



CBS Corporation
Neal's Landfill Project

Report

**Development, Calibration, and Application of a
Mathematical Model of Surface Water PCB Fate,
Transport, and Bioaccumulation at the Neal's Landfill
Site, Bloomington, IN**

Prepared for:
CBS Corporation

Prepared by:
Quantitative Environmental Analysis, LLC
Liverpool, NY

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- Appendix B. Technical Memorandum. To: Russ Cepko, CBS. From: David Glaser, QEA. April 20, 2006. RE: Analysis of PCB Trends at the Neal's Landfill Site: Fate and Bioaccumulation Models.
- Appendix C. Schematic Diagrams for Representation of Storage and Settling Basins in Model Simulation of Remedial Alternatives.

SECTION 1 INTRODUCTION

Quantitative Environmental Analysis, LLC (QEA) has developed this report on behalf of CBS Corporation to document the development, calibration, and application of a PCB fate, transport, and bioaccumulation model of Conard's Branch and Richland Creek. Conard's Branch and Richland Creek have been impacted by polychlorinated biphenyls (PCBs) originating from the Neal's Landfill site, located near Bloomington, IN. The model was developed and calibrated based upon site specific data and subsequently applied to assess a number of different remedial alternatives for the site. This report updates a model development and calibration document previously developed for the site (QEA 2005b) and presents:

- updates and revisions to the model calibration based on an additional year of monitoring data;
- statistical analysis of the temporal trends in water-phase PCBs originating from the springs located downstream of the landfill that form Conard's Branch; and
- application of the calibrated model to simulate different remedial alternatives for the site.

Section 1 of this report provides a brief site background and presents the modeling objectives. In Section 2, the modeling approach and framework is discussed, while Section 3 provides a discussion of the model development and calibration approach, and presents the calibration results. Section 4 describes model sensitivity analyses to assess PCB sources within the system, as well as the means by which the model was applied to assess different remedial alternatives for the site. Section 5 provides a brief summary of the model development, calibration, and application.

1.1 BACKGROUND

Detailed discussion of the history and background of the Neal's Landfill site has been provided in previous project reports (e.g., Viacom 2002a; Viacom 2004a). Thus, only a brief

summary of the site's background, with a focus on Conard's Branch and Richland Creek, is presented here.

Between 1950 and 1972, Neal's Landfill, which is located near Bloomington, IN, received solid waste from both municipal and industrial sources. Between 1966 and 1967, PCB-containing capacitors and other wastes that originated from the Westinghouse Bloomington Plant were disposed of at the landfill. Subsequently, PCBs associated with these wastes were transported to the groundwater beneath the site. The site is underlain by a limestone formation that is characterized as karst terrain, containing numerous solution cavities, sinkholes, and emerging springs. This geologic setting provides a pathway for PCB-impacted groundwater to be transported to surface water downgradient of the site. Springs emerging near the landfill, the most significant being South Spring and North Spring (Viacom 2002a), flow into Conard's Branch, a small stream situated in the northwest corner of the site. Conard's Branch flows northward for approximately 0.75 miles into Richland Creek, which is a much larger stream that flows approximately 40 miles from the mouth of Conard's Branch in a westerly and southwesterly direction, ultimately emptying into the White River. Due to the discharge of PCBs associated with spring water flowing into Conard's Branch, PCBs have impacted the water, sediments, and through bioaccumulation, the fish of Conard's Branch and the upper portions of Richland Creek.

A number of remedial measures have been conducted at the site, beginning in the early 1980s. Interim remedial measures consisting of institutional controls, removal of PCB-impacted materials, capping, and drainage and erosion control were completed at the landfill in 1984. Two additional interim remedial measures targeted the streams:

- Removal of sediments and bank soils from Conard's Branch and a 300-ft. reach of Richland Creek just downstream of the mouth of Conard's Branch was conducted in 1988.
- A spring water collection and treatment system was constructed and began operating in 1990. This system collects groundwater emerging from the North and South Springs through a number of hydraulic controls (Viacom 2004a). Modifications to this system

made in February 2003 improved the collection efficiency (Viacom 2002c), resulting in a decrease in the flow rate of untreated spring flow entering Conard's Branch under base flow conditions. Spring water collected by the system is conveyed to the Spring Treatment Facility (STF), which was designed with a 450 gallon per minute (gpm) capacity, to treat base groundwater flows. The STF treats spring water prior to discharge into Conard's Branch under a NPDES permit with a limit of 1 µg/L PCBs. The STF includes filtration and granular activated carbon (GAC) sorption. Effluent PCB concentrations have been found to be below detection (<0.1 ppb) until breakthrough occurs. After breakthrough, PCB levels were generally just above detection. The GAC was replaced in August 2003 after 13 years of service (Viacom 2003).

Remediation of Neal's Landfill itself was conducted between April and November 1999. Specific activities associated with the landfill remediation included: removal and off-site disposal of materials with PCB concentrations exceeding 500 ppm; moving of waste originally located within low-lying areas to higher elevations; installation of a RCRA Subtitle C cap on the remaining waste; and construction of lined storm water ditches to convey surface runoff away from the site.

Extensive post-construction monitoring has indicated that the remedial measures described above diminished PCB transport from the site and greatly reduced PCB concentrations within Conard's Branch and Richland Creek relative to pre-remedy levels. However, sampling of water, sediment, and biota from the streams has indicated that PCBs remain in Conard's Branch and Richland Creek. USEPA has identified the risk associated with consumption of fish as the main concern associated with PCB impacts in these streams. Sources of PCBs to the fish in these streams include the groundwater/spring flows entering Conard's Branch, the STF effluent, additional groundwater seeps recently identified along the banks of Conard's Branch (Viacom 2004b), and the sediments within the streams. The PCBs associated with groundwater/spring flows include a portion of the base flow that is not captured and conveyed to the STF for treatment, as well as storm water flows. During storm conditions, the flow rates exceed the STF design flow, and untreated spring water bypasses the STF and flows into Conard's Branch.

1.2 MODELING OBJECTIVES

The evaluation of potential future remedial actions to reduce PCB levels within the fish of Conard's Branch and the upper portion of Richland Creek requires a quantitative means of linking fish tissue PCB concentrations with the various sources of PCBs to the fish. Thus, the principal objective of this work was to develop a quantitative tool (i.e., a mathematical model) to assess the impact various potential management options would have on PCB fate, transport, and bioaccumulation within Conard's Branch and Richland Creek. Corollary objectives of the model include:

- differentiate base flow and storm flow PCB sources;
- quantify the relative importance of sediment and water column PCB sources to fish; and
- assess the response of fish PCB concentrations to potential remedial alternatives for the site.

SECTION 2

MODELING APPROACH

The mathematical model developed for Conard's Branch and Richland Creek is based on the first principles of mass and energy balance. The model framework, which is discussed in Section 2.1, consists of a set of general equations that describe the basic physical, chemical, and biological processes affecting PCB fate, transport, and bioaccumulation within an aquatic system. Application of the general framework to the Neal's Landfill site was accomplished by using site-specific data (e.g., see Section 2.3), literature, experience from modeling other systems, and professional judgment to specify the parameters of the governing equations such that the model reproduces the trends in PCB concentrations within the system over relevant spatial and temporal scales (see Section 2.2).

2.1 MODEL FRAMEWORK

The modeling framework used for this project consists of QEA's existing models QEAFATE and QEAFDCHN. Both of these frameworks have a long history of successful application to a number of sites across the country. The QEAFATE model consists of hydrodynamic, sediment transport, and chemical fate submodels. This framework has been applied to evaluate sediment and contaminant transport at numerous sites, including Grasse River PCBs, Lavaca Bay mercury, and Upper Hudson River PCBs. Such site-specific applications of QEAFATE 1) have been documented in a number of peer reviewed technical publications (Gailani et al. 1991; Ziegler and Nisbet 1994; Ziegler and Nisbet 1995; Gailani et al. 1996; Connolly et al. 2000; Ziegler et al. 2000); 2) have been reviewed and accepted by regulatory agencies (Alcoa 2001, 2002, 2003; HydroQual 1998; QEA 2005a); and 3) have been favorably evaluated by the USEPA (Imhoff et al. 2003). QEAFDCHN simulates contaminant bioaccumulation from water column and sediment exposure and has an application history similar to that of QEAFATE. This framework has been applied to simulate bioaccumulation at numerous sites, including the Green Bay Mass Balance study, the Fox River PCBs RI/FS, Grasse River PCBs, Hudson River PCBs, and Housatonic River PCBs. Such site-specific applications of QEAFDCHN have been documented in peer reviewed technical

publications (Thomann and Connolly 1984; Connolly and Tonelli 1985; Connolly 1991; Thomann et al. 1992; Connolly and Glaser 2002; Glaser and Connolly 2002), and the model has been reviewed and accepted by the regulatory community (Connolly et al. 1992; QEA 2002; Alcoa 2001, 2002; USEPA 2006).

