Lower Fox River/Green Bay Remedial Investigation and Feasibility Study

Enhancement and Application of a PCB Fate and Transport Model for Green Bay

Prepared by:

HydroQual

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1.0 SUMMARY

This report is provided in support of U.S. Environmental Protection Agency (USEPA) Cooperative Agreement #V985769-01 with the Wisconsin Department of Natural Resources (WDNR). As part of this agreement, WDNR developed remedial investigation (RI), risk assessment (RA) and feasibility study (FS) reports to describe the degree and extent of contamination, risks to human health and the environment, and aspects of implementing remedial approaches for the Lower Fox River and Green Bay study area. These reports were prepared for, and in cooperation with, the USEPA Region V Superfund Division as authorized under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

The water quality model presented in this report is one of several tools to examine contaminant transport in Green Bay. The primary contaminant of concern is polychlorinated biphenyls (PCBs). The goal of this effort is to enhance and reevaluate an existing Green Bay water quality model GBTOX developed by Bierman et al (1992) and updated by De Pinto et al (1993) . Enhancements were made to GBTOX as part of this project, resulting in the model referred to as GBTOXe. The enhancements made to GBTOX include the following: development of a new model segmentation; incorporation of water column circulation and mixing processes from a high resolution hydrodynamic model (GBHYDRO); incorporation of sediment resuspension and sediment solids flux rates from a high resolution sediment transport model (GBSED); updated loading functions based on more recent estimates.

Water column circulation included in GBTOXe is based on results from GBHYDRO, a high resolution three dimensional hydrodynamic model (HydroQual, 1999), which contains over 10,000 water column segments. Analyses conducted as part of the development of GBHYDRO indicated that course grid resolution in GBTOX (12 water column segments) resulted in an underestimation of the residence time in Green Bay. Computational resource constraints, however, make running 100 year contaminant fate projection analyses infeasible with the GBHYDRO segmentation. An aggregation of the GBHYDRO grid, therefore, was performed to develop the GBTOXe segmentation, which contains 1490 water column segments. Hydrodynamic information from GBHYDRO was aggregated onto the GBTOXe grid and used in the analyses presented in this report.

A sediment transport model, GBSED, coupled to GBHYDRO, was developed (HydroQual, 1999) and used to calculate the transport of cohesive solids in Green Bay. GBSED results indicate that wind driven waves are the dominant factor affecting resuspension of PCB contaminated sediments in Green Bay, particularly in the shallow portions of the lower bay near the mouth of the Fox River. Because the sorbent systems in GBTOXe, living and detritial particulate organic carbon (POC), are different than the non-living cohesive solids included in GBSED, only a portion of the GBSED results were used in GBTOXe. Settling velocities calculated for cohesive solids in GBSED were not applied to the GBTOXe POC systems. The primary information from GBSED, which is used by GBTOXe, includes time variable resuspension and sedimentation velocities.

GBTOXe was calibrated for a 17 month period from January 1989 through May 1990 using data from the Green Bay Mass Balance Study (GBMBS). Comparisons between computed and measured water column PCB concentrations indicate that the model generally reproduces the available data. Computed PCB concentrations in the shallow portions of the lower bay exhibit much more variability than deeper areas of the bay due to wind-wave induced resuspension. Monitoring data are generally not available during these resuspension events, and therefore, an assessment of the magnitude of the computed water column PCB concentrations during resuspension events can not be made. Water column data are generally available at times when computed PCB concentrations are declining after resuspension events. At these times the model results are in general agreement with the measured concentrations. Because measurements of PCB concentrations in the sediment are not available for multiple times within the duration of the 17 month calibration, comparisons between computed and measured PCB concentrations were not developed for the sediment segments of the model.

The GBTOXe model was applied to generate a series of fifteen future projection simulations combining various Fox River and Green Bay remedial action scenarios. The projection simulation period was 100 years in length. For this 100-year period, the advective and dispersive flows, resuspension events, sediment transport information, minor tributary loads (Menominee, Peshtigo, Oconto, and Escanaba), and atmospheric PCB loads used in the calibration effort were reapplied as a repeating annual pattern. The 16% annual rate of decline estimated in TM2b (for watershed PCB sources were applied to the annual pattern of the minor tributary and atmospheric PCB loads.

The results of 100 year-long term projection simulations for 15 combinations of natural attenuation and various levels of remediation of sediments in the Fox River and Green Bay indicate that a small fraction of the PCB mass in Green Bay is exported to Lake Michigan. Losses of PCBs from the Bay due to volatilization to the atmosphere exceed the estimated loads to the Bay, which are dominated by loads from the Fox River. Reductions in loadings from the Fox River associated with remediation of Fox River sediments with PCB concentrations greater than 5000 ug/kg result in lower water column and sediment concentrations in Zone 2 of Green Bay, but fairly small changes in the remainder of the Bay. Remediation of additional Fox River sediments, with concentrations between 125 and 5000 ug/kg, produces little incremental reduction in Green Bay water and sediment PCB concentrations. Remediation of Green Bay sediments with concentrations above 1000 ug/kg produces substantial changes in Zone 2 of Green Bay and results in fairly uniform water and sediment concentration throughout much of the bay after roughly 25 years. Expanding the remediation to sediments with PCB concentrations between 500 and 1000 ug/kg produces smaller incremental improvements, which diminish with time. The effect of these computed changes in exposure concentrations on the food web of Green Bay have been evaluated (QEA,2001).

2.0 INTRODUCTION

2.1 PROJECT OVERVIEW

This report is provided in support of U.S. Environmental Protection Agency (USEPA) Cooperative Agreement #V985769-01 with the Wisconsin Department of Natural Resources (WDNR). As part of this agreement, WDNR developed remedial investigation (RI), risk assessment (RA) and feasibility study (FS) reports to describe the degree and extent of contamination, risks to human health and the environment, and aspects of implementing remedial approaches for the Lower Fox River and Green Bay study area. These reports were prepared for, and in cooperation with, the USEPA Region V Superfund Division as authorized under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

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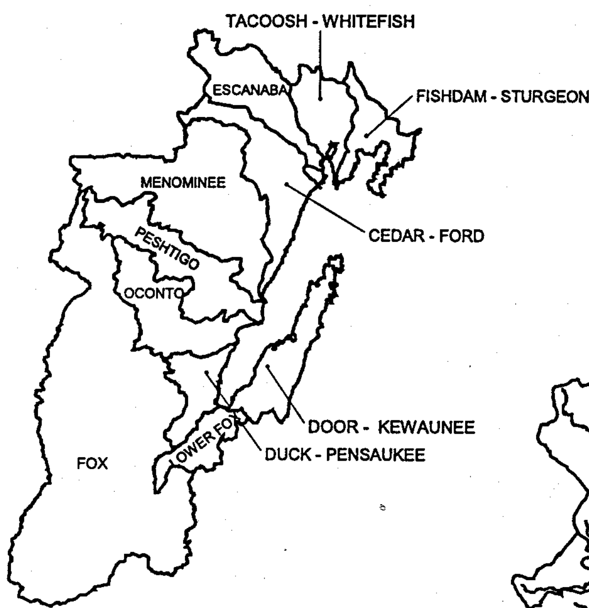
The state variables simulated were 3 phases of carbon and total PCBs (the sum of all congeners). Short-term and long-term simulations were conducted. The short-term simulation period was 1989-90 and was used for model calibration using data collected during the 1989-90 Green Bay Mass Balance Study (GBMBS). The long-term simulation period was 100 years and was used to calculate future PCB trends in Green Bay in response to natural attenuation and various potential remedial activities.

2.2 SITE DESCRIPTION AND PROBLEM IDENTIFICATION

Located in Wisconsin and Michigan, Green Bay is an embayment connected to Lake Michigan (Figure 2-1) and has a total watershed area of over 40,600 km^2 (15,675 mi^2). The major drainage basin flows discharging to Green Bay are from the Fox, Menominee, Peshtigo, Oconto, and Escanaba rivers.

Discharge from the Fox river is a major source of PCBs. Portions of the Fox River basin adjacent to the river are heavily industrialized and include one of the greatest concentrations of pulp and

A. Drainage Basins



B. Green Bay Tributaries and
Bordering Cataloging Units

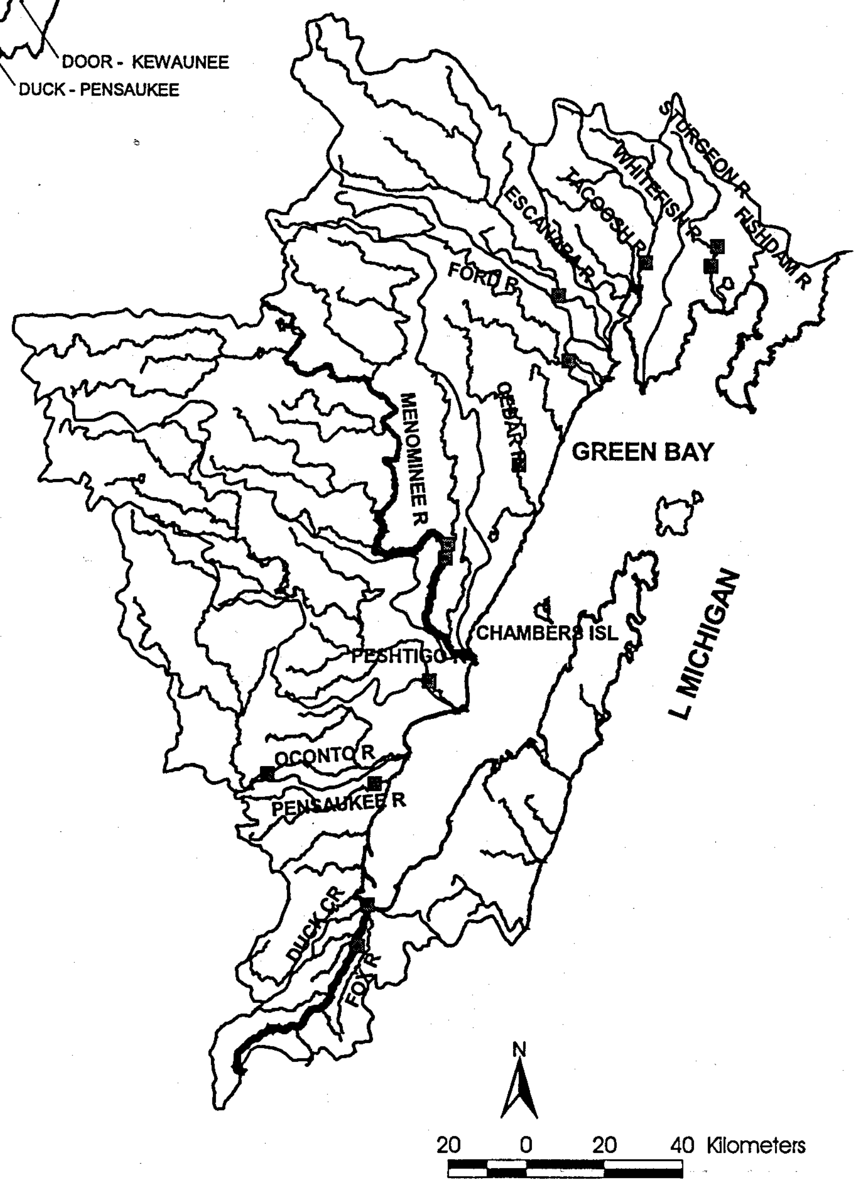


Figure 2-1. Green Bay Study Area

paper manufacturing facilities in the world. Within the study area boundaries, more than 25 major facilities discharge wastewater to the river (WDNR, 1999a). The river sediments are highly contaminated by PCBs, the contaminant of primary concern for human health and ecological risks.

Over the period 1954-1997, more than 300,000 kg of PCBs were discharged to the river (WDNR, 1999a). Of that amount, the vast majority was discharged between 1954 and 1971. The PCB mass inventory of Lower Fox River sediments was estimated to be 40,000 kg (WDNR, 1999b). The minimum PCB mass inventory of Green Bay sediments was estimated to be 70,000 kg (WDNR, 2000). Based on the GBMBS results, major PCB fate pathways in Green Bay include sediment storage, net transport to Lake Michigan, and net volatilization (Bierman et al. 1992; DePinto et al. 1993). The Renard Island and Bayport sediment disposal facilities (as well as several other shoreline sediment placement sites) also contain an additional mass of PCBs that was associated with dredged sediments placed into these facilities as a result of navigation channel maintenance operations (WDNR, 1999c).

2.3 CONCEPTUAL MODEL FRAMEWORK

The conceptual framework of the GBTOXe water quality model is presented in Figure 2-2. The transport and fate processes included in the model are:

- External inputs of carbon and chemicals;
- Advective and dispersive water column transport;
- Sediment transport (settling, resuspension, and burial)
- chemical partitioning between water (truly dissolved), dissolved organic compounds (DOC) (DOC-bound), and particulate carbon phases (POC) (POC-bound);
- Sediment-water exchange of dissolved and DOC-bound chemicals;
- Sediment-water exchange of POC-bound chemicals; and
- Air-water exchange of dissolved chemicals.

In their most general form, the mass balance equations are a system of partial differential equations and are functions of time and space. These equations describe the relationship between material inputs (loads) and concentration (water quality).

2.4 GENERAL DESCRIPTION OF THE COMPUTATIONAL FRAMEWORK

GBTOXe uses a finite segment implementation of the generalized contaminant mass balance equation and Euler's method for numerical integration. To generate solutions, the framework computes dynamic mass balances for each state variable simulated and accounts for all material that enters, accumulates within, or leaves a control volume (segment) through loading, transport, and physicochemical and biological transfers and transformations.

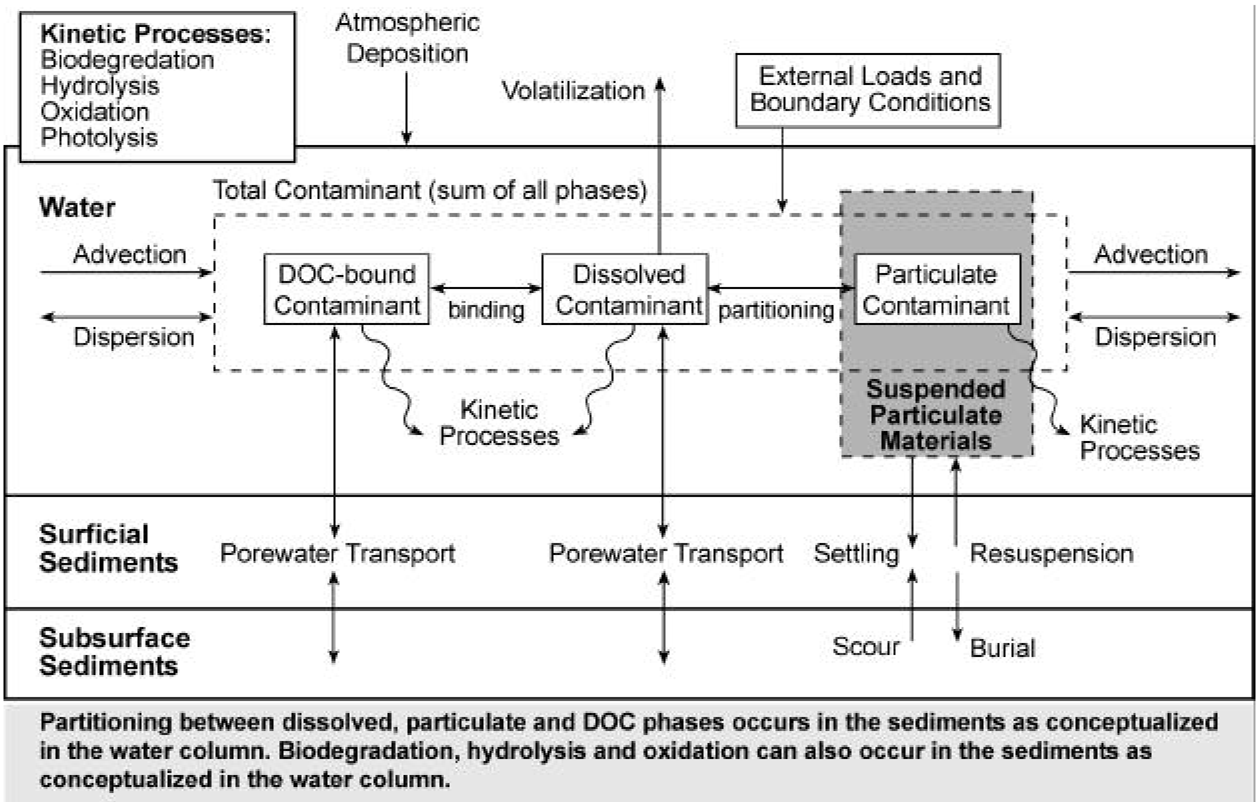


Figure 2-2. Conceptual model framework.

2.5 COMPUTATIONAL CONSIDERATIONS

GBTOXe source code is written in FORTRAN77. Simulations were performed on Pentium IV computers running either the Mandrake Linux (version 7.2 with version 2.4 Kernel) or the Debian Linux (version 2.2 with version 2.2.17 Kernel) operating system. Model code was compiled on a Pentium III computer running the Red Hat Linux (6.2) operating system (2.2.16-3smp Kernel) using a Portland Compiler with optimization for a Pentium IV processor.

2.6 DISTRIBUTION OF MODEL CODES AND INPUT AND OUTPUT FILES

A user's manual and source code for the GBTOXe water quality modeling framework, model input files, and selected model output files are included on a CD-ROM that accompanies this report. An overview of model input and output files is presented in Table 2-1. The root name of the simulation is presented in Column 1 and reflects the action level criteria of sediment initial conditions for both Green Bay and the Fox River. All input file names are followed with a ".inp" suffix.

GBTOXe generates two groups of output files. The first group represents output of instantaneous results for each model segment for the duration of the simulation at time intervals specified in the input file. Seven of these files are generated, one for each state variable. They are given the same name as the input file and are suffixed with a ".dm" followed by the number corresponding to the system number (same as WASP). The output starts with a header that describes the information it contains. However, in the process of modifying the GBTOX source code, not all of the functionality that generates the various output parameters listed in the header was preserved. Therefore only the concentration information (volume and carbon based) should be considered valid output.

Table 2-1. Input File Description.

Root Name	Description
gbNOAC-frNOAC	Green Bay no action; Fox River No action
gbNOAC-fr5000	Green Bay no action; Fox River sediments > 5000 ppb removed.
gbNOAC-fr1000	Green Bay no action; Fox River sediments > 1000 ppb removed.
gbNOAC-fr0500	Green Bay no action; Fox River sediments > 500 ppb removed.
gbNOAC-fr0250	Green Bay no action; Fox River sediments > 250 ppb removed.
gbNOAC-fr50125	Green Bay no action; Fox River sediments > 125 ppb removed.
gb1000-fr1000	Green Bay sediments > 1000 ppb removed; Fox River sediments > 1000 ppb removed.
gb1000-fr0500	Green Bay sediments > 1000 ppb removed; Fox River sediments > 500 ppb removed.
gb1000-fr0250	Green Bay sediments > 1000 ppb removed; Fox River sediments > 250 ppb removed.
gb1000-fr0125	Green Bay sediments > 1000 ppb removed; Fox River sediments > 125 ppb removed.
gb0500-fr0500	Green Bay sediments > 500 ppb removed; Fox River sediments > 500 ppb removed.
gb0500-fr0250	Green Bay sediments > 500 ppb removed; Fox River sediments > 250 ppb removed.
gb0500-fr0125	Green Bay sediments > 500 ppb removed; Fox River sediments > 125 ppb removed.
gbNOAC-fr000I	Green Bay no action; Fox River (see Table 5-2 for details)
gbNOAC-fr000H	Green Bay no action; Fox River (see Table 5-2 for details)

The second group represents the spatially and temporally averaged chemical concentration results. The spatial and temporal extent of averaging is specified in the input file. Currently this feature is only implemented for a single chemical state variable. GBTOXe creates two files that contain the averaged results for the "zones" specified in the input file. Averaged results are output in a sequential, columned format. A description of each field is presented in Table 2-2. It can be seen from Table 2-2 that the difference between the information in these two files is that gbtoxe2.avg provides a depth weighted average of organic carbon normalized chemical concentrations in the sediments of thickness 0-5 cm and 0-10 cm. The water column information in these files is identical but it should be noted that 1) gbtoxe2.avg does not have a biotic carbon normalized chemical concentration field and 2) the units of the dissolved chemical concentration field in gbtoxe2.avg are μg/L.

Table 2-2. Output File Description.

File Name	Column Range	Field Description
Gbtoxe1.avg	1-12	Time (Days)
	32-24	Zone Label
	25-39	Average water column dissolved chemical concentration (ng/L)
	40-54	Average water column organic carbon normalized chemical concentration (ug/gOC)
	55-69	Average water column biotic carbon normalized chemical concentration (ug/gOC)
	70-84	Average sediment organic carbon normalized chemical concentration 0-2 cm (ug/gOC)
	85-99	Average sediment organic carbon normalized chemical concentration 2-4 cm (ug/gOC)
	100-114	Average sediment organic carbon normalized chemical concentration 4-10 cm (ug/gOC)
Gbtoxe2.avg	1-12	Time (Days)
	32-24	Zone LabelF4.3.1
	25-39	Average Water column dissolved chemical concentration (μg/L)
	40-54	Average Water column biotic carbon normalized chemical concentration (ug/gOC)
	55-69	Average Sediment organic carbon normalized chemical concentration 0-5 cm (ug/gOC)
	70-84	Average Sediment organic carbon normalized chemical concentration 0-10 cm (ug/gOC)

3.0 MODEL DEVELOPMENT

3.1 BACKGROUND

The Lower Fox River/Green Bay ecosystem was extensively studied as part of the 1989-90 Green Bay Mass Balance Study (GBMBS) (USEPA 1989; USEPA 1992a,b). As part of that study, a suite of coupled water quality models describing PCB transport in the Lower Fox River and Green Bay were developed. One of those coupled models described PCB transport in Green Bay.

Since the end of the GBMBS, efforts to examine and assess the performance of Green Bay water quality models have continued. Three generations of water quality model development have been initiated. The initial models calibrated to GBMBS conditions represent the first generation of model development for the Green Bay portion of the project area (Bierman et al. 1992). The re-calibration of that model to better reflect solids dynamics in the bay represents the second generation of development (DePinto et al. 1993). The model developed as part of RI/FS efforts is the result of continued assessments of Green Bay water quality model performance and represents the third generation of model development. To distinguish it from prior generations of development, the third generation model is identified as the “enhanced” Green Bay Toxics model (GBTOXe).

3.2 EVALUATIONS OF MODEL PERFORMANCE

Development of GBTOXe for the RI/FS was based on the results of a 1997 agreement and other efforts to evaluate model performance. On January 31, 1997, the State of Wisconsin entered into a Memorandum of Agreement with seven companies that have primary responsibility for PCB discharges to the Lower Fox River. Those seven companies form the Fox River Group. One component of the Agreement was to “evaluate water quality models for the Lower Fox River and Green Bay.” The intent was to establish goals to evaluate the quality of model results. As specified by the Agreement, the Model Evaluation Workgroup (MEW) was formed. The MEW was comprised of technical representatives for the FRG and WDNR in order to undertake “cooperative and collaborative” evaluations of model performance. Development of a series of technical reports followed. As an extension to MEW efforts, WDNR also initiated further evaluations of Green Bay model performance as presented by HydroQual (1999).

The series of reports developed by the MEW were each prepared as a Technical Memorandum (TM). A listing of selected MEW TMs is presented in Table 3-1. Each TM listed provides detailed analyses of key aspects of model development such as solids and PCB loads, sediment transport dynamics, and initial conditions. These analyses were designed to take maximum advantage of information from a wide array of sources and were not restricted to the exclusive consideration of information generated during GBMBS or LMMBS data collection efforts. The reports examining solids inputs to the river are of particular importance. Successful simulation of PCB (or any hydrophobic chemical) transport is critically dependent and the transport of the particles with which the contaminant is associated. As described in TM3a (WDNR, 2001a), the MEW reports listed in Table 3-1 were the source of the majority of the information necessary for model development. Other critical information was obtained from the GBHYDRO/GBSED effort completed by HydroQual (1999).

Table 3-1. List of Selected Model Evaluation Workgroup Technical Reports.

Report[1]	***Title/Topic***	***Source***
Workplan	Workplan to Evaluate the Fate and Transport Models for the Fox River and Green Bay	LTI and WDNR (1997)
TM1	Model Evaluation Metrics	LTI and WDNR (1998)
TM2b	Computation of Monthly Watershed Solids and PCB Load Estimates for Green Bay	LTI (1999a)
TM2c	Computation of Internal Solids Loads in Green Bay and the Lower Fox River	LTI (1999b)
TM2d	Compilation and Estimation of Historical Discharges of Total Suspended Solids and Polychlorinated Biphenyls from Lower Fox River Point Sources	WDNR (1999a)
TM2f	Estimation of Sediment Bed Properties for Green Bay	WDNR (2000)
TM3a	Evaluation of Flows, Loads, Initial Conditions, and Boundary Conditions	WDNR (2001)

3.3 MODEL SEGMENTATION AND SPATIAL ORGANIZATION

The GBTOX model grid consisted of 12 water column and 37 sediment segments. Tracer simulations using a high spatial resolution hydrodynamic modeling framework showed that GBTOX tends to under predict hydrodynamic residence time due to numerical despersion attributable to the large size of the water column segments (HydroQual, 1999). To reduce the effects of numerical mixing in the water column, a higher resolution water quality model grid was developed. Figure 3-1 presents the GBTOXe model grid spatial resolution in the horizontal compared with the GBTOX model grid. The GBTOXe model domain consists of 1490 water column and 596 sediment segments. The water column consists of 10 layers of 149

[1] TM = Technical Memorandum

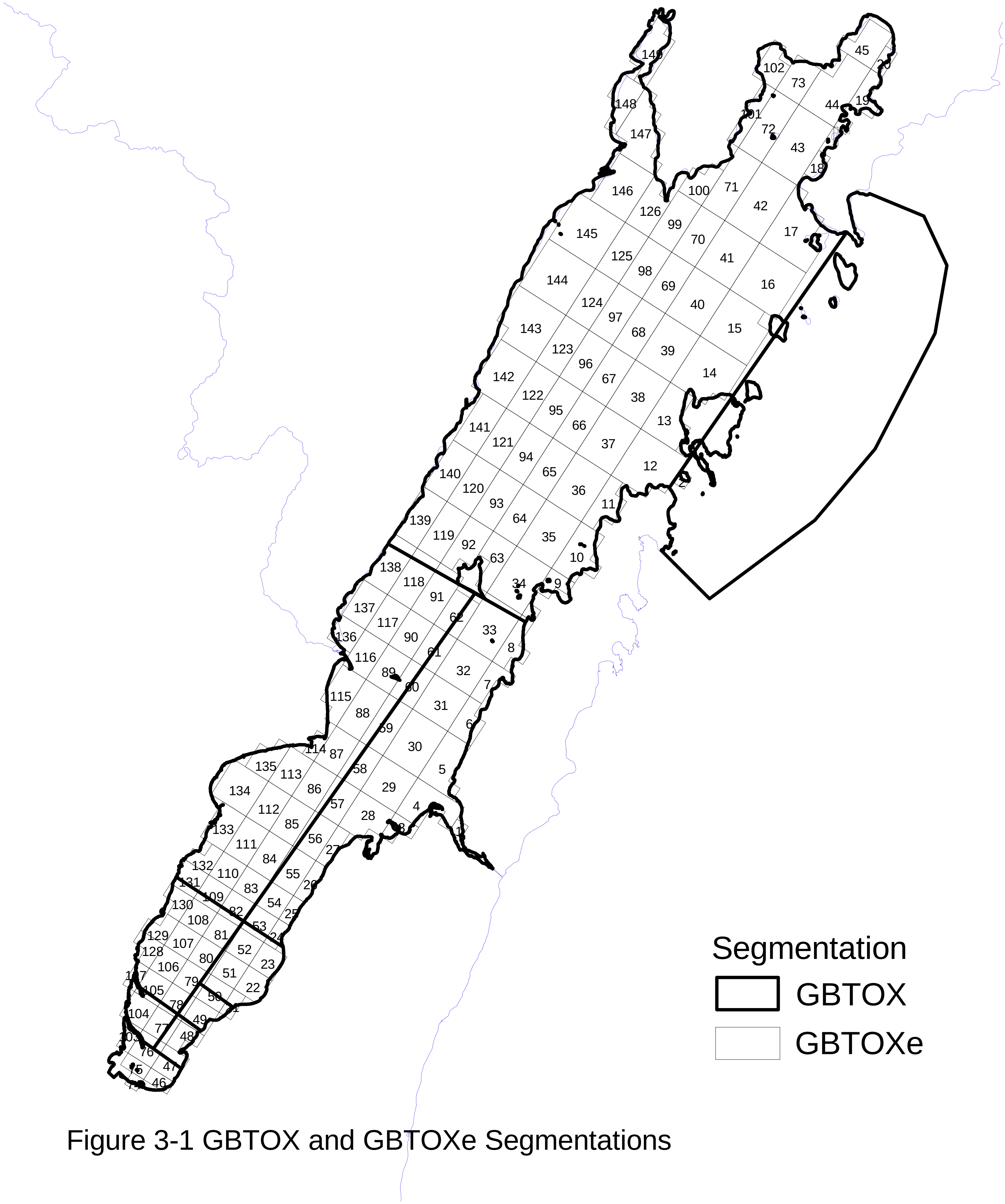


Figure 3-1 GBTOX and GBTOXe Segmentations

horizontal segments. Water column segment volumes vary to maintain a water balance. The sediments of the bay are represented by 4 layers of 149 grid elements. The upper two layers are each 2 centimeters thick and represent biologically active sediments. The third layer is 6 centimeters thick and represents biologically inactive sediments. The fourth layer has an initial thickness of 21 centimeters. This thickness was reduced from 10 meters (as assigned in GBTOX) to be consistent with the estimated 70,000 kg inventory of PCBs in the Bay sediments (WDNR, 2000). The depth of this layer is permitted to vary in response to deposition and resuspension fluxes. In a previous analysis of Green Bay sediment transport (HydroQual, 1999), a 2x2 kilometer sediment bed map delineating areas of cohesive and non-cohesive (hard-bottom) sediments was developed based on sediment samples reported by Manchester et al. (1996). This grid was used to estimate the percent hard-bottom within each surface sediment cell of the GBTOXe model grid.

3.4 HYDRODYNAMICS AND SEDIMENT TRANSPORT

GBTOXe is coupled with a calibrated and validated high resolution, three-dimensional hydrodynamic model (GBHYDRO) that was one of three models developed in an effort to reevaluate GBTOX (HydroQual, 1999). As shown in Figure 3-2, the GBHYDRO model domain is a 2x2 kilometer hydrodynamic grid covering the extent of Green Bay up to and bordering Lake Michigan. Inter-segment advective and dispersive flows were computationally collapsed with a program developed to redistribute the GBHYDRO time series of hydrodynamic information from the hydrodynamic model grid to the more spatially course GBTOXe model grid while maintaining overall hydrodynamic characteristics. The following information from GBHYDRO is saved for use by GBTOXe:

- Hourly flows from watershed rivers (Fox, Menominee, Peshtigo, Oconto, and Escanaba)
- Hourly flows across boundary with Lake Michigan
- Hourly inter-segment flows
- Hourly inter-segment dispersion
- Hourly bulk dispersion across boundary with Lake Michigan

GBHYDRO was calibrated for a 17 month period from January 1989 through May 1990. The short term GBTOXe simulations were performed for the same 17 month period. Long term simulations, performed to evaluate the response to potential remedial actions over a 100 year period, use the transport information from the 1989 calendar year portion of the 17 month calibration. This period was selected to include a complete annual cycle in the long term simulations. The transport information from 1989 is repeated annually through the 100 year simulations.

Figure 3-2 2x2 Kilometer Hydrodynamic Grid
(HydroQual, 1999)

Dispersive transport input to GBTOXe includes hourly inter-segment dispersion rates and hourly dispersion rates across the boundary between Green Bay and Lake Michigan. Comparison of residence time estimates between GBHYDRO, GBTOX and GBTOXe tracer simulations revealed that the GBTOXe model grid reduced the residence time by a factor of 2 relative to GBTOX tracer simulations but was still shorter than the GBHYDRO residence time by a factor of 2. Further analysis showed that the exclusion of horizontal inter-segment dispersion in the water column made only a modest reduction in residence time relative to GBHYDRO tracer simulations.

An increase in the resolution of the GBTOXe model grid to approach the residence time estimated by GBHYDRO would require unreasonably long simulation times because of the increase in the number of segments and a likely decrease in the allowable integration step size. Horizontal inter-segment dispersion in the water column was scaled to zero to offset numerical mixing introduced by the GBTOXe model grid. The first 364 days of the 1989-90 dispersive flows generated by GBHYDRO were repeated annually for the 100 year projection simulations.

The sediment transport model, GBSED (HydroQual, 1999), was configured to run in conjunction with GBHYDRO. GBSED used the same numerical grid (i.e. 2x2 km), structure and computational framework as GBHYDRO. Sediment dynamics inherent in the model include sediment resuspension, transport and deposition. GBTOXe utilizes the following transport information from GBSED:

- Hourly resuspension rates
- Hourly solids flux rates to and from the sediment bed

3.5 CARBON SOURCES

Organic carbon was simulated as three state variables: dissolved organic carbon (DOC), biotic carbon (BIC), and particulate detrital carbon (PDC). Total organic carbon (TOC) is the sum of these three carbon phases. An overview of carbon inputs utilized by GBTOXe is presented in Table 3-2.

