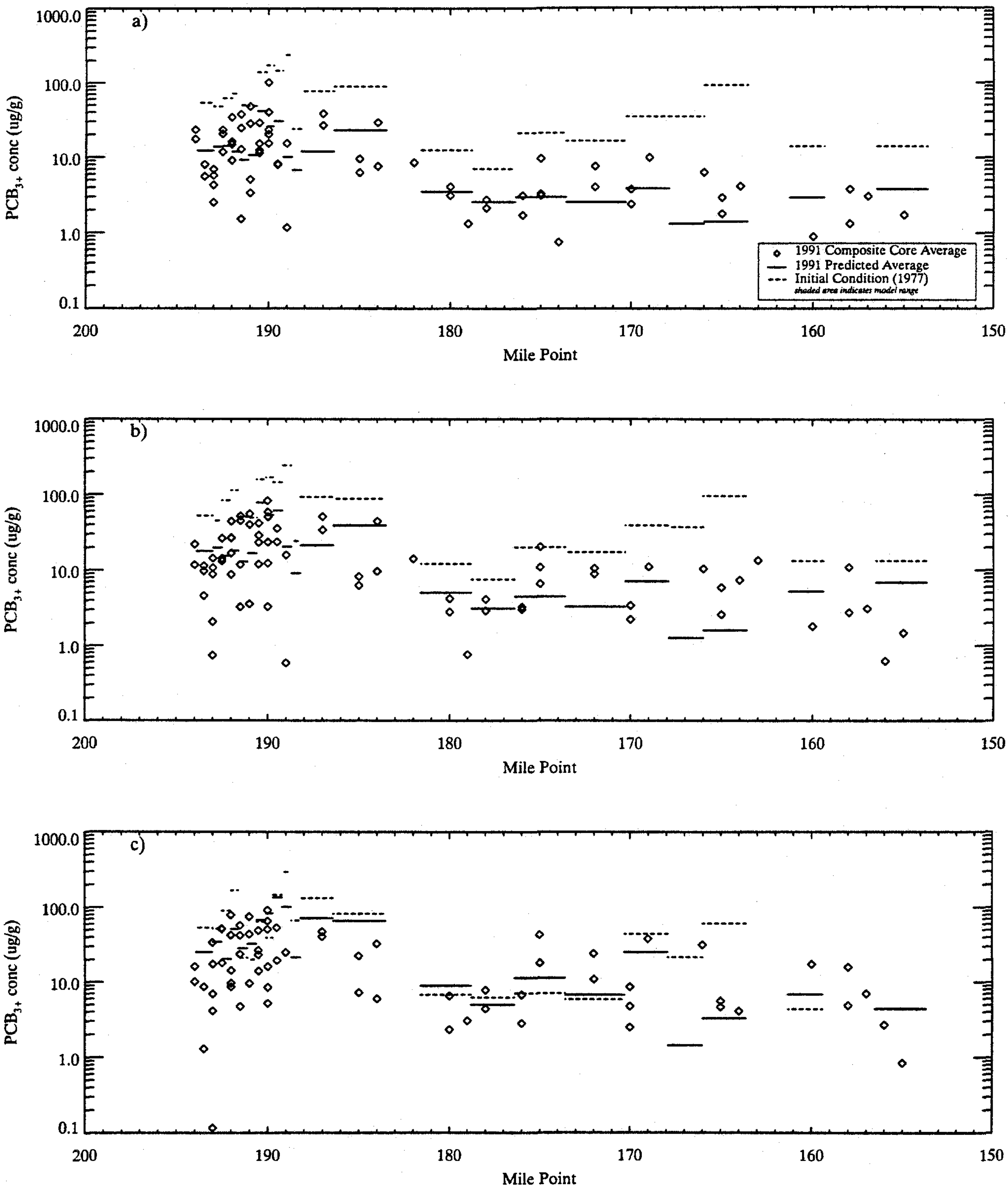


Figure 3-8. Data (symbols) to model (lines) comparison of 0-5 cm non-cohesive surface PCB_{3+} sediment concentrations at nine select model segments in the TIP.



Note: 1977 levels used as initial conditions in the model are shown as dashed lines for comparison to the 1991 levels.

Figure 3-9. Spatial pattern of a) 0-5 cm, b) 5-10 cm, and c) 10-25 cm cohesive sediment PCB_{3+} concentrations calculated by the model (solid lines) and measured (symbols) in 1991.

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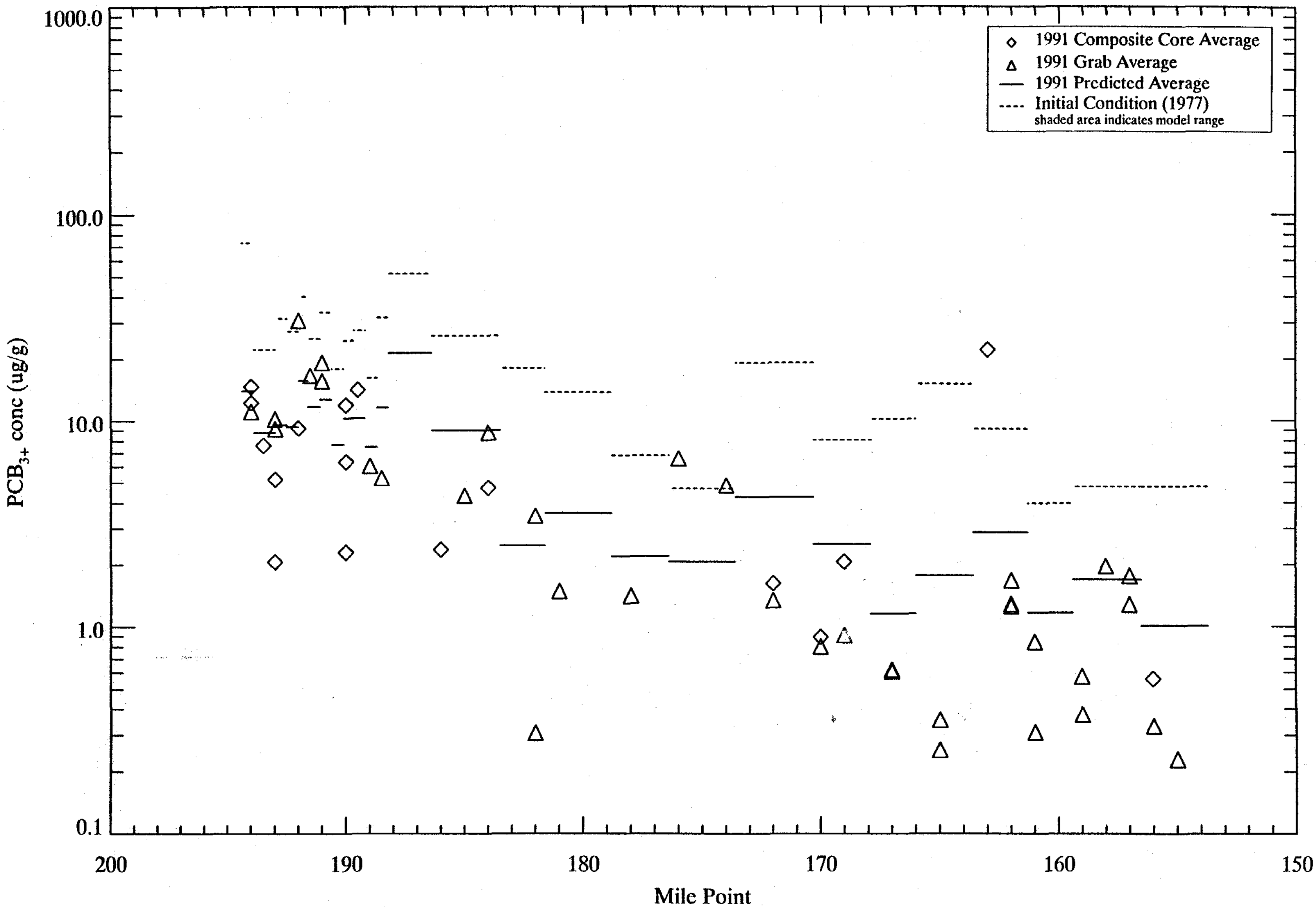

Note: 1977 levels used as initial conditions in the model are shown as dashed lines for comparison to the 1991 levels.