The hydrodynamics, sediment transport, PCB fate, and PCB bioaccumulation submodels that constitute the modeling framework are linked, such that information that is calculated by one sub-model is passed on to the other sub-models for use in their calculations. The linkages between these models and the processes they simulate are illustrated in Figure 2-1; brief descriptions of the sub-models are provided in the following subsections.

2.1.1 Hydrodynamics

The hydrodynamic model solves the vertically-averaged free-surface (continuity) equation and momentum equations, each with a barotropic term, a bottom friction term, viscous terms, and advective terms (e.g., Ziegler et al. 2000; QEA 1999; Hamrick 1992). Based on input flow rates and water surface elevations (i.e., stage height) at the model boundaries, the model computes temporal and spatial variations in flow rate, water depth, current velocity, horizontal dispersion (i.e., mixing), and bed shear stress. This information is passed onto the PCB fate/sediment transport sub-model (Figure 2-1) to calculate sediment deposition and resuspension and the downstream transport of PCBs and sediments within the water column.

2.1.2 Sediment Transport and PCB Fate

Because PCBs strongly bind to particles, simulation of PCB fate and transport within an aquatic system also requires simulation of the processes affecting sediments. The sediment transport sub-model applied to the Neal's Landfill site is an enhanced version of the widely-used SEDZL model (e.g., Ziegler and Lick 1986; Ziegler et al. 2000; Imhoff et al. 2003). The sediment transport sub-model simulates advective and dispersive transport of suspended sediments within the water column, sediment deposition and erosion at the bed/water interface, and includes bed processes such as bed armoring and consolidation effects (Figure 2-1). The

formulations for cohesive sediment particles in SEDZL were used to represent the bulk sediment transport within the system.

The fate and transport portion of this sub-model predicts changes in water column and sediment concentrations of PCBs; a description of the underlying theory can be found elsewhere (Connolly et al. 2000; Imhoff et al. 2003). Fate and transport processes simulated include:

- advective and dispersive transport of PCBs within the water column;
- organic-carbon-based partitioning of PCBs between the dissolved and particulate phases (e.g., Karickhoff 1984);
- diffusive flux of dissolved phase PCBs at the sediment-water interface (e.g., Thibodeaux and Bierman 2003); and
- volatilization of PCBs at the air-water interface based on two-film theory (e.g., O'Connor 1983, 1984).

PCB fate within the sediment bed is directly coupled with that in the water column, and the PCB transport associated with deposition and erosion (computed by the sediment transport sub-model), molecular diffusion within sediment pore water, and particle mixing (i.e., bioturbation) are simulated within the sediment bed (Figure 2-1).

2.1.3 PCB Bioaccumulation

The bioaccumulation sub-model is a mathematical description of the transfer of PCBs within the food web (Figure 2-1). The food web includes the primary energy transfer pathways from the exposure sources (i.e., sediment and water) to the species of interest. The model framework (i.e., QEA FDCHN) is generic and has been discussed in detail elsewhere (Thomann and Connolly 1984; Connolly 1991; Connolly et al. 1992). It has been applied to organic compounds and metals; rivers, lakes and coastal environments; and food webs including fish, birds, and mammals (e.g., QEA 1999; Glaser and Connolly 2002). The site-specific component of the model includes the food web structure, species-specific bioenergetics and body

composition, water temperature, chemical properties of the contaminant and contaminant exposure concentrations.

QEAFDCHN uses a time-variable mechanistic simulation for all trophic levels, representing an organism as two compartments, blood and lipid. PCBs diffuse across the gill surface between the blood and water. They are taken up across the gut surface during digestion, and move from the central compartment, blood, to the deep or peripheral compartment, lipid.

Gill exchange involves diffusion between dissolved contaminant pools on either side of the gill membrane (e.g., Erickson and McKim 1990). Contaminant mass transfer at the gut wall is determined by the amount of food consumed and the assimilation efficiency. The rate of consumption of food is calculated from the rate of energy usage for growth and metabolism. The model computes growth rates based upon a relationship between age and weight that is determined from site-specific data. Respiration is computed using standard weight- and temperature-based relationships. The chemical and food assimilation efficiencies are estimated from published experimental data.

The model computes the weight, lipid content, metabolic rate, and PCB concentration for each age class of each species on a daily basis.

2.2 MODEL CONFIGURATION

Because numerical models are a discretization of space and time, configuration of the general model framework to Conard's Branch and Richland Creek required specification of the spatial and temporal domain and resolution. Domain refers to the reaches of the streams and the time period that are simulated by the model. Resolution refers to how many computational elements the model domain is discretized into (i.e., the length of model stream segments and the time increment at which model results are computed).

2.2.1 Spatial Domain and Resolution

The spatial extent of the model domain consists of the stretch of Conard's Branch from the weir located downstream of where the South Spring flows and overflows emerge to its mouth at Richland Creek, and Richland Creek, from the mouth of Conard's Branch to the State Route 43 Bridge, a total distance of approximately 3.0 miles (Figure 2-2). This model domain was selected based upon the fish sampling locations of interest (i.e., Locations B and D; Figure 2-2), and the need for the hydrodynamic sub-model to have measured stage height data at the downstream boundary (the RC43 flow station; Figure 2-2).

The model domain includes a number of locations where tributaries introduce additional flow and materials (i.e., TSS and potentially PCBs) into the modeled stream reach. These include the STF, North Spring and its bypass flows (NS; Figure 2-2), the upstream portion of Richland Creek (RCUP; Figure 2-2), and two surrogate tributaries that represent the aggregate ungaged flows that enter along the two stream reaches via minor tributaries and surface runoff, or direct drainage (DD). The ungaged tributaries were situated in the model at the locations of Pig Pen Spring on Conard's Branch (DD1; Figure 2-2) and near the location where the Southwest Seep Branch discharges to Richland Creek (DD2; Figure 2-2). Further discussion of the tributaries is provided in Section 3.1.1.1. There are four flow monitoring stations located within the model domain: on Conard's Branch at the weir at the upstream end (CBW; Figure 2-2) and at the Vernal Pike Bridge (CBVP; Figure 2-2), and on Richland Creek at the Vernal Pike and Route 43 Bridges (RCVP and RC43, respectively; Figure 2-2).

The three-mile stretch of stream was simulated with a two-dimensional Cartesian grid consisting of 547 active model elements (Figure 2-3). The dimensions of the grid elements are 4-ft. wide by 100-ft. long. The number of lateral elements in the grid was driven by the need to simulate the large change in stream channel width over the model domain (Figure 2-3). The number of longitudinal elements in the model grid (approximately 150) was determined by the need to keep the aspect ratio of grid cells below a value of 100, for numerical stability purposes. This number of longitudinal elements allows for variations in system geometry and gradients in sediment PCB concentrations and bed properties to be captured by the model.

In areas of the stream containing sediment deposits, the uppermost 12 in. of sediments was simulated in the model. The sediment bed (where simulated) was discretized into six 2-in. layers.

2.2.2 Calibration Period and Temporal Resolution

The model calibration spans the five year period from January 1, 2001 through December 31, 2005. This period begins with the time at which continuous monitoring of flow was initiated at the Conard's Branch weir. The calibration period encompasses a significant portion of the more recent sampling data collected at the site (see Section 2.3), and as such, represents contemporary site conditions with respect to the operation of the spring water collection system and the STF.

The hydrodynamic, sediment transport, and PCB fate sub-models perform calculations at a fine temporal resolution – the computational time step needed to maintain numerical stability is computed internally by the model, and is on the order of a few minutes during high flow conditions. These sub-models are capable of providing outputs at this fine temporal resolution, but the outputs were generally averaged over longer periods, depending on the total simulation time. Simulations of short-term storm sampling events made use of hourly outputs (for comparison with high frequency sampling data), while long-term (i.e., five-year) simulations were output on a daily basis. The bioaccumulation sub-model performs calculations on a daily basis.

2.3 SITE-SPECIFIC DATA

A wide variety of site-specific sampling data were available to support the development and calibration of the models. These data include: physical data such as sediment bed thickness mapping, channel geometry measurements, and sediment texture characteristics; chemical data such as measurement of total organic carbon (TOC) and PCBs in water and sediment, and measurement of lipid content and PCBs in biota samples; and biological characteristics, such as classification of fish stomach contents, and measurement of the age, length, and weight of fish

samples. A summary of these various data sets, including a listing of the locations and time period of the associated sampling, is included in Table 2-1.