Water column-sediment exchange of carbon is driven by the GBSED resuspension rates and solids flux rates to and from the sediment bed, and the temporally and spatially invariant settling rates through the water column. Carbon concentrations represented in the sediment segments of the model are assumed to be constant with time. However the bottom layer segment volumes are permitted to change in response to deposition and resuspension fluxes to simulate net bed elevation changes. Constant carbon concentrations in the bottom layer segments were maintained by permitting carbon mass to enter and leave the bottom layer in proportion to volume change. Monthly internal BIC loads were examined as part of TM2c (LTI, 1999b). Internal DOC loads were estimated from BIC loads assuming BIC and DOC are 80% and 20% of TOC respectively. Monthly DOC loads were computed as DOC load = BIC load / 0.8 * 0.2.

Table 3-2 Carbon Sources

Carbon Input	Source of Input
Watershed (Fox, Menominee, Peshtigo, Oconto, Escanaba)	De Pinto, 1993
Internal	TM2c, 1999
Boundary with Lake Michigan	De Pinto, 1993

The 1989-90 monthly time series of internal BIC and computed DOC loads were spatially distributed across the GBTOXe model grid on a surface area weighted basis. The total load to a grid element was distributed vertically to the 10 water column layers based on the effect of light on algal growth.

$$P_i = P_T f_i$$

where P_i = Portion of grid element load applied to vertical layer i

P_T = Total load to grid element

f_i = Light factor for algal growth for vertical layer i

Using the depth and time integrated expression of Steele's light limitation formulation (Bowie, et.al., 1985), The light factor, $f_{i,}$ was computed each of the 10 water column layers in a grid element as:

$$f_i = \frac{(z_2 - z_1)G(I)_i}{H_T G(I)_T}$$

where i = 1,2,3...10

z_1, z_2 = top and bottom depth, respectively, of layer i

H_T = Total depth of water column

$$G(I) = \frac{2.718 f_p}{K_e (z_2 - z_1)} \left(e^{-a2} - e^{-a1} \right)$$

$$a2 = \frac{I_o}{I_s} e^{-K_e z_2}$$

$$a1 = \frac{I_o}{I_s} e^{-K_e z_1}$$

For $G(I)_T$, $z_2 = H_T$ and $z_1 = 0$. The monthly light extinction coefficient, photo period, and light intensity values were taken from TM2c.

3.5.1 Sediment Bed (Initial Conditions)

To estimate initial conditions for the purpose of evaluating the existing Green Bay models, data related to sediment bed properties in the bay were examined in Task 2f (WDNR, 2000). In this task, sediment depth of analysis (a surrogate for sediment thickness), surface area, volume, dry dry bulk density, organic carbon (TOC), PCB concentration, and other observations were used to estimate sediment bed properties for Green Bay. TM2f examined a larger data base of sediment bed property observations collected since the end of the GBMBS (often in areas not sampled during the GBMBS). As described in TM3a (WDNR, 2001a), these sediment bed property estimates were based on a large database of observations and define model initial conditions for the short-term and long term simulation periods. The physical properties of the sediment bed were assumed to equal those defined in TM2f.

Sediment bed PDC initial conditions were extracted from the ArcView GIS bed maps developed in TM2f (WDNR, 2000). Each bed map grid (100x100 meters) provides a horizontally continuous representation of a particular sediment property at 5 depth intervals: 0-2, 2-4, 4-6, 6-10, and 10> centimeters. Since PDC bed maps were not directly available, they were generated by multiplying the dry dry bulk density grids (mg/L) by the corresponding total organic carbon grids (foc,%) for the five bed map layers. Because the depth interval of the third GBTOXe sediment layer is 4-10 cm, a new PDC grid representative of a 4-10 centimeter depth interval was generated by taking the depth weighted average of the 4-6 and 6-10 centimeter PDC grids.

The minimum surface area of the GBTOXe model grid is 2x2 kilometers, making its spatial resolution considerable more coarse than the bed map grids. To generate the sediment PDC initial conditions, the GBTOXe model grid and the PDC grids were overlaid and each model grid segment was assigned the mean of the bed map cell values within the model segment’s bounds. This process was repeated for each GTOXe sediment layer.

3.5.2 Settling

Water column settling velocities for PDC and BIC were adjusted as part of the model calibration effort. A reasonable agreement between model results and observed water column carbon data was achieved using a spatially and temporary invariant settling rate of 1.0 m/day and 0.2 m/day for PDC and BIC, respectively.

3.5.3 Deposition

Sediment sampling carried out between 1987 and 1990, as reported by Manchester et al. (1996), revealed two types of sediment beds in Green Bay: the first type is comprised essentially of glacial till material that underlies the entire Bay, while the second type is characterized as sediment with a high organic carbon content, overlying the glacial till. Based on the Manchester sampling data, sediment beds with high organic carbon content were specified as cohesive sediment beds, while beds with glacial till material were specified as hard-bottom, as shown in Figure 3-3.

Carbon and PCB deposition to areas characterized as hard-bottom is assumed to be a transient process which can be neglected in this analysis. Areas characterized as hard-bottom are identified through a mask variable and adjustments are made to deposition and resuspension velocities so that transport between the water column and sediment is computed only for areas where sediment deposits were observed. This masking effect was incorporated into the GBTOXe model grid by overlaying the 2x2 kilometer bed mask grid above and the GBTOXe model grid and computing for each model segment the percentage of the area characterized as cohesive. The spatial distribution of the depositional velocities was then computed by multiplying this percentage by the settling velocity of the water column bottom layer. In this way, the deposition fluxes to the sediment bed are scaled proportionally to the percent of sediment surface area characterized as cohesive. For example, if the overlap of the bed mask grid and the GBTOXe grid shows that several of the GBTOXe model grid segments are characterized as 30 % hard bottom, then the PDC deposition rate assigned to those segments is 1.0 m/day * (1.0 - 0.3) or 0.7 m/day.

3.5.4 Resuspension (Erosion)

GBTOXe utilizes hourly resuspension velocities generated by GBSED. The spatial distribution of the GBSED resuspension velocity information corresponds to the hydrodynamic grid. Consequently, the raw GBSED resuspension information was computationally collapsed to correspond to the GBTOXe grid. GBSED’s calculation of resuspension velocities accounts for non-cohesive sediment conditions, and therefore the effect of masked resuspension fluxes is reflected in collapsed resuspension information used as input to GBTOXe.

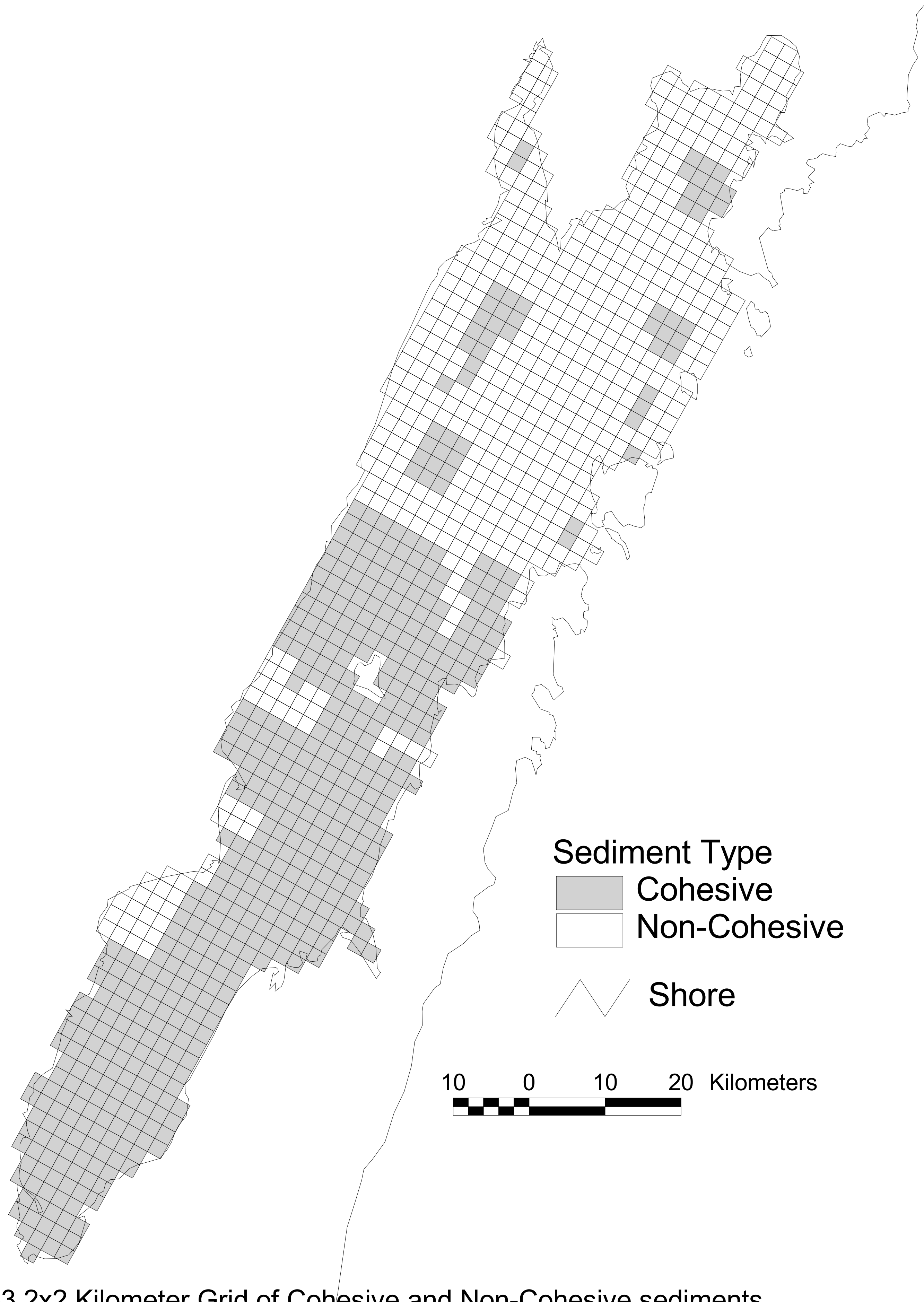


Figure 3-3 2x2 Kilometer Grid of Cohesive and Non-Cohesive sediments (HydroQual, 1999)

Initial GBTOXe calibration attempts incorporated sediment transport results from GBSED analyses described in HydroQual, 1999. Resuspension fluxes computed in that analysis are characterized by high frequency events which coincide with wind events. Increased wind velocities generate wind-driven waves, which produce significant fluctuations in shear stress at the sediment water interface, particularly in the shallow portions of the bay. Parameterization of the resuspension processes was based on very limited site specific studies (Lick, et.al, 1995). The lack of water column suspended solids data collected during significant wind events limited the ability to evaluate the original GBSED calibration for these important conditions. Use of resuspension fluxes computed in the original GBSED calibration resulted in a flux of PCBs from the sediment to the water column, particularly in the shallower near shore areas of Zone 2 near the mouth of the Fox River, which was clearly inconsistent with available water column PCB data. Based on the bed maps described in TM2f (WDNR, 2000), this area contains the maximum PCB concentrations in the Bay. The magnitude of the resuspension fluxes from the initial calibration carried these highly contaminated sediments to the water column, which resulted in computed PCB concentrations exceeding measured concentrations by nearly an order of magnitude in some cases. With the added constraint imposed by reproducing water column PCB data in addition to water column solids, it was clear that the parameterization of the resuspension processes needed to be revised.

The resuspension formulation in GBSED describes a finite amount of cohesive sediment that can be resuspended at a constant shear stress. This formulation, given by Gailani, et.al. (1991) as:

$$\varepsilon = \frac{a_0}{T_d^m}\left(\frac{\tau_b}{\tau_c} - 1\right)^n$$

where

å= resuspension potential (mg cm^{-2})

a_0 = site specific constant

T_d = time since deposition (days)

ô$_b$ = bed shear stress (dy cm^{-2})

ô$_c$ = critical bed shear stress for erosion (dy cm^{-2})

m and n are constants

Parameters values a_0 (1.6), and m (0.8) and n (2.5) as reported in Table 4 of Lick, et.al. (1995), were used in the original GBSED calibration for the entire bay. Those parameters were derived from an analysis of data from a shaker experiment of a single core, described by Lick, et.al. (1995) as Green Bay mud. Revised values of a_0 (4.7) and n (1.6) were derived by including data from shaker studies of two additional Green Bay cores (Lick, et.al. 1995). These revised parameter estimates were used in locations where the TM2f (WNDR, 2000) bed maps indicated sediment dry density less than 0.4 kg/L. Parameter values for locations with dry density greater than 0.4 kg/L were derived from an analysis of shaker study data from four cores collected in roughly the lower two kilometers of the Fox River and two cores collected in Green Bay, all of which were described by Lick, et.al. (1995) and sandy cores. The distinction based on a dry density of 0.4 kg/L was based on the dry density at the locations from which the Green Bay cores were collected.

Figure 3-4 identifies the location of sampling stations in Green Bay from which solids data are taken for comparison to GBSED model results. Water column solids concentrations computed with the revised resuspension formulation parameters are compared to data on Figure 3-5a through 3-5e. Note that a change in the scale of the y-axis is made on each page to accommodate the decreasing magnitude of solids concentrations with increasing distance from the Fox River. Depth averaged model results are shown along with results from the surface and bottom layers. The frequency and magnitude of the resuspension events in the shallow portion of Zone 2 near the Fox River is apparent in the results for stations 1 – 3 (Figure 3-5a). In general the model agrees fairly well with the data, although the data are generally not available at times of significant resuspension events. The revisions made to the resuspension parameters significantly improved the agreement between computed and measured PCB concentrations, as discussed in section 4.

3.5.5 Sedimentation - Burial and Scour

The redistribution of PCBs in sediments is largely governed by the transport mechanisms that redistribute sediment solids. Initial conditions of carbon concentration in the sediment bed were based on the TM2f bed maps (see section 3.5.1) and were held constant throughout the calibration period and long term projections as a representation of the long term carbon characteristics of the sediment bed. While not applied to carbon, spatially and temporally variable subsurface burial and scour rates were computed using net surface sediment solids fluxes generated in GBSED and dry dry bulk density concentrations extracted from the bed maps of TM2f. As with carbon concentrations, dry dry bulk density concentrations are assumed constant and represent the long term characterization of green bay sediments. The mass balance equations in GBTOXe that describe transport between the subsurface layers are as follows:

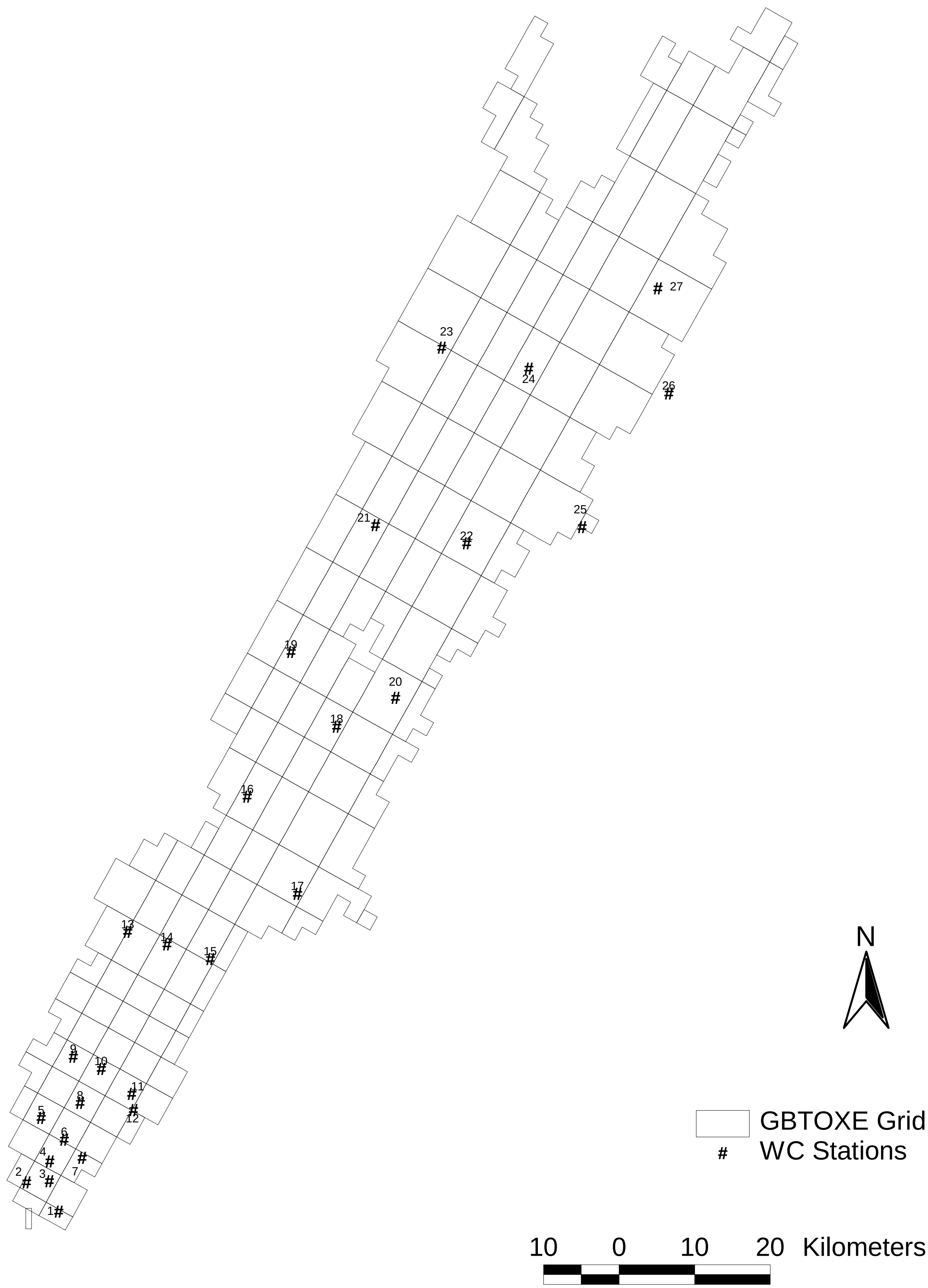


Figure 3-4 GBTOXE Grid and Water Quality Stations

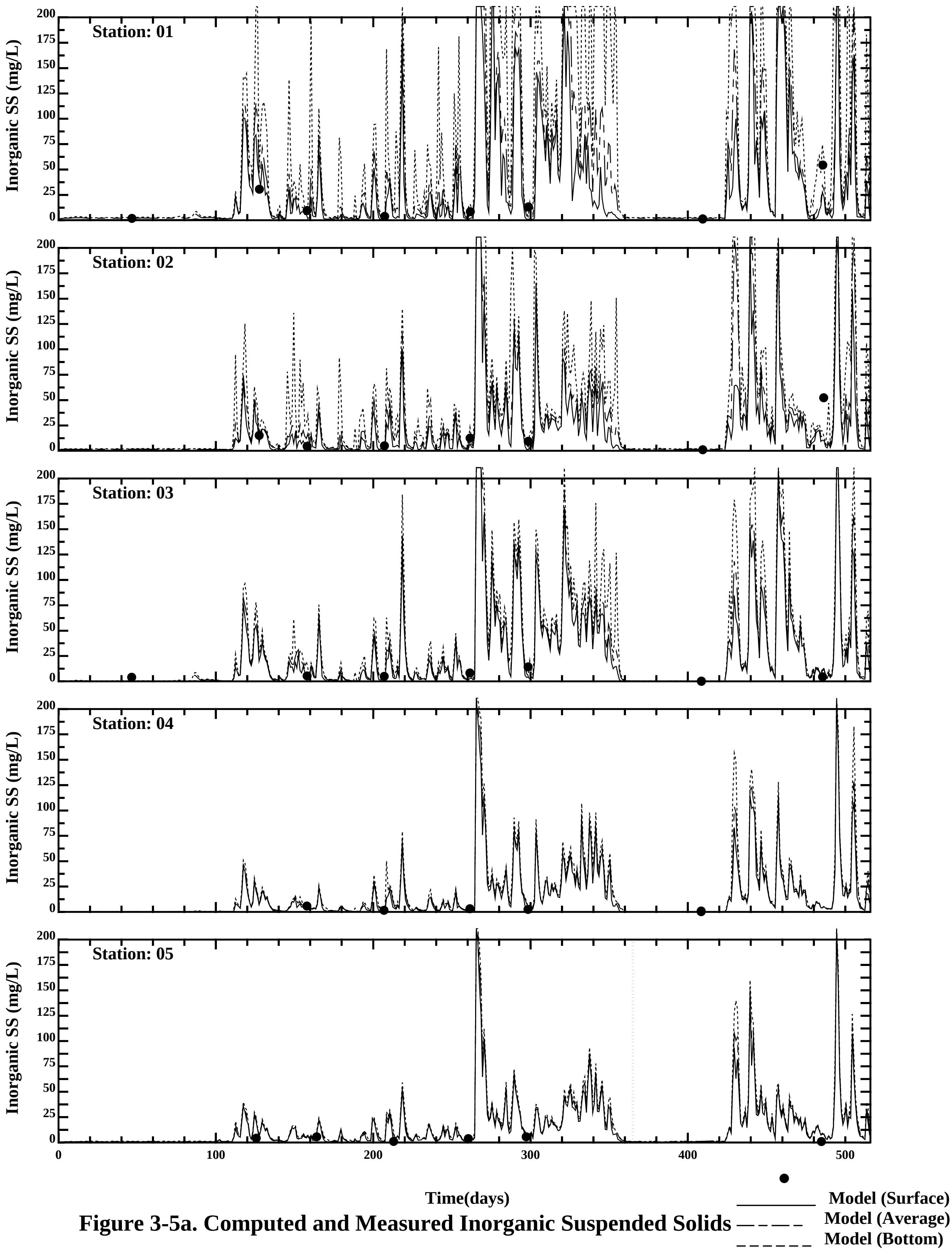
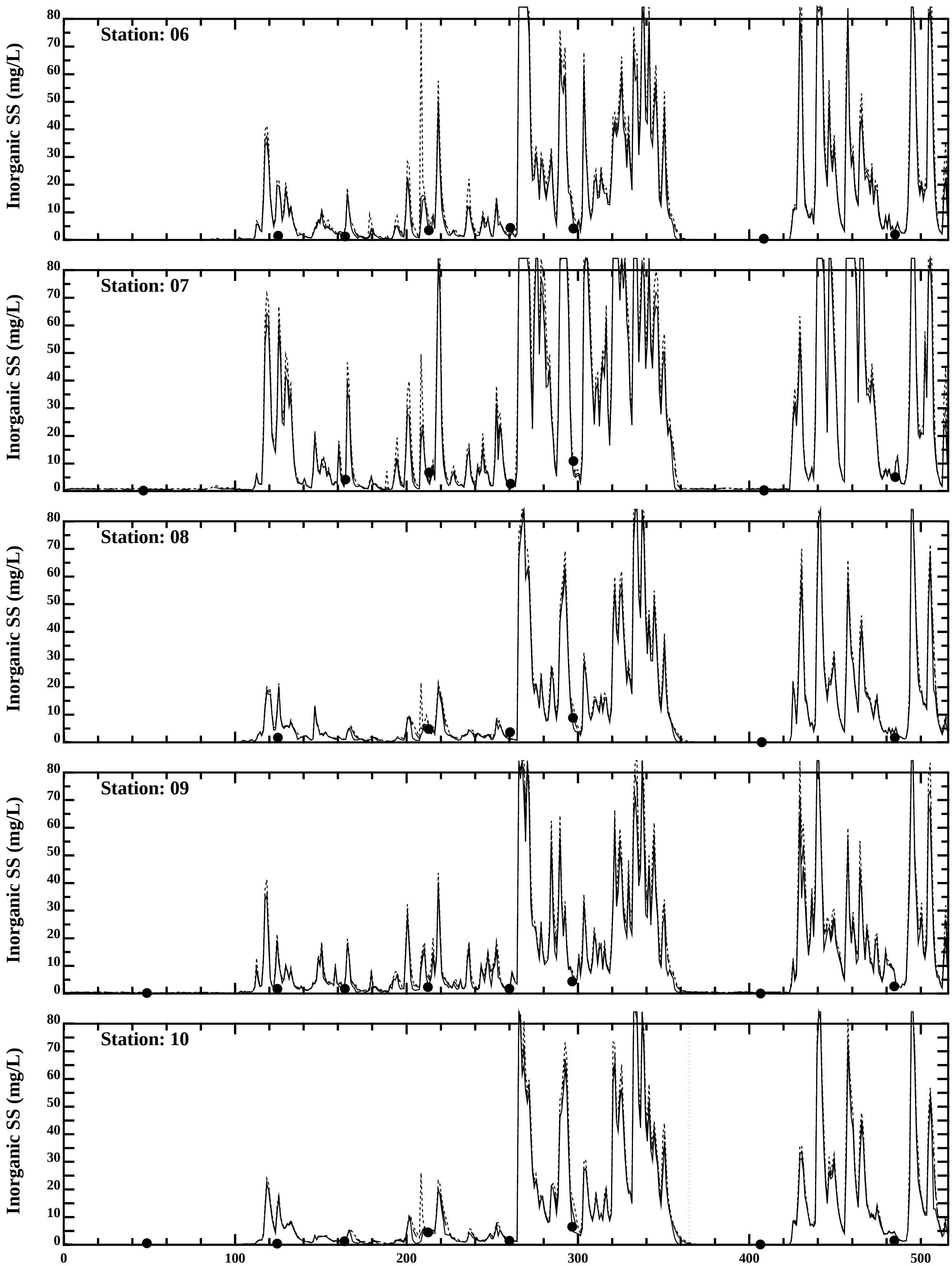


Figure 3-5a. Computed and Measured Inorganic Suspended Solids



Model (Surface)
Model (Average)
Model (Bottom)

Figure 3-5b. Computed and Measured Inorganic Suspended Solids

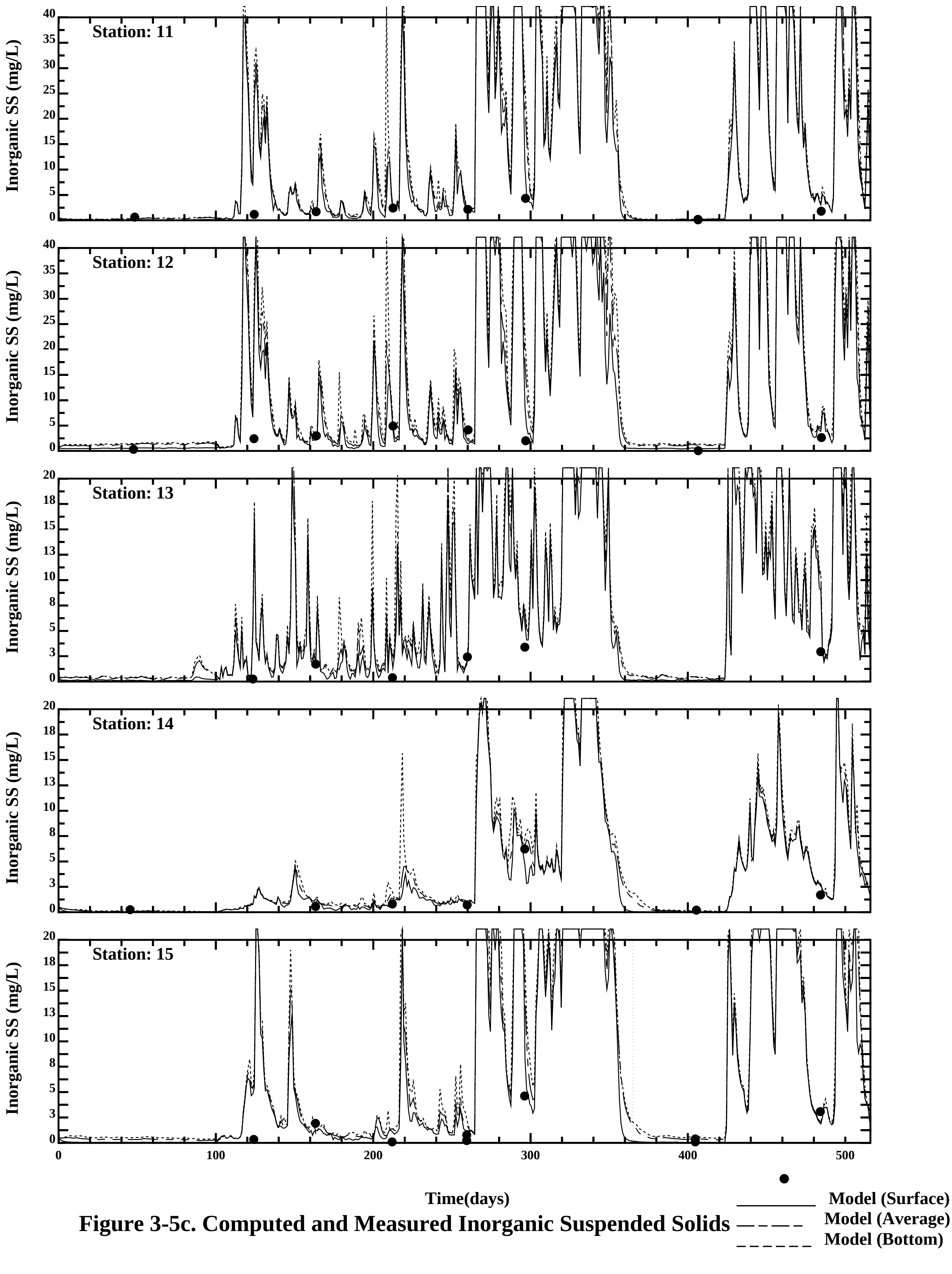


Figure 3-5c. Computed and Measured Inorganic Suspended Solids

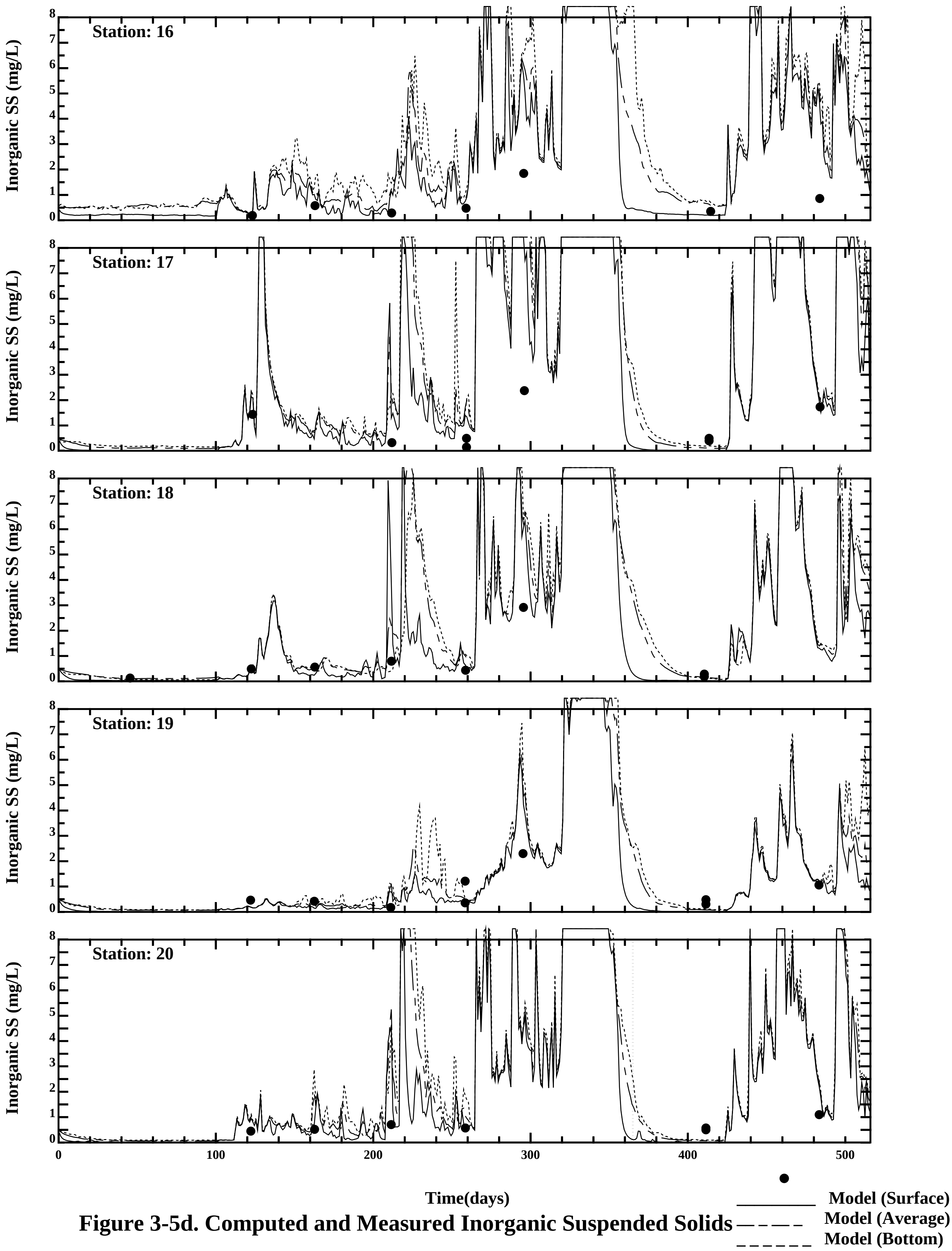


Figure 3-5d. Computed and Measured Inorganic Suspended Solids

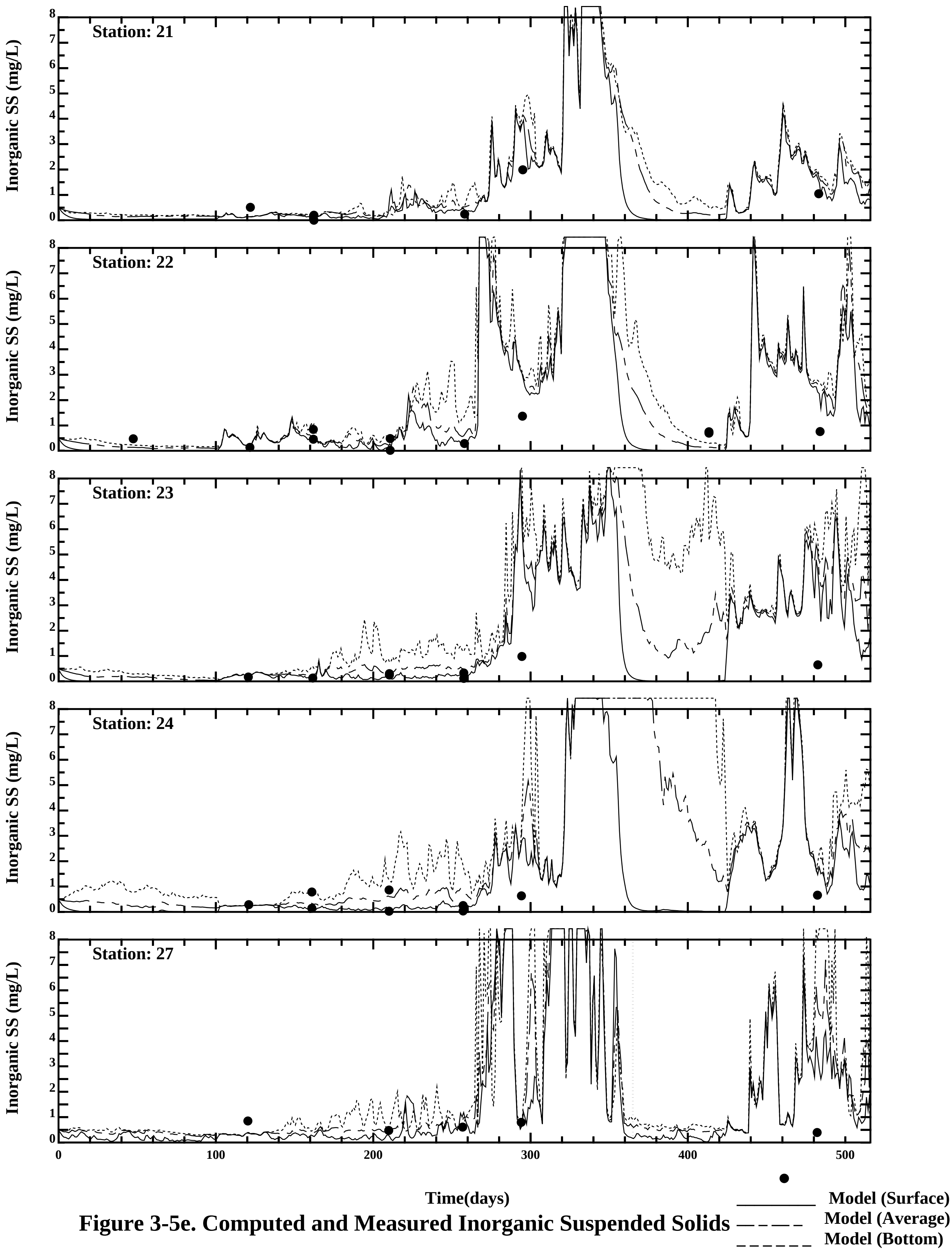


Figure 3-5e. Computed and Measured Inorganic Suspended Solids

Burial: Solids flux is from water column to surface sediment (***$J_{0,1}$*** is positive)

$$J_{i,i+1} = J_{i-1,i} + E_{i,i+1}(C_{i+1} - C_i) + E_{i-1,i}(C_{i-1} - C_i)$$

$$w_{i,i+1} = \frac{J_{i,i+1}}{C_i}$$

Scour: Solids flux is from surface sediment to water column (***$J_{1,0}$*** is negative)

$$J_{i+1,i} = J_{i,i-1} + E_{i,i+1}(C_{i+1} - C_i) + E_{i-1,i}(C_{i-1} - C_i)$$

$$w_{i+1,i} = \frac{J_{i+1,i}}{C_{i+1}}$$

where *i = 1, 2, 3 = sediment layers*

J = Solids flux ($M/L^2/T$)

E = Mixing coefficient (L^3/T)

C = Dry bulk density concentration (M/L^3)

w = Burial/Scour velocity (L/T)

The burial/scour velocities are determined from the net solids fluxes computed at each subsurface layer interface, starting from the sediment surface. Subsurface exchange velocities are updated hourly. The bottom layer segment volumes are permitted to vary to simulate the gain or loss of solids during burial and scour events. For sediment segments where there is net deposition, burial is simulated by increasing the bottom layer thickness (and volume). For sediment segments where there is net scouring, the thickness of the bottom layer is decreased, although a minimum thickness of 2 cm is maintained to avoid computational problems resulting from volumes approaching zero. If a bottom layer thickness is maintained at the 2 centimeter minimum thickness computations are performed to represent the upward flux of clean sediments from below. The flux between the third and forth sediment layers is used to compute the change in volume of the bottom sediment layer segments.