Figure 3-10. Spatial pattern of 0-5 cm non-cohesive sediment PCB$_{3+}$ concentrations calculated by the model (solid lines) and measured (symbols) in 1991.

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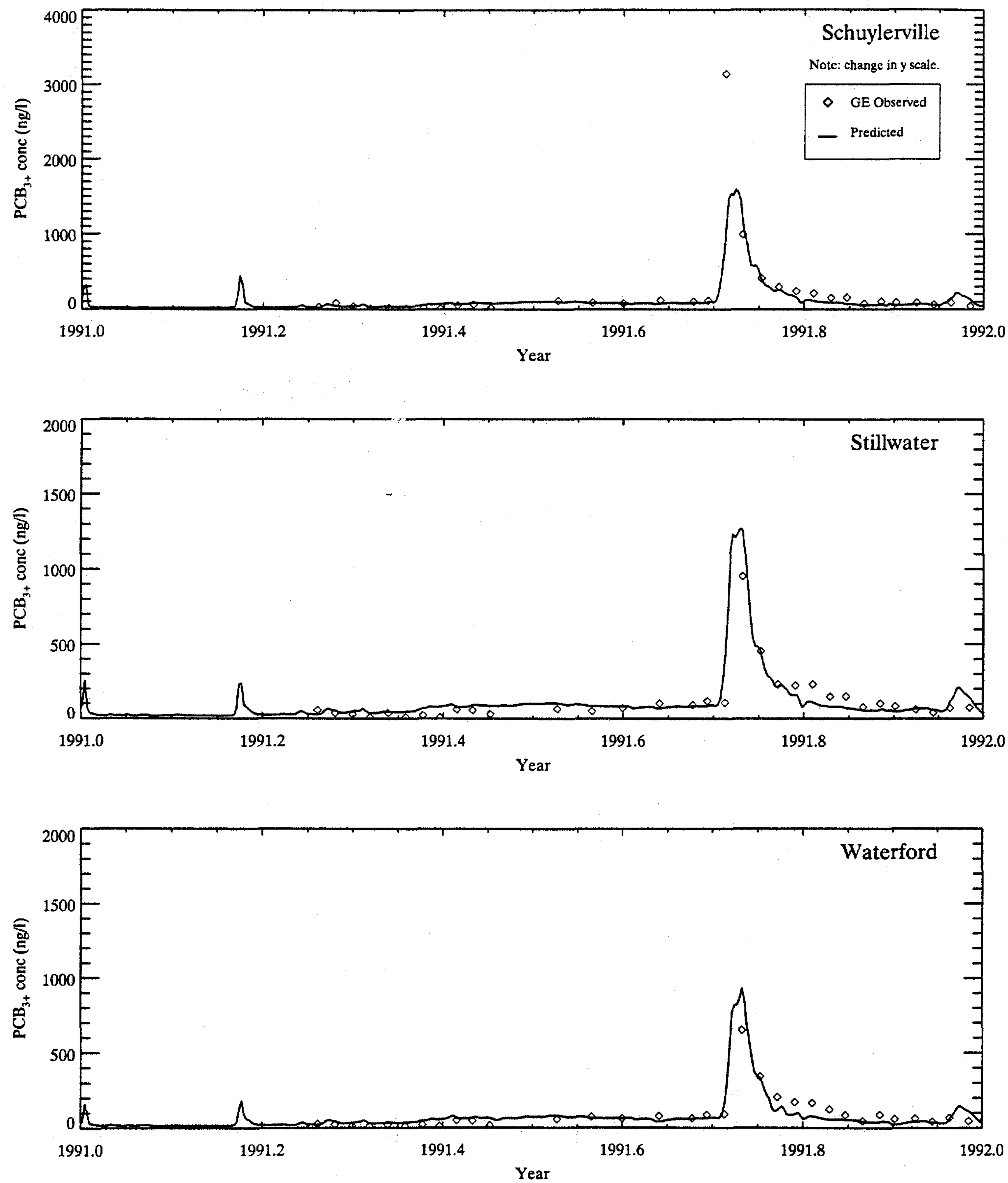

Figure 3-11. Comparison of computed and observed water column PCB_{3+} measured by GE at Schuylerville, Stillwater, and Waterford for 1991.

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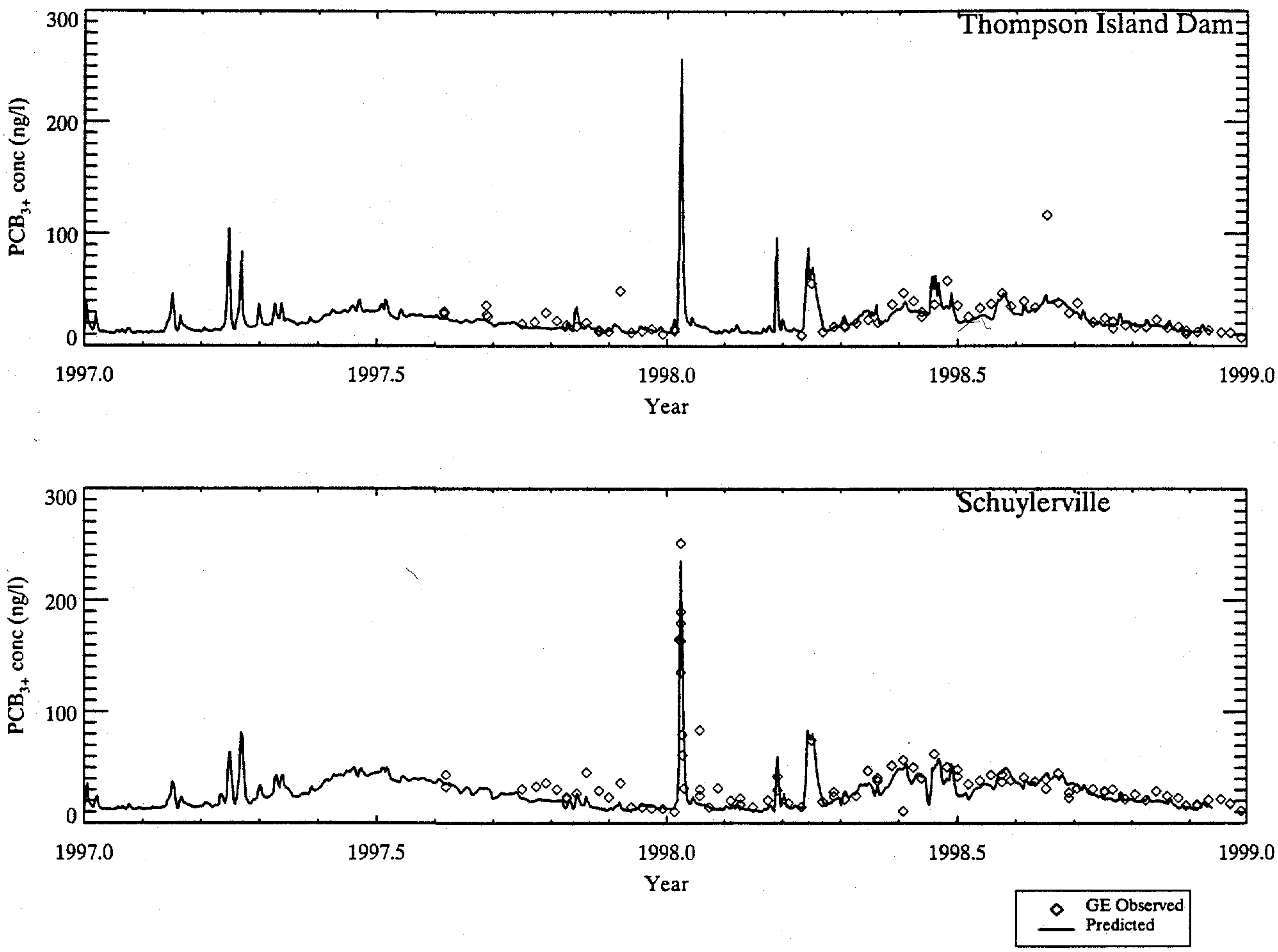