Table 2-1. Summary of site-specific data used for model development and calibration.

Sub-Model	Media/ Sample Type	Type of Data	Spatial Resolution (per survey)	Temporal Resolution	
				Frequency/ # of Events	Year(s)
All	Geometry	Channel width	~5 locations in CB, ~30 locations in RC	1 event	Nov. 2003
		Stream depth	~70 locations in CB, ~70 locations RC	1 event	Nov. 2003
		Channel elevation	USGS Topos (10-ft contours)	---	---
Hydrodynamic	Water column	Groundwater elevation	MW5A	Hourly	2001-2005
		Flow monitoring	CBW	Hourly	2001-2005
			STF Influent	Hourly	2002-2005
		Flow measurements	CBW, CBPL	2 events	2005
			CBVP, RCVP, RC43	9-15 events per station	2003-2005
		Stage height monitoring	CBVP, RCVP, RC43	Hourly	Nov. 2003-Jan. 2005
Sediment Transport	Water column	TSS	NS and SS	Monthly	2001-2005
			Mostly CBPL, CBVP, and RCVP	8 events; grab samples	2001-2004
			CBVP	Approximately monthly	2005
			CBW (mainly), CBVP, RCVP, RC43	Hourly; 17 storm events	1998-2005
	Sediment	Bulk density	~50 locations in CB, ~15 locations in RC	1 event	2004
		Percent solids	~60 locations in CB, ~15 locations in RC	4 events	1998, 2002-2004
		Sediment thickness	~60 locations in CB, ~70 locations in RC	1 event	Nov. 2003
	Settling tests	TSS in barrels over time	Springs	1 event, 2 treatments, 30 samples	June 2002

Sub-Model	Media/ Sample Type	Type of Data	Spatial Resolution (per survey)	Temporal Resolution	
				Frequency/ # of Events	Year(s)
PCB Fate	Water column	PCBs	NS and SS	Monthly	2001-2005
			STF influent/effluent	Biweekly	2001-2005
			NS bypass sampling	2 events; grab samples	2005
			CBW (mainly), CBVP, RCVP, RC43	Hourly; 17 storm events	1998-2005
			Mostly CBPL, CBVP, RCVP	10 events; grab samples	2001-2004
			CBVP	Approximately monthly	2005
	Sediment	POC	CBW, CBVP, RCVP, RC43	2 storm events	2004-2005
		Total PCBs, TOC	~50 locations in CB, ~15 locations in RC	6 Events	1998, 2001-2004
		PCB partitioning and settleability tests	Springs	2 events, 40 samples	Oct. 2001, June 2002
Bioaccumulation	Creek chubs	Weight, lipid content, PCBs	CBVP, RCVP, and RC43	2-5 events (3-20 samples per event)	2001-2005
		Age	CBVP and RCVP	1 event (6-12 samples)	Nov. 2003
		Stomach contents	Near CBVP and RCVP	1 event (10-20 samples)	Nov. 2003
	Longear sunfish	Weight, lipid content, PCBs	RCVP	5 events (6-10 samples per event)	2001-2005
		Age	RCVP	1 event (6 samples)	Nov. 2003
	Crayfish	Weight, lipid content, PCBs	CBVP and RCVP	1 events (3 samples per event)	May 2003
	Benthic invertebrates	Weight, lipid content, PCBs	CBVP	1 sample	Nov 2004
	Fish	PCB congeners	---	3 events	2002 - 2003

Notes:

CB = Conard's Branch

STF = Spring Treatment Facility

CBPL = Conard's Branch at Property Line

MW5A = Monitoring Well 5A

SS = South Spring

RCVP = Richland Creek at Vernal Pike

CBW = Conard's Branch at the Weir

NS Bypass = North Spring Bypass

CBVP = Conard's Branch at Vernal Pike

NS = North Spring

RC = Richland Creek

RC43 = Richland Creek at Route 43

Discussion of how these data sets were used during model development and calibration is provided in Section 3.

SECTION 3 MODEL DEVELOPMENT AND CALIBRATION

3.1 HYDRODYNAMICS

3.1.1 Model Development

3.1.1.1 Boundary Conditions

The hydrodynamic sub-model is driven by specification of two types of time-variable boundary conditions: 1) stage height at the downstream boundary (i.e., Richland Creek at Route 43; RC43); and 2) flow rates at all inflow boundaries (see Figure 2-3).

Hourly stage height data at RC43 were available from November 2003 through January 2005 (Table 2-1). Prior to November 2003 and after January 2005, hourly stage height at RC43 was estimated based on hourly groundwater elevation data from the on-site monitoring well MW5A, and the relationship shown in the lower left panel Figure 3-1.

Three approaches were used to estimate flow rates at various locations for the hydrodynamic sub-model, depending on data availability:

- measured hourly flow rates were used directly when such data were available;
- flow rating curves were developed and used to calculate flow rates at a given location as a function of measured stage height; and
- relationships between measured stage height or flow rate at a particular location and MW5A elevations or flow rates from other stations were established and then used to estimate flow rate in the absence of measurements at that location.

For each of the model inflow boundaries, one or more of these approaches were used to construct a complete hourly flow record for the entire five-year (2001-2005) calibration period.

Details about how flow rates were generated at each inflow boundary are provided in the following subsections.

3.1.1.1.1 Conard's Branch at the Weir (CBW)

Hourly flow rates at CBW were measured from January to October 2001 and from 2002 through 2005, by USGS and Viacom, respectively. A relationship between hourly CBW flow and hourly MW5A elevation was developed using 2002 data (see Figure 3-2), to represent conditions prior to the February 2003 improvements in STF capture efficiency. This relationship was then used to estimate the hourly flow rate at CBW during November and December 2001, when data were unavailable.

3.1.1.1.2 Spring Treatment Facility (STF)

Hourly flow rate data for the STF effluent were available for 2002-2005. A relationship between STF flow rate and MW5A elevation (see Figure 3-3) was developed based on 2002 data (to represent conditions prior to the February 2003 improvements in STF capture efficiency). This relationship was applied to estimate STF hourly flow rates in 2001. The estimated 2001 STF flow rates compared well with biweekly measurements taken in association with the NPDES discharge monitoring (Figure 3-4; estimated flows are daily averages).

3.1.1.1.3 North Spring and its Bypass

The flow from North Spring (NS) is largely captured by the STF; the uncaptured portion that enters Conard's Branch typically represents less than 1% of the total system flow (i.e., CBW + STF + NS flows; e.g., Viacom 2002a). A relationship between NS flow and MW5A elevation was used to define model inputs flow rates over the 2001-2005 calibration period, although this flow has little significance in the model given its low magnitude.

Measurements conducted by Viacom in 2004 and 2005 (Viacom 2004b) have indicated that additional flow enters Conard's Branch in the vicinity of NS. This flow, which is presumably groundwater bank seepage, has been termed the North Spring Bypass (NSB). A two-stage relationship was developed to estimate the NSB flow as a function of total system flow rate (see Figure 3-5). A linear relationship was used when total system flow rate is less than 615 gpm, and a power relationship was used to yield a relatively lower fraction of NSB flow during storm conditions, which is consistent with field observations of in-stream flow downstream of this area (i.e., CBVP; Figure 2-2).

3.1.1.1.4 Richland Creek Upstream and Direct Drainages

Because there were no direct measurements of flow rates in Richland Creek upstream of the mouth of Conard's Branch, and the direct drainage inputs are used in the model to represent aggregates of several distributed flow inputs, flows at these boundaries were estimated by differences, based on measured/estimated in-stream flow rates:

$$Q(DD1) = Q(CBVP) - [Q(CBW) + Q(STF) + Q(NS + Bypass)] \quad (3-1)$$

$$Q(RCUP) = Q(RCVP) - Q(CBVP) \quad (3-2)$$

$$Q(DD2) = Q(RC43) - Q(RCVP) \quad (3-3)$$

For example, the flow in Richland Creek upstream of the mouth of Conard's Branch (RCUP; Equation 3-2) was calculated based on the difference between flow measured in Richland Creek downstream of the mouth of Conard's Branch at RCVP, and the flow in Conard's Branch measured just upstream of its mouth at CBVP.