3.6 SOURCES OF PCBS AND PCB TRANSPORT

PCBs can enter Green Bay from several sources: the boundary with Lake Michigan, major tributary rivers (Fox, Menominee, Peshtigo, Oconto, and Escanaba), atmospheric deposition, and the sediment bed. These possible PCB sources were examined in the development of GBTOX (Bierman et al, 1992), the recalibration of GBTOX (De Pinto et al, 1993), and as part of TM2f (WDNR, 2000) and TM3a (WDNR, 2001a)). This information was used to describe the magnitude and temporal dynamics of PCB inputs in GBTOXe.

PCBs were simulated as one state variable: total PCBs. Total PCBs represents a family of 209 possible related compounds. Each of these different PCB compounds is known as a congener. Total PCBs are the sum of all congeners present.

3.6.1 Fox River PCB Loads

As part of the RI/FS effort, the Whole Lower Fox River water quality Model (wLFRM), was developed to examine contaminant transport in the Lower Fox River (WDNR, 2001b). The wLFRM describes the transport of suspended solids and total PCBs for the Lower Fox River based on data collected during the 1989-90 Green Bay Mass Balance Study (GBMBS), the 1994-95 Lake Michigan Mass Balance Study (LMMBS), and other sampling efforts. The state variables simulated were suspended solids (three classes) and total PCBs (the sum of all congeners).

Short-term and long-term wLFRM simulations were conducted. The short-term simulation period was 1989-95. From this period, PCB loading information from January 1, 1989 through May 31, 1990 was used in the GBTOXe calibration. Figure 3-6 presents the wLFRM time series of the PCB export to Green Bay for the calibration period. The sum of the Fox River PCB load for this period (514 days) is approximately 180 kg.

The long-term simulation period was 100 years and was used to project future PCB export to Green Bay and exposure trends in the river. Eight forecast simulations were developed. Each simulation used a different set of sediment bed PCB initial conditions. Each set of initial conditions represents a different action level for managing PCBs in the river sediments. Each action level represents a specific management goal and was expressed as a categorical maximum sediment PCB concentration limit for each reach of the river. Six action levels were explored: no action (no change to initial conditions; no action level applied), 5000 μg/kg, 1000 μg/kg, 500 μg/kg, 250 μg/kg, and 125 μg/kg (1 mg/kg = 1000 μg/kg).

Watershed PCB loads include all PCB loads that may enter Green Bay from the Menominee, Peshtigo, Oconto, and Escanaba rivers. PCB loads from these rivers were carried over from De Pinto (1993). For the period 1989-1990, the daily PCB loads entering Green Bay from the watershed rivers are presented in Figure 3-7. For projection simulations, the 1989 watershed

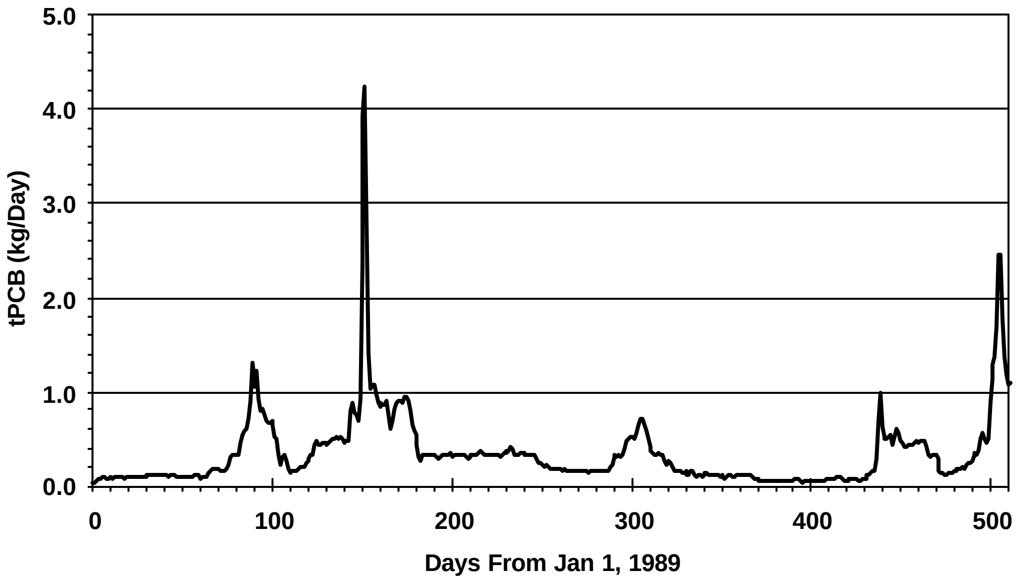


Figure 3-6. PCB export from the Lower Fox River to Green Bay: 1989-90.

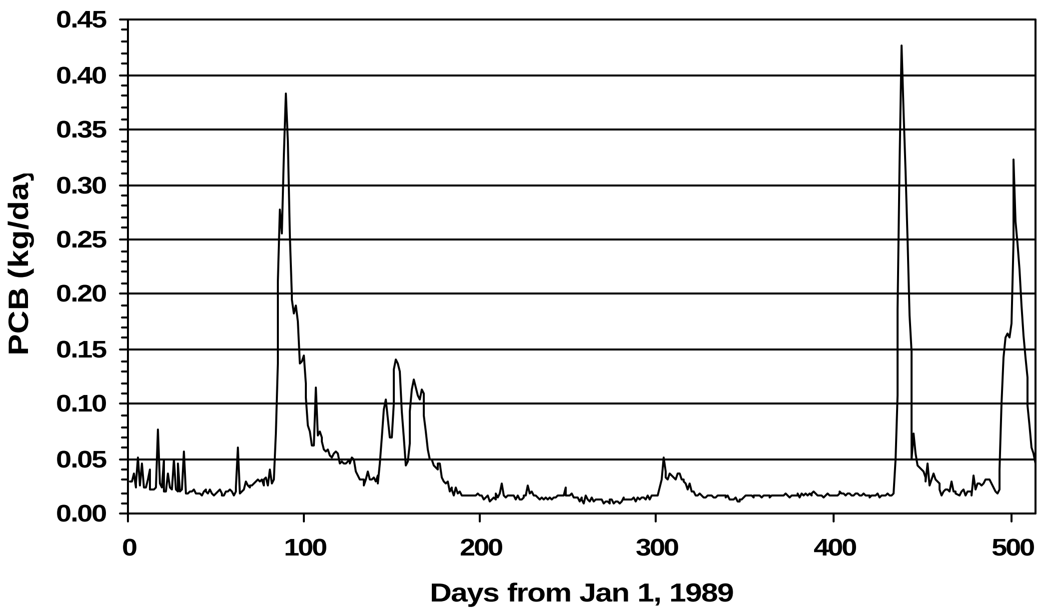


Figure 3-7. PCB loads to Green Bay from Watershed Rivers: 1989-90.

PCB input pattern were repeated annually with a decrease by 16% per year for the first 25 years and were set to zero for all subsequent years. The sum of the PCB load from the watershed for 1989-1990 period (514 days) is approximately 22.5 kg.

3.6.2 Sediment Bed PCBs

To estimate initial conditions for the purpose of evaluating the existing Green Bay models, data related to sediment bed properties in the bay were examined in TM2f (WDNR, 2000). In this task, sediment depth of analysis (a surrogate for sediment thickness), surface area, volume, dry dry bulk density, organic carbon (TOC), PCB concentration, and other observations were used to estimate sediment bed properties for Green Bay. TM2f examined a larger data base of sediment bed property observations collected since the end of the GBMBS (often in areas not sampled during the GBMBS). As described in TM3a (WDNR, 2001a), these sediment bed property estimates were based on a large database of observations and define model initial conditions for the short-term and long term simulation periods. The physical properties of the sediment bed were assumed to equal those defined in TM2f.

Sediment bed total PCB initial conditions were extracted from the ArcView GIS bed maps developed in TM2f. Each total PCB grid (100x100 meter grid) provides a horizontally continuous representation of solids based PCBs at 5 depth intervals: 0-2, 2-4, 4-6, 6-10, and 10> centimeters. Volume based total PCB Bed map grids were generated by multiplying the solids based totals PCB grids (ug/kg) by the corresponding dry bulk density grids (mg/L). Since the depth interval of the third GBTOXe sediment layer is 4-10 cm, a new grid representative of a 4-10 centimeter depth interval was generated by taking the depth weighted average of the 4-6 and 6-10 centimeter grids. To generate the sediment total PCB initial conditions, the GBTOXe model grid and the PCB grids were overlaid and each model grid segment was assigned the mean of the bed map cell values within the segments bounds. This process was repeated for each GTOXe sediment layer.

3.6.3 Partitioning

In GBTOX, a water column K_{oc} value of $10^{6.4}$ was used. For GBTOXe, a water column PCB K_{oc} value was estimated based on site-specific partitioning analyses of GBMBS data. Figure 3-8 presents the range of K_{oc} values computed from the GBMBS data using two methods. The solid points of Figure 3-6 are the total PCB K_{oc} values computed as the average of the homolog distribution of literature based K_{oc} values weighted by the GBMBS homologue concentration data. This K_{oc} distribution was generated by computing individual K_{oc} values (Mackay, 1992) for each sample using the expression:

$$K_{oc} = \frac{\sum_{n=1}^{10} K_{oc_n} C_n}{\sum_{n=1}^{10} C_n}$$

where: Koc_n = Homolog specific K_{oc} [Kg/L]

C_n = Homolog concentration [ng/L]

n = homolog index = 1, 2, … 10 [No of chlorines]

The hydrophobicity of homolog PCBs is known to increase with increasing numbers of chlorine atoms. Hydrophobicity is reflected in the homolog partitioning coefficient. Table 3-3 summaries the homolog K_{oc} values used in the calculation.

Table 3-3 Homolog Log K_{oc} Values from Literature

Homolog	LogKoc (log L/kg)
1	4.61
2	5.09
3	5.55
4	5.98
5	6.4
6	6.8
7	7.17
8	7.52
9	7.85
10	8.2

Source: Mackay et al, 1992

The open circles shown in Figure 3-8 are total PCB K_{oc} values computed from a back calculation of K_{oc} using the fraction dissolved term of the equation describing the equilibrium relationship between dissolved and sorbed chemical phases:

$$C_d = C_{total} f_d$$

$$f_d = \frac{1}{1 + K_{oc} PDC}$$

where: C_{total} = Total chemical [M/L^3]

C_d = Dissolved chemical [M/L^3]

f_d = Fraction dissolved chemical [dimensionless]

PDC = Particulate Detrital Carbon [M/L^3]

K_{oc} = Organic carbon partition coefficient [L^3/M]

Solving for K_{oc} gives:

$$K_{oc} = \frac{1 - f_d}{f_d PDC}$$

Particle organic carbon content (PDC) and fraction dissolved values for the water column were determined from GBMBS data.

The K_{oc} values computed with the dissolved fraction approach exhibit considerably more variability than those computed from the homolog weighted distribution approach, as seen on Figure 3-8. The homolog weighted analysis of log K_{oc} resulted in a mean of 6.0 with a log-standard deviation of 0.10. The analysis of the dissolved fractions resulted in a mean of 6.1 with a log-standard deviation of 0.33. A log K_{oc} of 6, was used in the calibration to better represent the K_{oc} values computed for the stations near the mouth of the Fox River, where the highest PCB concentrations are observed. This approach was selected rather than incorporate spatially varying K_{oc}'s into the GBTOXe framework.

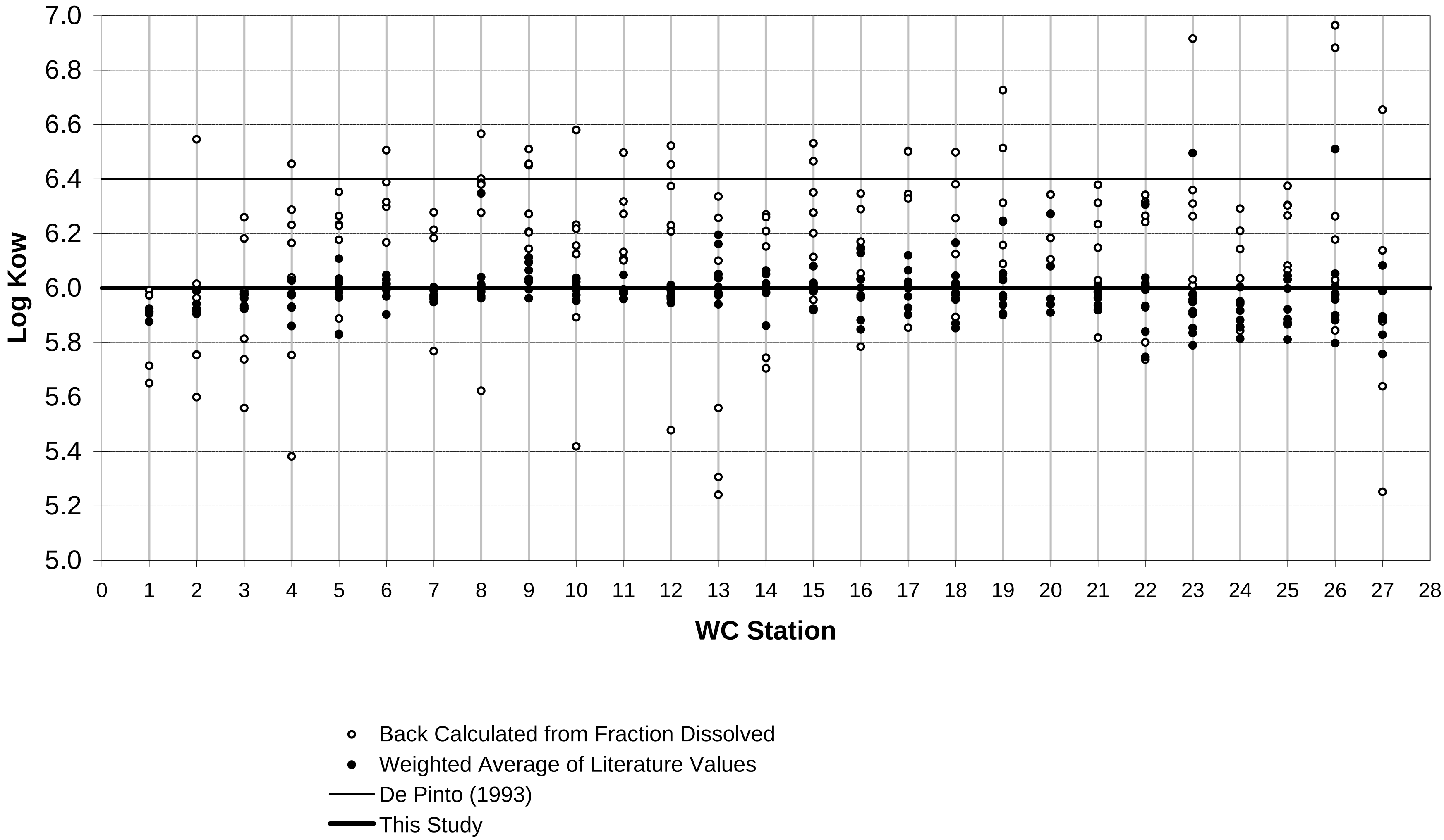


Figure 3-8 Estimated Total PCB Log Koc from Analysis of GBMBS Data

4.0 MODEL CALIBRATION RESULTS AND EVALUATION

4.1 OVERVIEW

GBTOXe was calibrated against Green Bay Mass Balance Study (GBMBS) data collected from 26 water quality stations for the period January 1, 1989 to May 31, 1990. In the time period between the application of GBTOX in 1993 and the effort presented here, Green Bay hydrodynamics, sediment transport, tributary and internal solids loads, and the PCB and solids contribution from the Fox River have all been re-evaluated for the calibration period (HydroQual (1999), LTI (1999a,b), WDNR (2000)). This new information was used to calibrate the spatial and temporal trends of water column PCBs, biotic carbon (BIC), detrital carbon (PDC) and dissolved carbon (DOC) for the calibration period. The main components that differentiate the calibration of GBTOXe from De Pinto’s 1993 recalibration of GBTOX are the following:

- Higher spatial resolution of model grid
- Linked to high resolution, 3D hydrodynamic model (GBHYDRO)
- Linked to high resolution, 3D sediment transport model (GBSED)
- Incorporates revised Internal BIC production loads (TM2c)
- Incorporates revised PCB loads from the Fox River (wLFRM)
- Re-evaluated water column partition coefficient (1996 GBMBS data analysis)

In this calibration of GBTOXe, some input parameters were carried over from De Pinto’s 1993 application of GBTOX. Table 4-1 presents those input parameters that were developed as part of the calibration effort presented here.

Table 4-1 Summary of GBTOXe Input Parameters

Variable Name	**Description of Variable**	**Values Used**	**Reference**
BR	Water column Dispersive flow	GBHYDRO hourly output (m3/sec)	GBHYDRO Calibration
QT	Water column advective flow	GBHYDRO hourly output (m3/sec)	GBHYDRO Calibration
	Settling, deposition and resuspension velocities	Resuspension: GBSED hourly output (cm/day)	GBSED Calibration
		Particulate carbon settling in water column: 0.2-1.0 m/day	GBTOXe 1989-90 Calibration
		Particulate carbon deposition at water/sediment bed interface: 0.2 -1.0 m/day	GBTOXe 1989-90 Calibration
		Particulate carbon deposition between sediment layers: GBSED hourly output (m/day).	GBSED 1989-90 Calibration
WKT	Fox River Total PCB Loads.	wLFRM output (kg/day)	wLFRM 100 year forecasts
	Tributary total PCB Loads (Menominee, Peshtigo Oconto, Escanaba).	Daily GBTOX tributary total PCB loads cycle annually with a 16% annual rate of decline for first 25 years and zero loads thereafter.	De Pinto,1993 & TM2b (LTI, 1999a)
	Atmospheric total PCB Loads.	GBTOX atmospheric total PCB loads distributed across GBTOXe grid with a 16% annual rate of decline for first 25 years and zero loads thereafter.	De Pinto,1993 & TM2b (LTI, 1999a)

Table 4-1 Summary of GBTOXe Input Parameters

Variable Name	Description of Variable	Values Used	Reference
	Internal dissolved organic carbon and internal biotic carbon loads	Monthly GBTOX internal carbon loads cycle annually and distributed vertically as a function of light limitation	TM2c, (LTI, 1999b) EPA, 1983
ATMC1	Atmospheric chemical concentration.	7.7×10^{-10} – 0.0 ug/L 16% annual rate of decline for first 25 years and zero concentration thereafter.	De Pinto,1993 TM2b
PIX1	Carbon Partition coefficient	1.0×10^{6} L/kg	Statistical analysis of GBMBS project data
KSB	Dissolved and particulate carbon transformation rate in sediment.	0.0 day^{-1}	GBTOXe 1989-90 Calibration

4.2 CALIBRATION PARAMETERS

Solids exchange across the sediment bed interface with the water column is an important component when considering the ultimate fate of PCBs that have accumulated in sediments. Given relatively low external PCB loads, deposition and resuspension events largely dictate the rates at which PCBs are transported through or from the sediment bed through burial or erosion.

Parameters that control net deposition of carbon to the sediment bed were adjusted as part of the calibration of water column PCB and carbon concentrations. In early calibration efforts, it was observed that the resuspension and deposition components of net solids deposition rates calibrated in GBSED were very large. When the resuspension and deposition fluxes were applied to GBTOXe, a large flux of PCBs from the sediment to the water column was computed. This flux resulted in computed water column PCB concentrations that were at times as much as an order of magnitude higher than measured PCB concentration, particularly for shallow and near shore segments with relatively high sediment PCB concentrations. To reduce resuspension and deposition fluxes without significantly affecting the net deposition rates, GBSED was recalibrated with adjustments made to the coefficients used to compute erosion potential, as discussed in section 3.5.4. A more detail discussion regarding GBSED is presented in HydroQual 1999.

Calibration efforts that utilized the revised resuspension flux component from GBSED in conjunction with constant settling and deposition velocities showed better agreement with observations. This improvement can be understand by considering that the settling and deposition velocities generated from GBSED are computed for non-living cohesive particulate material of various sizes and densities. While resuspension velocities for solids and particulate carbon should be the same because these reflect a depth of erosion, particulate material settle and deposit at various rates depending on size, density, and other factors. Since GBSED settling and deposition flux rates account for particles of variable sizes and densities, it was conclude that GBSED depositional flux rates were not appropriate for characterizing particulate carbon settling and deposition to the sediment bed.

Table 4-2 Calibration Parameters

Parameter	Value	Units
PDC Settling Rate	1.0	m/day
BIC Settling Rate	0.2	m/day
Particulate Carbon Deposition Rate	Particulate carbon phase settling rate * surface sediment area characterized as non-cohesive	m/day

As a result of the observations stated above, particulate carbon settling rates were set as spatially invariant and constant with time to represent the overall, long term settling characteristics of carbon in Green Bay. The carbon phase deposition rates were set as the product of their associated settling rates and the factors related to the fraction of the sediment characterized as hard-bottom (section 3.5.3). Table 4-2 presents the final particulate carbon settling rates used in the calibration. An evaluation of the results is discussed the Section 4.3 below.

4.3 MODEL RESULTS EVALUATION

Time series comparisons of observations and model results for the calibration period were developed for the water column segments of the model grid that correspond to the twenty six water quality stations designated in GBMBS study area (Figure 4-1). Model results of dissolved PCBs (ng/L) particulate PCBs (µg/gOC), PDC (mg/L), BIC (mg/L), and DOC (mg/L), and POC (mg/L sum of BIC and PDC) were compared with the January 1, 1989 to March 31, 1990 GBMBS data set. Figure 4-2 presents the times series of weekly averaged dissolved and particulate PCB concentrations spatially averaged by zone compared with the water quality stations within zones 2, 3A, 3B, and 4. Figures 4-3 through 4-6 present four time series comparisons between both PCB and carbon concentrations and observations at individual water

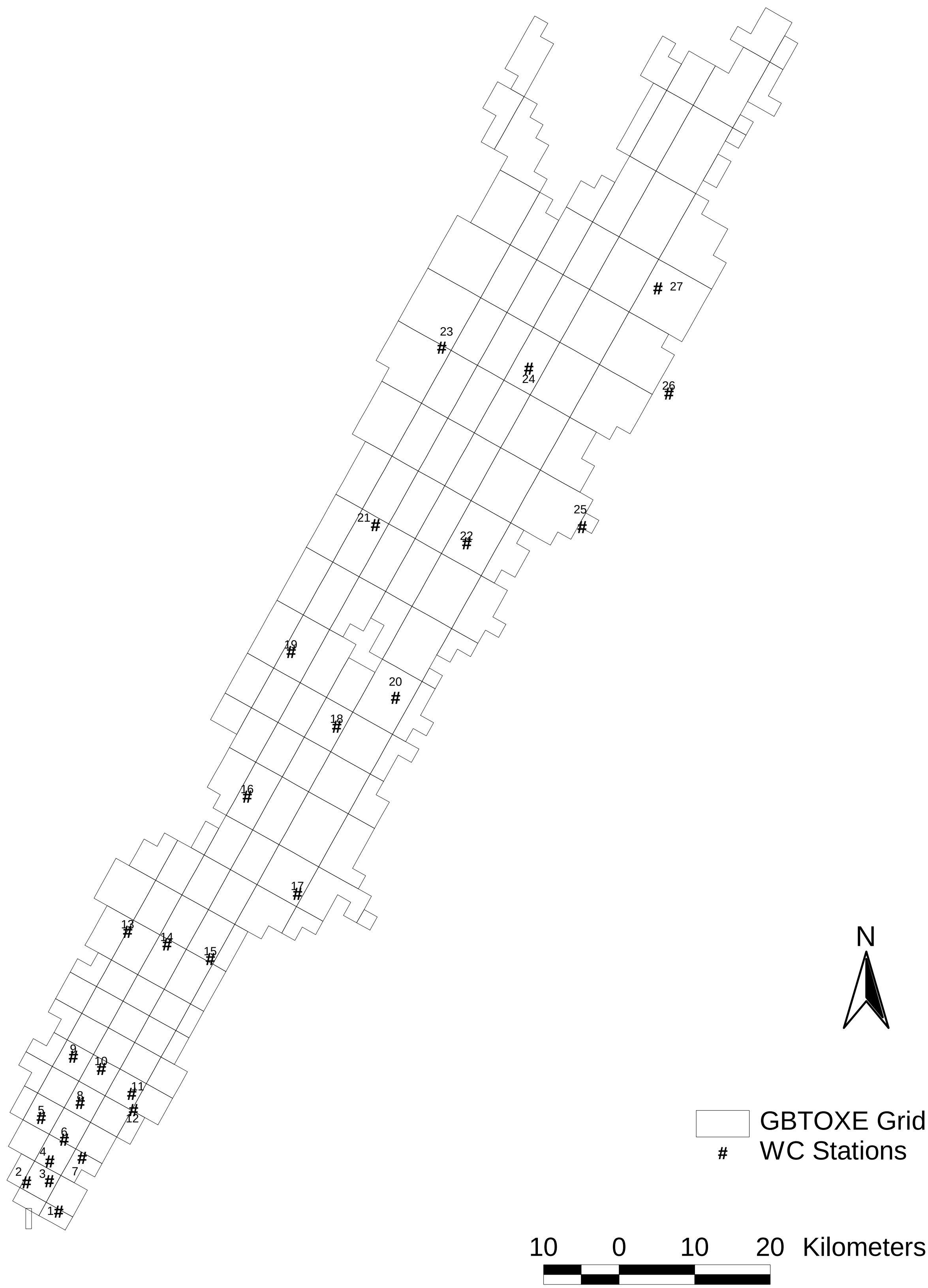


Figure 4-1 GBTOXE Grid and Water Quality Stations

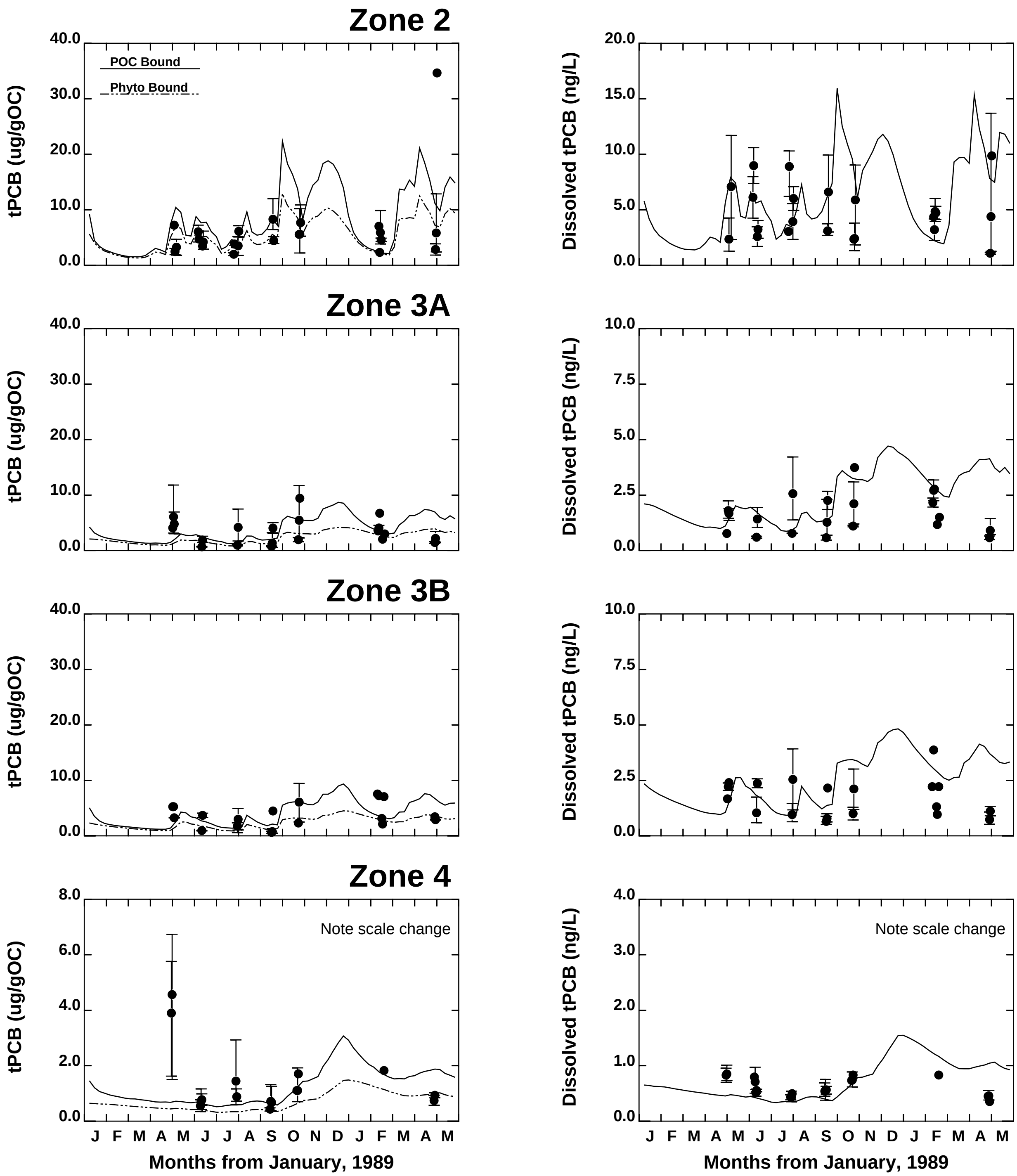


Figure 4-2 Weekly Averaged Dissolved And Carbon Normalized Sorbed Fraction of tPCBs, Spatially Averaged by Zone