Figure 3-12. Comparison of predicted (line) and measured (symbols) water column PCB_{3+} concentrations at Schuylerville and the Thompson Island Dam for 1997 and 1998.

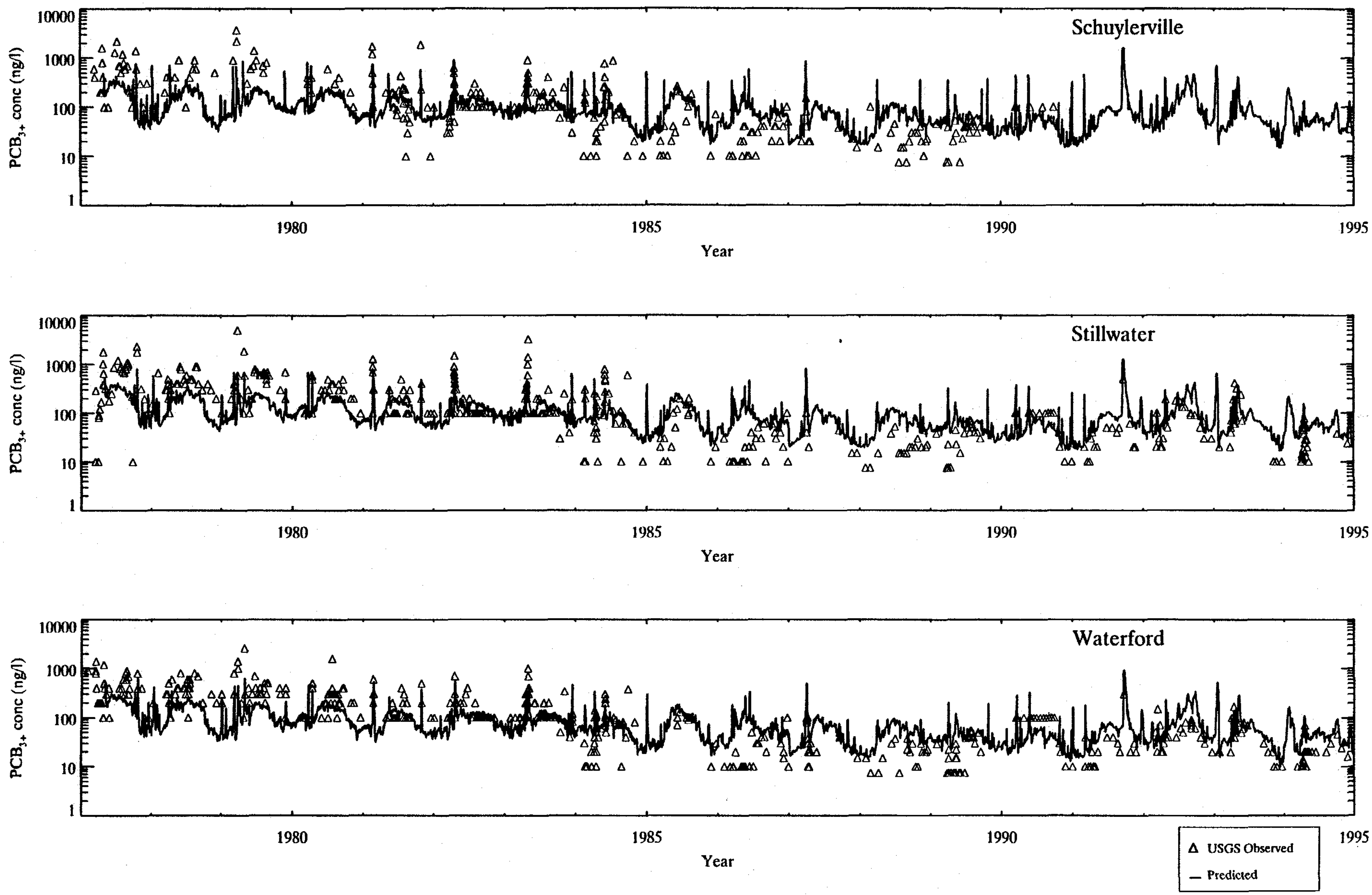

Figure 3-13. Comparison of computed and observed water column PCB$_{3+}$ measured by USGS at Schuylerville, Stillwater, and Waterford.