At the in-stream flow stations CBVP, RCVP, and RC43, flow rating curves were established based on manual measurements of flow and stage height taken at these locations between November 2003 and January 2005 (see Figure 3-6). Hourly stage height data from these in-stream stations were available from November 2003 through January 2005. Prior to November 2003 and after January 2005, hourly stage heights at CBVP, RCVP, and RC43 were

estimated as a function of hourly MW5A elevation data using the relationships shown in Figure 3-1. The flow rating curves were then used to convert the estimated and measured hourly stage heights to hourly flow rates for the 2001-2005 calibration period.

3.1.1.1.5 Flow Balance

Because flow rates at NS, CBVP, RCVP, and RC43, as discussed above, were estimated independently, it was possible to compute negative model inflows (e.g., with Equations 3-1 through 3-3), which is unrealistic. To ensure that flow within the system balanced and to avoid negative inflow rates at the model boundaries, a series of adjustments of the calculated flows was performed. Two criteria were applied to ensure the flow balance at each station was maintained throughout the 2001-2005 modeling period:

- Flow rates for a given location were required to be greater than those measured at an upstream location (i.e., it was assumed that the stream was gaining throughout).
- Flow rates for stations in Richland Creek were required to be at least twice as high as those at Conard's Branch, based on the large size difference between these two streams. (This criterion was invoked to avoid computation of unrealistically high flows in Conard's Branch due to variability at the upper end of the flow rating curve).

The in-stream flow rates were adjusted based on these criteria from upstream to downstream (i.e., CBVP → RCVP → RC43). Flow rates entering Conard's Branch at the upstream end (i.e., the sum of CBW, STF, and NSB) were not subject to such adjustments. As a final adjustment, flow rates calculated at RCVP and RC43 were bounded by daily flow rates estimated for Richland Creek at Bloomfield, IN, which is located approximately 34 miles downstream of RCVP. This adjustment was used to screen out some unrealistically high flows that resulted from variability in the rating curve calculations. Based on drainage area proration, the flow rate of Richland Creek at Bloomfield was estimated to be 0.7% of the flow measured in the White River at Newberry, IN, the upstream-most USGS gage that measures flow from the Richland Creek basin.

The flow rates at CBVP, RCVP, and RC43, calculated based on these adjustments, are shown in Figure 3-7. Approximately 60% of the calculated flow rates at CBVP were subjected to flow adjustments. Nearly all of these adjustments occurred at very low flows, where the CBVP flow estimated from the rating curve was less than the total calculated flow entering Conard's Branch from upstream sources. These discrepancies are likely attributed to two factors: 1) there is a large uncertainty associated with the estimated NSB flow (Figure 3-5); and 2) the low flow values for CBVP requiring adjustment most often occurred at flows that were less than the lowest measured point on the rating curve (Figure 3-6). Since the NSB flow is a small contributor to total system flow at low flows, the uncertainty associated with extrapolation of the rating curve appears to be the more significant cause. Nonetheless, these adjustments of CBVP flow have a minor impact on the overall system flow budget. Fewer flow rate adjustments were required at RCVP and RC43 (approximately, 1% and 7%, respectively; Figure 3-7).

The final adjusted flow values shown in Figure 3-7 were the basis for the inflow boundary conditions used in the hydrodynamic sub-model, which were computed based on Equations 3-1 to 3-3. Figure 3-8 shows the long-term average inflow rate at each boundary for the 2001-2005 calibration period.

3.1.1.2 Parameterization

The only parameters used by the hydrodynamic model are those describing stream channel geometry and coefficients that represent the amount of channel friction and turbulent mixing within the water column. Channel widths and mean water depths were initially set from aerial photography and the USEPA probing study (USEPA 2003; Figure 3-9). Channel width was adjusted slightly during model calibration. A uniform channel slope over the model domain was estimated based upon USGS topographic quadrangle maps. The channel friction and turbulent mixing coefficients were determined by model calibration. A summary of the hydrodynamic sub-model parameters and the methods used to specify the values in the model is provided in Table 3-1.

Table 3-1. Hydrodynamic sub-model parameters.

Parameter	Site-Specific Data	Literature	Calibration
Channel geometry and slope	✓		
Bathymetry	✓		
Eddy diffusivity (mixing)		✓	✓
Bottom roughness (friction)		✓	✓

3.1.2 Model Calibration

3.1.2.1 Approach

The hydrodynamic sub-model was calibrated by adjusting the uncertain parameters, within a reasonable range, such that the best agreement between model-predicted values and observed data was achieved. Two types of data were available for the calibration. First, dye tests conducted by Viacom in 2004 (Table 2-1) provided good estimates of mean current velocity as well as the extent of mixing and dilution along the channel. The stage height monitoring data from CBVP and RCVP provided a long-term verification of model performance under a range of flow regimes.

The channel width, to which the mean current velocity is most sensitive, was estimated from aerial photos and the probing study conducted by USEPA (2003). The effective channel width in Conard's Branch was adjusted to match the travel time along Conard's Branch observed during the dye tests. The eddy diffusivity and bottom roughness coefficients were then fine-tuned to match the shape of the measured dye concentration curves during the tracer studies, as well as the long-term stage height data. The best calibration result was achieved with an eddy diffusivity of $1 \text{ m}^2/\text{s}$ and an effective bottom roughness height of 5 mm.

3.1.2.2 Results

Two dye tests were conducted by Viacom in 2004 under low and relatively stable flow conditions in Conard's Branch. Dye was released from the STF outlet and measured at the site property line at Conard's Branch (CBPL) and CBVP on January 16, 2004. A similar test was conducted on February 3, 2005, and dye concentrations were measured at CBVP and RCVP.

The hydrodynamic sub-model was configured to simulate these short-term events by adding the same mass of tracer to the model that was injected in the STF effluent. For the February 3, 2004 test, the model-predicted dye concentrations at CBVP and RCVP showed generally good agreement, both in the timing between the peaks, and the general shape of the tracer curves (Figure 3-10, bottom panel). This indicates that the model properly represented the mean current velocity, dilution, and mixing within the channel between the STF and RCVP. The model did compute a higher amount of dispersion (i.e., more spread in the dye trace) than the data, which would be expected given the relatively coarse grid resolution – the model represents averages over 100-ft. longitudinal segments (see Section 2.2.1), while the data were collected at a discrete point. The hydrodynamic sub-model over-predicted the amount of dispersion occurring during the January 16, 2004 dye test (Figure 3-10, top panel). This over-prediction of model mixing is likely due to complexities associated with the cycling STF effluent flows, the relatively coarse model grid, and the close proximity of the first measurement point to the dye injection point. Nonetheless, the model-computed travel time between the CBPL and CBVP locations was within 20% of the data (Figure 3-10, top panel).

Long-term stage height data were recorded at CBVP and RCVP from November 2003 through January 2005. Figure 3-11 demonstrates good agreement between the measured stage heights and those predicted by the hydrodynamic model at these two locations. The ability to predict the increases in stage height during elevated flow conditions indicates that the channel slope, mean water depths, and bottom friction are properly represented in the hydrodynamic sub-model.

3.2 PCB FATE AND SEDIMENT TRANSPORT

3.2.1 Model Development

3.2.1.1 Boundary Conditions

Similar to the hydrodynamic sub-model, the sediment transport and PCB fate sub-models required input values for TSS and PCB concentrations at the inflow boundaries (i.e., CBW, STF,

NS + Bypass, DD1, DD2, RCUP; Figure 2-3) over the five-year calibration period. In general, relationships between measured concentrations and a parameter that was measured more frequently (e.g., flow rate) were used to define these boundary conditions. A description of the development of each boundary condition is provided in the following subsections.

3.2.1.1.1 TSS

TSS data available for CBW include high frequency sampling during storm events, as well as monthly sampling of South Spring (Table 2-1). Given that South Spring represents a majority of the uncaptured spring flow entering Conard's Branch, these data sets were combined and used to develop a sediment rating curve for CBW (Figure 3-12). The form of the CBW sediment rating curve is characterized by a constant TSS concentration at lower flow rates, with a power-function increase with flow at higher flows, which is similar to that used for many streams (e.g., Ferguson 1986). The rating curve equations shown on Figure 3-12 were used to generate the CBW TSS boundary condition used in the model. A comparison between the TSS boundary condition and the CBW and South Spring TSS data indicates that the function used in the model captures the general trend in TSS entering Conard's Branch during the 2001-2005 calibration period (Figure 3-13).