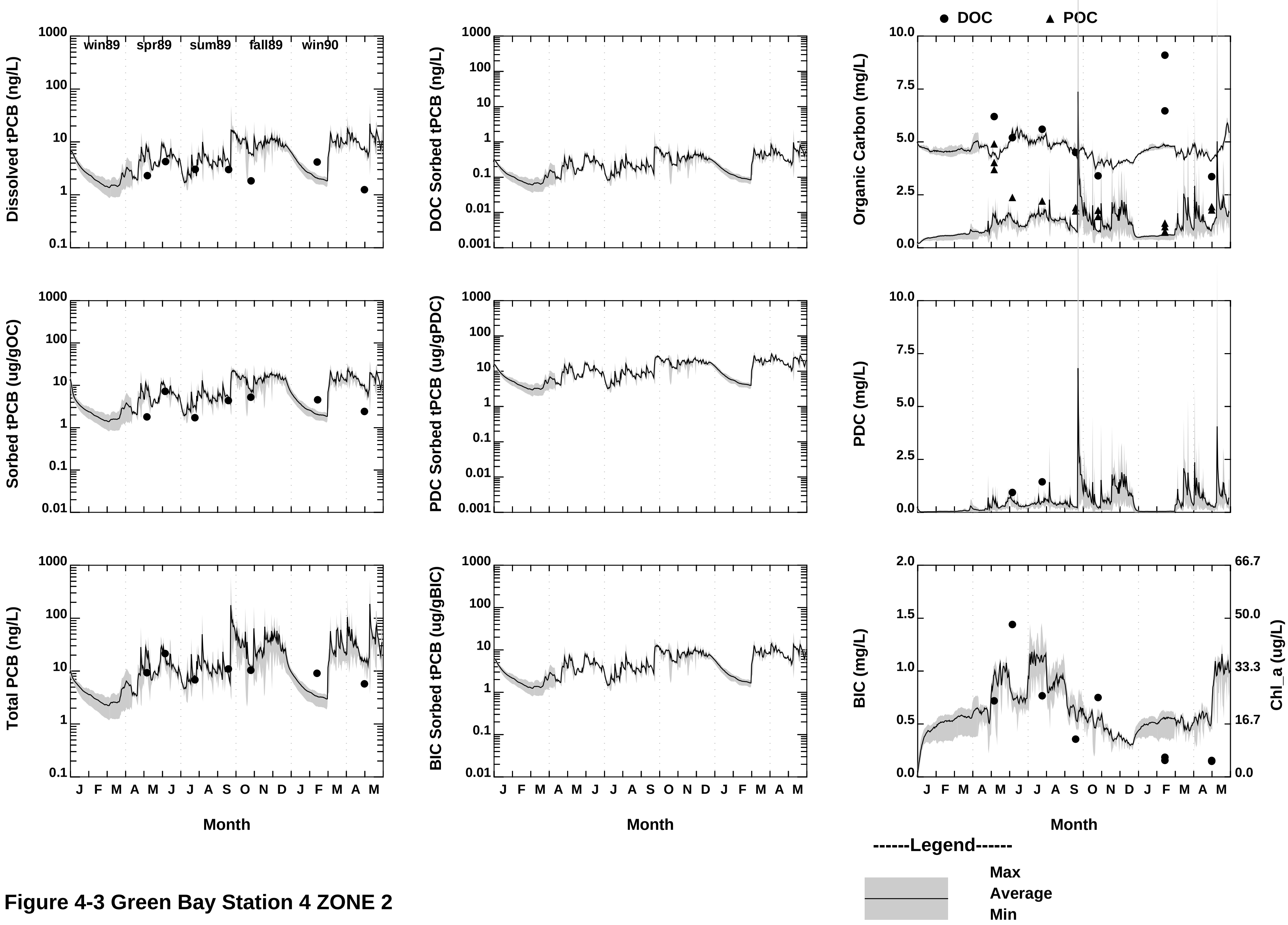


Figure 4-3 Green Bay Station 4 ZONE 2

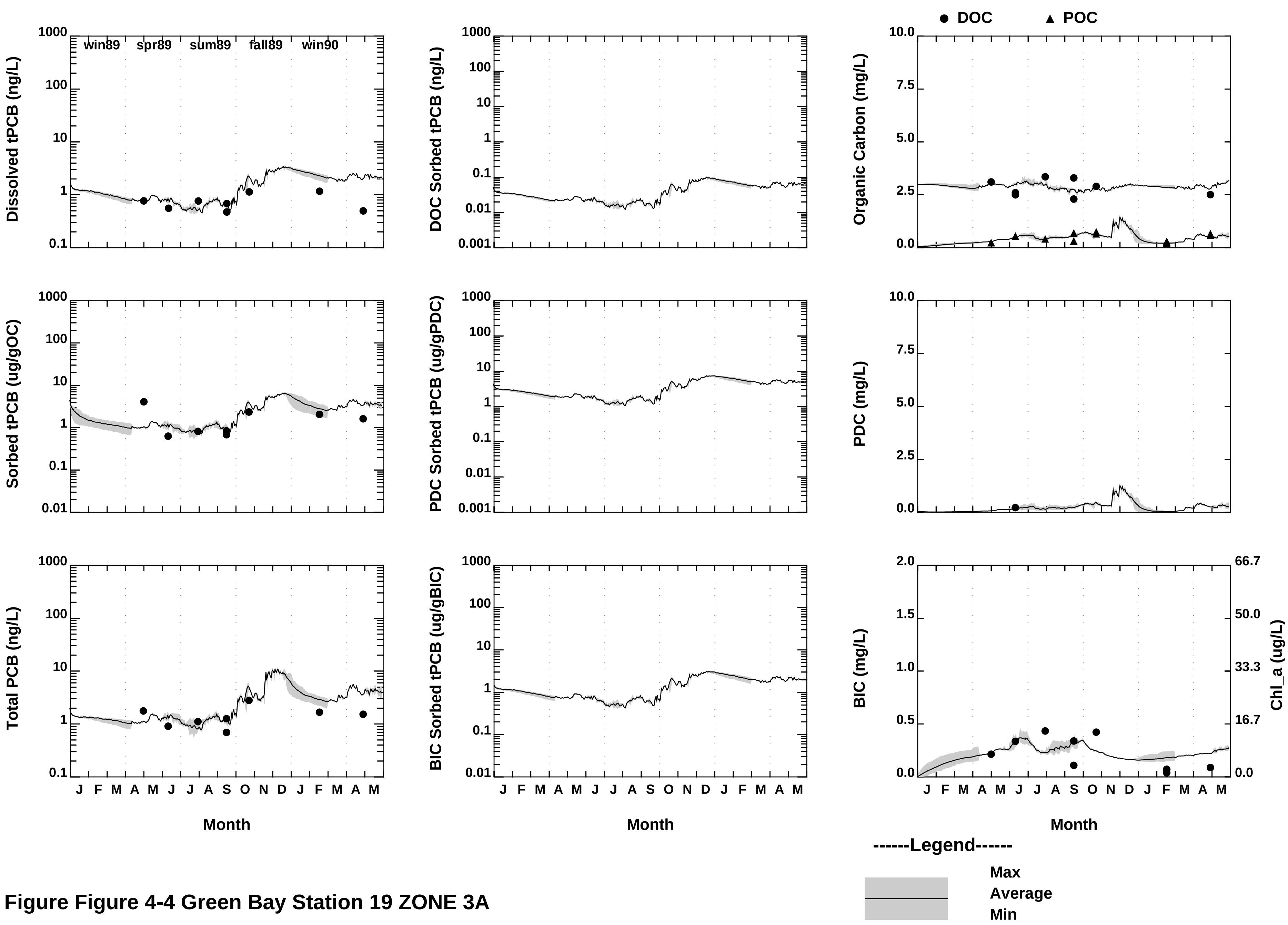


Figure Figure 4-4 Green Bay Station 19 ZONE 3A

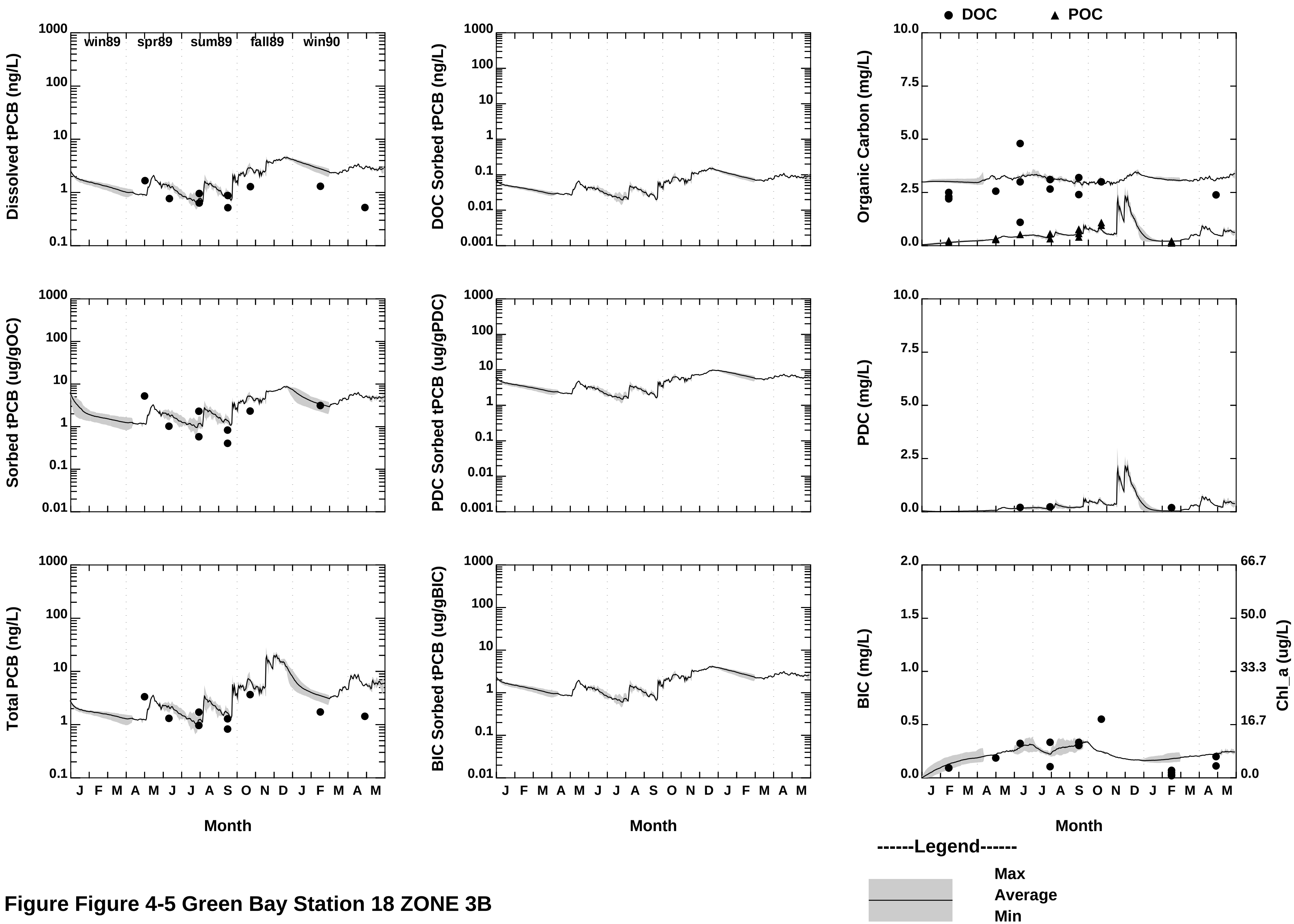


Figure Figure 4-5 Green Bay Station 18 ZONE 3B

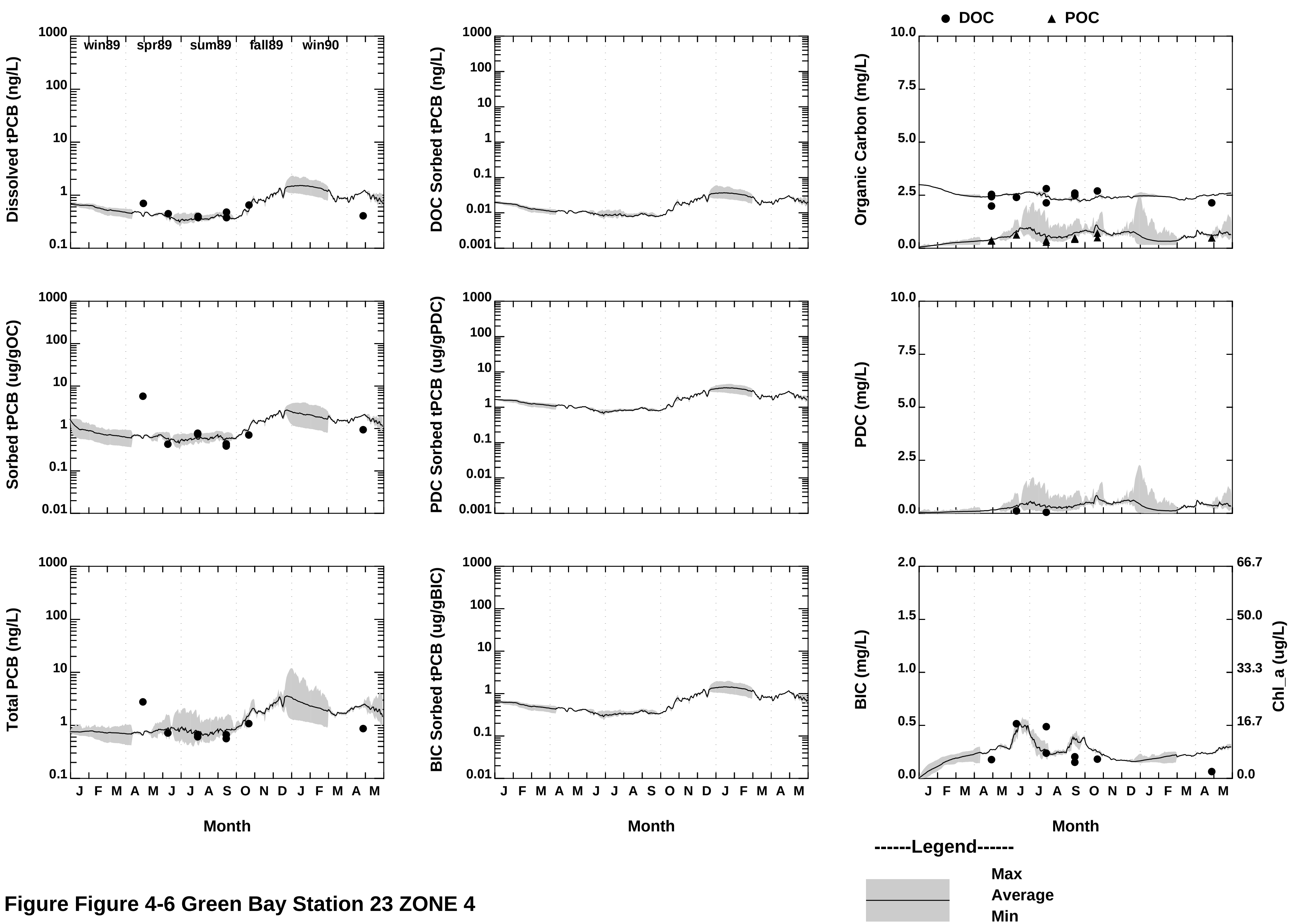


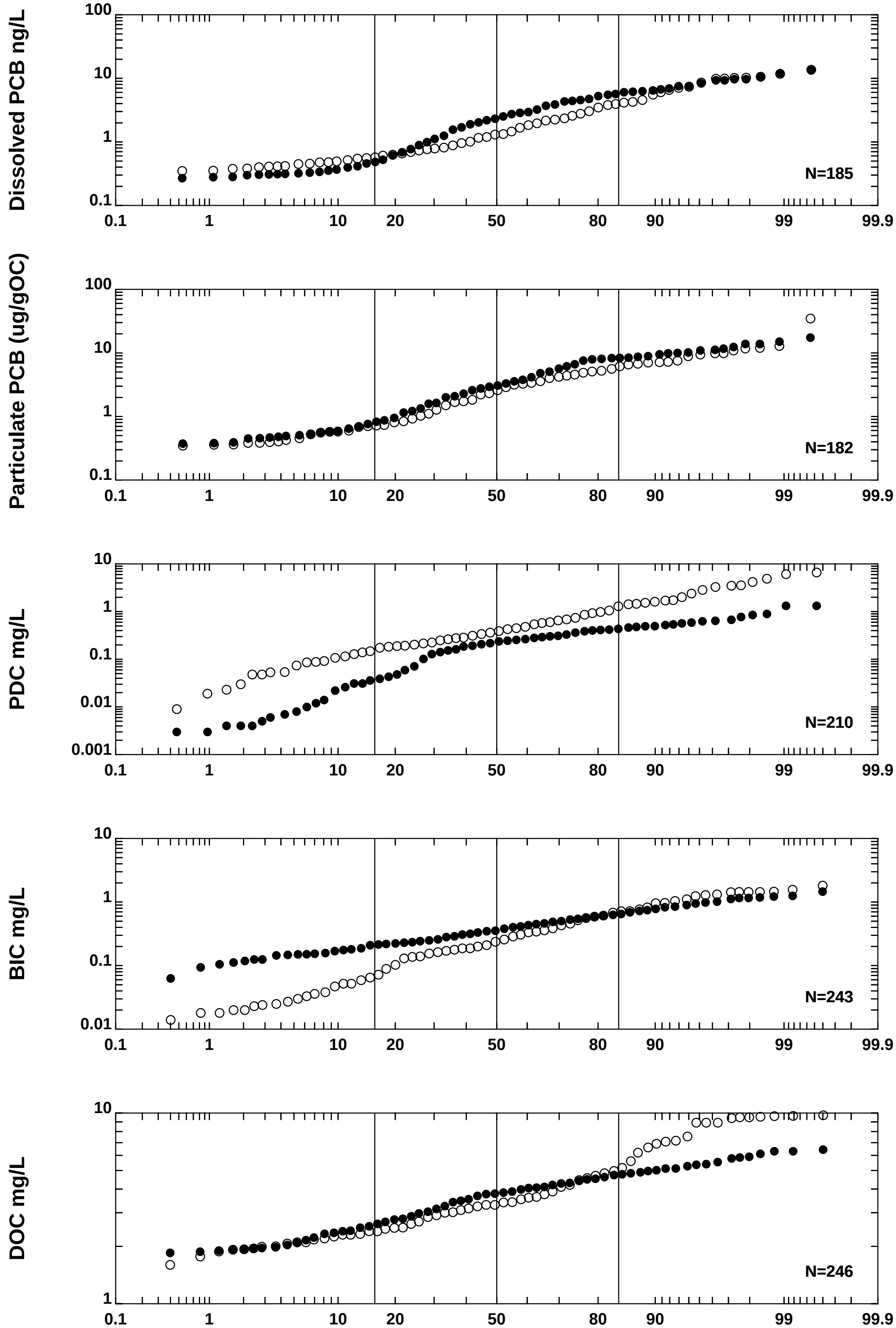
Figure Figure 4-6 Green Bay Station 23 ZONE 4 stations within each zone. Comparisons to the remaining water quality stations are presented in Appendix A. Bay wide (Figure 4-7) and zone probability distributions of dissolved PCBs (ng/L) particulate PCBs (µg/gOC), PDC (mg/L), BIC (mg/L), and DOC (mg/L) (Figures 4-8 - 4-12) were developed. Tables 4-3 and 4-4 summarize the relative differences between observed and modeled PCB and carbon concentrations for comparison to the +/- 30 percent metric indicated in TM1.

The time series of PCB concentrations show considerable variability in response to wave induced resuspension events. In the inner bay (Figure 4-3), PCB concentrations vary by as much as 3 orders of magnitude in response to the sediment transport dynamics generated by GBSED. The model's sensitivity to resuspension events is further evident in the contrast of the PCB concentration profiles between the period of high variability (open water) and the troughs during the ice cover period from December to March. On a bay wide basis the time series comparisons indicate that the PCB and carbon concentration variability is highest in the shallow, near shore inner bay area, and gradual decreases to less than an order of magnitude in the outer bay. The effect of resuspension events on water column PDC concentrations in the inner bay is most clearly evident in the large short lived concentration peak in September 1989 in response to high wind and wave events (41 mph with wave heights > 2.5 meters). This peak is less pronounced in the deeper outer bay where sediment resuspension is less affected by wave action.

4.3.1 PCB Evaluation

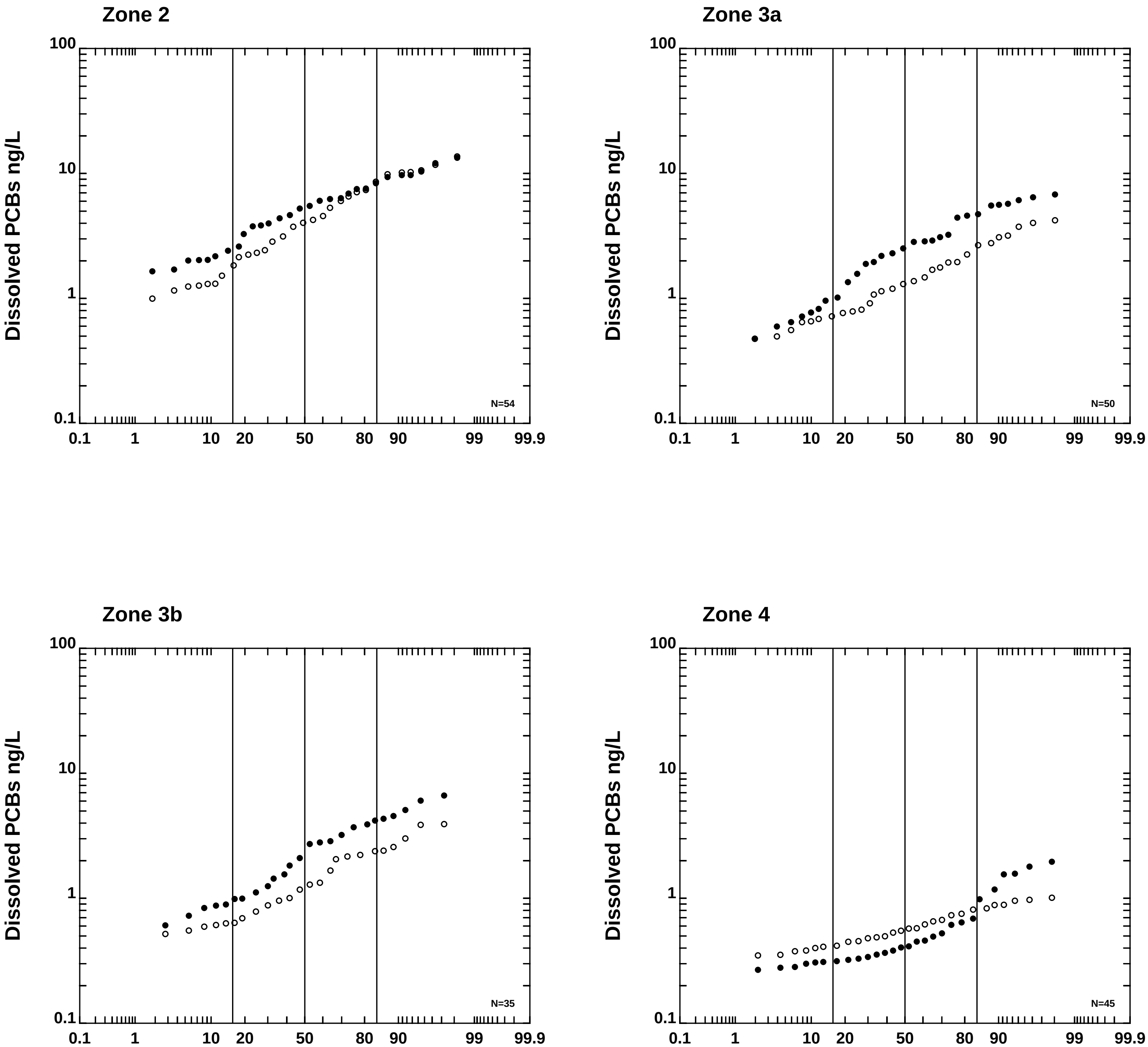
PCB time series comparisons show that the model generally reproduces the trend and magnitude of the observations. The times series of weekly averaged dissolved and particulate PCB concentrations spatially averaged by zone shows good agreement with observations in all zones as indicated in Figure 4-2. However, the particulate PCB trend in Zone 4 (Figure 4-6) does not capture the observed trend in late April. Although observed PCB and carbon concentrations are temporally sparse on a station by station basis, Figures 4-3 through 4-6 indicate that the model reasonably reproduces the various PCB trends in each zone.

The dissolved and particulate PCB distributions indicate that the model is biased high on a bay wide basis (Figure 4-7) but primarily in zones 2, 3a, and 3b (Figures 4-8 and 4-9). While Zone 4 dissolved PCB distributions (Figure 4-8) are similar, zone 4 particulate PCB distributions (Figure 4-9) indicate a low bias. Table 4-3 presents a summary of the relative differences between mean observed and modeled PCB concentrations. While the relative difference between means of particulate PCBs falls within the TM1 quality criteria (25%) on a bay wide basis, the difference in the distribution means of dissolved PCBs falls just outside the criteria upper bound of +30% (34%). This is primarily due to the high bias in zones 3A and 3B as indicated in Table 4-3.



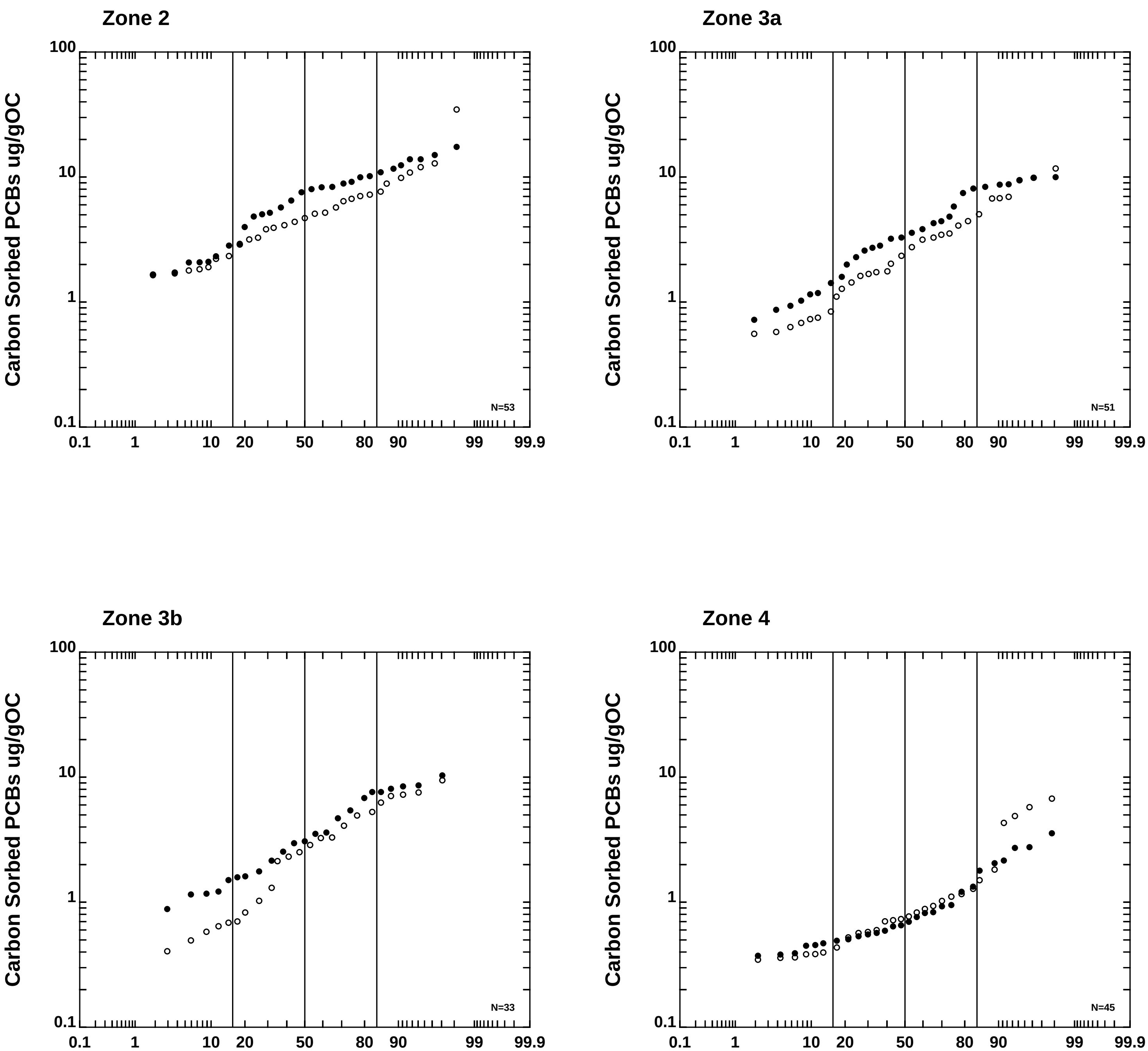
Data: Open Circle   Model: Filled Circle

Figure 4-7 PCB and Carbon Probability Distributions for Whole Bay



Observed: Open   Model: Filled

Figure 4-8 Dissolved PCB Probability Distributions by Zone



Observed: Open   Model: Filled

Figure 4-9 Particulate PCB Probability Distributions by Zone

Table 4–3 Relative Difference Between Mean Observed and Modeled PCB Concentrations

State Variable	Zone 2	Zone 3A	Zone 3B	Zone 4	Bay Wide
Dissolved PCBs (ng/L)	16.1 %	81.2 %	68.2 %	-4.0 %	34 %
Particulate PCBs (µg/g OC)	28.2 %	34.0 %	24.3 %	-20.3 %	25 %

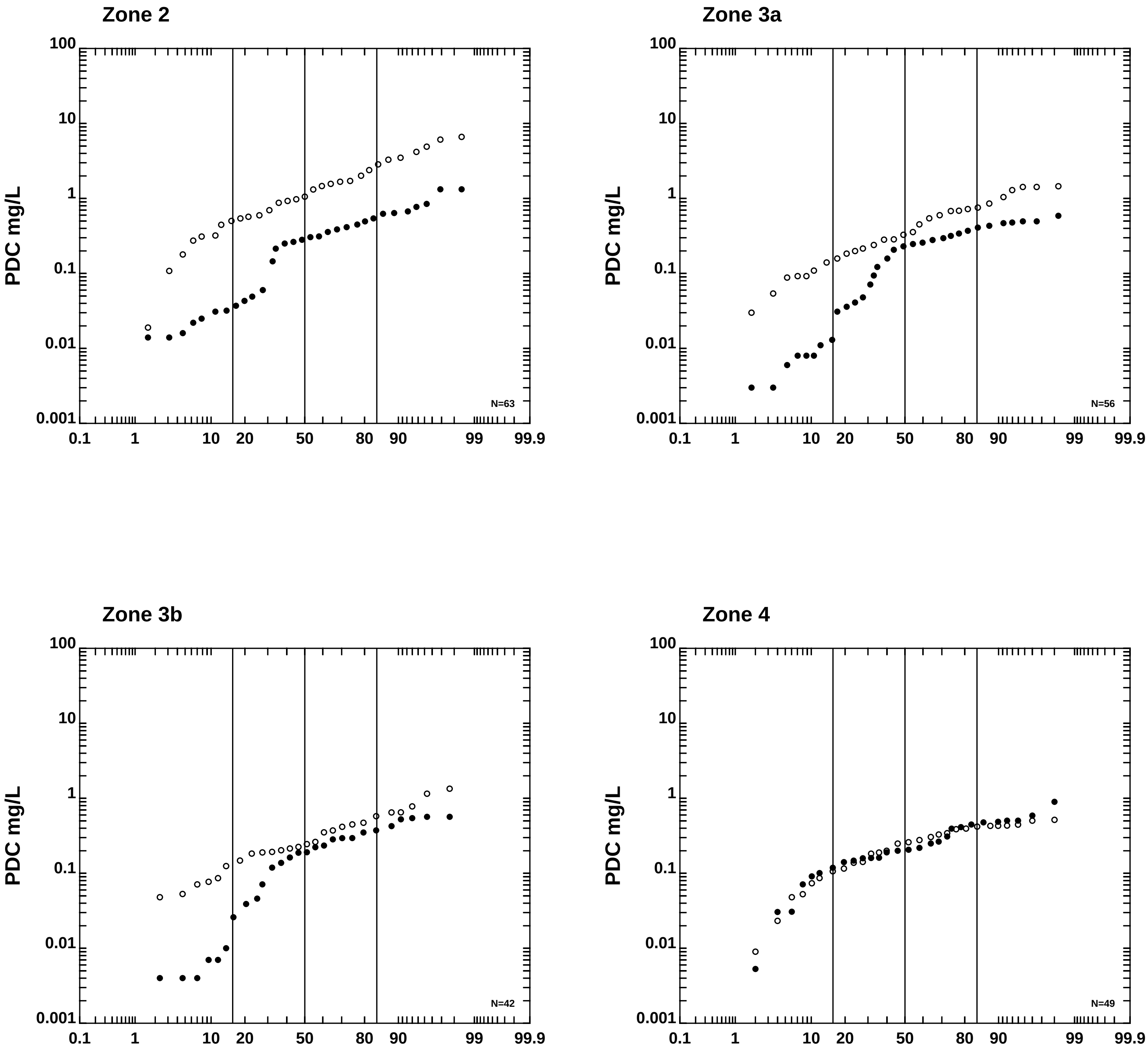
4.3.2 Carbon Evaluation

The time series comparisons of the carbon phases in each zone indicate that the model is biased high for all carbon phases in zone 2, particularly PDC (Figure 4-10). The range of variability of the carbon phases indicates that zone 2 is more sensitive to resuspension events relative to zones 3A, 3B, and 4 primarily because zone 2 is relatively shallow. As discussed earlier, model bias may be more pronounced in zone 2 because of the low bias of the data.