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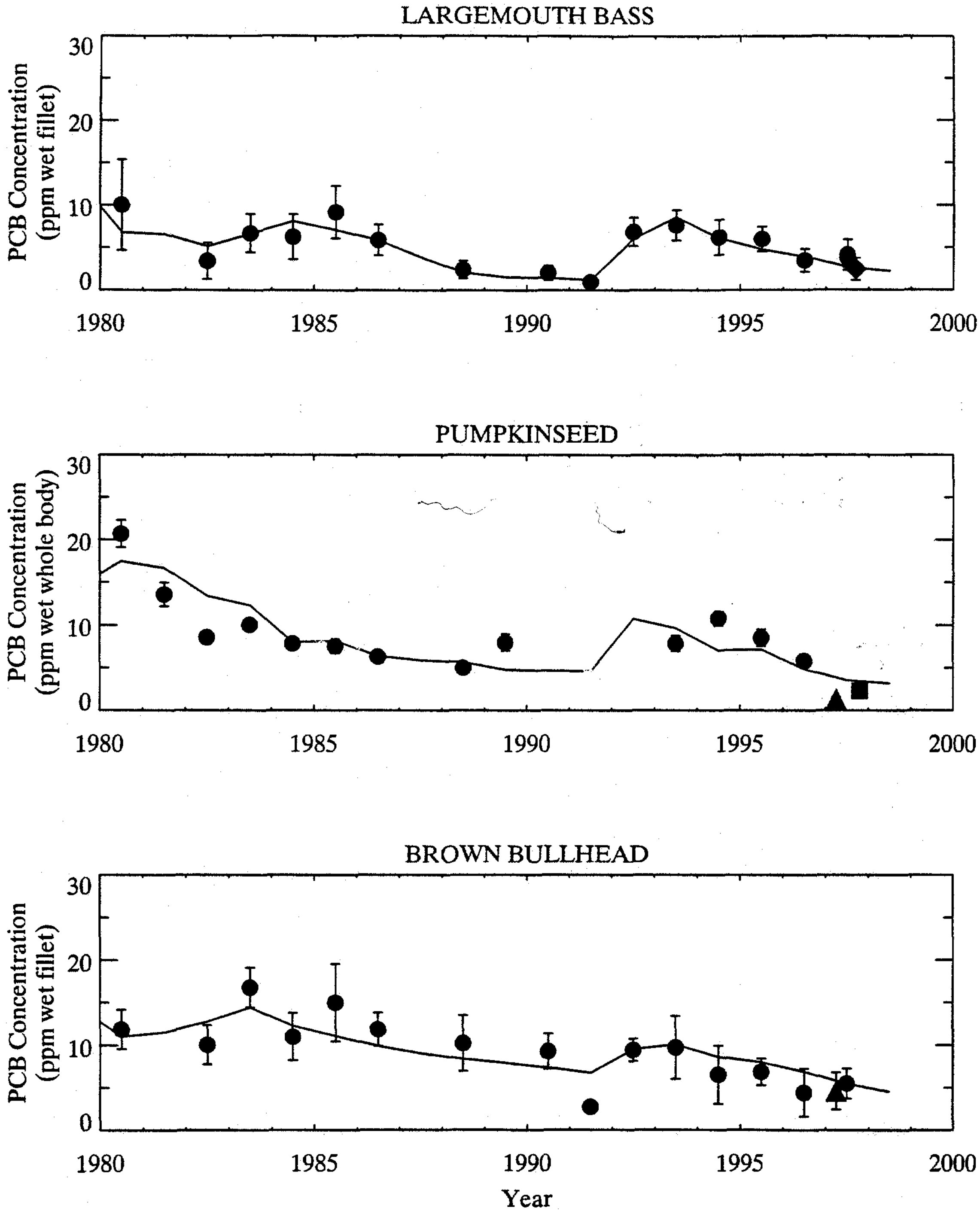
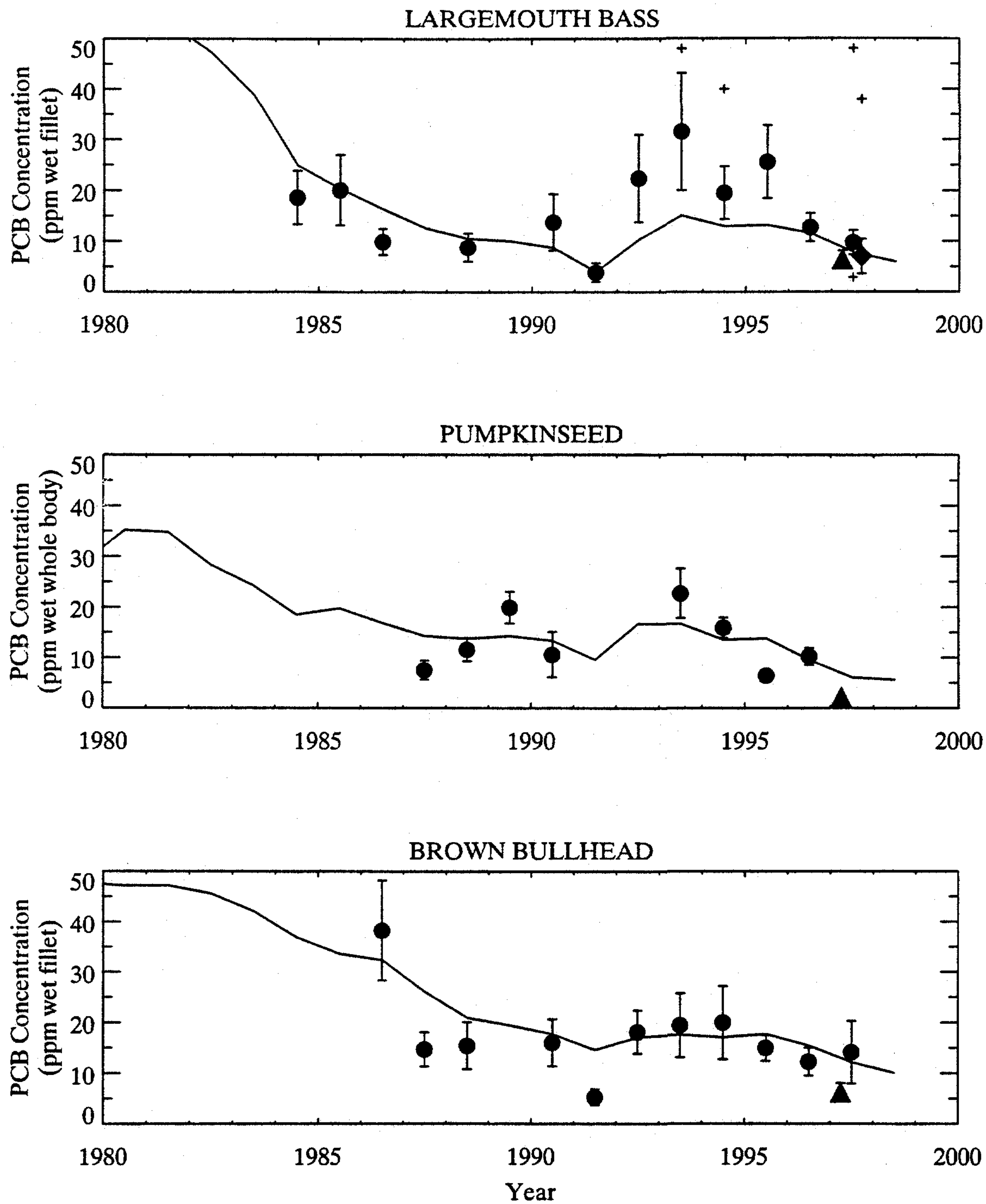


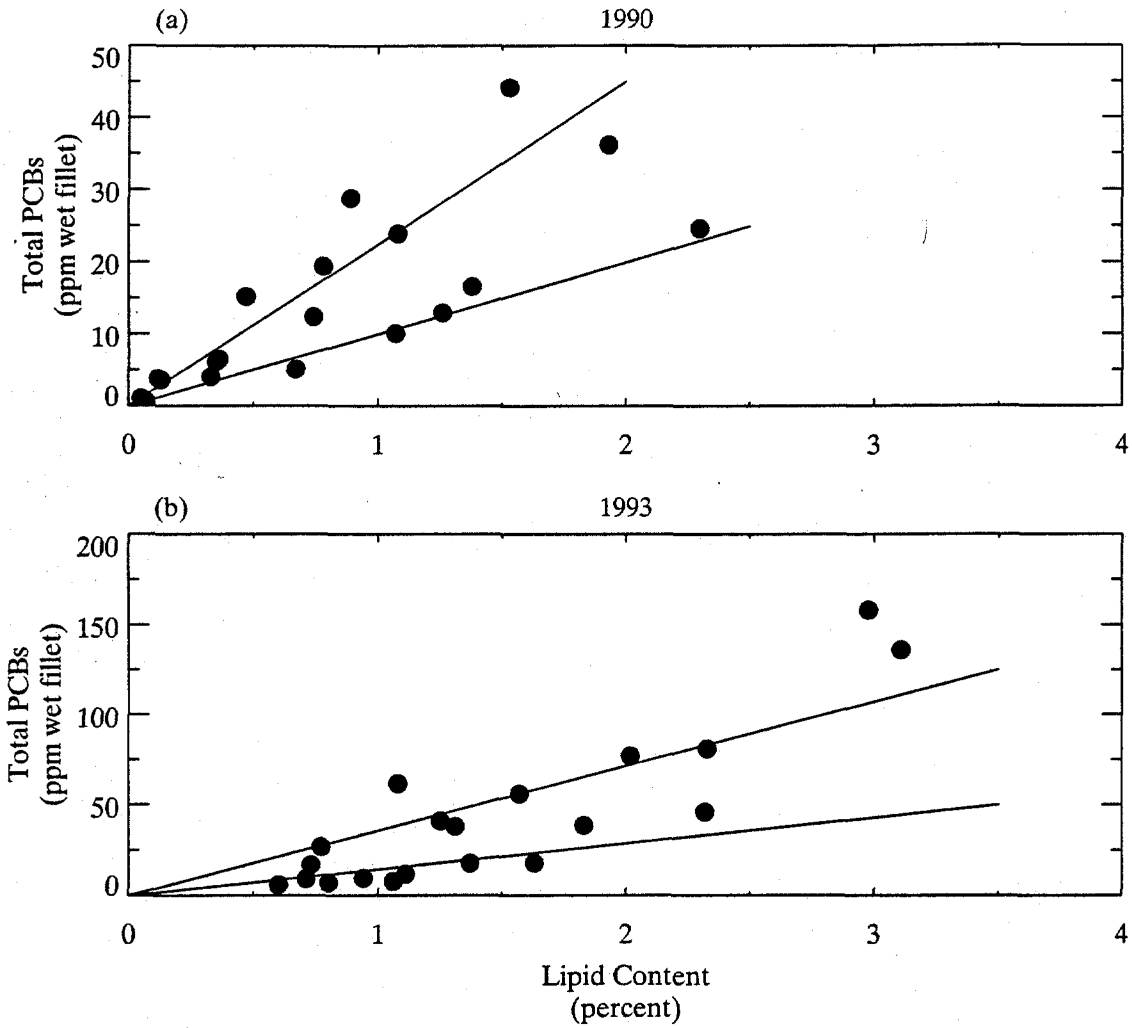
Solid lines indicate model results.
Data are arithmetic means +/- 2 standard errors.
Circles = NYSDEC, Squares = NYSDOH, Triangles = Exponent, Diamonds = GE.