No sampling data were available to specify TSS for the other model inflow boundaries. TSS concentrations in NS and its bypass were specified to be the same as TSS at CBW, since those spring flows are of similar origin. TSS concentrations for the STF effluent were set to a nominal constant value of 1 mg/L, which would be expected based on the filtration processes used at the STF. During model development, the ungaged tributaries and flow inputs to the model (i.e., RCUP, DD1, and DD2) were identified to be important sources of solids to the system. Because no direct measurements of solids associated with these flows were made, TSS concentrations for these model boundaries were determined through model calibration (see Section 3.2.2.1).

3.2.1.1.2 PCBs at CBW

PCB concentrations at CBW have been characterized through an extensive sampling and analysis program (e.g., Viacom 2002a). These data include high-frequency PCB measurements collected at CBW during storms events since 1998 and routine PCB data measured monthly during 2001 to 2005 at South Spring, which accounts for the majority of untreated spring flow entering Conard's Branch near CBW (Table 2-1). The general approach used to specify the PCB concentration entering the model at CBW was based upon relationships between PCB concentrations and flow that also account for the long-term temporal trend in observed spring PCB levels (e.g., Viacom 2005b).

The CBW PCB boundary condition consists of separate relationships between PCBs and flow for storm and non-storm conditions, where storm conditions are defined by hourly CBW flow exceeding 300 gpm for a duration of six hours or more.

Non-Storm Conditions

For non-storm conditions, the CBW PCB boundary condition was based on a statistical trend model that relates PCB concentrations at South Spring to system flow rate and time (see Appendix A). This statistical model includes an inverse power relationship with flow and a first-order time decay term to account for the long-term decline in observed spring PCB concentrations. The relationship is given by:

$$C_{CBW} = a Q_{sys}^b e^{-kt} \quad (3-4)$$

where:

- C_{CBW} = low flow CBW PCB concentration;
- Q_{sys} = total hourly system flow rate;
- a, b = constants for South Spring statistical model (see Appendix A);
- k = South Spring decline rate (0.06 yr^{-1} ; see Appendix A); and
- t = time in years since 1/1/2001.

This low flow PCB boundary condition provides a good fit to the data, which are characterized by an inverse relationship between PCB concentration and total system flow, suggestive of dilution of the PCB source with increasing flow (Figure 3-14).

Upon applying this equation to the hourly flow data for the entire 2001-2005 calibration period, it was found that for a small fraction of the time (i.e., <1%), the total system flow was extremely low (<1 gpm), which caused the statistical model to compute very high PCB concentrations (i.e., >4 µg/L). Because the maximum PCB concentration measured at South Spring during the 2001-2005 routine monitoring was 2.6 µg/L, it was decided to adjust these unrealistically high values (i.e., >4 µg/L at total system flow of <1 gpm) by capping the low flow CBW boundary concentration at 3 µg/L.

Storm Conditions

For higher flows at CBW, a simple relationship with system flow could not be developed to capture the trends in the data. Previous analyses of the storm flow data had indicated a large degree of variability among the sampled storm events (Viacom 2002a). Therefore, a different approach was taken, whereby the PCB mass and the event mean PCB concentration (i.e., flow-weighted average) from a storm were related to the strength of the storm. Based on review of the storm PCB and flow data, it was found that a concentration-based relationship that includes an exponential flow term provided a good fit to both the mean storm concentration and the total storm PCB mass (see Appendix B for details). This relationship, which also includes the exponential decay term to account for long-term temporal trends, is given by:

$$C_{avg} = a Q_{avg} e^{-m Q_{avg}} e^{-kt} \quad (3-5)$$

where:

- C_{avg} = event-mean PCB concentration at CBW during a given storm event;
- a, m = best fit constants (see Appendix B); and
- Q_{avg} = average CBW flow over a given storm event.

The flow relationship in this equation represents the current understanding of the nature of the spring system during storm conditions: at relatively lower flows, event-mean PCB concentration increases with increasing flow, representing increased mobilization of PCB-containing material by the increasing flows. As flow rises further, the relationship produces a leveling off of the PCB mass that is mobilized, eventually resulting in a PCB load that is relatively independent of flow. This suggests that a finite mass of PCBs may be available for mobilization from the subsurface for a given flow event.

The parameters of Equation 3-5 (i.e., a and m) were estimated by least squares fitting. For the 17 storm events sampled between 1998 and January 2005, the event mean PCB concentration at CBW was calculated based on hourly flow and PCB data and was regressed against the mean storm flow rate (see Appendix B). For consistency with the spring statistical model used for low flow conditions, the South Spring PCB decline rate determined from the trend analyses of 0.06 yr^{-1} was used for the CBW storm flow PCB boundary condition. The function used to define the CBW event mean PCB concentration during storms provides a good representation of the data, as shown in Figure 3-15.

In addition to the event mean PCB concentration, Equation 3-5 provides an estimation of total PCB load that enters Conard's Branch at CBW for a given storm event (i.e., by multiplying event mean concentration by average storm flow). The PCB mass entering Conard's Branch is important for simulation of PCB transport at downstream locations during storms. Additionally, review of the CBW data indicated that the PCB concentrations measured during storms were generally characterized by an increase to a peak value during the rising limb of the hydrograph. It was desired to also represent this characteristic in the CBW PCB storm flow boundary condition. Analysis of peak hourly PCB concentrations normalized to the event mean concentration during storms, which can be thought of as a scaling factor, indicated a general positive relationship with the peak hourly flow rate. A regression of these data was used to represent this feature in the CBW storm PCB boundary condition.

The functions representing the event-mean PCB concentration, the total PCB mass, and the peak concentration scaling factor used for the CBW storm boundary condition are compared

with the data in Figure 3-16. The colors of the symbols and the different lines represent different years over the analysis period. The rise in event mean PCB concentration with flow is seen in Figure 3-16, upper-left panel, and the leveling off of total storm PCB load with flow is seen in Figure 3-16, upper-right panel. The relationship that defines the peak storm PCB concentration as a function of peak flow, which is based on a scaling factor that is applied to mean storm PCB concentration, is shown in Figure 3-16, lower-left panel.

Thus, for a given storm event, defined as total system flow exceeding 300 gpm for six hours or more, PCB concentrations at the CBW model boundary were assigned according to the following steps:

1. The event mean PCB concentration for the storm was calculated based on the average storm flow and Equation 3-5. This value was initially assigned for the duration of the given storm event.
2. The peak storm PCB concentration, calculated using the peak flow scaling factor relationship shown in Figure 3-16 (lower-left panel), was then assigned to the time at which the peak hourly flow occurred during the given storm event, for a one-hour duration.
3. The event mean PCB concentration estimated in Step 1 was then adjusted so that the total PCB mass during the storm (Figure 3-16, upper-right panel), which had been increased due to the specification of the peak concentration in Step 2, was preserved.

A comparison of the time-variable PCB concentrations used as the model boundary condition at CBW indicates that the low flow and high flow approaches discussed above provide a good representation of the variations in PCB concentrations entering Conard's Branch from the springs (Figure 3-17).

3.2.1.1.3 STF Effluent PCBs

Biweekly effluent PCB data collected as part of NPDES monitoring were used to specify the model boundary conditions for the STF. Linear interpolation was used to define concentrations between sampling dates (Figure 3-18). For non-detect PCB data, one half the detection limit was assigned (i.e., 0.05 ppb), except for days after August 2003, when the media in the STF's GAC units was regenerated (Viacom 2003). Although the reported PCB detection limit increased to 0.2 ppb after August 2003, a value of 0.02 ppb was assigned to the STF boundary condition for non-detect values, to represent the expected lower concentration associated with the fresh carbon.

3.2.1.1.4 PCBs at North Spring and its Bypass

Sampling by Viacom during 2004 and 2005 (Viacom 2004b) identified additional sources of PCBs entering Conard's Branch in the vicinity of North Spring. Based on these data, the NS + Bypass (NSB) PCB boundary condition was developed to represent a combination of three inputs: 1) 'true' flow from North Spring entering Conard's Branch; 2) additional PCB-containing spring/groundwater seepage found to be entering Conard's Branch in the vicinity of North Spring (i.e., the bypass); and 3) PCB loads associated with the cycling of the STF effluent, in which PCBs are desorbed from bank soils that are inundated during periods of STF discharge and are subsequently released to Conard's Branch when the stage height in the branch decreases and the water drains from the banks. Note that the first two inputs are associated with additional water flowing into Conard's Branch, while the third is not. The NSB boundary condition was represented in the model using a function that: 1) explicitly accounts for each of the three inputs comprising the PCB load entering Conard's Branch in the North Spring area; and 2) reflects the temporal trend in North Spring PCB concentrations quantified by statistical modeling (Appendix A). The function is given by (see Appendix B for a detailed derivation):

$$C_{NSB} = \frac{(W_{bank} + (Q_{NS} + \alpha Q_{bypass}) a Q_{sys}^b) e^{-kt}}{Q_{NS} + Q_{bypass}} \quad (3-6)$$

where:

- C_{NSB} = effective PCB concentration associated with the NSB inputs (= total PCB load divided by total flow);
- Q_{NS} = ‘true’ flow from NS (estimated as a function of MW5A groundwater elevation; see Section 3.1.1.1.3);
- Q_{bypass} = NSB flow calculated as a function of total system flow (Figure 3-5);
- W_{bank} = PCB load associated with bank recharge/discharge caused by the STF effluent cycling;
- α = a dilution factor that represents the ratio of PCB concentration in seepage water relative to the NS concentration, which was estimated based on sampling conducted by Viacom in April and May 2005 to be in the range of 0.5 to 0.8;
- Q_{sys} = total hourly system flow rate;
- a, b = constants for the NS statistical model (see Appendix A);
- k = NS decline rate (0.06 yr^{-1} ; see Appendix A); and
- t = time in years since January 1, 2001.