Table 4-4 summarizes the relative difference between observed and modeled carbon phases. Both DOC and BIC concentration distributions achieve the calibration metric on a bay wide basis (Figure 4-7) and by zone (Figures 4-11 and 4-12). In Figure 4-12, the range and variability of the probability distribution of observed and modeled DOC compare well. However, the BIC distribution, shown in Figure 4-11, indicates that the model is biased high for the low range of BIC concentrations. As indicated in the BIC time series comparisons of Figures 4-3 through 4-6, observed BIC concentrations tend to be lowest during the ice cover period. Each zone exhibits a divergence of the low values of the distribution, suggesting that BIC may settle more rapidly during the ice cover period than is parameterized in the model.

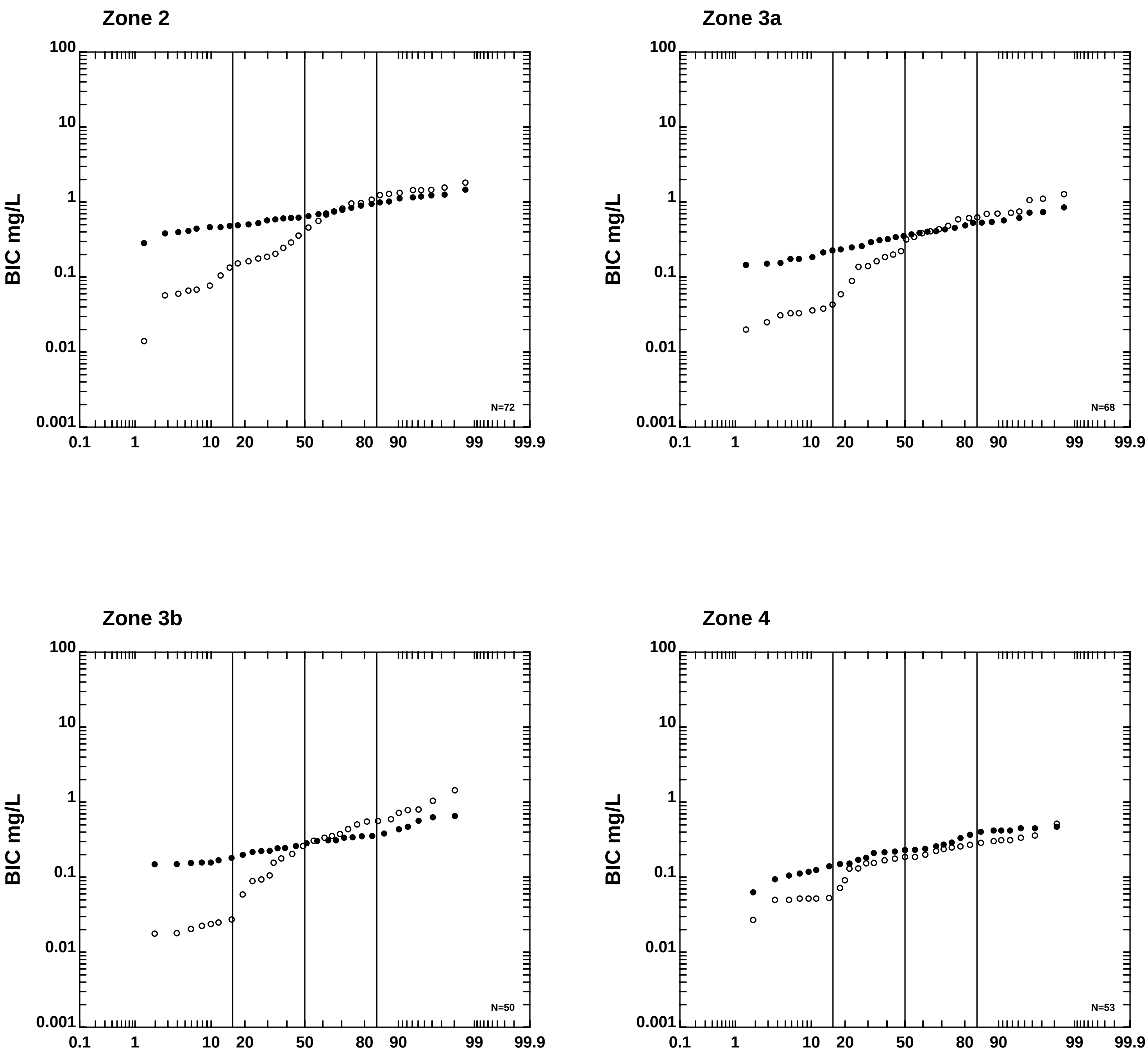
Table 4–4 Relative Difference Between Mean Observed and Modeled Carbon Concentrations

State Variable	Zone 2	Zone 3A	Zone 3B	Zone 4	Bay Wide
PDC (mg/L)	-79.4 %	-54.5 %	-38.5 %	1.5 %	64 %
BIC (mg/L)	23.3 %	9.2 %	-8.0 %	30.6 %	15 %
DOC (mg/L)	-17.4 %	11.0 %	7.8 %	1.5 %	4 %



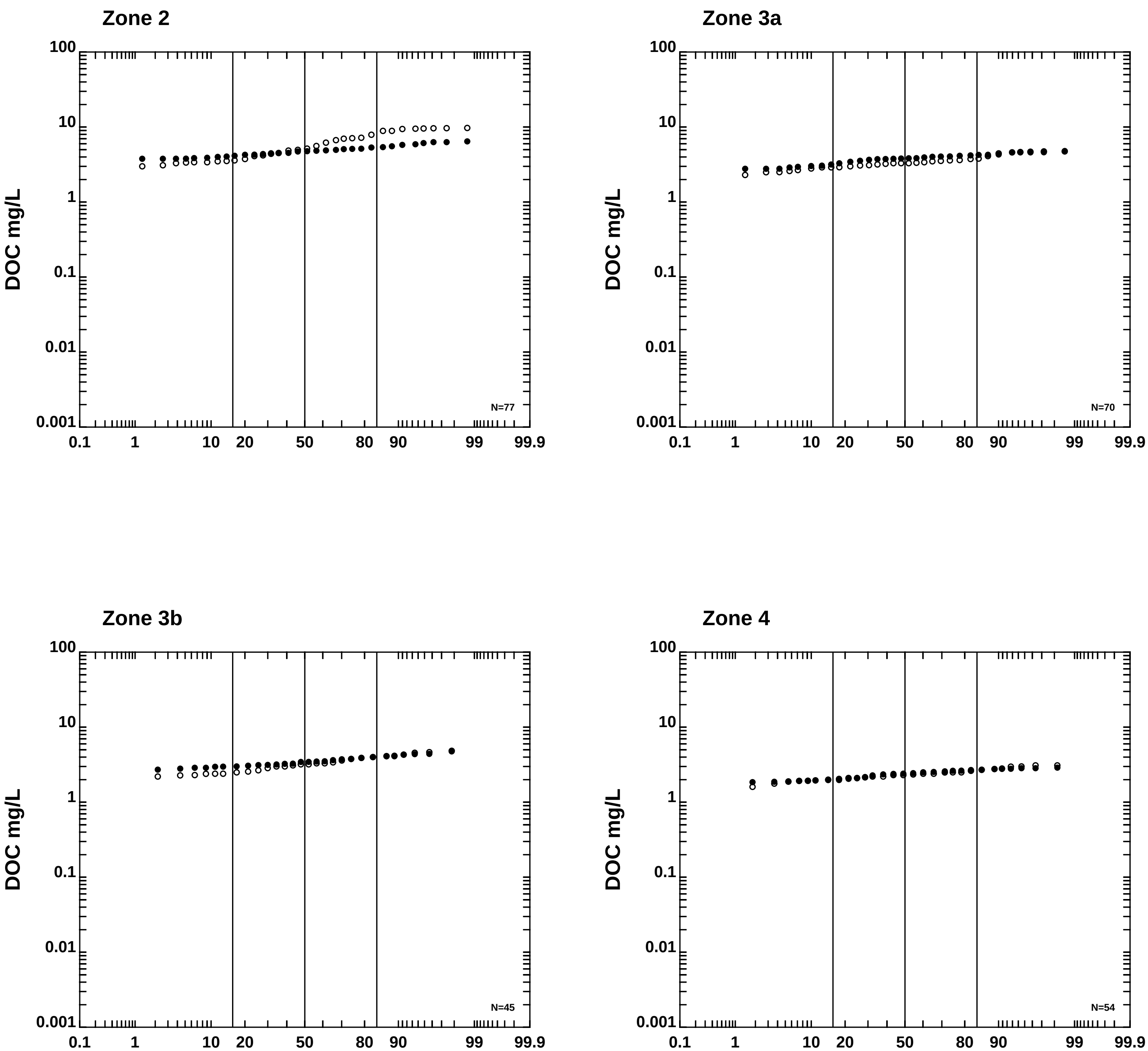
Observed: Open   Model: Filled

Figure 4-10 PDC Probability Distributions by Zone



Observed: Open   Model: Filled

Figure 4-11 BIC Probability Distributions by Zone



Observed: Open   Model: Filled

Figure 4-12 DOC Probability Distributions by Zone

The observed and modeled PDC distribution clearly indicates that the model is biased low for predicting PDC concentrations. With the exception of zone 4, the PDC distributions in zones 2, 3A, and 3B show that the model consistently under predicts PDC concentrations throughout most of the bay. While decreasing the PDC settling rate would improve the PDC distribution comparisons, a subsequent rise in predicted water column PCB concentrations would result because of the decreased PCB flux to the sediments. Given that the model is currently biased high for predicting PCBs in the water column, decreasing the settling rate would not improve the overall calibration.

It should noted that the PCB and carbon data collected during the GBMBS cruises are likely biased low with respect to the actual temporal trends of water column PCBs in Green Bay because environmental conditions were relatively calm (it appears that data were rarely collected during high wind induced resuspension events). The data fall on the low end of the computed range of water column PCB concentrations. The model data comparisons can only be made for a portion of the computed PCB concentrations that are biased to the low end of the range of computed concentrations. In general, the comparison of computed and measured PDC suggests that it would be beneficial to incorporate more refined analyses describing carbon dynamics in Green Bay into this analysis.

5.0 MODEL APPLICATION: FORECAST SIMULATIONS

5.1 OVERVIEW

The calibrated GBTOXe model was applied to generate a series of fifteen future projection simulations combining various Fox River and Green Bay remedial action scenarios. The projection simulation period was 100 years in length. For this 100-year period, the advective and dispersive flows, resuspension events, sediment transport information, minor tributary loads (Menominee, Peshtigo, Oconto, and Escanaba), and atmospheric PCB loads used in the calibration effort were reapplied as a repeating annual pattern. The 16% annual rate of decline estimated in TM?? for watershed PCB sources was applied to the annual pattern of the minor tributary and atmospheric PCB loads.

The Green Bay remedial action component of the projection simulations consists of three sets of different sediment PCB initial conditions. Each set of PCB initial conditions represents a different action level for managing PCBs in Green Bay sediments. The Fox River remedial action component of the projection simulations consists of Fox River PCB export to Green Bay generated from eight wLFRM projection simulations in which different Fox River sediment PCB initial conditions represented different action levels. For both Green Bay and the Fox River, each action level represents a specific management goal expressed as a categorical maximum sediment PCB concentration limit. Development of the sediment PCB initial conditions for Green Bay action levels is described in Section 5.2.

5.2 ACTION LEVELS AND SEDIMENT BED INITIAL CONDITIONS

Three sets of initial conditions for sediment PCBs in Green Bay were developed. The no action set is based on the historical data described in TM2f (WDNR, 2000) and refers to sediment PCBs prior to remedial activity. Remedial action sets were developed for two maximum PCB action levels: 1000 μg/kg, and 500 μg/kg. Application of an action level represents remediation of sediments with PCBs above a specified maximum. This results in a vertical redistribution of the PCB concentrations associated with each sediment layer. When a sediment layer exceeds the action level maximum, that layer and any sediment layers above it are considered “removed,” and the PCB concentrations of deeper layers, if any remain, are redistributed across the 4 sediment layers based a depth weighted average.

Table 5-1 summaries the Green Bay and Fox River remedial components of the fifteen projection simulations. The differences between each projection simulation are identified by the Green Bay PCB inventories associated with the three action levels described above and the Fox River loads to Green Bay (presented in Table 5-1 as an annualized average) associated with the action levels applied to the wLFRM.

Table 5-1. Projection Simulation Remedial Action Componets.

Fox River Remedial Action (µg/kg)	Green Bay Remedial Action (µg/kg)					
	No Action		1000		500	
	Inventory kg	Annualized Load kg/year	Inventory kg	Annualized Load kg/year	Inventory kg	Annualized Load kg/year
No Action	70,740	69.7	-	-	-	-
5000	70,740	9.17	-	-	-	-
1000	70,740	1.95	48,820	1.95	-	-
500	70,740	1.40	48,820	1.40	46,040	1.40
250	70,740	0.99	48,820	0.99	46,040	0.99
125	70,740	0.77	48,820	0.77	46,040	0.77
Schedule H*	70,740	2.66	-	-	-	-
Schedule I*	70,740	2.95	-	-	-	-

* Schedule H and I are not part of the RI/FS – see Table 5-2 for details

Table 5-2. Variable Fox River PCB Action Levels (ug/kg) for Schedules H & I

Schedule	Reach 1 Little Lake Butte des Morts	Reach 2 Appleton to Little Rapids	Reach 3 Little Rapids to DePere	Reach 4 Depere to Green Bay
H	500	No Action	250	250
I	1000	No Action	500	500

5.3 PROJECTION SIMULATION RESULTS

The results of these 15 simulations are summarized through a presentation of zone-wide annual average PCB concentrations computed in the water column (dissolved and sorbed) and in the upper 10 cm of the sediment (0-2, 2-4, 4-10 cm layers). Figure 5-1 presents the results of the no-action simulation, which represents natural attenuation of sediments in both the Fox River and Green Bay. The left hand panels of these projection figures present water column dissolved and sorbed (ug/ g organic carbon) concentrations and the right hand panels present PCBs in the 0-2,

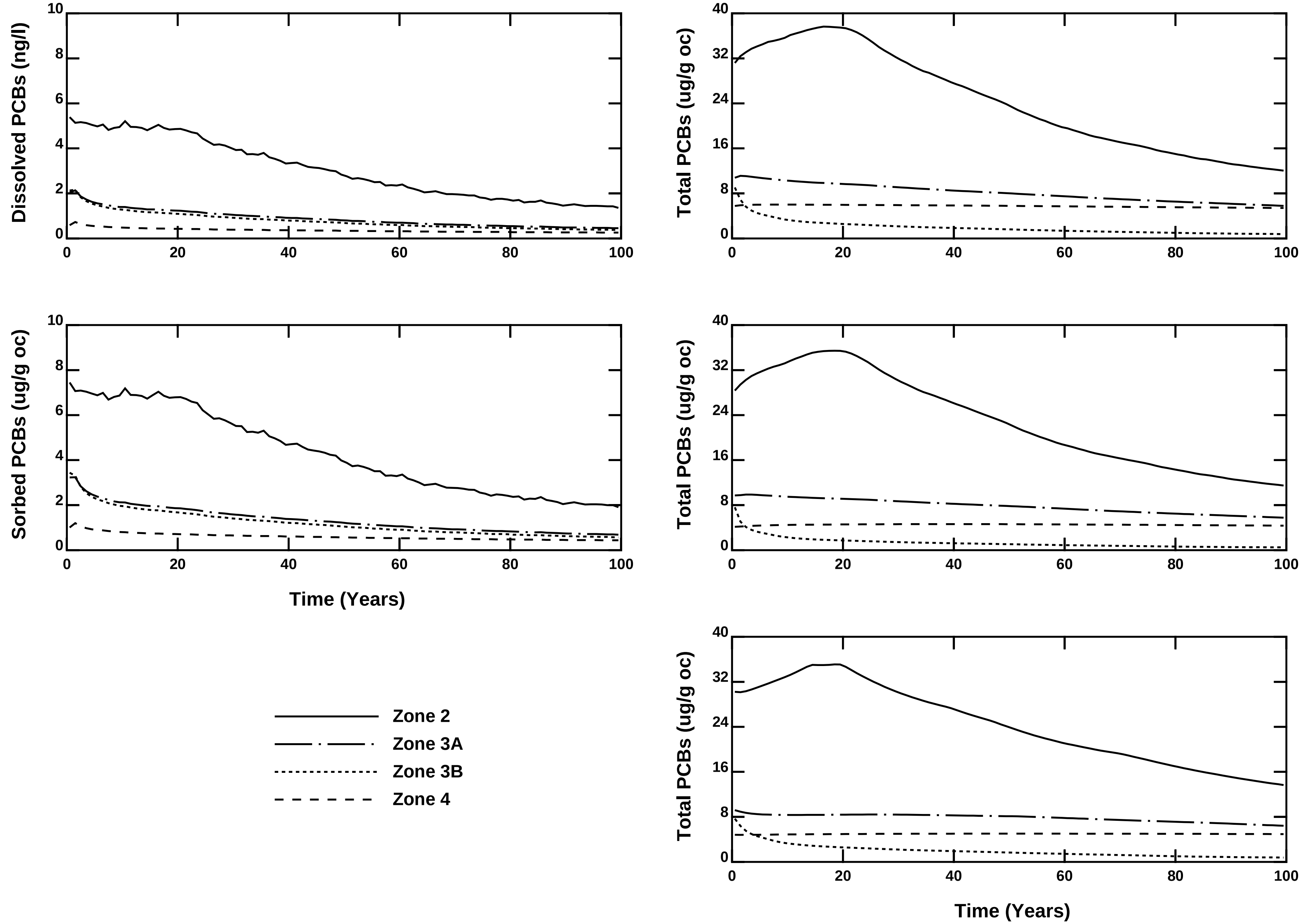


Figure 5-1 **Annual Average Water Column and Sediment PCBs**
Fox River Scenario No Action **Green Bay Scenario No Action**

2-4, and 4-10 cm layers of the sediment. Results for the no action simulation show Zone 2 water column PCBs declining fairly gradually with annual average dissolved concentrations decreasing from approximately 5.5 ng/l to 1.5 ng/l over the 100 year simulation. Sorbed PCBs in the water column of Zone 2 follow a similar pattern decreasing from approximately 7.5 ug/gOC and leveling off near 2 ug/gOC. A buildup of PCBs in the sediments of Zone 2 is calculated during the first 20 years of the simulation. This increase of between 15 and 25 percent is due to resuspension events which transport PCBs present in deeper sediments upward into the upper 10 cm of the sediment. This feature is influenced by the annually repeating sediment transport and hydrodynamic circulation patterns. The vertical segmentation of the sediment influences the rate at which this buildup occurs. Loads from the Fox River contribute to the sediment PCBs in Zone 2, particularly in the surface layer. After the maximum concentrations of near 35 ug/gOC are reached near year 20, sediment PCB concentrations decrease to between 11.5 and 13.5 ug/gOC1 at the end of the 100 year simulation.

Computed water column PCB concentrations in Zones 3A and 3B for the no-action simulation are very similar, with annual average dissolved concentrations decreasing from near 2 ng/l to approximately 0.45 ng/l over the 100 year simulation. Sorbed PCB concentrations in the water column decrease from between 3.2 and 3.4 ug/gOC to between 0.6 and 0.7 ug/gOC. Sediment PCB concentrations in Zone 3A decline gradually through the 100 year simulation from initial conditions of between 9.2 and 10.8 ug/gOC to between 5.8 and 6.4 ug/gOC at the end of the simulation. Zone 3B sediment PCB concentrations decrease very rapidly through the first 5 to 10 years and then decline more slowly. This trend is due to resuspension in the segments adjacent to the Door Peninsula which results in exposure of less contaminated deeper sediments and deposition in significant parts of Zone 3B, which results in burial of surface sediments with cleaner sediments. Both water column and sediment concentrations in Zone 4 change much more slowly than in the other zones of the bay.

A series of wLFRM simulations were executed with changes in sediment initial conditions representing the effect of remediation of Fox River sediments with PCB concentrations exceeding a range of target concentrations (125 to 5000 ug/kg). PCB loads frrom the river to the bay from these runs were incorporated in 7 projection simulations. Results from the simulation with the first level of PCB load reductions (Figure 5-2), with a Fox River remediation target of 5000 ug/kg, are somewhat lower in Zone 2 but follow a similar trend compared to the no-action simulation. Zone 2 dissolved PCB concentrations in the water column decrease by between 0.5 and 0.6 ng/l and sorbed PCBs in the water column decrease by between 0.6 and 0.8 ug/gOC as a result of the remediation of Fox River sediments with concentrations greater than 5000 ug/kg. Zone 2 sediment PCB concentrations are reduced between 10 and 20 percent as a result of the remediation of Fox River sediments with concentrations greater than 5000 ug/kg. No significant change in PCB concentrations in Zones 3A, 3B, or 4 are calculated in response to the change in loads associated with the 5000 ug/kg remediation target.

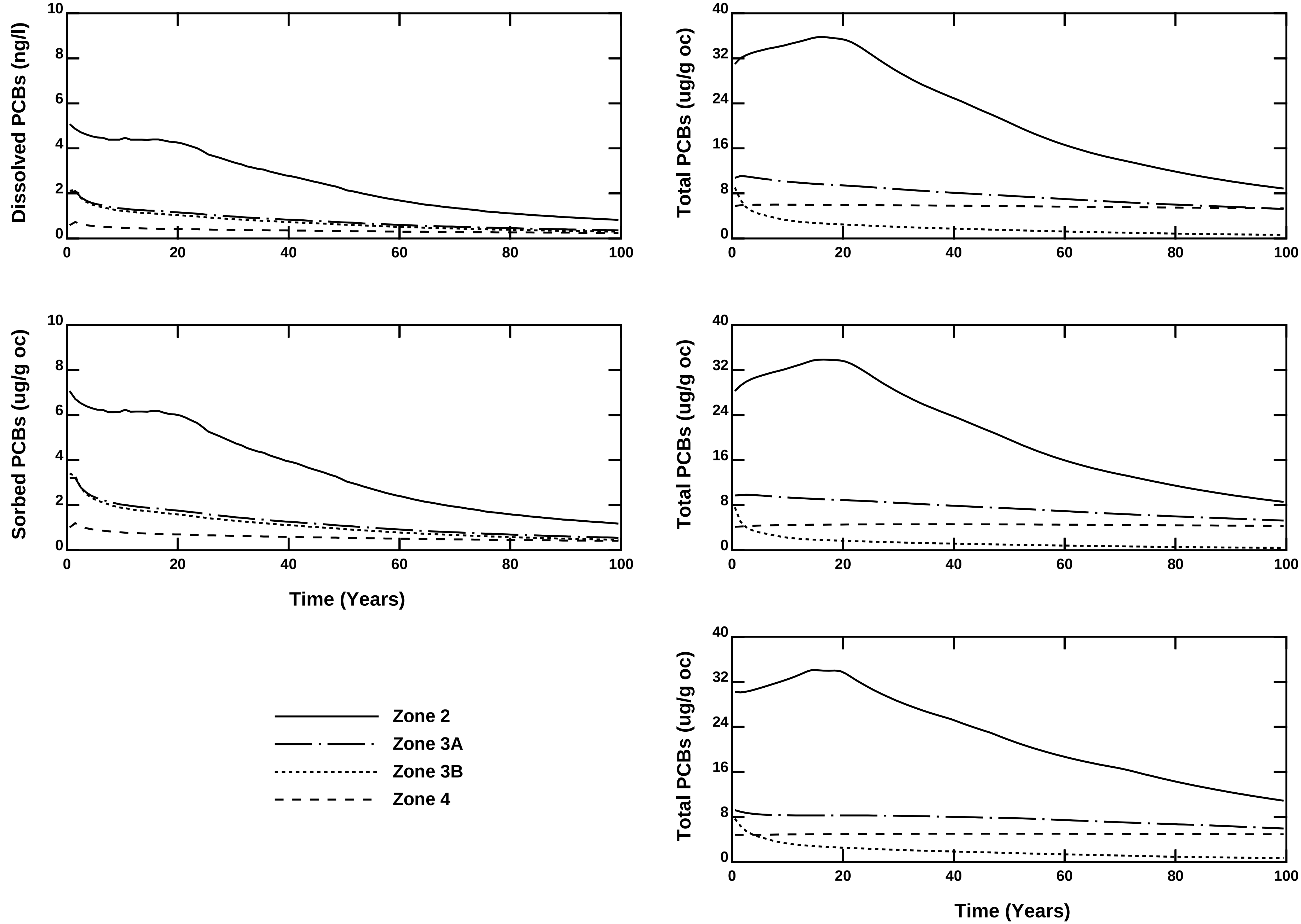


Figure 5-2 **Annual Average Water Column and Sediment PCBs**
Fox River Scenario 5000 ug/kg Target Green Bay Scenario No Action

Results from projections which simulate with additional remediation efforts in the Fox River are presented on Figures 5-3 through 5-8. The incremental reduction in PCB loading to Green Bay computed in these simulations produces little change in computed water or sediment concentrations of PCBs in Green Bay. The results of these runs, however, are included for completeness.

The effects of two levels of remediation of sediments in Green Bay were investigated by changing initial concentrations of PCBs in the sediment segments of GBTOxe. The first level simulated the remediation of sediments with PCB concentration greater than 1000 ug/kg and the second represented the remediations of sediments exceeding 500 ug/kg. Each of these target levels for Green Bay were incorporated in simulations with some level of load reduction associated with remediation target levels for the Fox River of between 125 and 1000 ug/kg.

Based on the results presented on Figures 5-3 through 5-8, water and sediment quality in Green Bay is not noticeably affected by this range in Fox River remediation targets.

The effect of remediation of Green Bay sediments with PCB concentrations greater than 1000 ug/kg has a substantial effect on water column and sediment PCB concentrations in Zone 2 (Figure 5-9). Sediment PCB concentrations decline from the initial conditions, rather than increasing, as was calculated in the no-action simulation, in response to the upward transport of more highly contaminated sediment during resuspension events. In the first year of the simulation annual average dissolved and sorbed water column PCB concentrations in Zone 2 are reduced by more than 50 percent as a result of the remediation of Green Bay sediments with concentrations greater than 1000 ug/kg. The greater than 50 percent reduction in Zone 2 persists through the 100 year simulation, although the absolute magnitude of the concentration changes decrease in time. The effect of the 1000 ug/kg remediation target for Green Bay is greater in Zone 3A sediments than in Zone 3B sediments, although the effect on the water column in these two zones is fairly similar. As a result of this remediation, the water column concentrations across the four zones are fairly uniform. PCB concentrations in the upper 4 cm of the sediment are also fairly uniform, with the exception of Zone 3B which is lower due to the higher rate of sediment deposition computed there.

Expanding the remediation of Green Bay sediments to include areas where PCB concentrations exceed 500 ug/kg produces fairly small incremental changes in Green Bay water and sediment quality. Figure 5-10 presents results for this simulation (coupled with a Fox River remediation target of 500 ug/kg). The incremental improvements are diminish over time so that through most of the simulation changes in concentration, in bot the water column and sediment, are fairly small. The component affected most by this incremental remediation is the sediment of Zone 3A, where concentrations decrease be roughly 10 percent in the first 10 years of the simulation. Water column concentrations in Zone 3A decrease by roughly 20 percent initially, however, by year five of the simulation the change approaches 10 percent and continues to decrease. Temporal plots of the remaining simulations which include Green Bay remediation targets of

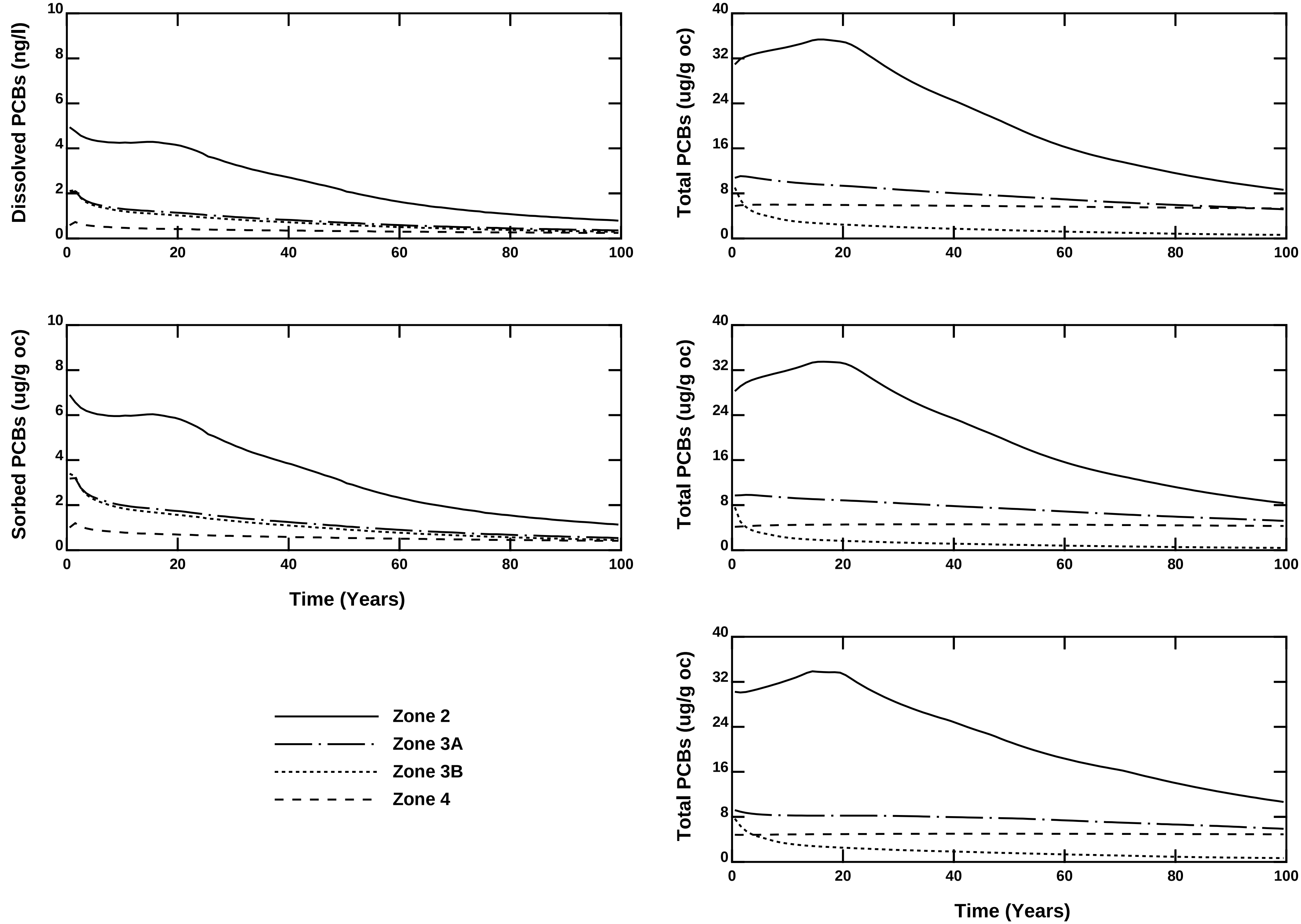


Figure 5-3 Annual Average Water Column and Sediment PCBs
Fox River Scenario 1000 ug/kg Target Green Bay Scenario No Action

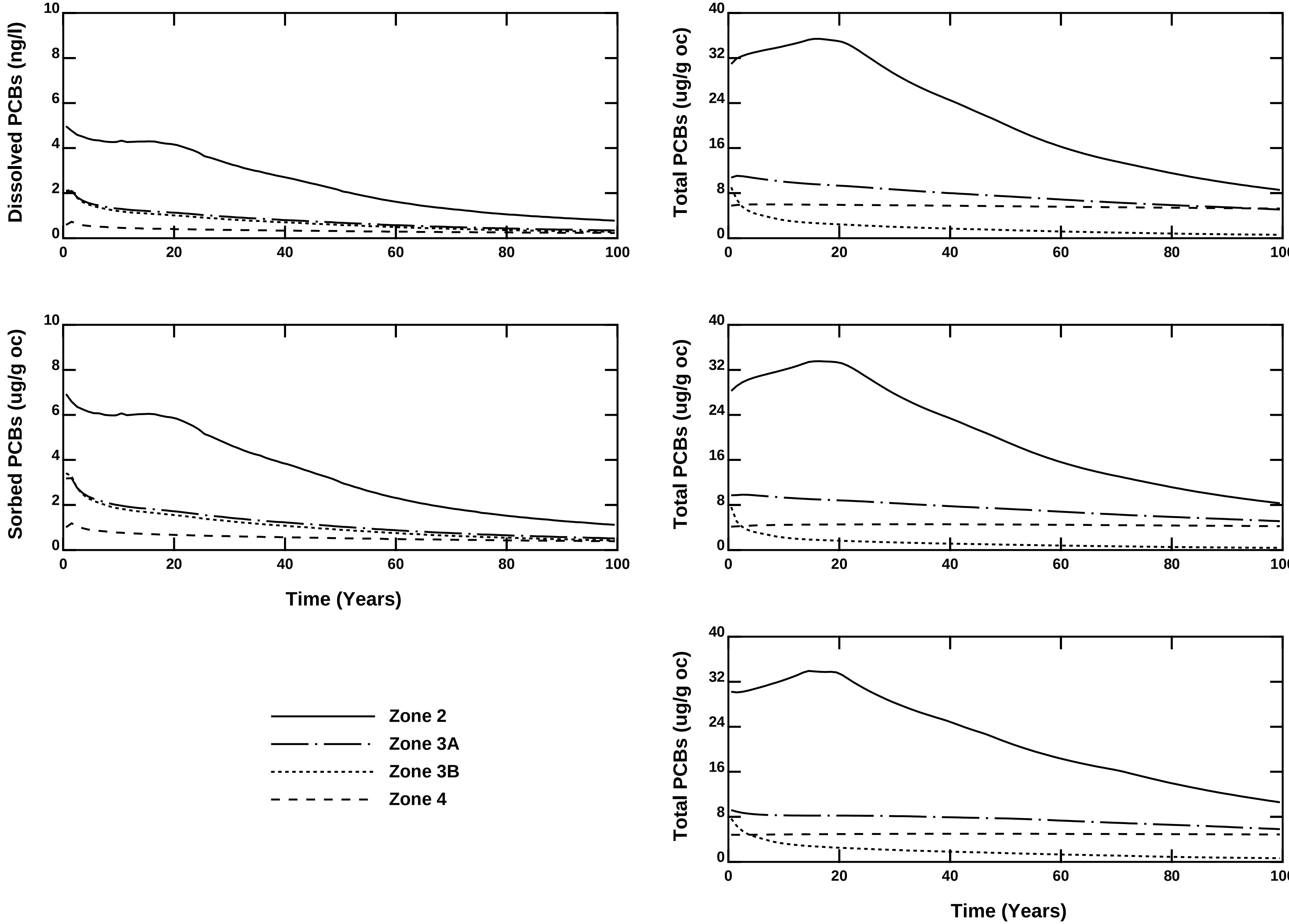


Figure 5-4 **Annual Average Water Column and Sediment PCBs**
Fox River Scenario I **Green Bay Scenario No Action**