Figure 3-14. Predicted (line) and measured (symbols) wet-weight PCB concentrations in largemouth bass, pumpkinseed and brown bullhead collected from Stillwater Pool.



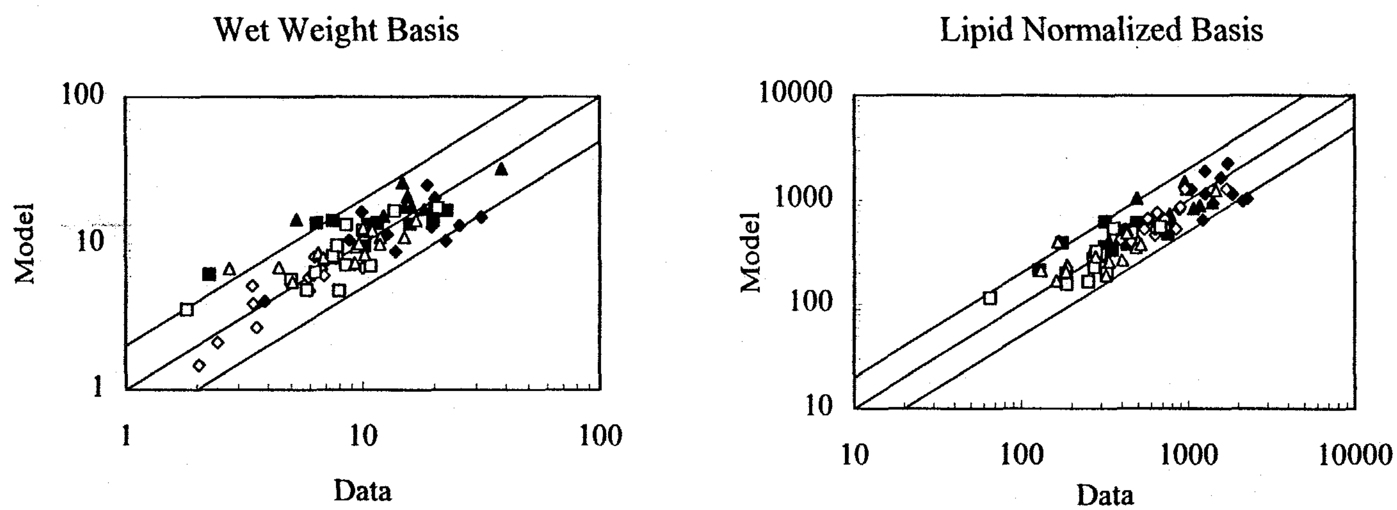
Solid lines indicate model results.
Data are arithmetic means +/- 2 standard errors.
Circles = NYSDEC, Triangles = Exponent, Diamonds = GE.
Crosses indicate values excluded from the annual averages.
Crosses at top of axes represent values off of scale.

Figure 3-15. Predicted (line) and measured (symbols) wet-weight PCB concentrations in largemouth bass, pumpkinseed and brown bullhead collected from Thompson Island Pool.



Data collected by NYSDEC.

Figure 3-16. Relationship between PCB concentrations and lipid levels in largemouth bass of Thompson Island Pool.



Diamonds = largemouth bass
Squares = pumpkinseed
Triangles = brown bullhead
Filled symbols = Thompson Island Pool values
Open symbols = Stillwater Pool values

Figure 3-17. Calibration of the food web model. Comparison of computed and observed PCB concentrations in fish.

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Predictions of Natural Recovery and the Effectiveness of Active Remediation

Section 4

Quantitative Environmental Analysis, LLC

SECTION 4
PREDICTIONS OF NATURAL RECOVERY AND THE EFFECTIVENESS OF ACTIVE REMEDIATION

The model was used to evaluate four remedies: natural recovery; elimination of the upstream PCB sources (i.e., sources upstream of Rogers Island); dredging cohesive sediments between Rogers Island and the Northumberland Dam; and dredging NYSDEC hot spots. The results are summarized in a series of graphs that present predicted largemouth bass PCB_{3+} concentrations in the TIP and Stillwater Pools and predicted PCB_{3+} loading passing Waterford to the Lower Hudson River for both natural recovery and active remediation. Each prediction is presented as a solid line and a shaded region. The solid line indicates the best estimate of the future condition and the shaded region delineates the range between the best estimate and a bounding estimate that reflects the uncertainty of the more important model parameters. In each graph the line associated with blue shading indicates the natural recovery prediction and the line associated with orange shading indicates the prediction with active remediation. The natural recovery prediction is plotted over the active remediation so that the active remediation prediction is only seen if it falls outside the range of natural recovery.

It is important to note that for the active remediation scenarios, the feasibility of large scale dredging has not yet been evaluated. Assumptions, that may prove to be untrue, about the implementation were made so that the theoretical effectiveness of the options could be evaluated. If any of the active remedial options are considered, a full evaluation of feasibility will need to be made, including a full evaluation of environmental, and community impacts, cost and technical capabilities.

4.1 NATURAL RECOVERY

Natural recovery, which is included in EPA's concept of No Action, is the decline of PCB concentrations due to processes that occur naturally in the river in the absence of additional reductions of remaining on-shore sources or active remediation of sediments. The model indicates that natural recovery will result in continued reductions of PCB concentrations in largemouth bass, the species at the top of the food chain. The model projects average largemouth bass PCB levels would reach the Federal Food and Drug Administration (FDA) tolerance level (2 ppm) by about the year 2000 in the Stillwater reach and 2010 in the TIP (Figure 4-1a and b). Using a more conservative estimate moderated by bounding calculations, which take into account the uncertainty of the more important model parameters, the model projects it could take until 2004 in Stillwater and 2023 in the TIP to reach 2 ppm (Figure 4-1a and b).