The only term in Equation 3-6 that was not known from either measurement or estimation is W_{bank} . Thus, the value for W_{bank} , along with an estimated value for α within the range of 0.5 to 0.8, was determined by calibration to the low flow monitoring data in Conard’s Branch. In addition, the value of W_{bank} was set to zero in the NSB boundary condition for the period spanning June 24, 2005 through December 31, 2005 to represent the relocation of the STF discharge 1000 ft. downstream of the NS area that occurred during this time.

Upon applying Equation 3-6 to the hourly flow data for the full 2001-2005 calibration period, it was found that for a small fraction of the time (i.e., <1%), the total system flow was extremely low (<1gpm), which caused the NS statistical model to compute very high PCB concentrations (i.e., >10 $\mu\text{g/L}$). Since the maximum PCB concentration measured at North Spring during the 2001-2005 routine monitoring was 1.6 $\mu\text{g/L}$, it was decided to adjust these unrealistically high values (i.e., >10 $\mu\text{g/L}$ at total system flow of <1 gpm) by capping the NSB

boundary concentration at 3 µg/L. One additional adjustment was made to the NSB boundary condition to avoid unrealistically high values for C_{NSB} at times when the total system flow and the STF flow were very low. When the STF flow was less than 20 gpm, W_{bank} was set to zero, to avoid unrealistically high values of C_{NSB} in the range of 5 to 10 µg/L. This adjustment is appropriate because the PCB loading associated with bank exchange would not be expected to occur at times of very low STF flow.

3.2.1.1.5 RCUP, DD1, and DD2

For the ungaged tributaries and flow inputs to the model, PCB concentrations were set to zero for the entire calibration period since there was no evidence that indicated the presence of PCB sources in these areas.

3.2.1.2 Initial Conditions

The only initial condition required by the sediment transport and PCB fate sub-models was the specification of sediment PCB concentrations at the beginning of the simulation period. Because limited data were collected at the beginning of the model simulation period (i.e., 2001), data collected from 1998 to 2004 (Table 2-1; Viacom 2002a, 2005a) were combined to develop the initial conditions. The 1998 survey focused on sediment samples between Conard's Branch and RCVP, while the 2004 sampling was more evenly distributed throughout the model domain. A few additional samples were collected in 2002 and 2003, focusing on locations where fish samples are collected and near the deeper sediment deposit within Conard's Branch. Given that sediment PCB concentrations change slowly and no significant differences were observed among these data sets, combining these data was deemed appropriate.

Variable sampling depths and vertical segmentation schemes were used in these sediment sampling programs. While sediment cores were generally segmented in 6-in. and 3-in. intervals in the 2001 and 2004 surveys, respectively, grab samples were collected in 1998 and 2002. Because the streams contain shallow sediment deposits in most locations (e.g., USEPA 2003)

and the model only simulates, at most, the upper 12 in. of sediment (Section 2.2.1), the PCB initial condition was based on data from either grab samples or the surface sections of cores.

The initial conditions for the PCB fate sub-model were developed by averaging the 1998-2004 surface sediment data over five reaches of the model domain: three in Conard's Branch and two in Richland Creek (Figure 3-19). These data averaging reaches were located to capture gradients in PCB concentrations and other measured bed properties, while smoothing out some of the local variability of the samples. The same average surface sediment concentration was applied to all six layers of the simulated model bed.

3.2.1.3 Parameterization

A number of parameters to represent the sediment and PCB characteristics within the system were specified in the sediment transport and PCB fate sub-models. These parameters and coefficients were developed from site-specific data, literature values, and experience with other systems. A brief description of the key parameters is included in the following subsections.

3.2.1.3.1 Sediment Bed Map

The representation of the sediment bed in the model was divided into two types of areas: 1) areas of active sediment, which were represented by cohesive sediment formulations in the model; and 2) areas of rock or hard bottom, where no particles are deposited or resuspended in the model. A sediment bed map was developed based on 2003 USEPA probing transect survey (Figure 3-20). The sediment thickness transect data were first averaged laterally, and were then linearly interpolated over the length of the model domain (Figure 3-20). Model grid cells were then specified to be cohesive if the corresponding average sediment thickness was greater than 1 inch. Otherwise, rock/hard bottom was assigned to the model cell. This approach allowed the model bed to reflect the variable nature of the streams' sediment bed, which can be characterized as mainly rocky, with intermittent depositional areas. Bed type in a few isolated areas exhibiting high erosion rates in the model was modified to be hard bottom to maintain numerical stability during model calibration.

3.2.1.3.2 *Sediment Bed Properties*

Sediment bulk density and porosity were used by the sediment transport and PCB fate sub-models in a number of calculations. Bulk density was measured for sediment samples collected during the 2004 survey. For previous data sets, bulk density was estimated based upon measured percent solids and an assumed solid specific gravity of 2.65 using standard geotechnical relationships (e.g., Das 1990). Porosity was then calculated from bulk density using standard geotechnical relationships.

Spatially-variable bulk density and porosity were assigned to the model using an approach similar to that for the sediment initial conditions (Section 3.2.1.2). Average values of the bulk density and porosity data were computed for four reaches of the model (Figure 3-21), and then assigned to all six layers of the model sediment bed for the corresponding model grid cells. A single data averaging segment was used for the entire length of Richland Creek in the model since no spatial differences were observed in the bed property data from that reach.

3.2.1.3.3 *Sediment Deposition*

The deposition of cohesive sediments is internally computed by the sediment transport sub-model based on a number of literature formulations. The deposition flux (D_s) is computed according to the following formulation (e.g., Ziegler and Nisbet 1994):

$$D_s = PW_s C_s \quad (3-7)$$

where:

- P = probability of deposition;
- W_s = sediment settling speed; and
- C_s = suspended sediment concentration.

The setting speed (W_s) is computed by the model based on the formulation for cohesive flocs in freshwater, which is a function of cohesive sediment concentration and water column shear stress (Burban et al. 1990). The probability of deposition (P), which is computed internally by the model as a function of particle size, accounts for the observation that only a fraction of cohesive sediments that settle to the bed are permanently deposited due to the effects of particle/floc size heterogeneity and near-bed turbulence (Partheniades 1992).

3.2.1.3.4 Sediment Erosion

The erosion rate of cohesive sediments (ε) is computed in the sediment transport sub-model by (Gailani et al. 1991):

$$\varepsilon = A \left(\frac{\tau - \tau_{cr}}{\tau_{cr}} \right)^n, \tau \geq \tau_{cr} \quad (3-8)$$

where:

- τ = bed shear stress computed by the hydrodynamic sub-model;
- τ_{cr} = the critical shear stress, below which no resuspension occurs (= 1 dyne/cm²); and
- A, n = site-specific constants, which were adjusted during calibration.

3.2.1.3.5 Organic Carbon

Organic carbon associated with particles has been identified to be the primary sorption site for PCBs (e.g., Karickhoff 1984). Thus, the model requires specification of organic carbon concentrations for both sediment and water column particulate matter to allow calculation of PCB partitioning.

Similar to the sediment bed properties, (Section 3.2.1.3.2), total organic carbon (TOC) concentrations in the sediment bed were defined in the model by averaging TOC data collected

from 1998 to 2004 into four data averaging segments (Figure 3-22). The resulting TOC values were assigned to all modeled sediment bed layers within each model grid cell.