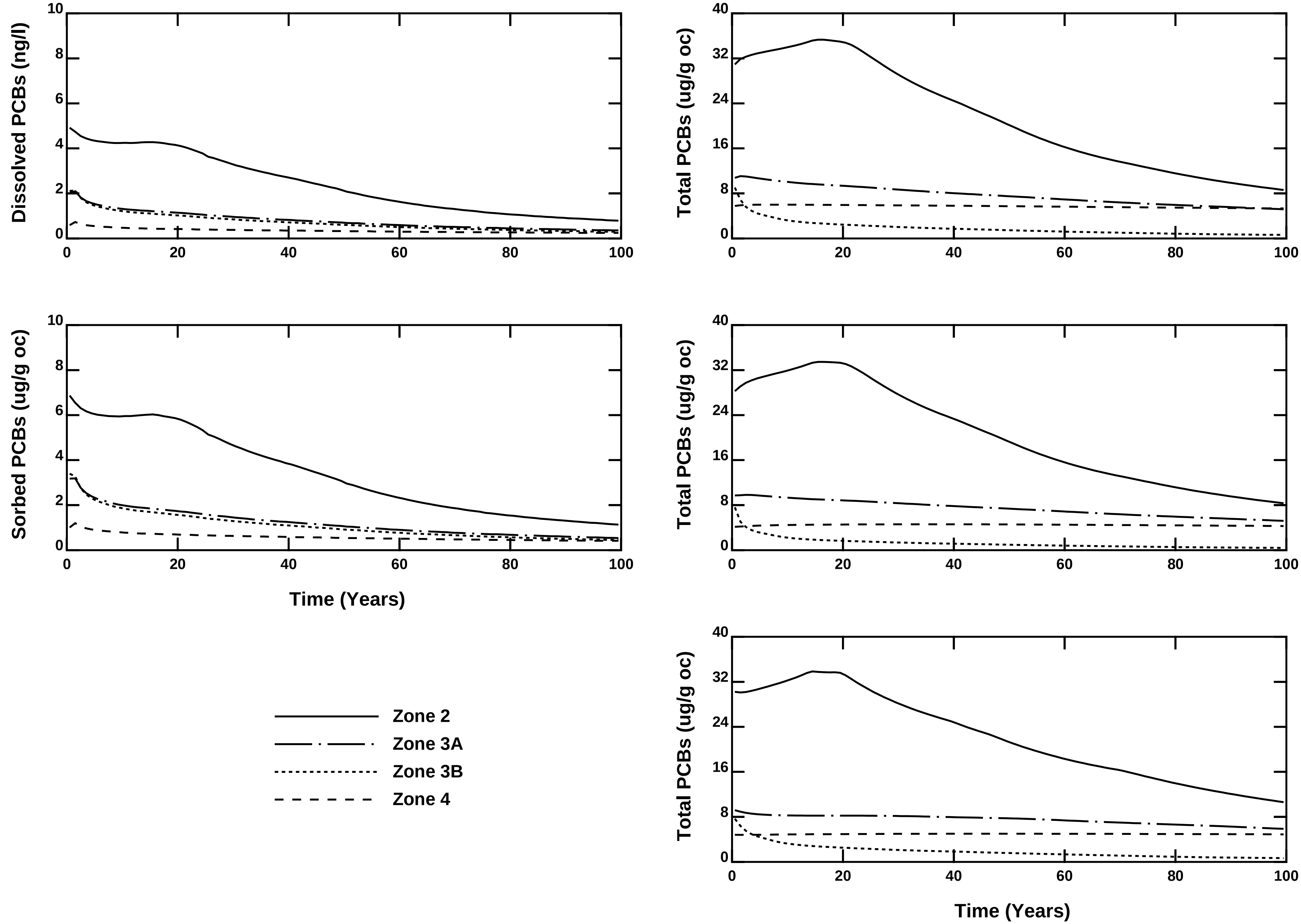


Figure 5-5 **Annual Average Water Column and Sediment PCBs**
Fox River Scenario 500 ug/kg Target Green Bay Scenario No Action

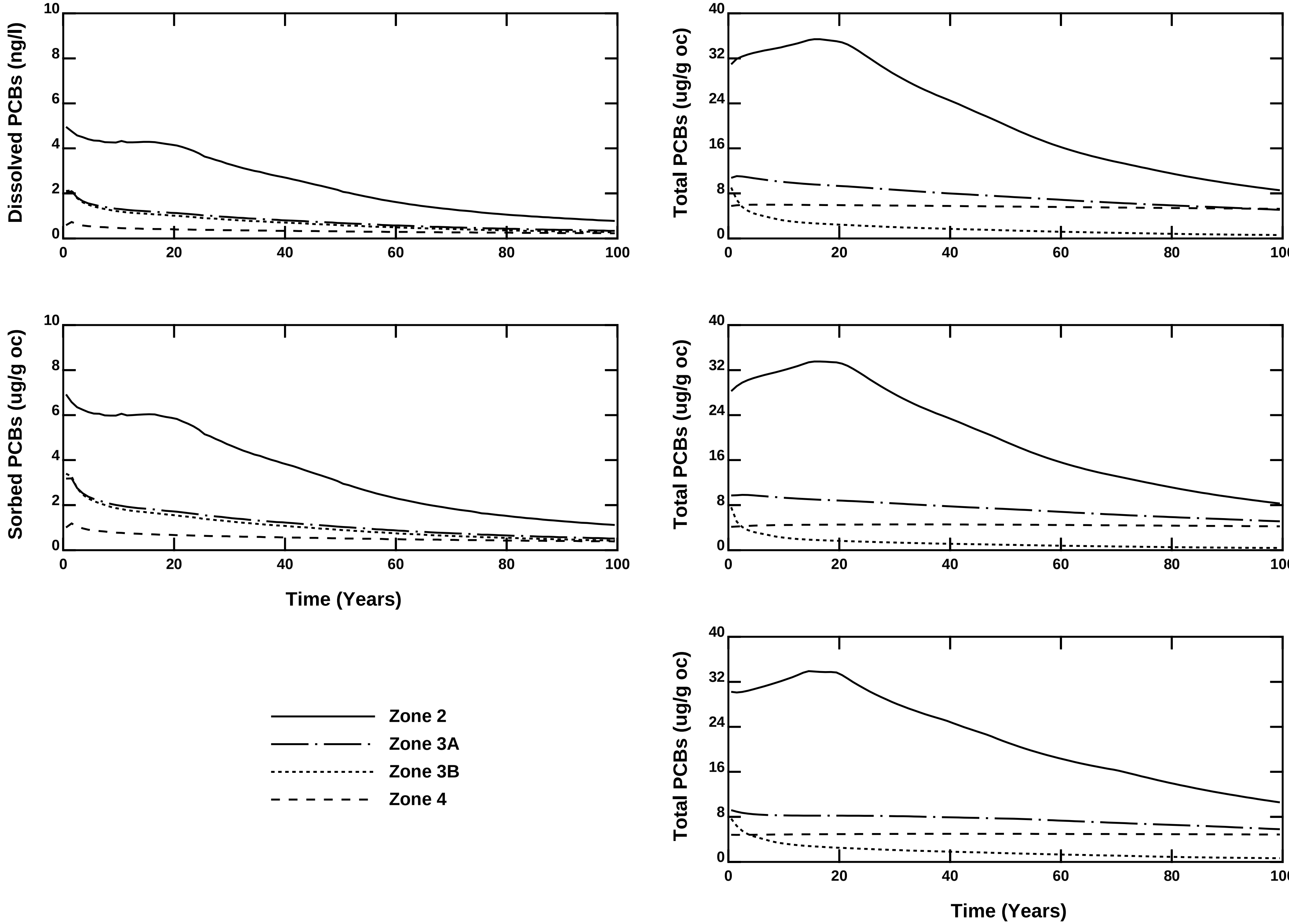


Figure 5-6 **Annual Average Water Column and Sediment PCBs**
Fox River Scenario H **Green Bay Scenario No Action**

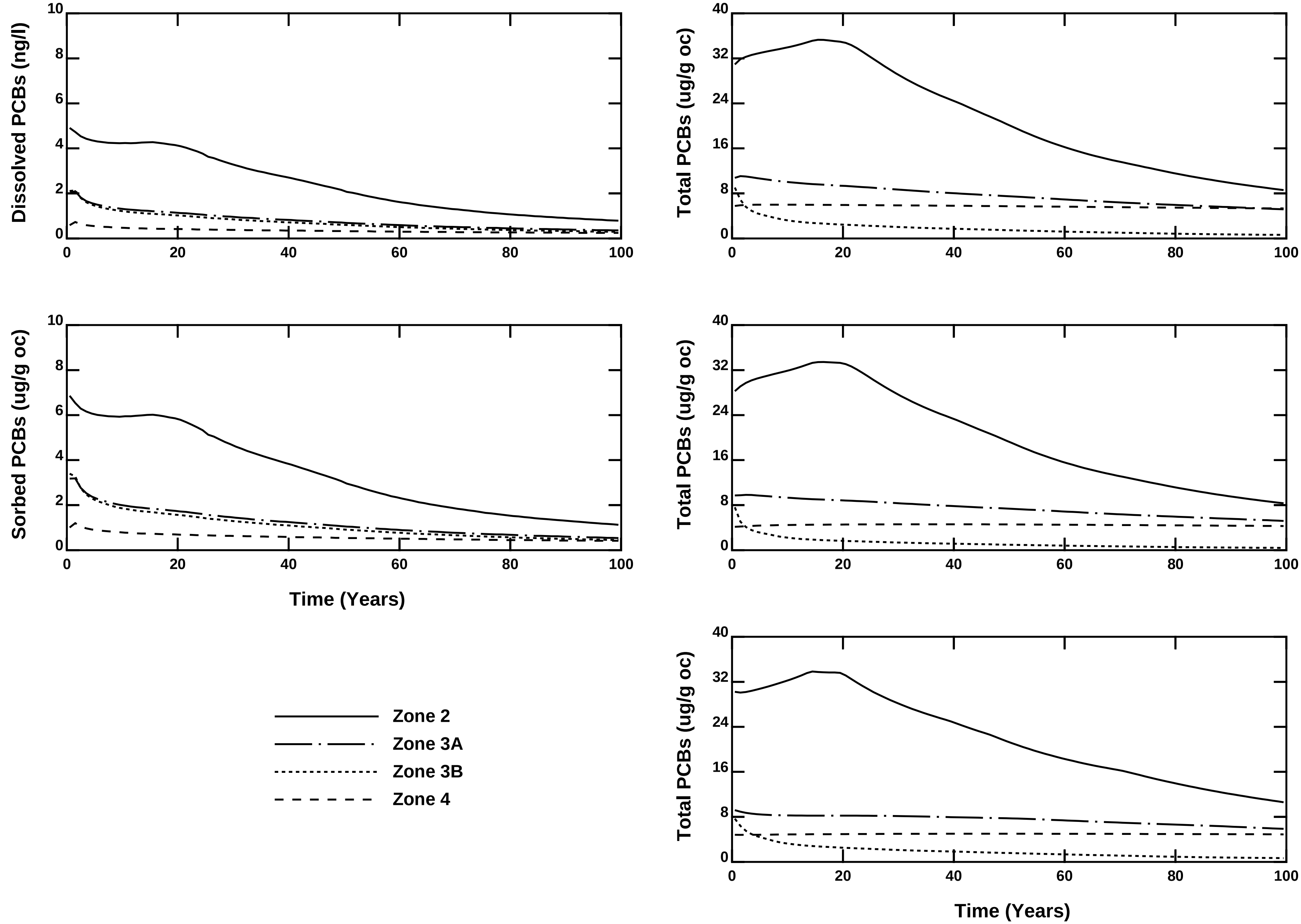


Figure 5-7 Annual Average Water Column and Sediment PCBs
Fox River Scenario 250 ug/kg Target Green Bay Scenario No Action

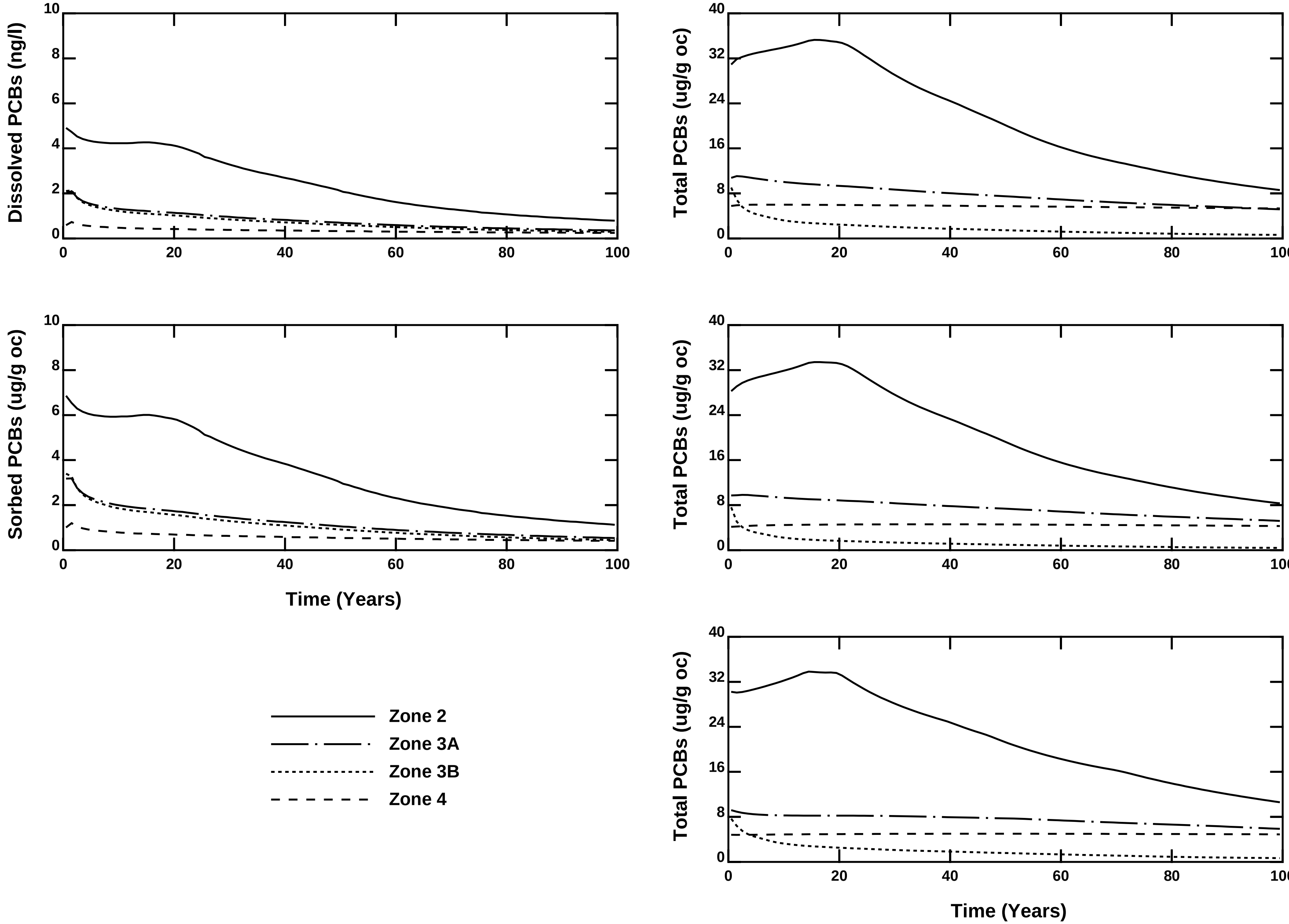


Figure 5-8 **Annual Average Water Column and Sediment PCBs**
Fox River Scenario 125 ug/kg Target Green Bay Scenario No Action

1000 and 500 ug/kg are presented on Figures 5-11 through 5-15, although these results are very similar to Figures 5-9 and 5-10.

5.4 COMPARISONS AMONG REMEDIATION SIMULATIONS

5.4.1 No Action Simulation

The most significant feature of the100 year GBTOXe simulations is the computed redistribution of PCB contamination in the sediments of the bay. Figure 5-16 shows the spatial distribution of PCBs (presented in units of mass per area) at the beginning and end of the no-action simulation. The spatial distributions shown on Figure 5-16 represent the sum of the PCB mass in each of the four sediment layers included in GBTOXe. The PCB distribution at the start of the simulation includes high concentrations of PCBs in the shallow areas of Zone 2 near the mouth of the Fox River and at the northern boundary of Zone 2 along the Door Peninsula. Through the 100 year no-action simulation, the net PCB export from the sediments of Zone 2 exceeds 20,000 kg. Coincident with this export are calculated accumulations of PCBs in Zones 3A, 3B, and 4, of approximately 8700, 6700, and 3300 kg, respectively. The spatial distribution of sediment PCBs at the end of the 100 year no-action simulation shows the export of PCBs from the more highly contaminated areas in the southern portion of Zone 2. Net accumulation of PCBs in Zone 4 are calculated predominantly in the southern portion of the zone. Net sedimentation through much of Zone 3B, with the exception of segments adjacent to the Door Peninsula results in a decline in PCB concentrations in the upper 10 cm, despite the net mass accumulation seen on Figure 5-16. Figure 5-17 presents the change in the PCB inventory in each of the zones of the bay at 25 year intervals through the 100 year simulation. The redistribution of PCBs from Zone 2 to the remaining zones is apparent as the mass of PCBs in Zone 2 declines from almost 28,000 kg to roughly 7,000 kg during the simulation. The transport of the resuspended PCBs to Zones 3A, 3B, and 4 contributes to the increase in PCBs in the remainder of the bay. At the start of the simulation, Zones 3A and 3B contained 27 and 21 percent, respectively, of the PCBs present in the sediments of the bay. At the end of the 100 year simulation, Zones 3A and 3B are calculated to contain roughly 40 and 32 percent, respectively, of the PCBs in the bay sediments.

The overall decline in the total PCB inventory from approximately 71,000 to 68,000 kg through the 100 year no-action simulation represents the net of several source and sink terms, as shown on Figure 5-18. Figure 5-18a presents source and sink terms for the no-action simulation averaged over the entire year 100 year simulation, along with the overall decline in the PCB inventory of the Bay. The average loading rate of 71 kg/yr is dominated by the loads from the Fox River, which decline in time by approximately a factor of two (Figure 5-18b). The average net export to Lake Michigan during the 100 year no-action simulation is approximately 10 kg/yr. This net flux represents a small difference between an average advective loss from Green Bay to Lake Michigan of 226 kg/yr which occurs when the flow direction is from the bay to the lake, and an average advective source of approximately 216 kg/yr which occurs when the flow direction is from the lake to the bay. The mass flux across the boundary with Lake Michigan is

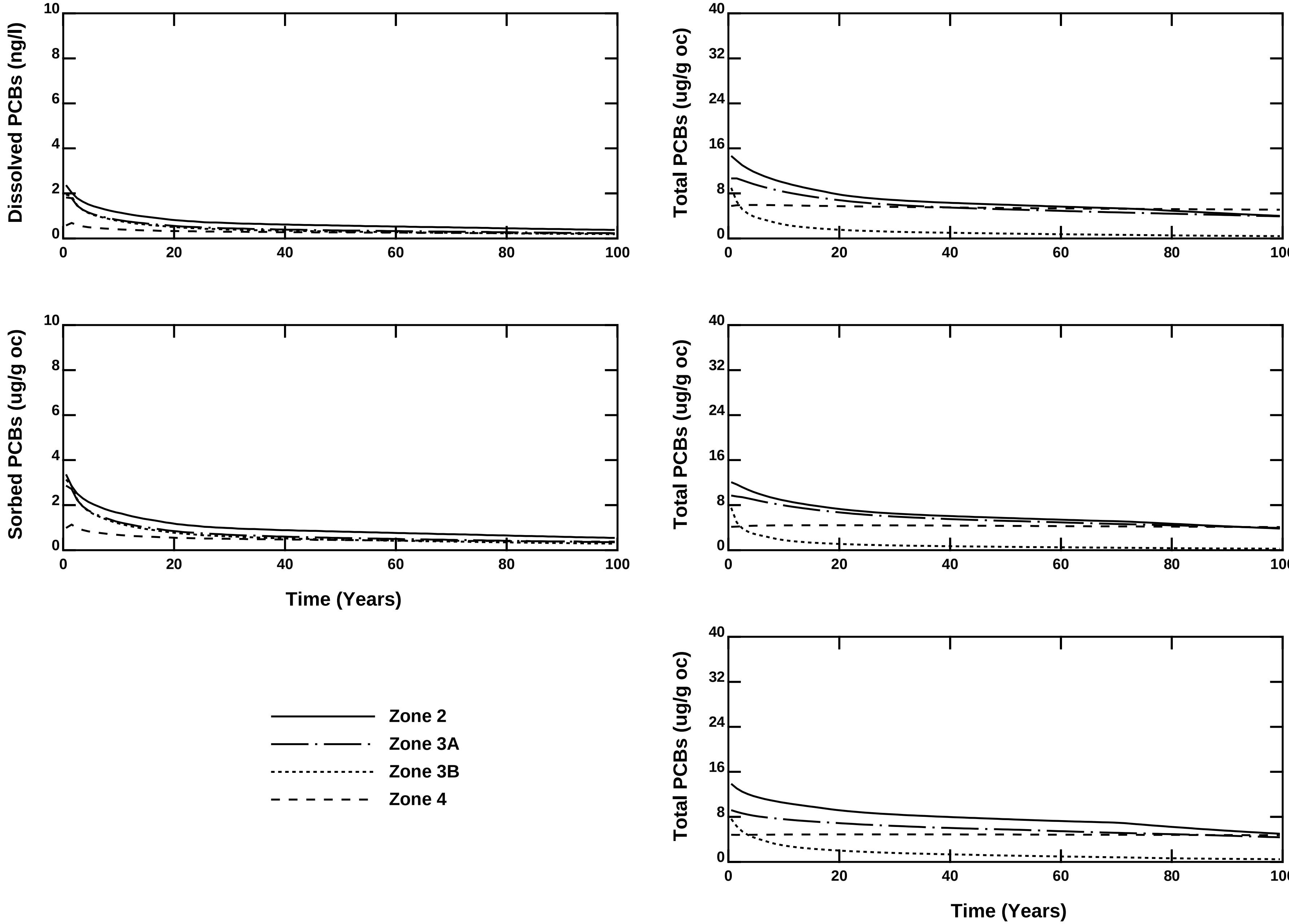


Figure 5-9 **Annual Average Water Column and Sediment PCBs**
Fox River Scenario 500 ug/kg Target Green Bay Scenario 1000 ug/kg Target

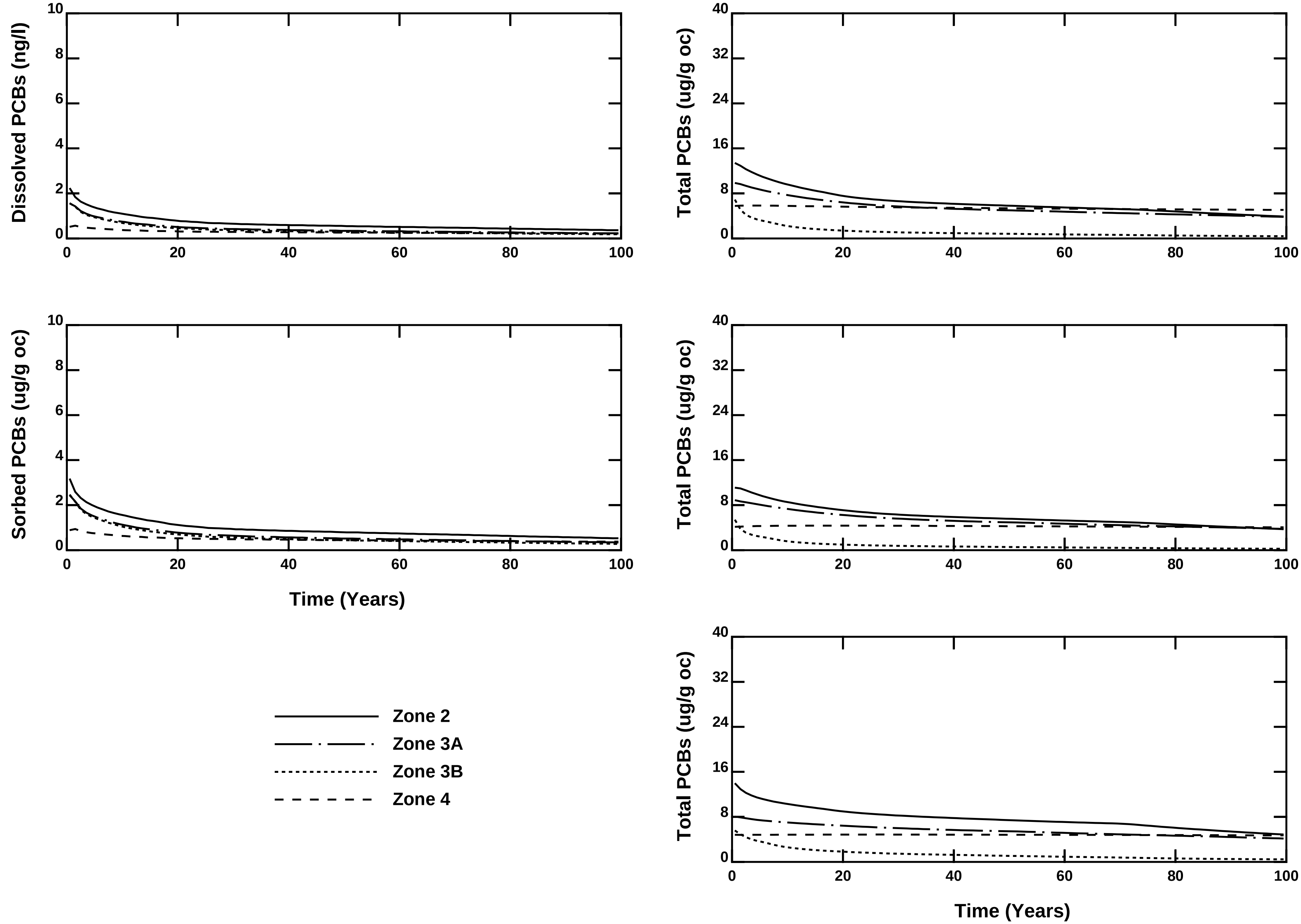


Figure 5-10 **Annual Average Water Column and Sediment PCBs**
Fox River Scenario 500 ug/kg Target **Green Bay Scenario 500 ug/kg Target**

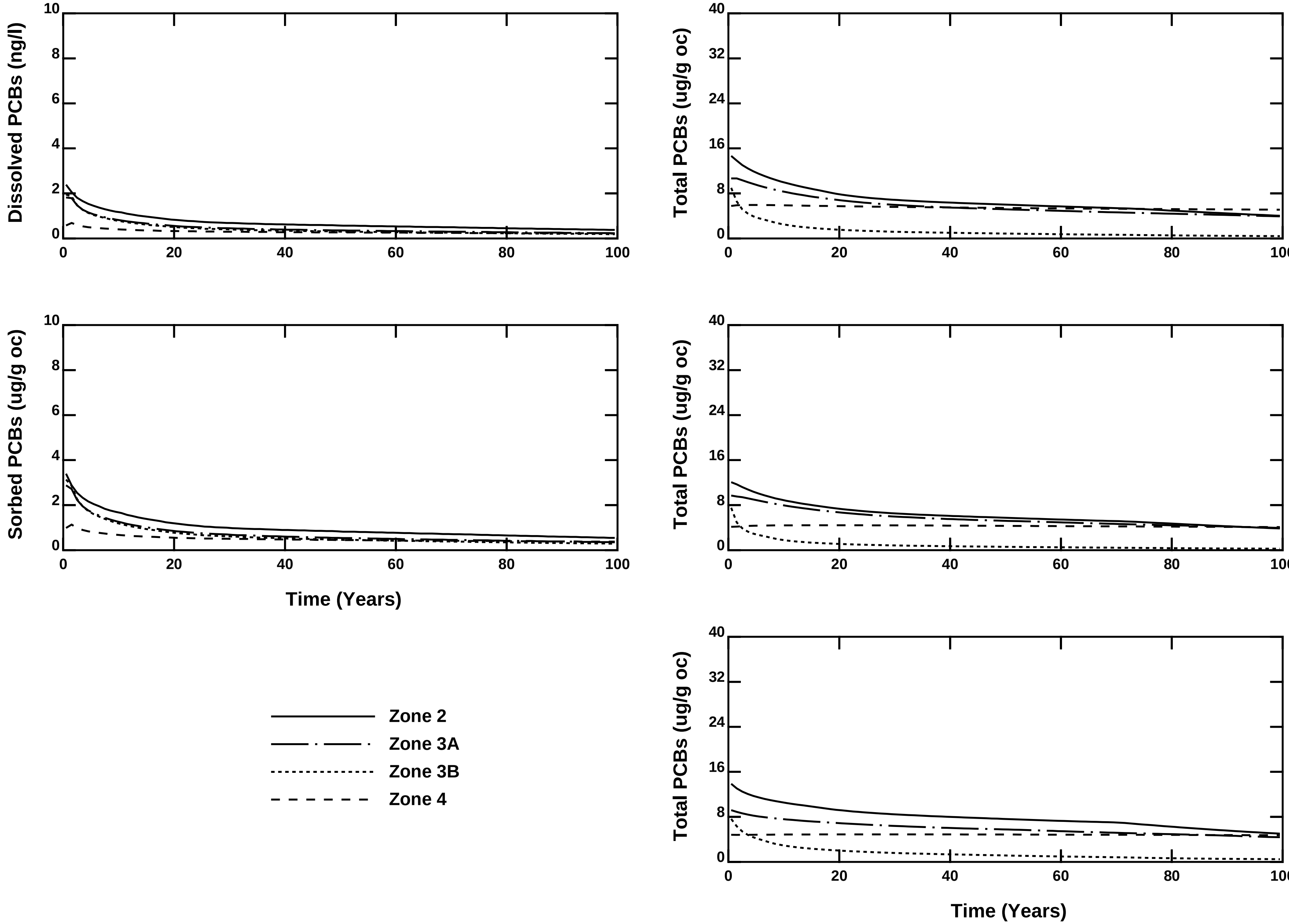


Figure 5-11 Annual Average Water Column and Sediment PCBs
Fox River Scenario 1000 ug/kg Target Green Bay Scenario 1000 ug/kg Target