The model simulated Upper Hudson River conditions for the thirty-year period from 1999 to 2029. It projects that, under natural recovery, PCB concentrations in fish continue to decline to levels in 2029 of about 0.9 ppm in the TIP and 0.4 ppm in the Stillwater Pool (Figure 4-1a and b). PCB flux to the Lower Hudson River was projected to drop from a current level of about 300 lb/yr to about 90 lb/yr by the year 2029 (Figure 4-1c).

4.2 ELIMINATION OF THE UPSTREAM PCB LOAD

The projections demonstrate that eliminating the upstream PCB source accelerates recovery more than the other remedial alternatives. Upstream source control would reduce PCB concentrations in largemouth bass throughout the Upper Hudson River. If the upstream sources were completely eliminated in 1999[3], the model projects that the average TIP largemouth bass would reach the 2 ppm level 4 years sooner than under natural recovery (Figure 4-2a). Furthermore, by 2029, the PCB level would be reduced about a factor of three beyond that achievable by natural recovery (0.3 ppm versus 0.9 ppm). In the Stillwater reach, the reduction by 2029 would be about a factor of two and one-half (0.15 ppm versus 0.4 ppm) (Figure 4-2b).

Upstream source control is projected to produce an immediate reduction in PCB flux to the Lower Hudson River to about 260 lb/yr (Figure 4-2c). This reduction would increase over

3 While various levels of future PCB loading from the Upstream Source area have been assumed, the actual loading level is uncertain due to the complexity of remediating PCB DNAPL from fractured bedrock adjacent to the Hudson River.

time as the surface sediment PCB concentrations declined. By 2029, the flux would be reduced to about 40 lb/yr, about a 50 lb/yr reduction beyond that achievable by Natural Recovery.

4.3 DREDGING

Dredging NYSDEC hot spots would cause largemouth bass tissue levels in the TIP to reach 2 ppm approximately one year sooner (2009 vs. 2010); there would be no impact on levels at Stillwater (Figure 4-3a and b). Similarly, dredging cohesive sediments would accelerate this time by 1 year and only in the TIP (Figure 4-4a and b). Dredging the hot spots would produce a temporary reduction in TIP largemouth bass levels of approximately 0.4 ppm (from 1.6 to 1.2 ppm in 2012). The difference between natural recovery and dredging would decline over time to approximately 0.1 ppm in 2029 and eventually to zero. Dredging cohesive sediments from Rogers Island to Northumberland Dam would produce a temporary reduction of 0.6 ppm; this reduction would also eventually decline to zero. In both cases, there would be essentially no reduction in Stillwater largemouth bass levels. The predicted reductions in largemouth bass PCB levels were small because the incremental reductions in surface sediment concentration achieved by dredging were small. Natural recovery was predicted to reduce TIP cohesive surface sediment PCB levels to about 3 to 5 ppm by the time dredging could start in 2005 and natural recovery would continue to reduce these levels as dredging progressed over 9 to 12 years. Thus, dredging would reduce concentrations by only a few parts per million. Assuming a zero post-dredging residual concentration would not provide significant additional reductions for the same reason. Further, the dredged areas would be subject to recontamination from non-cohesive sediments and from upstream sources.

Dredging would have only a minor impact on the PCB flux to the Lower Hudson River, reducing the annual flux by about 2-10 lb/yr (Figures 4-3c and 4-4c). The reduction achieved by dredging would decline over time as surface sediments became recontaminated.

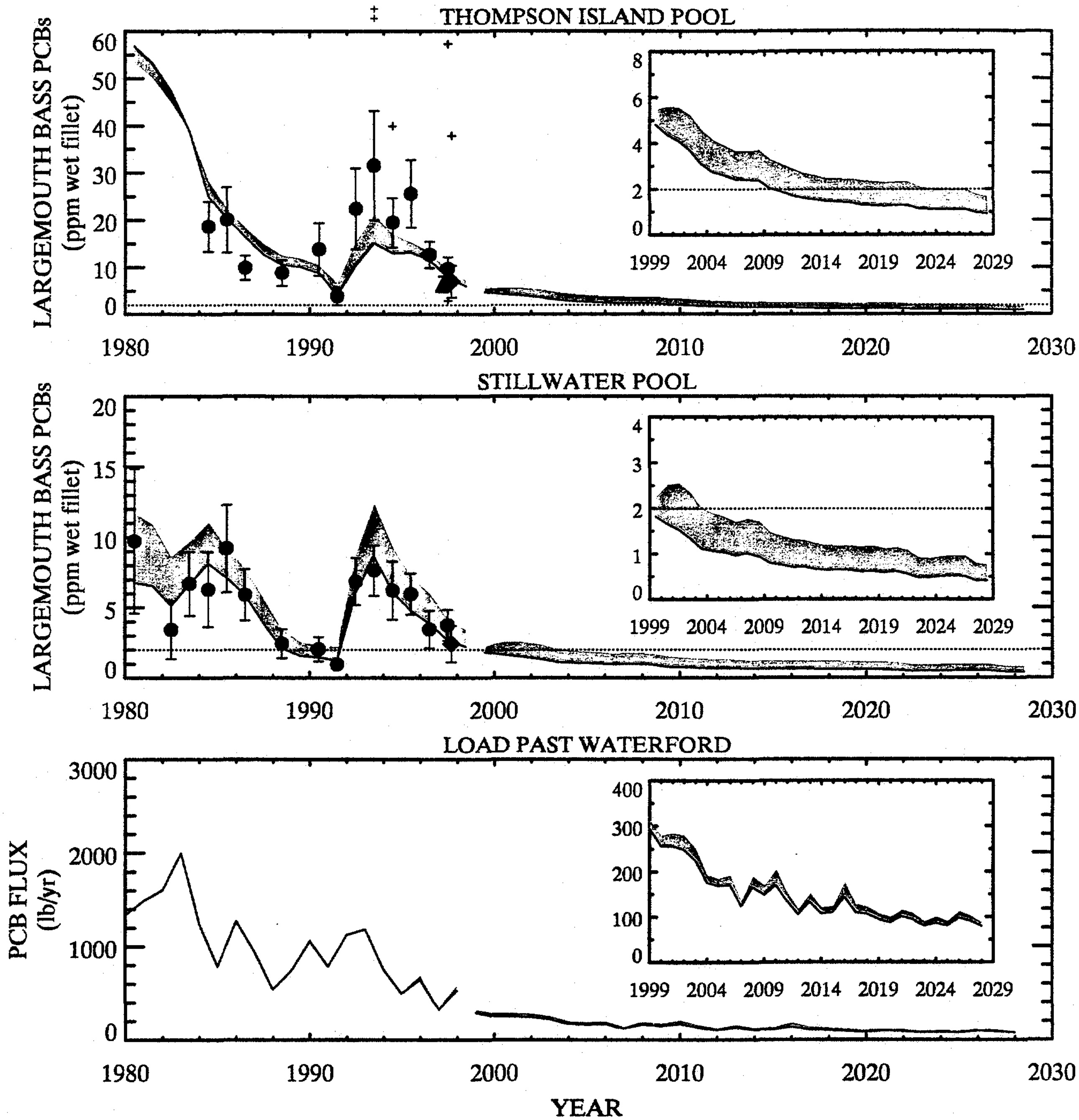
4.4 THE 100-YEAR FLOOD

The calibrated and validated sediment transport model was used to investigate the impacts of a 100-year flood, a flood that has a one percent chance of occurring in any year and may have last occurred in 1976, on sediment transport and PCB levels in the Upper Hudson River. The model predicted that 2,500 MT of sediment were eroded from the Upper Hudson River and transported to the Lower Hudson River during the flood. This amount of sediment corresponds to approximately 1% of the average annual sediment load at Waterford. The model predicted that a total of 5,100 MT of sediment would be transported out of the TIP during the 100-year flood. This mass corresponds to mean erosional depths of 0.84 and 0.14 cm for the cohesive and non-cohesive bed, respectively. Maximum erosional depths for the cohesive and non-cohesive bed were predicted at approximately 9 and 8 cm, respectively, with erosion in approximately 94% of the cohesive bed area and net deposition in the remaining area. In the eroded portions of the TIP cohesive bed, erosional depths of 2 cm or less were predicted for 78% of the total cohesive area with about 4% of the area predicted to have erosional depths greater than 5 cm. Scour depths of 1 cm or less were predicted in approximately 97% of the non-cohesive bed area of the TIP.