Particulate organic carbon (POC) concentrations in the water column were measured during the March 2004 and January 2005 storm surveys (Table 2-1). Based on the POC and TSS measurements, the average fraction of organic carbon associated with these data was calculated to be 2% to 4% during these events. Due to the limited data set, and the observation that stream POC typically varies seasonally and is much higher than that found in the sediments (due to decay of deposited organic matter by benthic bacteria), a constant POC fraction of 10% was used in the PCB fate sub-model. This value was based on the typical range of 5% to 20% observed in other stream systems (e.g., Avnimelech 2001; BBL and QEA 2003; QEA 1999).

3.2.1.3.6 PCB Partitioning Coefficient

The PCB partitioning coefficient (K_d) is defined as the ratio of the dissolved PCB concentration to the concentration of PCBs adsorbed to particles for a given system that is at equilibrium. Two-phase (particulate-dissolved) equilibrium partitioning can be expressed as:

$$K_d = \frac{C_d}{C_p m_{ss}} \quad (3-9)$$

where:

- C_d = the dissolved phase PCB concentration (M/L³);
- C_p = the particulate phase PCB concentration (M/M); and
- m_{ss} = the concentration of solids in the system (M/L³).

Because PCBs tend to associate with organic carbon, partition coefficients are commonly expressed on an organic carbon basis (K_{oc}). The organic carbon partition coefficient can be calculated from K_d based on the organic carbon fraction of the solids (f_{oc}):

$$K_{oc} = \frac{K_d}{f_{oc}} \quad (3-10)$$

When modeling PCB partitioning, K_{oc} , which varies based on the degree of chlorination, is typically treated as a chemical-specific property. For the Neal's Landfill PCB fate sub-model, a site-specific K_{oc} was estimated based on data from the barrel test study conducted by Viacom and Indiana University in October 2001 (Viacom 2002b). In this study, four large volume samples of spring water were collected during various stages of a storm that occurred October 24 to 25, 2001, and added to barrels to observe settling characteristics. A total of ten samples were collected from the barrels and analyzed for TSS and dissolved and particulate PCB concentrations. Based on these data and an average f_{oc} of 2% (based on the March 2004 storm event data), K_{oc} values were calculated using Equations 3-9 and 3-10. The resulting average log K_{oc} value of 5.58 is well within the range of literature log K_{oc} values for Aroclors 1242 and 1248 (5.38 and 5.66, respectively; Mackay et al. 1992), which are considered representative of the PCB composition at the Neal's Landfill site (e.g., CBS 1998).

3.2.1.3.7 PCB Volatilization

Transfer of PCBs at the air-water interface is calculated by the PCB fate sub-model as a function of the chemical's Henry's Law Constant (HLC), and a volatilization mass transfer coefficient. The HLC of PCBs varies with chlorination level; a site-specific value was estimated based on published HLC values for PCB congeners (Brunner et al. 1990), and the average congener composition (i.e., weight percent) of the source Aroclors at the site. The final HLC value used in the model was adjusted within the range of values corresponding to Aroclors 1242 and 1248 during model calibration. The volatilization mass transfer coefficient is calculated internally by the model as a function of the PCB diffusivity in water (after Hayduk and Laudie 1974; Mackay et al. 1992) and the water depth and current velocity (from the hydrodynamic sub-model) based on the O'Connor and Dobbins (1958) formulation.

3.2.1.3.8 PCB Mass Transport Processes within the Sediment Bed

In addition to deposition and resuspension, the PCB fate sub-model simulates three processes by which PCBs are transported vertically within the sediment bed. First, PCBs are transported by molecular diffusion within sediment porewater. This process is parameterized by a diffusion coefficient, which was based on the PCB diffusivity in water (Hayduk and Laudie 1974) adjusted for the tortuosity of the sediments (Lerman 1978). Second, the model simulates the upward flux of dissolved phase PCBs at the sediment/water interface, which typically occurs at a rate that exceeds that of molecular diffusion due to biological activity (e.g., Thibodeaux et al. 2001). This process is characterized by a mass transfer coefficient; a value within the range of those found in others aquatic systems (e.g., Thibodeaux and Bierman 2003), was determined by calibration for this site. Third, the model simulates the vertical mixing of sediment particles (and associated PCBs) by bioturbation. This mixing within the bed is parameterized by a dispersion coefficient, which was set to a value typical of other freshwater systems (e.g., Thoms et al. 1995).

A summary of the key sediment transport and PCB fate sub-model parameters and the methods used to specify the values in the model is provided in Table 3-2.

Table 3-2. Sediment transport and PCB fate sub-model parameters.

Parameter	Site-Specific Data	Literature	Calibration
Sediment texture, density, porosity	✓		
Particle settling characteristics	✓	✓	
Erosion rate parameters		✓	✓
Water column POC	✓	✓	
Sediment TOC	✓		
Partitioning coefficient	✓		
Henry's Law Constant	✓	✓	
Volatilization mass transfer coefficient		✓	✓
Sediment/water mass transfer coefficient.		✓	✓
Pore water diffusion coefficient		✓	
Sediment mixing rate (bioturbation)		✓	

3.2.2 Model Calibration

3.2.2.1 December 2003 and March 2004 Storms

The sediment transport and PCB fate models were first calibrated to the high frequency data collected during the December 2003 and March 2004 storm sampling events. For these simulated storm events, high frequency TSS and PCB data were collected at CBW. Thus, these boundary conditions were specified directly from data rather than the formulations discussed in Section 3.2.1.1, to eliminate this source of uncertainty from the storm calibration.

Analyses of these storm event data indicated a significant increase in the mass of solids between the upstream end of Conard's Branch and CBVP. Initial model testing and sensitivity analyses indicated that the model-predicted PCB concentrations during storm events were relatively insensitive to the extent of sediment erosion simulated in Conard's Branch (due to the relatively low sediment PCB concentrations present). This result indicated that the source of the increase in solids mass observed at CBVP could have originated from sediment erosion or from external sources (i.e., the aggregate flows associated with DD1). Because of this insensitivity to erosion, the sediment transport and PCB fate sub-models were calibrated together.

This calibration approach consisted of first setting the sediment erosion parameters based upon those measured from another site (such that the model matched measured PCB concentrations). The best calibration was achieved by setting the parameters of Equation 3-8 to $A = 0.019$ and $n = 2.5$, which are within the range of resuspension parameters measured in a relatively small river system, Housatonic River, MA (BBL and QEA 2003).

Once the erosion parameters were set, the inflow TSS concentrations for the ungaged tributary and direct drainage boundaries (i.e., RCUP, DD1, and DD2; Figure 2-3) were adjusted to best match the increase in solids mass transport observed throughout the system. The TSS concentrations for these boundaries were specified to follow the same general sediment rating curve formulation used for CBW (Section 3.2.1.1.1; Figure 3-12):

$$Cs_i = a_i \quad , \quad Q_i \leq m_i \bar{Q}_i \quad (3-11)$$

$$Cs_i = b_i \left(\frac{Q_i}{\bar{Q}_i} \right)^{n_i} \quad , \quad Q_i > m_i \bar{Q}_i$$

where, for a given tributary i :

$\bar{Q}_i$ = mean flow rate for tributary i ; and

a_i, b_i, n_i, m_i = constants for tributary i .

The calibrated coefficients in Equation 3-11 used to calculate TSS for each of the ungaged tributary and direct drainage inputs (i.e., DD1, RCUP, and DD2) are listed in Table 3-3.

Table 3-3. Calibrated sediment rating curve coefficients for ungaged model tributaries.

Boundary	a	b	n	m
DD1	4	2.46	0.50	1.84
RCUP	3	4.48	1.05	0.95
DD2	3	2.72	0.90	1.52

The resulting calibrated TSS rating curves for ungaged tributaries shown in Figure 3-23 demonstrated responses to flow rate that were similar to those observed in CBW as well as in another small nearby stream, Beanblossom Creek, which is located approximately 30 miles east of Bloomington, IN¹.

Temporal profiles of the model calibration results are plotted against the data in Figures 3-24 and 3-25 for the December 2003 and March 2004 storms, respectively. Each plot shows temporal profiles of hourly data and model predictions for flow rate, TSS, and water column PCB concentrations at four sampling locations: CBW, CBVP, RCVB, and RC43. The model data comparisons in Figures 3-24 and 3-25 indicate that the model generally captures the observed system dynamics during these storm events. Although there is significant variability and the model does not perfectly match the data from every location for both events, the model

¹ Beanblossom Creek flow and TSS data were obtained from USGS gage # 03354500 (http://nwis.waterdata.usgs.gov/in/nwis/nwisman/?site_no=03354500&agency_cd=USGS).

captures the general increases in peak TSS concentrations and total solids loading from upstream to downstream (Figures 3-24 and 3-25, middle panels). Storm PCB concentrations exhibit significant decreases from upstream to downstream; this trend is captured by the model (Figures 3-24 and 3-25, bottom panels). The total storm PCB mass at CBVP is similar to that at CBW for both model and data, suggesting that dilution was the primary fate mechanism during these storm events. The large number of non-detect PCB samples at the Richland Creek stations precluded an evaluation of mass transport at these locations, but the model-predicted PCB concentrations are consistent with the measured concentrations, including the two apparent detected concentrations at the RCVF station during the March 2004 event.