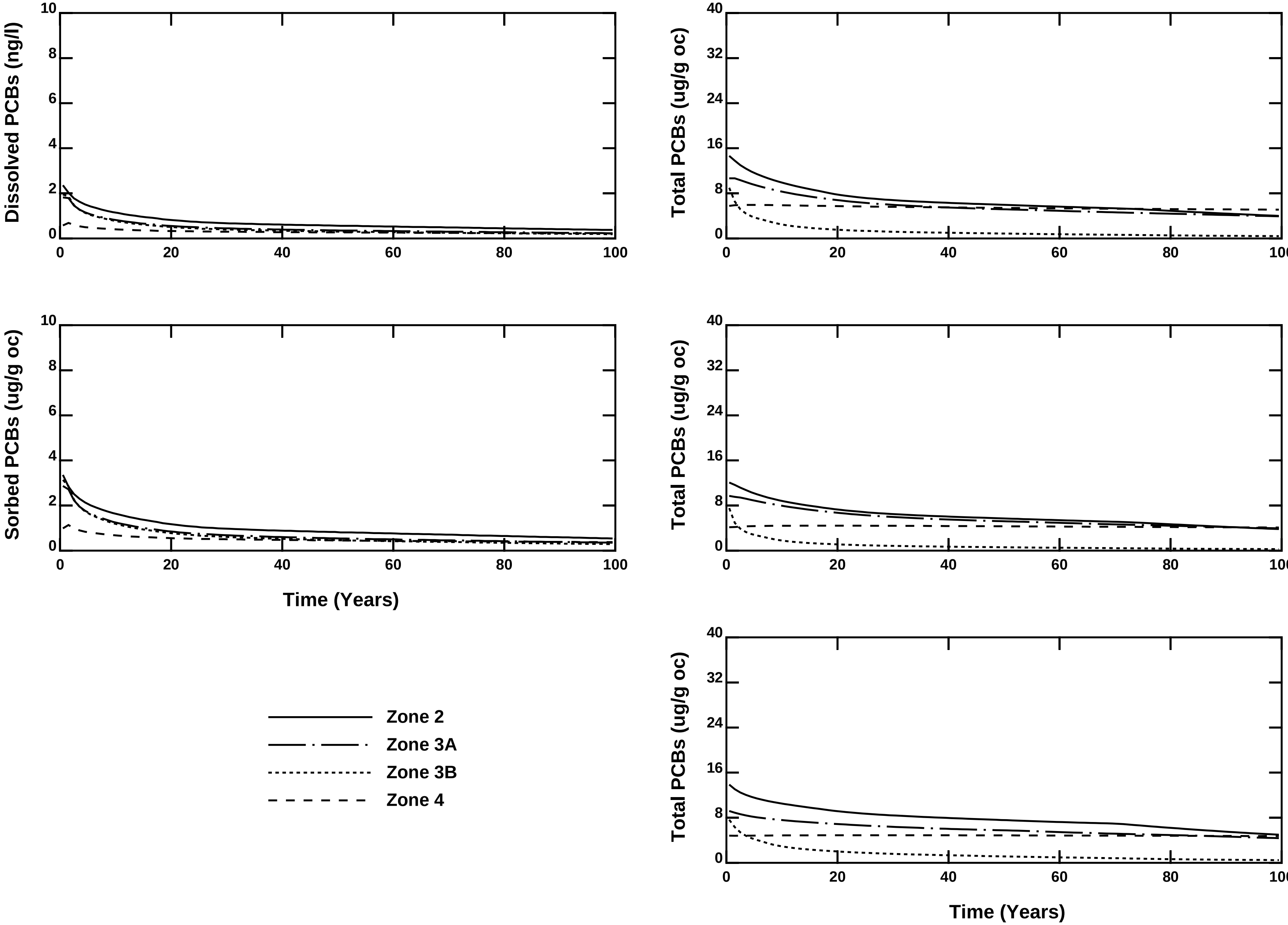


Figure 5-12 Annual Average Water Column and Sediment PCBs
Fox River Scenario 250 ug/kg Target Green Bay Scenario 1000 ug/kg Target

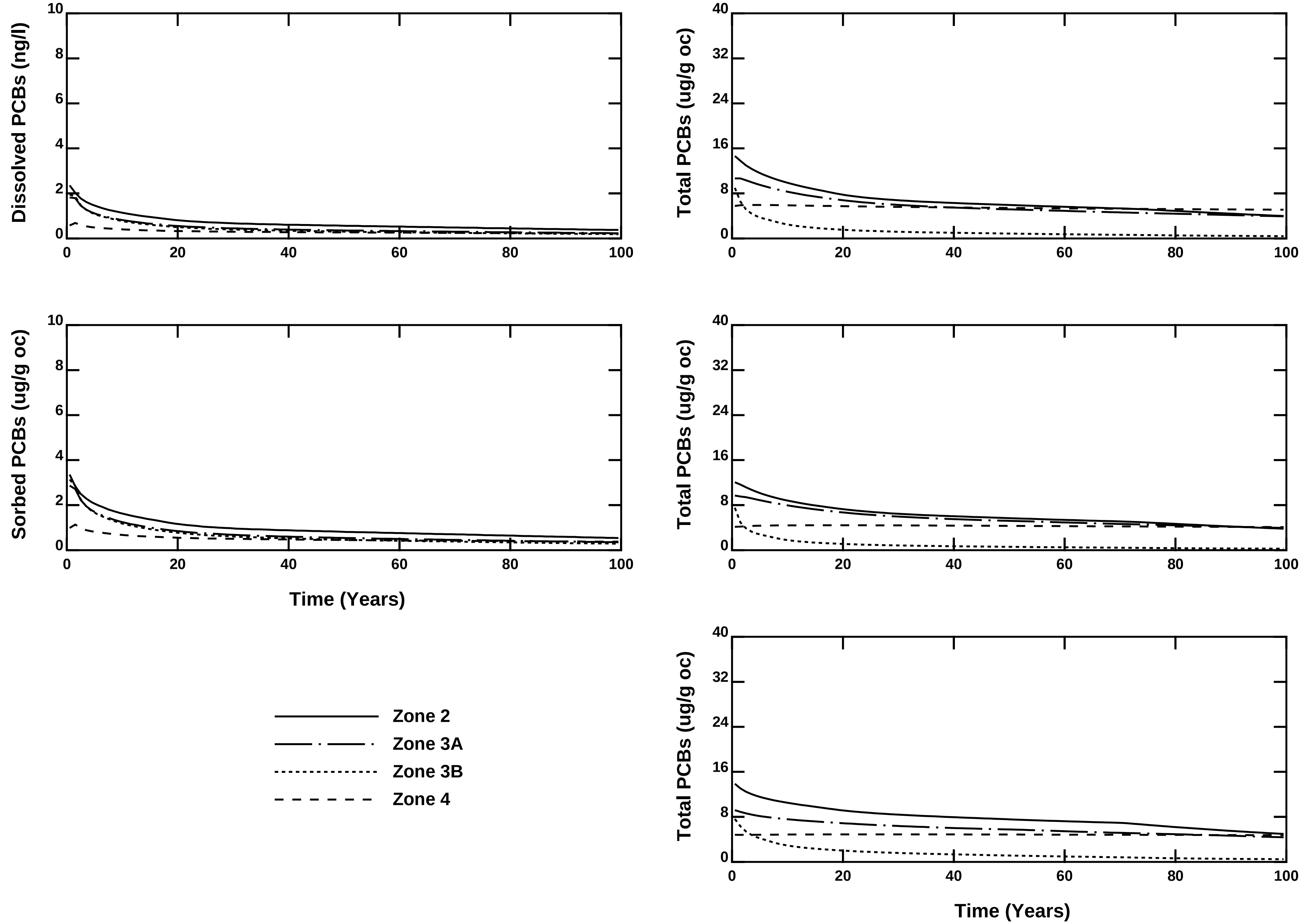


Figure 5-13 Annual Average Water Column and Sediment PCBs
Fox River Scenario 125 ug/kg Target Green Bay Scenario 1000 ug/kg Target

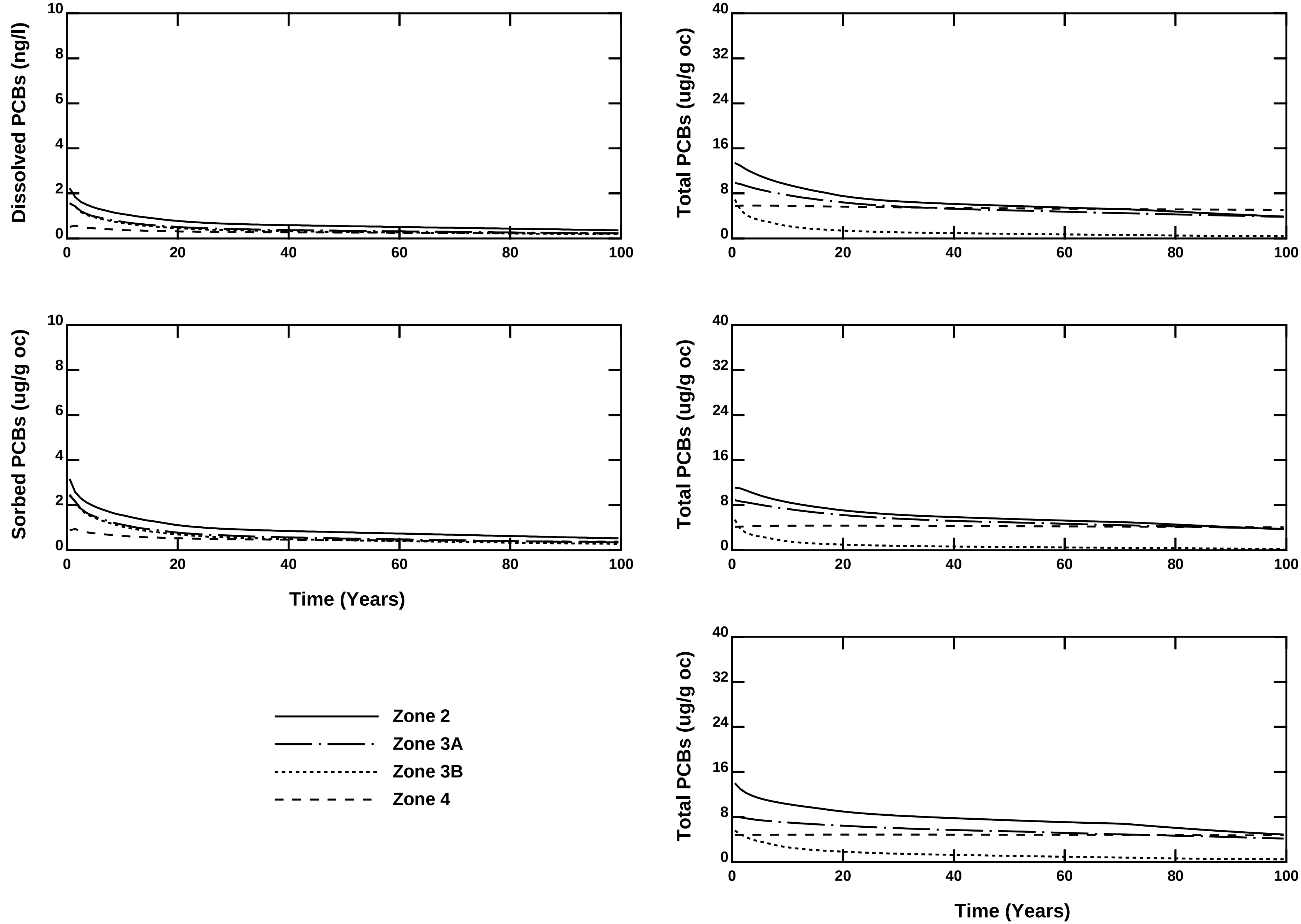


Figure 5-14 **Annual Average Water Column and Sediment PCBs**
Fox River Scenario 250 ug/kg Target Green Bay Scenario 500 ug/kg Target

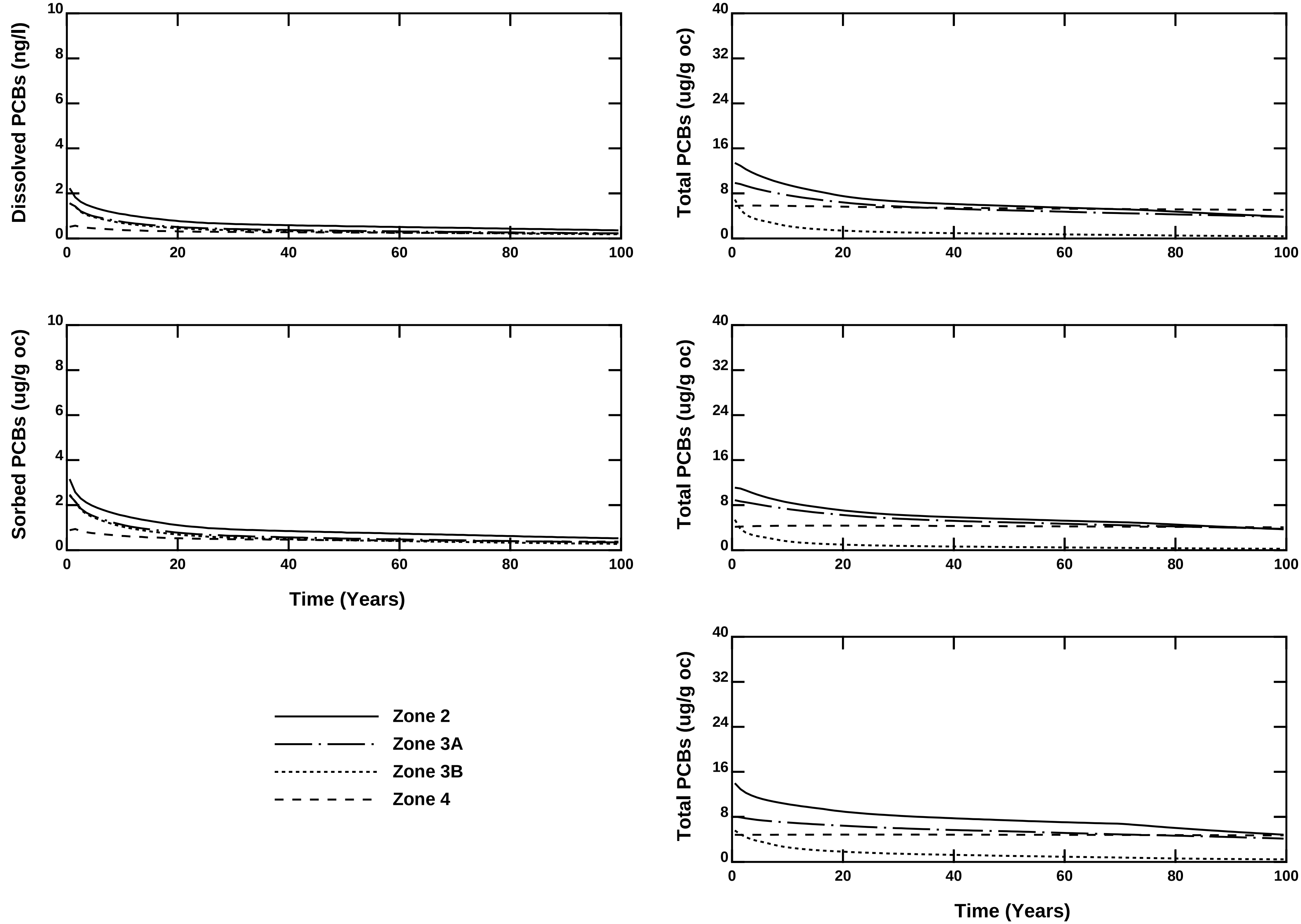


Figure 5-15 Annual Average Water Column and Sediment PCBs
Fox River Scenario 125 ug/kg Target Green Bay Scenario 500 ug/kg Target

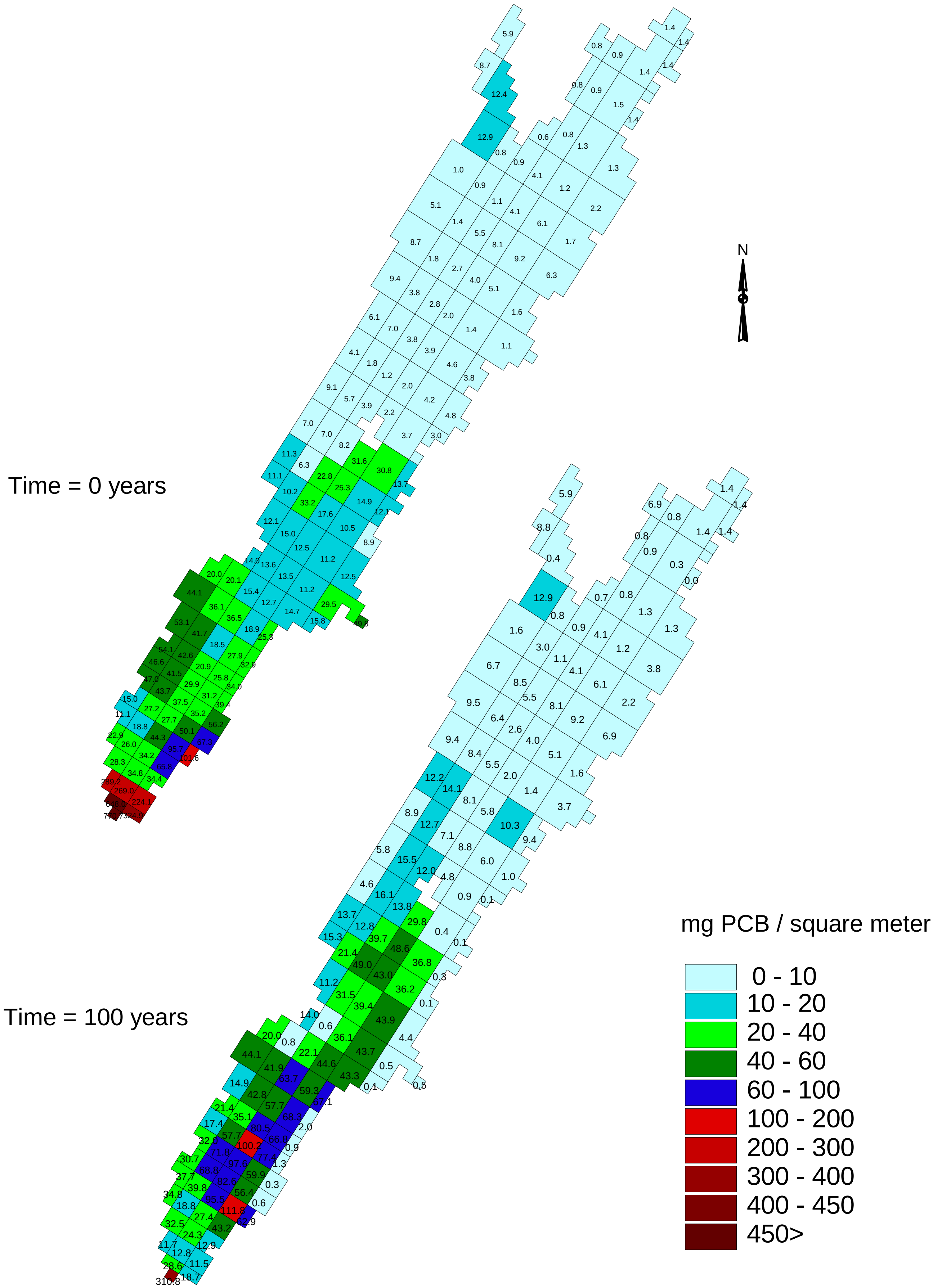
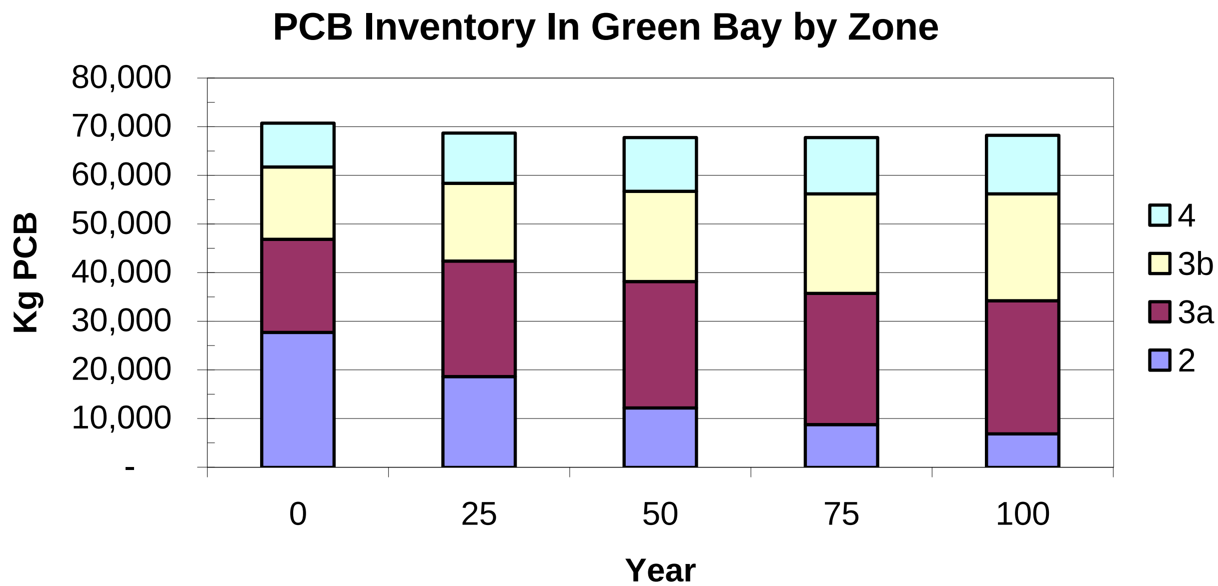


Figure 5-16 PCB Mass per Unit Area in Sediments
Before and After Natural Recovery Simulation



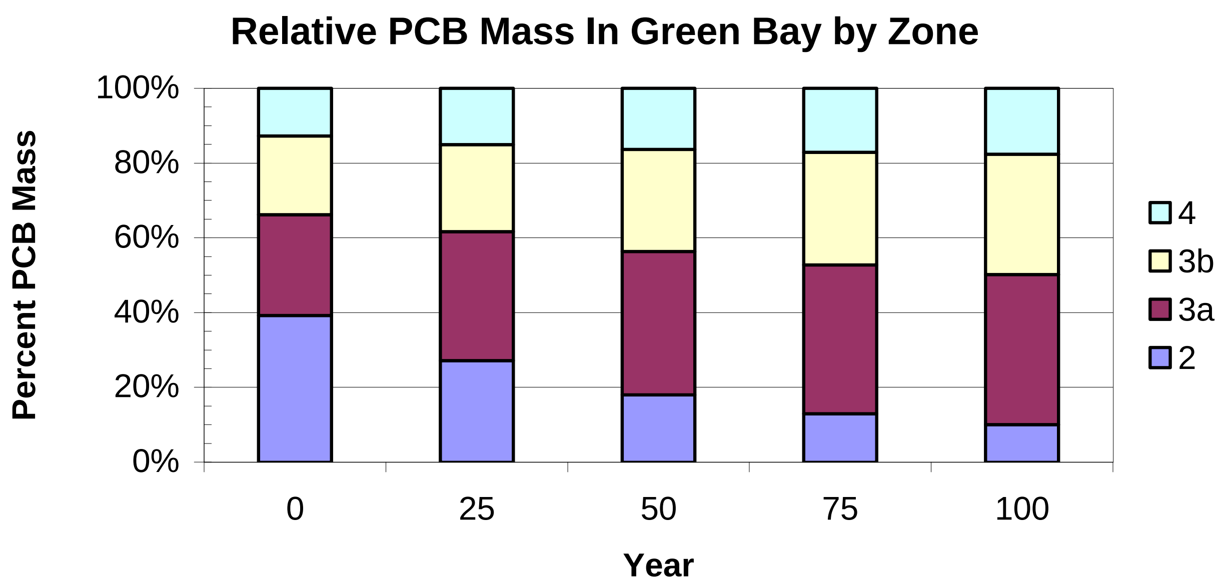


FIGURE 5-17 PCB Mass Inventory Distributed By Zone - No Action Scenario

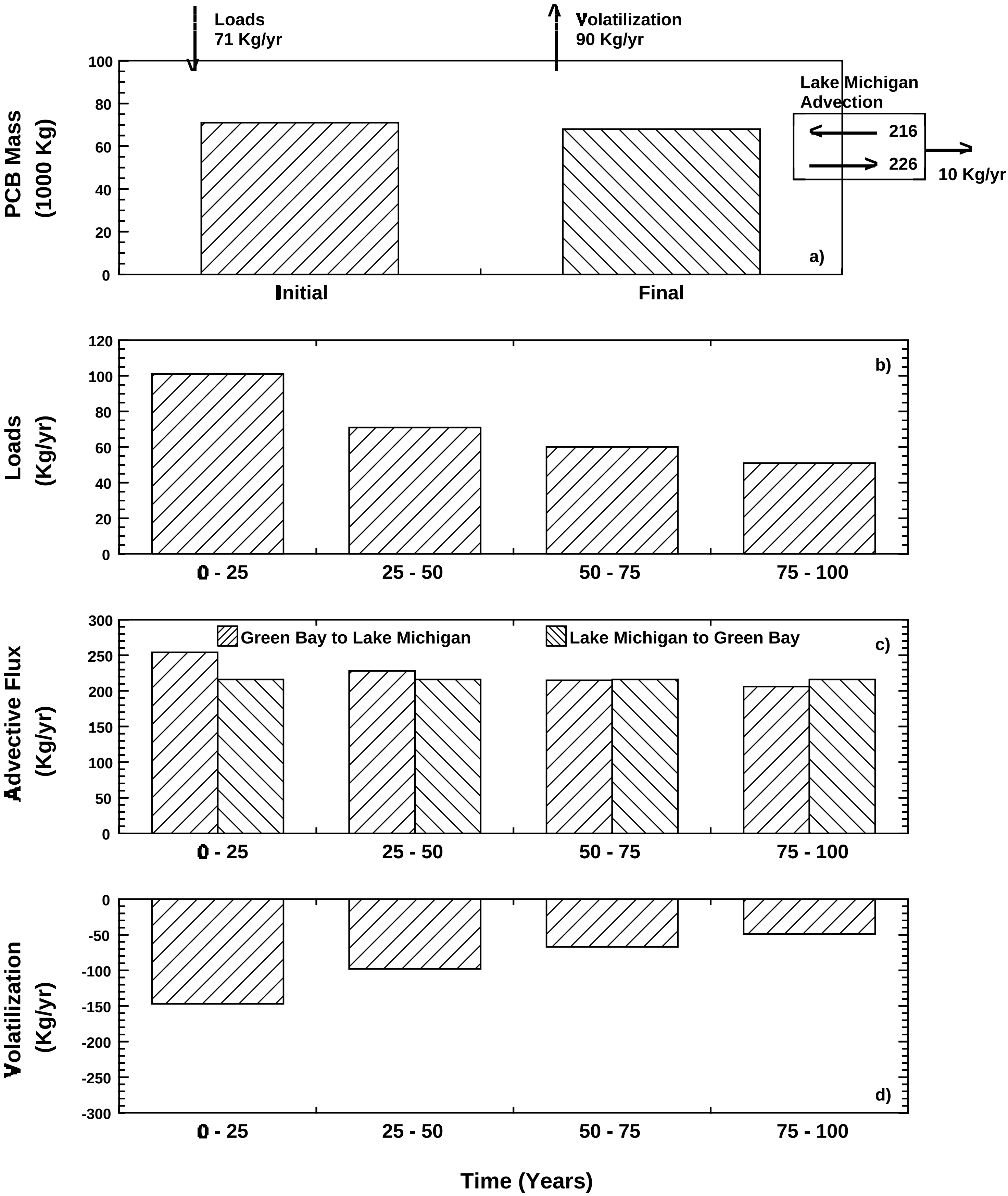


Figure 5-18. Summary Of Green Bay PCB Inventory And Source/Sink Pathways From 100 Year No Action Simulation

influenced by an assigned PCB boundary condition in the lake of 0.52 ng/l, which was carried forward from GBTOX (DePinto et.al, 1993) and maintained constant in time. The constant Lake Michigan boundary condition and the annually repeating hydrodynamic transport patterns combine to produce a temporally constant annual average advective source term for periods when the flow direction is from the lake to the bay. The advective loss of PCBs during periods when the flow direction is from the bay to the lake decreases in time (Figure 5-18c) as the water column concentrations in the bay decrease through the 100 year simulation. During the last 25 years of the simulation, advection across the Lake Michigan boundary represents a net source of PCBs to the bay due to the constant boundary condition in Lake Michigan and the decreasing water column concentrations in the bay. PCB losses from Green Bay due to volatilization average 90 kg/yr during the 100 year simulation, with temporal variations between almost 150 kg/yr during the first 25 years to approximately 50 kg/yr during the final 25 years of the simulation (Figure 5-18d). The decrease in the volatilization loss is due to decreases in water column concentration through the 100 year simulation.

The overall conclusion drawn from this simulation is that the transport of PCBs to Lake Michigan and volatilization to the atmosphere represents a only a relatively small fraction of the total PCB inventory in Green Bay. The more dramatic feature in computed PCB concentrations is the change in the spatial distribution of PCBs within Green Bay. These computed results are influenced by the use of the hydrodynamic circulation patterns from 1989, which vary from hour to hour for a duration of 1 year but are repeated annually for each of the 100 years of the simulation.

5.4.2 Response to Fox River Remediation Scenarios

The response of Fox River water and sediment quality to a range of remediation scenarios was evaluated by WDNR through application of wLFRM (WDNR, 2001b). The response of Green Bay water and sediment quality to alternate Fox River remediation scenarios was evaluated by incorporating wLFRM results describing PCB loads from the Fox River to Green Bay, into 100 year-long GBTOXe simulations. Comparisons of the results of runs with changes in Fox River loads due to a range of remediation alternatives, are presented on Figure 5-19 through 5-22. The results summarized on Figures 5-19 through 5-22 are from simulations in which no remedial action in Green Bay is included. These figures present a summary of annual average PCB concentrations computed in the water column (dissolved and sorbed) and in the upper 10 cm of the sediment (0-2, 2-4, 4-10 cm layers). For 25 year blocks of the simulation, the average and range of the concentrations are presented for the various remediation scenarios. The first column in each group represents the results from a simulation with no remedial activity of the Fox River sediments. The second column in each group represents results from the simulation with reduced Fox River loading, due to remediation of Fox River sediments with concentrations greater than 5000 ug/kg. Results for the remaining six Fox River remediation scenarios are very similar and are plotted together. The range in the 25 year block averages for these six scenarios are seen in the thickness of the top of the un-hatched column on the right of each group on Figures 5-19 through 5-22.