A 100-year flood event would cause a temporary increase in TIP largemouth bass PCB levels, but almost no increase in levels at Stillwater. The extent of the increase in the TIP would depend on when the flood occurred. For example, if the flood occurred in 2006 it would result in about an 0.8 ppm increase in TIP largemouth bass, whereas the increase would be about 0.6 ppm if the flood occurred in 2013 or 0.4 ppm if it occurred in 2020. The decreasing impact further in the future is attributable to the declining surface sediment concentrations resulting from natural recovery.

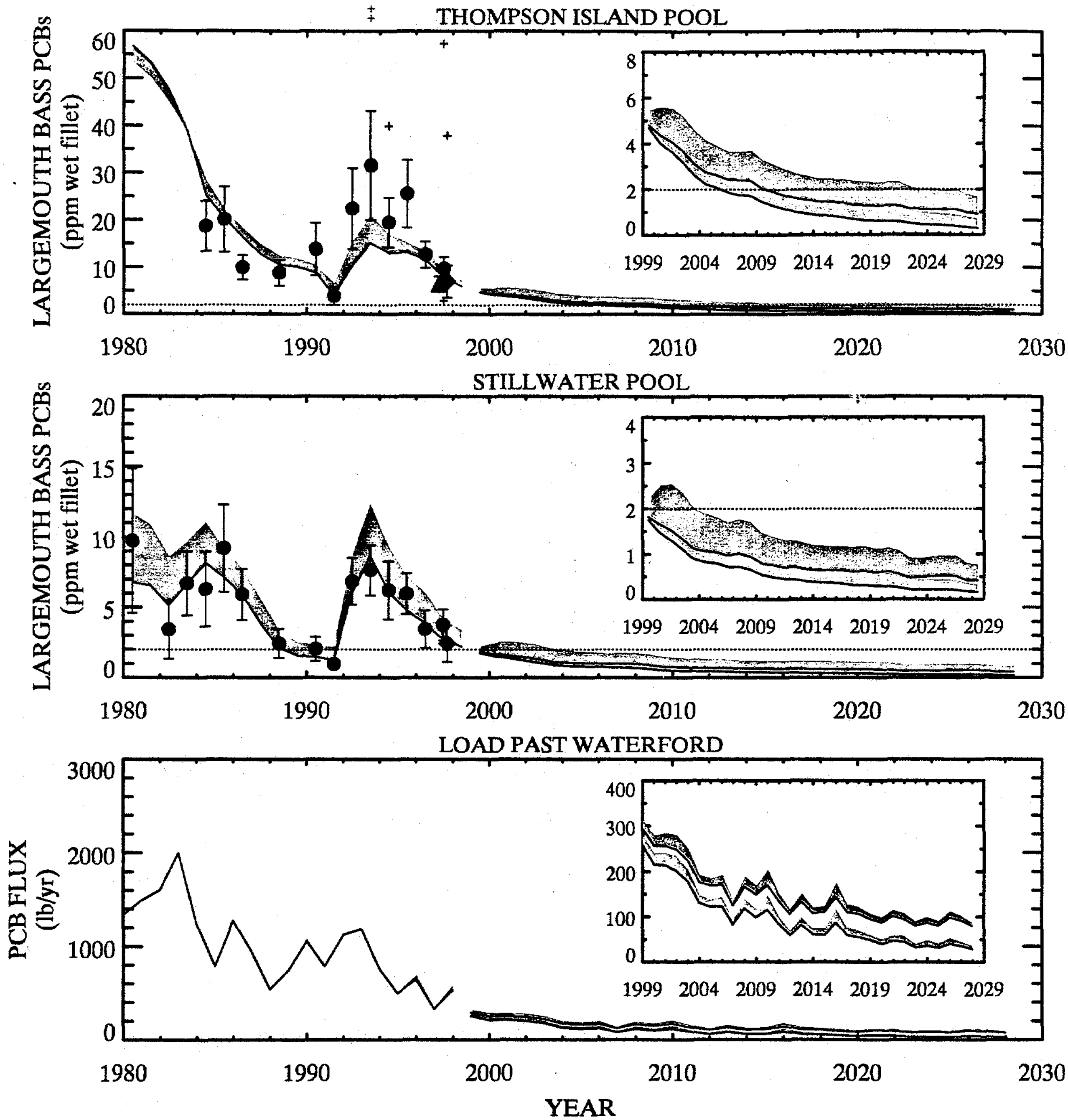
4.5 CONCLUSIONS

The Upper Hudson River is undergoing a natural recovery that will result in average largemouth bass concentrations reaching 2 ppm in all reaches of the river within about 10 to 24 years and levels of 0.4 to 0.9 ppm within 30 years. The recovery can be accelerated by upstream source control because the upstream source becomes the dominant source as surface sediment concentrations decline through natural recovery. Dredging would be ineffectual because it would achieve only small reductions in surface sediment PCB concentrations.



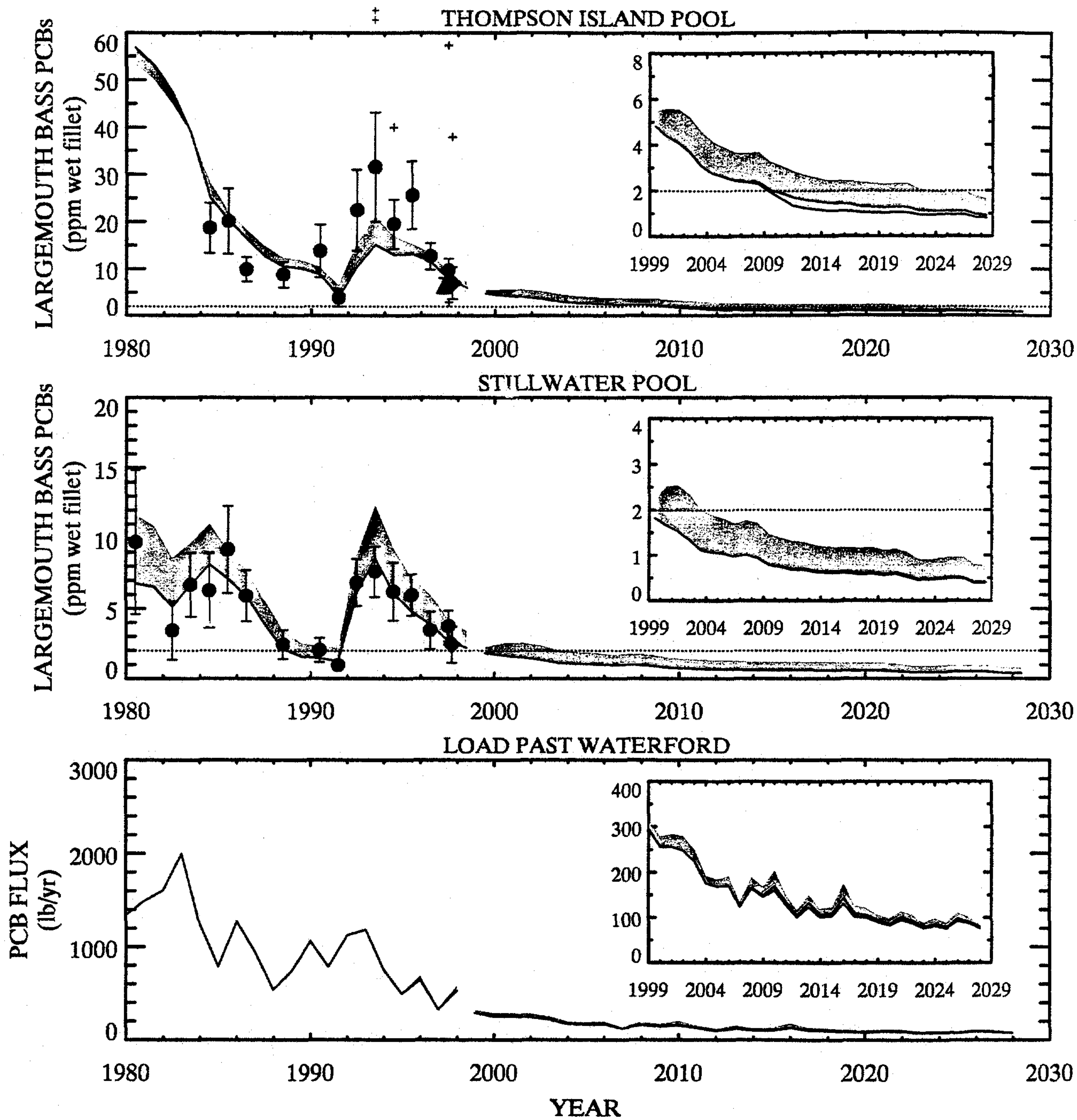
Dotted line indicates 2 ppm level.
Circles = NYSDEC
Triangles = Exponent
Diamonds = GE
Crosses indicate values excluded from the annual averages.
Solid line represents best estimate of the future condition.
Shaded region delineates range between best estimate and bounding estimate that reflects the uncertainty of the more important model parameters.