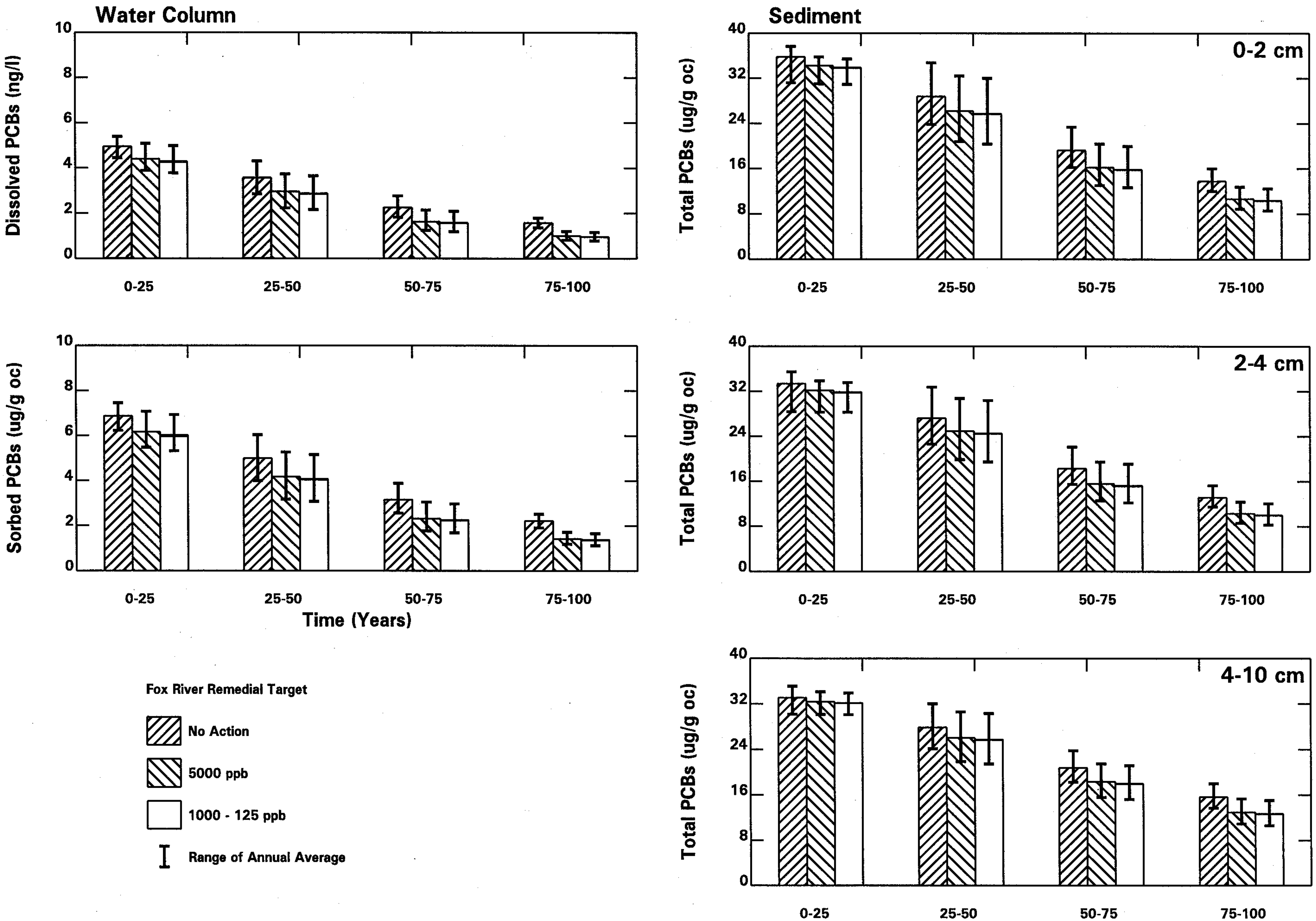


FIGURE 5-19 EFFECT OF FOX RIVER REMEDIATION ALTERNATIVES ON GREEN BAY PCBs - Zone 2
RESULTS FOR RUNS WITH NO REMEDIAL ACTIVITY IN GREEN BAY

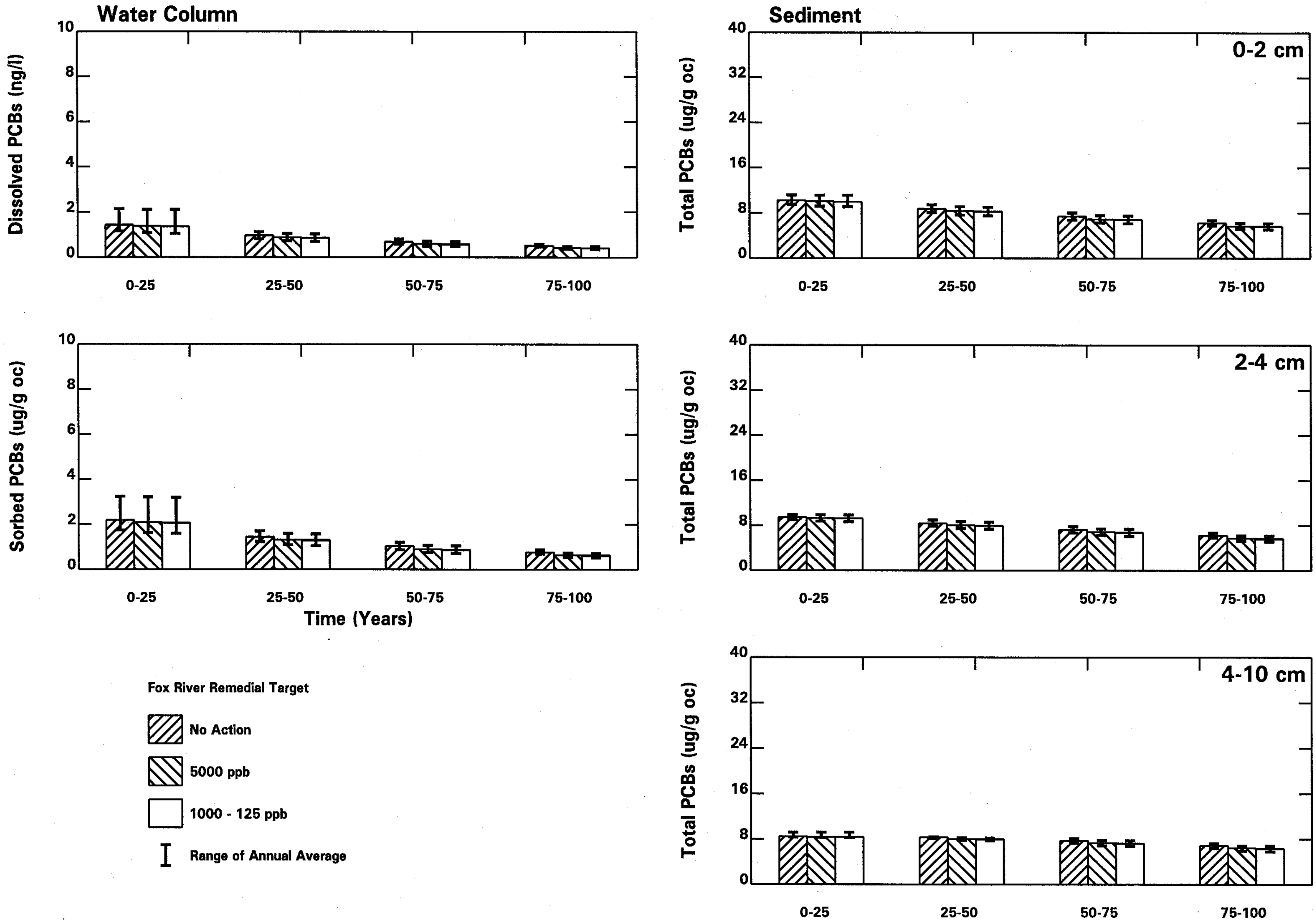


FIGURE 5-20 EFFECT OF FOX RIVER REMEDIATION ALTERNATIVES ON GREEN BAY PCBs - Zone 3A RESULTS FOR RUNS WITH NO REMEDIAL ACTIVITY IN GREEN BAY

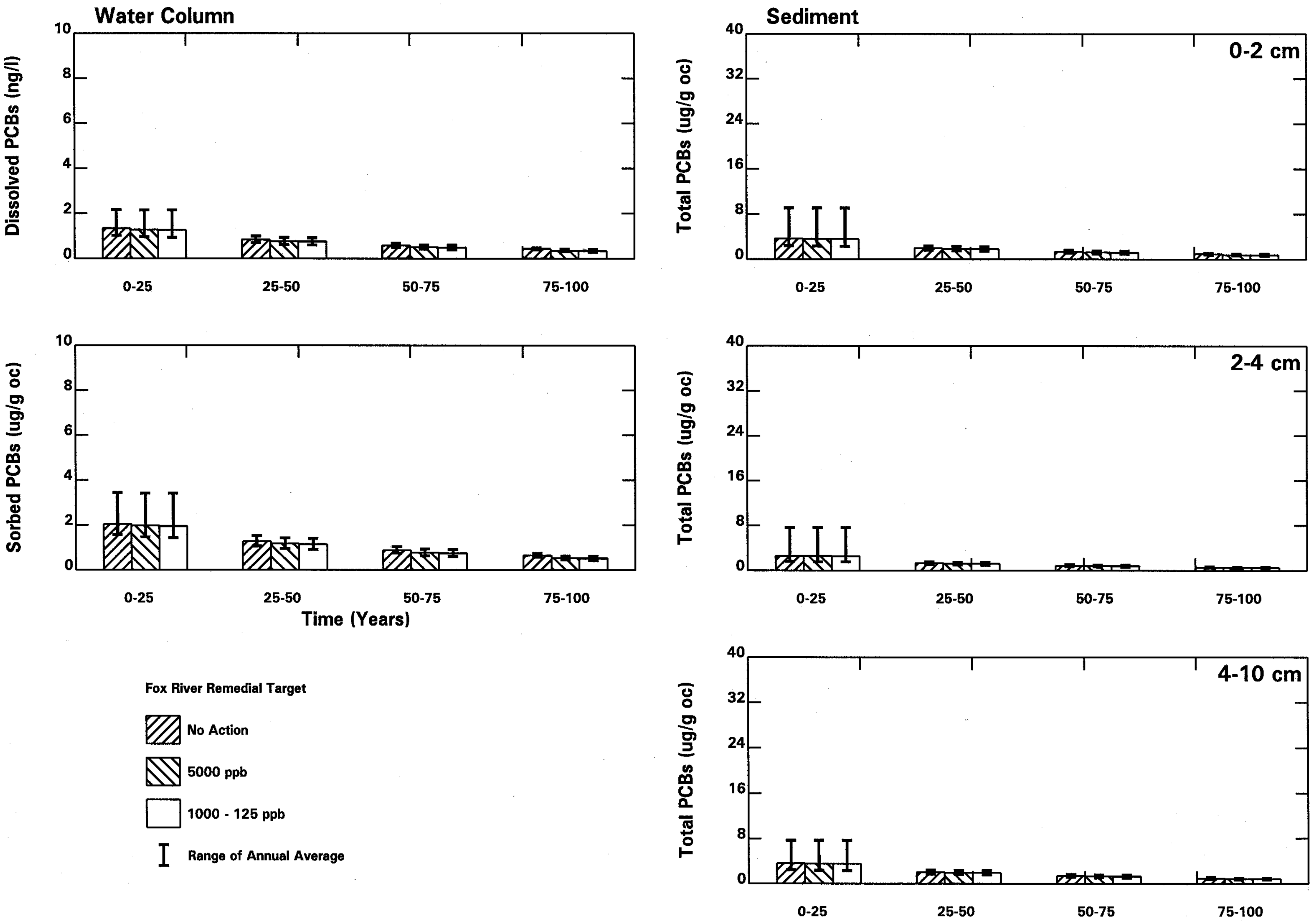


FIGURE 5-21 EFFECT OF FOX RIVER REMEDIATION ALTERNATIVES ON GREEN BAY PCBs - Zone 3B RESULTS FOR RUNS WITH NO REMEDIAL ACTIVITY IN GREEN BAY

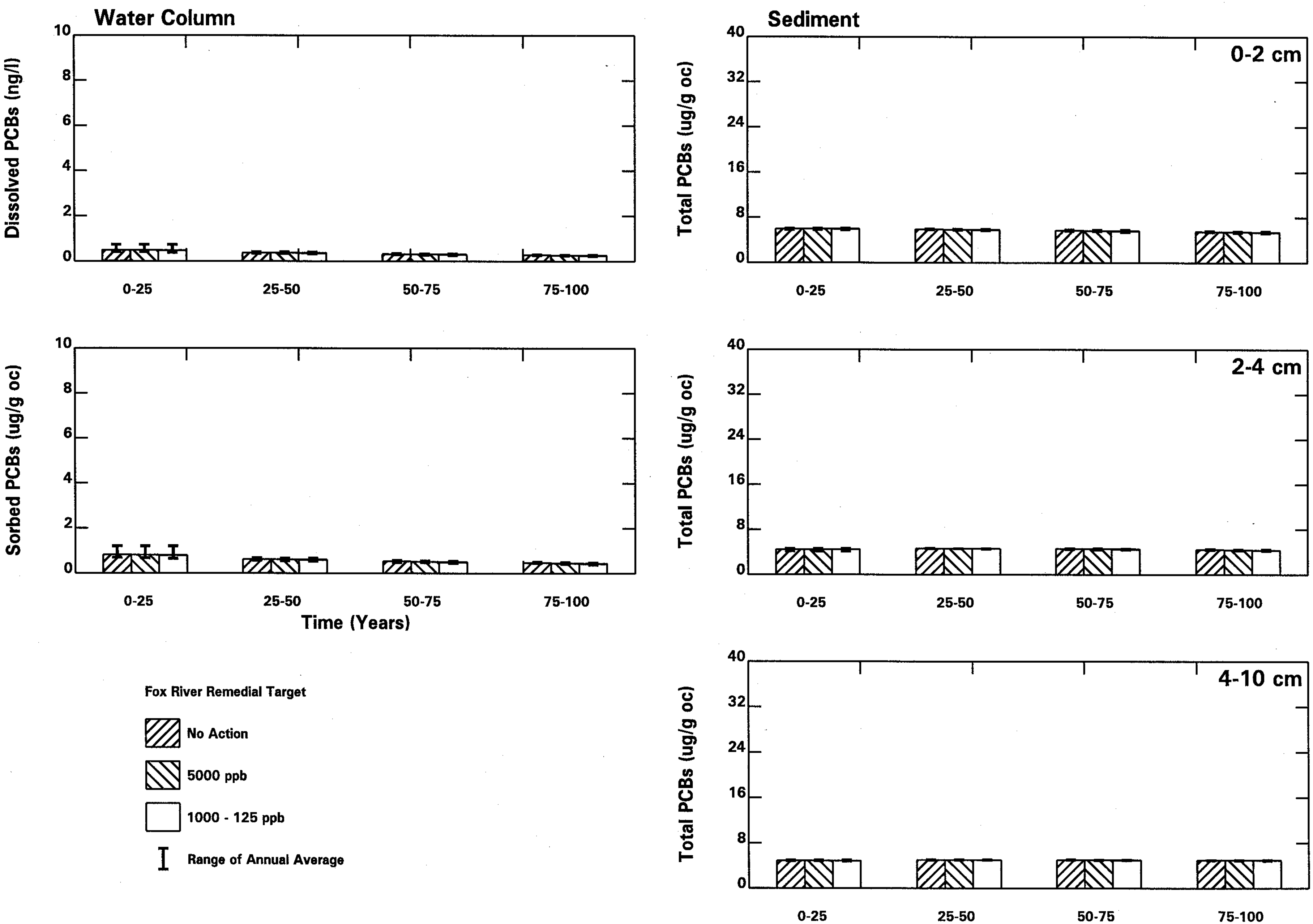


FIGURE 5-22 EFFECT OF FOX RIVER REMEDIATION ALTERNATIVES ON GREEN BAY PCBs - Zone 4 RESULTS FOR RUNS WITH NO REMEDIAL ACTIVITY IN GREEN BAY

The remediation of Fox River sediments with PCB concentrations greater than 5000 ug/kg results in a calculated reduction in PCB concentrations in Zone 2 of Green Bay (Figure 5-19). Calculated annual average dissolved PCB concentrations in the water column decrease by between 0.5 and 0.6 ng/l through the 100 year simulation in response to the reduction in PCB loading associated with this remediation scenario. In the first 25 year period, this decrease represents approximately a 10 percent reduction from the no action scenario, however, in the final 25 year block this change is more than a 35 percent reduction. The calculated percent reductions of sorbed PCBs in the water column, relative to the no action scenario, follow a pattern almost identical to the results for water column dissolved PCBs. The response of the Zone 2 sediments to the 5000 ug/kg remediation target for the Fox River is significant, but of a smaller magnitude than the response of the Zone 2 water column. The reductions in Zone 2 sediment PCB concentrations exceed 20 percent in the upper 4 cm of the sediment and is more than 17 percent in the 4 to 10 cm layer during the final 25 year. Zones 3A, 3B, and 4 are not affected to a significant degree by remedial activity in the Fox River, as shown by the minor differences in water column and sediment concentrations computed in the no action and the various remediation simulations (Figures 5-20, 5-21, and 5-22).

5.4.3 Response to Green Bay Remediation Scenarios

Simulations were performed to investigate the response of Green Bay water and sediment quality to two levels of remediation of Green Bay sediments as well as a no-action case. The no-action case for Green Bay was coupled with eight different scenarios for the Fox River, consisting of a no-action scenario and 7 levels of remediation of Fox River sediments. The two scenarios for remediation of Green Bay sediments, representing remediation of sediments exceeding 1000 or 500 ug/kg, were coupled with 4 and 3 scenarios for remediation of Fox River sediments, respectively (Table 5-1). The response of Green Bay to remediation of Green Bay sediments is shown on Figures 5-23 through 5-26 for scenarios coupled with remediation of Fox River sediments with PCB concentrations greater than 500 ug/kg. Based on the lack of sensitivity of Green Bay water and sediment quality to Fox River remediation targets below 1000 ug/kg (Figures 5-19 - 5-22), the results presented on Figures 5-23 through 5-26 are representative of the remaining simulations with alternate Fox River remediation targets coupled with Green Bay remediation scenarios.

The response of Zone 2 water and sediment quality to remediation of Green Bay sediments with PCB concentrations greater than 1000 and 500 ug/kg is summarized on Figure 5-23 through comparisons of annual average dissolved and sorbed water column PCB concentrations and total PCBs in 3 layers of the sediment. Because the effect of remediation is represented in the simulation by adjusting the initial conditions of PCBs in the sediment, the greatest change in the absolute magnitude of the concentrations is calculated in the first 25 year block. On a percentage basis the maximum difference is calculated in the second 25 year block. Zone 2 annual average water column PCBs, both dissolved and particulate, decrease by between 55 and approximately 75 percent in response to the remediation of sediments with PCB concentrations greater than

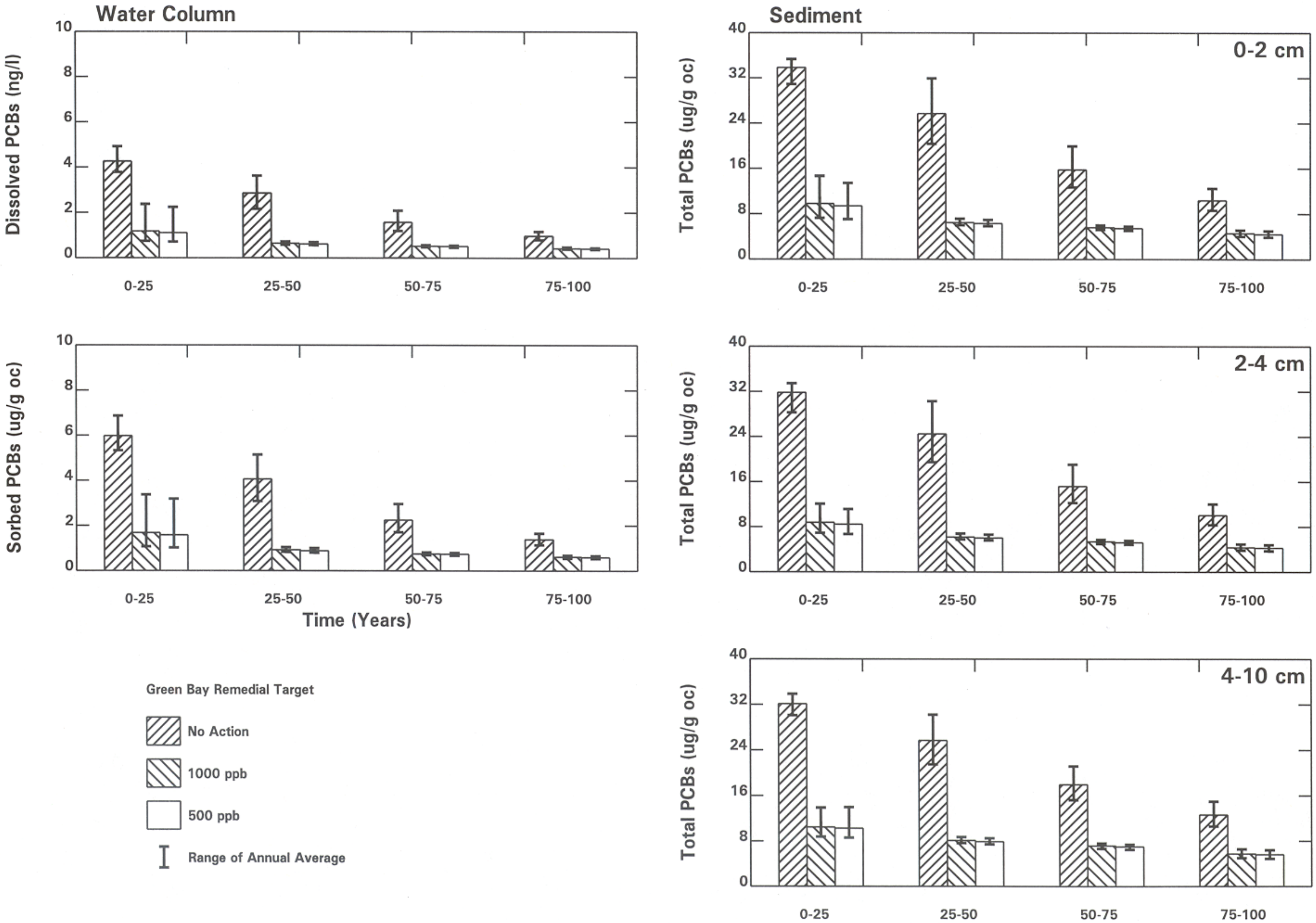


FIGURE 5-23 EFFECT OF GREEN BAY REMEDIATION ALTERNATIVES ON GREEN BAY PCBs - Zone 2
RESULTS FOR RUNS WITH 500 PPB REMEDIAL TARGET IN FOX RIVER

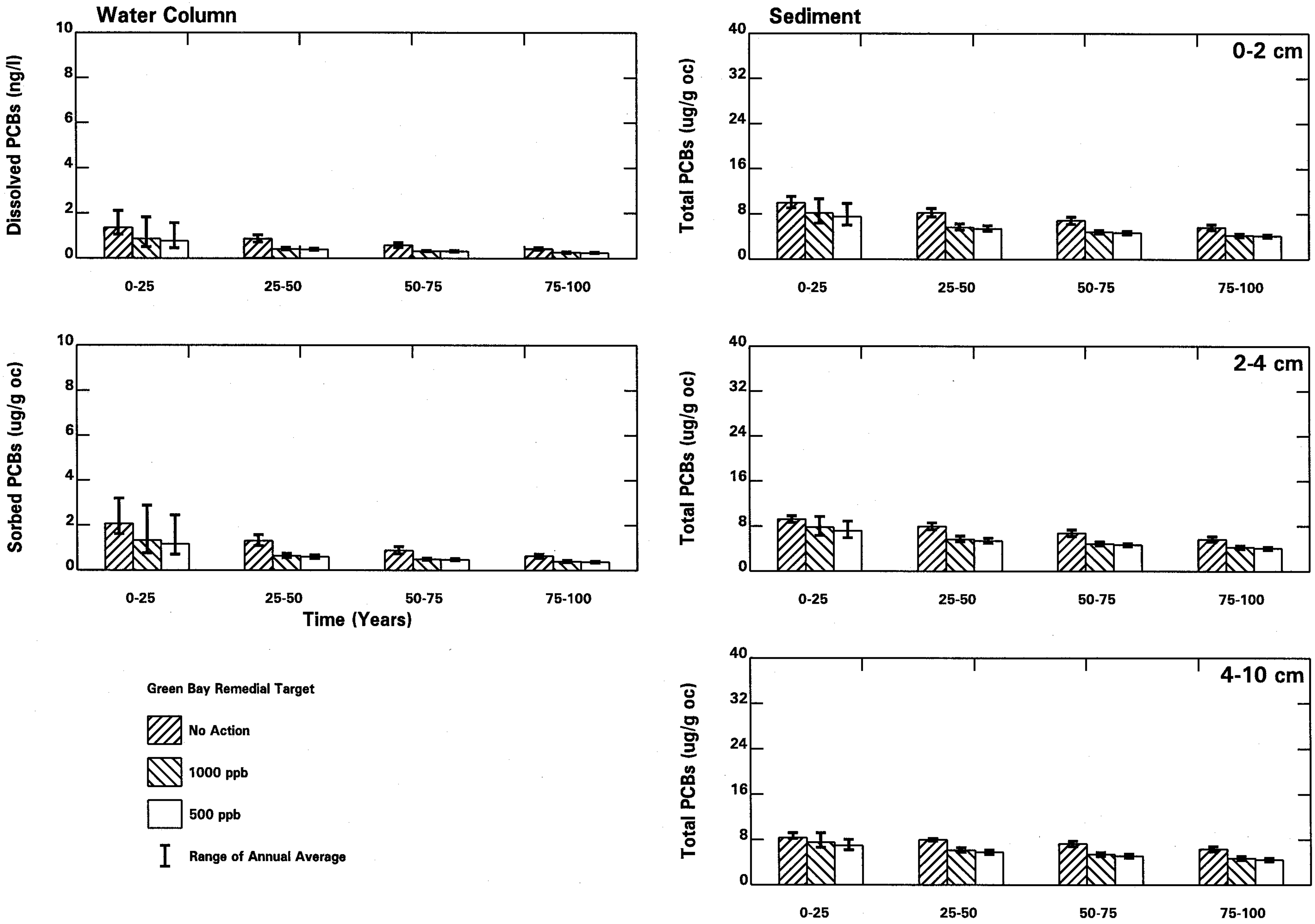


FIGURE 5-24 EFFECT OF GREEN BAY REMEDIATION ALTERNATIVES ON GREEN BAY PCBs - Zone 3A RESULTS FOR RUNS WITH 500 PPB REMEDIAL TARGET IN FOX RIVER

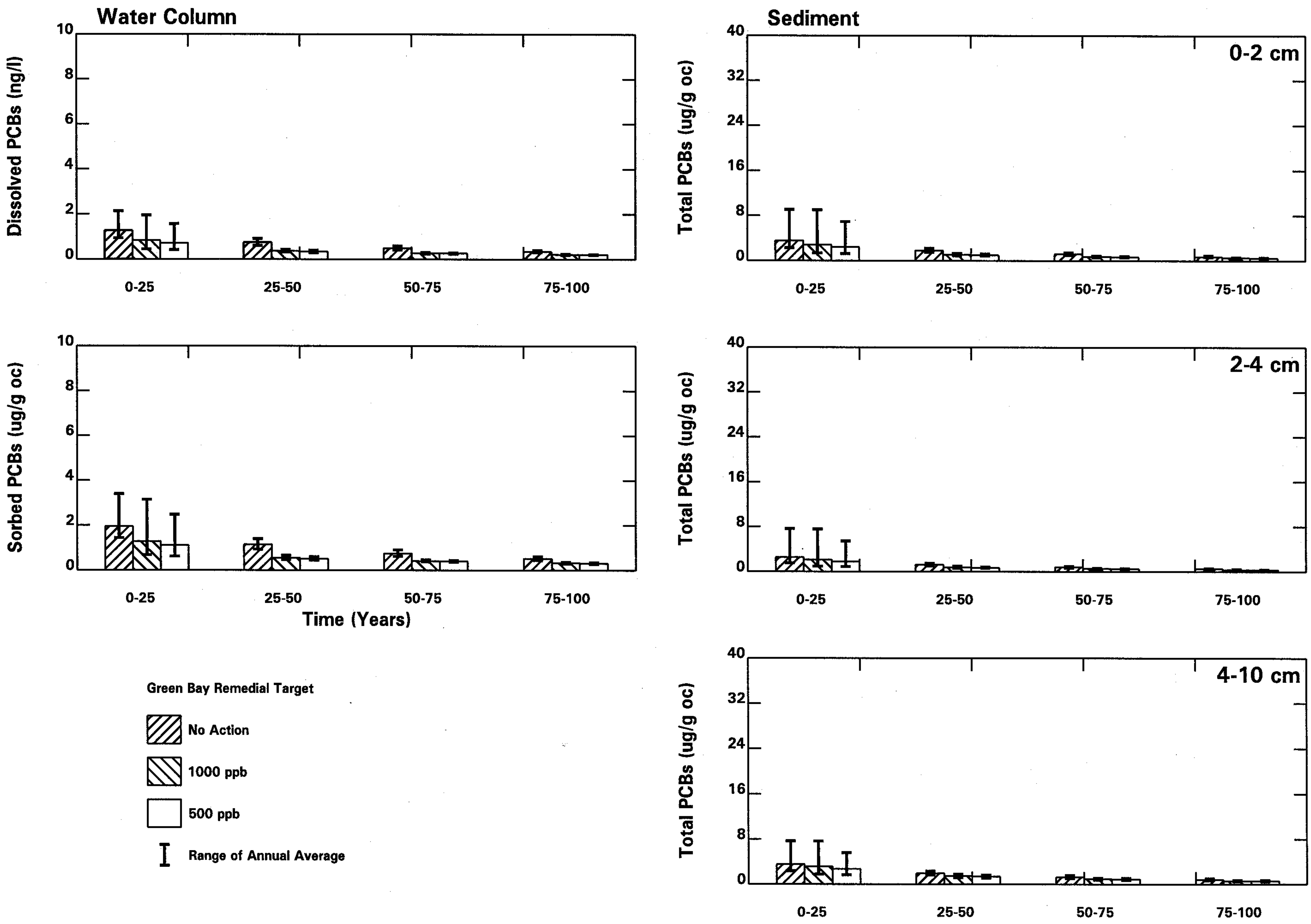


FIGURE 5-25 EFFECT OF GREEN BAY REMEDIATION ALTERNATIVES ON GREEN BAY PCBs - Zone 3B RESULTS FOR RUNS WITH 500 PPB REMEDIAL TARGET IN FOX RIVER

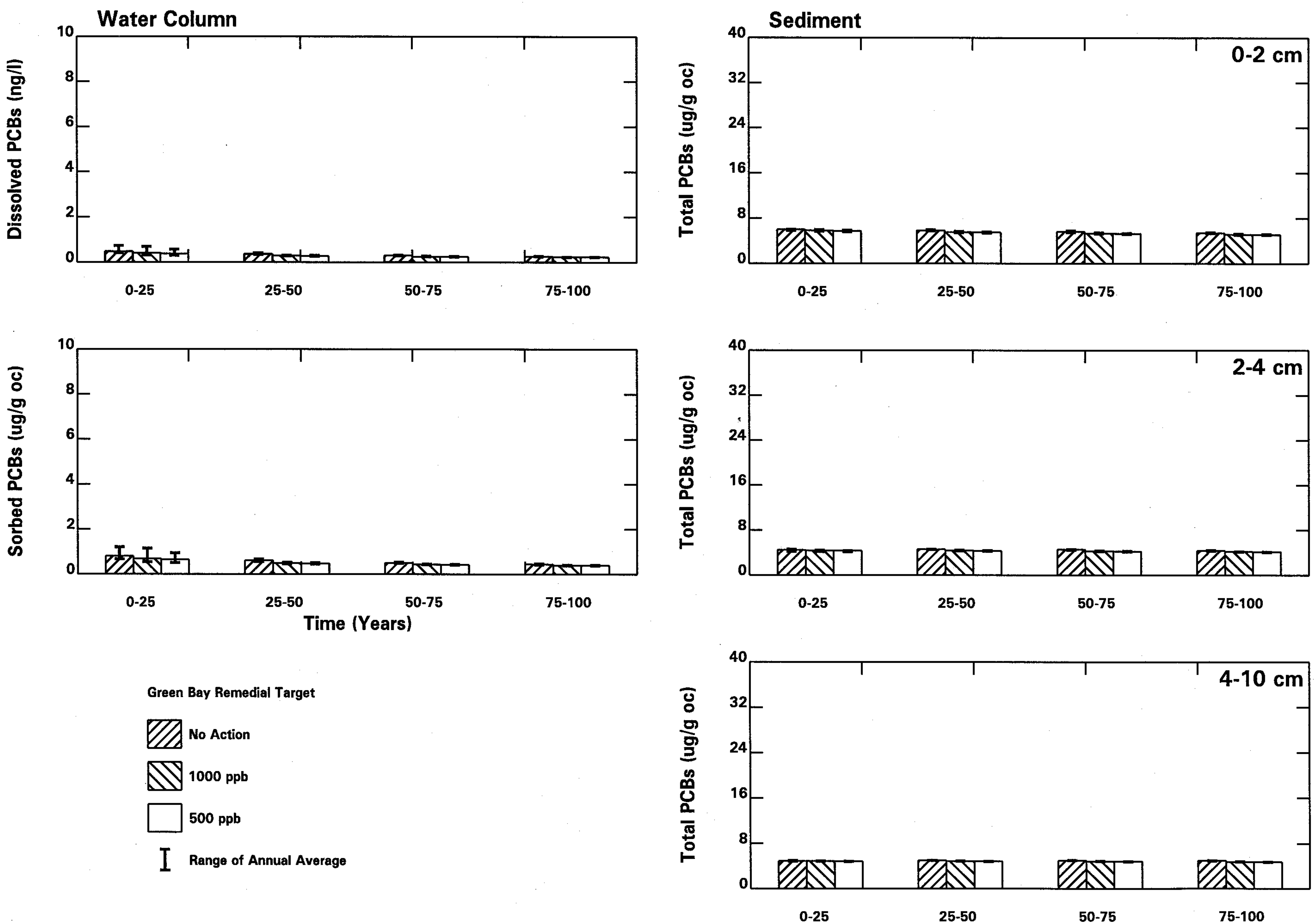


FIGURE 5-26 EFFECT OF GREEN BAY REMEDIATION ALTERNATIVES ON GREEN BAY PCBs - Zone 4
RESULTS FOR RUNS WITH 500 PPB REMEDIAL TARGET IN FOX RIVER

1000 ug/kg. Relatively small incremental improvements are calculated in Zone 2 in response to the remediation of sediments with PCB concentrations greater than 500 ug/kg.

Improvements in water column and sediment PCB concentrations in Zones 3A and 3B are fairly similar when expressed on a percentage basis, although the absolute magnitude of the changes in Zone 3A are slightly higher than in 3B. Reductions in Zone 3A and 3B water column PCBs of approximately 35 to over 50 percent are computed for the four 25 year blocks as a result of the remediation of sediments with PCB concentrations greater than 1000 ug/kg. Remediation of sediments with PCB concentrations greater than 500 ug/kg produces a reduction in Zone 3A and 3B water column PCBs of approximately 40 to 55 percent. Sediment PCBs in Zones 3A and 3B decrease by 10 to 20 percent in the first 25 year block and by 20 to 30 percent in the remainder of the simulation with the 1000 ug/kg target. Results from simulations with the 500 ug/kg remediation target indicate greater percent reductions in sediment PCB concentrations in Zone 3B (23-45 %)compared to Zone 3A (17-35%). As with the results for the water column, the absolute magnitudes of the reductions in sediment PCBs are less in Zone 3B than in Zone 3A.

PCB concentrations in Zone 4 are lower than those in the remaining portions of Green Bay. The response of water column and sediment PCB concentrations in Zone 4 to remediation of sediments is smaller, in both absolute magnitude and percent change, than in Zones 2, 3A, or 3B. Simulation of the 1000 ug/kg target produced reductions of between 10 and 20 percent in the water column and less than 6 percent in the sediment. Results from the simulation of the 500 ug/kg remediation target are somewhat similar, with reductions of between 10 and 22 percent in the water column and less than 7 percent in the sediment.

5.5 SUMMARY AND CONCLUSIONS

The results of 100 year-long term projection simulations for 15 combinations of natural attenuation and various levels of remediation of sediments in the Fox River and Green Bay indicate that a small fraction of the PCB mass in Green Bay is exported to Lake Michigan. Losses of PCBs from the Bay due to volatilization to the atmosphere exceed the estimated loads to the Bay, which are dominated by loads from the Fox River. Reductions in loadings from the Fox River associated with remediation of Fox River sediments with PCB concentrations greater than 5000 ug/kg result in lower water column and sediment concentrations in Zone 2 of Green Bay, but fairly small changes in the remainder of the Bay. Remediation of additional Fox River sediments, with concentrations between 125 and 5000 ug/kg produces little incremental reduction in Green Bay water and sediment PCB concentrations. Remediation of Green Bay sediments with concentrations above 1000 ug/kg produces substantial changes in Zone 2 of Green Bay and results in fairly uniform water and sediment concentration throughout much of the bay after roughly 25 years. Expanding the remediation to sediments between 500 and 1000 ug/kg produces smaller incremental improvements, which diminish with time. The effect of these computed changes in exposure concentrations on the food web of Green Bay have been evaluated (QEA,2001).

Computational resource constraints associated with performing 100 year projection simulations, influenced the technical approach adopted for this analysis. Hydrodynamic and sediment transport models were calibrated for a 17 month period and results from the first 12 months were extracted to provide a full annual cycle of circulation and sediment transport information for projection analyses. This annual cycle was repeated for each year of the 100 year projection simulations. The consequence of using results from a single year rather than a pattern covering multiple years or even decades was not evaluated since such an evaluation would require calibrating the hydrodynamic and sediment transport model over a substantially longer time period. This was not possible within the time and resource constraints of this project. Data limitations, particularly for evaluating the resuspension potential of Green Bay sediments, affected the degree to which a unique sediment transport calibration could be developed. The degree to which this influences the long term projections could not be evaluated because of computational resource and schedule constraints.

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APPENDIX A

CALIBRATION TEMPORAL PLOTS