Figure 4-1. Predictions of PCB_{3+} levels in TIP and Stillwater largemouth bass and PCB_{3+} flux passing Waterford under natural recovery.



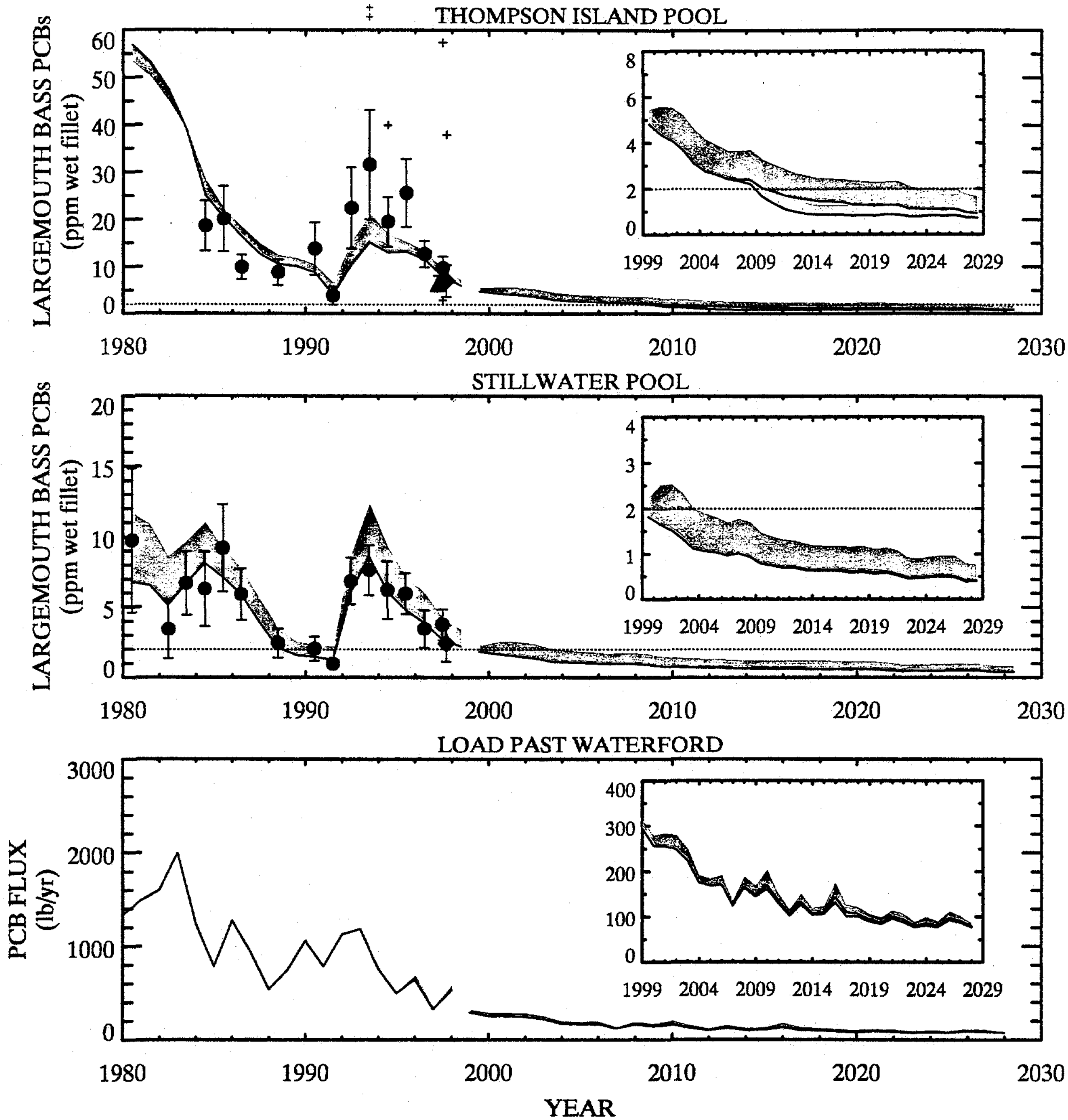
Dotted line indicates 2 ppm level.
Circles = NYSDEC
Triangles = Exponent
Diamonds = GE
Crosses indicate values excluded from the annual averages.
Solid line represents best estimate of the future condition.
Shaded region delineates range between best estimate and bounding estimate that reflects the uncertainty of the more important model parameters.

Figure 4-2. Predictions of PCB_{3+} levels in TIP and Stillwater largemouth bass and PCB_{3+} flux passing Waterford: comparison between natural recovery (blue) and elimination of upstream sources (orange).



Dotted line indicates 2 ppm level.
Circles = NYSDEC
Triangles = Exponent
Diamonds = GE
Crosses indicate values excluded from the annual averages.
Solid line represents best estimate of the future condition.
Shaded region delineates range between best estimate and bounding estimate that reflects the uncertainty of the more important model parameters.

Figure 4-3. Predictions of PCB_{3+} levels in TIP and Stillwater largemouth bass and PCB_{3+} flux passing Waterford: comparison between natural recovery (blue) and hot spot dredging (orange).



Dotted line indicates 2 ppm level.
Circles = NYSDEC
Triangles = Exponent
Diamonds = GE
Crosses indicate values excluded from the annual averages.
Solid line represents best estimate of the future condition.
Shaded region delineates range between best estimate and bounding estimate that reflects the uncertainty of the more important model parameters.

Figure 4-4. Predictions of PCB_{3+} levels in TIP and Stillwater largemouth bass and PCB_{3+} flux passing Waterford: comparison between natural recovery (blue) and cohesive sediment dredging (orange).