3.2.2.2 January 2005 Storms

Following calibration to the first two storm events, the sediment transport and PCB fate sub-models were checked against additional storm sampling events conducted in January 2005. The January 2005 storm events produced much higher flows, with the peak CBW flows of approximately 10,000 gpm (as compared to values of approximately 500 and 1000 gpm for the December 2003 and March 2004 storm events, respectively). The sediment transport and PCB fate sub-models were configured to simulate these events by setting the CBW TSS and PCB boundary conditions equal to the measured data, and not modifying any of the calibration parameters. Thus, these events essentially served as a model validation.

Temporal profiles of the flow, TSS and water column PCBs for the January 2005 storm events are plotted in Figures 3-26 and 3-27. Comparison of the model predictions of TSS and PCBs with the observed data at the downstream sampling locations indicates that the model provided a reasonable fit to these data. The model does not always capture the timing and magnitude of the peak TSS concentrations, but the general increases in solids mass and concentrations from upstream to downstream are captured (Figures 3-26 and 3-27, middle panels). The model provides a good match to the PCB concentrations observed at CBVP, indicating that the level of dilution is specified correctly. Analysis of the model outputs from this storm events indicated that there was no strong signal from the sediments within Conard's Branch (i.e., no significant net deposition or erosion), which is indicative of near steady-state

conditions and is consistent with the conceptual model of small transient sediment deposits within the system.

3.2.2.3 Low Flow

Following the storm evaluations, the PCB fate sub-model was calibrated for low flow conditions by adjusting the NSB bank PCB load and seepage dilution factor (W_{bank} and α ; see Section 3.2.1.1.4) and the HLC to match data from low flow surveys conducted at multiple locations in April and July 2004 and monthly monitoring at CBVP from March to December 2005. The low flow calibration results are plotted as a spatial profile in Figure 3-28. The increase in PCB concentration observed in the vicinity of North Spring was captured by the NSB loading, which included final calibrated values of $\alpha = 0.8$ and $W_{bank} = 27$ mg/day (subject to a 0.06 yr^{-1} decline starting on January 1, 2001). Downstream of NS, the water column PCB data within Conard's Branch exhibit large variability, but no consistent spatial trend. The model-predicted concentrations generally match the means of the data, but exhibit a decline due to volatilization losses, which resulted from calibration of the HLC within a realistic range. A balance was required for calibrating HLC, as the model needed to match PCB levels at multiple locations within Conard's Branch, and decreases in water column PCBs from volatilization needed to offset increases due to diffusive flux from the underlying sediments. The model predictions at low flow provide a good match to the large reduction in concentrations at RCVP, which are produced by the large dilution from Richland Creek upstream of the mouth of Conard's Branch.

3.2.2.4 Long Term Results

Water Column

Model-data comparisons of TSS and PCB concentrations for the 2001-2005 long-term calibration period are plotted in Figures 3-29 through 3-33 for the following sampling locations: Conard's Branch at NS, Conard's Branch at the property line, CBVP, RCVP, and RC43. The long-term results for these locations, viewed as a whole, indicate that the model generally provides a good match to the observed PCB concentrations throughout the system at both base

flows and storm conditions. The model also captures the dominant feature in the water column PCB data: the substantial decrease caused by dilution.

Sediment

The data and calibrated model results for PCB concentrations in surface sediment (as well as water column) are presented in Figures 3-34 and 3-35 for CBVP and RCVP, respectively. The model results for surface sediment concentrations exhibited very little change over the five-year calibration period, which is generally consistent with the various data sets collected over that period.

Mass Balance

The PCB mass balance for Conard's Branch in Figure 3-36 further illustrates the long-term system dynamics predicted by the model. For the 2001-2005 period, 2.92 kg of PCB was calculated to enter Conard's Branch from the upstream area, with most of this mass (2.87 kg) leaving the stream via flow to Richland Creek. CBW accounted for the majority of the PCB mass entering Conard's Branch, with the NSB and STF effluent accounting for less than 10% together. PCB mass transport associated with volatilization and the sediments is relatively small (~0.1 kg associated with net diffusion, deposition, and erosion). Diagnostic model calculations that quantify PCB sources to the system under different flow conditions are discussed further in Section 4.1.

Based on these model calibration results, the sediment transport and PCB fate sub-models provide a sufficiently accurate representation of the system with which to calculate PCB exposure concentrations for use in the bioaccumulation sub-model.

3.3 PCB BIOACCUMULATION

3.3.1 Model Development

3.3.1.1 Food Web Structure

In a general aquatic food web, particulate matter is consumed by water column invertebrates (WCI) and benthic macroinvertebrates (BMI), invertebrates are consumed by fish and, in larger systems, small fish are consumed by predatory fish (Figure 3-37). Many invertebrates have diets that include both water column and benthic sources of particulates and associated PCBs. In the bioaccumulation sub-model, two representative invertebrates were modeled: one that consumes only from the water column (WCI) and one that consumes only from the sediment bed (BMI). In this way, the full range of exposure levels available to the fish was represented. During model calibration, crayfish data were compared qualitatively with model results for the invertebrates; calibration was not attempted because of uncertainty regarding the precise feeding behavior of the crayfish.

The bioaccumulation sub-model was applied to Location B in Conard's Branch, which is near CBVP (Figure 2-2). Conard's Branch supports small fish (primarily creek chub) and crayfish (TetraTech 2003). Thus, only one trophic level of fish is represented in the model for Conard's Branch. Creek chubs are the only fish species with an appreciable amount of PCB data in Conard's Branch (Table 2-1). Therefore, the model food web for Conard's Branch consists of WCI, BMI, and creek chub. Creek chub consume a mixture of WCI and BMI; the precise mixture was determined by calibration.

The bioaccumulation sub-model was also applied in Richland Creek at Location D (Figure 2-2), which is near RCVP, a location with considerably more diversity in the fish community: about 20 species of fish have been observed there (TetraTech 2003). Recent PCB data exist at this site for crayfish, creek chub, longear sunfish, rock bass, and white suckers. Creek chub were included in the model, because they are omnivorous and thus are representative of the fish community, insofar as they are likely to accumulate PCBs from both water column

and sediment sources. Sunfish data at Location D are sufficient to support calibration and were therefore included as well. Both species consume a mixture of WCI and BMI; the precise mixtures were determined by calibration.

In small streams, terrestrial invertebrates that fall or are washed into the stream can provide a significant amount of the energy needs of the fish community (Lotrich 1973; Stair et al. 1984; Kawaguchi and Nakano 2001). Terrestrial-derived food sources can comprise up to 90% of the diet of some species in summer in small streams (Stair et al. 1984; Kawaguchi and Nakano 2001). Therefore, a terrestrial component was included in the model diet. Terrestrial food was assumed to contain no PCBs. The proportion of terrestrial food in each species at each location was determined by calibration. Following calibration, the resulting dietary composition was further evaluated in light of information reported in the published literature regarding the terrestrial contribution of aquatic food webs: the terrestrial contribution to fish diets is greater in summer than in winter (Zaranko 1994), it is greater in smaller streams than larger ones (Stair et al. 1984), and creek chub have been found to include more terrestrial food in their diet than longear sunfish (Lotrich 1973).

The food web used in the bioaccumulation sub-model is presented in Figure 3-38. The final dietary percentages are presented with the model calibration (Section 3.3.2).

3.3.1.2 Parameterization – Fish

3.3.1.2.1 Theory

The accumulation of PCBs by aquatic animals is described by Equation 3-12 (Thomann and Connolly 1984; Connolly 1991; Connolly et al. 1992):

$$\frac{dv_i}{dt} = K_{ui}c + \alpha_c \sum_{j=1}^n C_{ij}v_j - (K_i + G_i)v_i \quad (3-12)$$

where:

- i and j = indices for predator and prey, respectively;
- v_i = the whole-body concentration of chemical in species i ($\mu\text{g/g wet}$);
- K_{ui} = the rate constant for respiratory chemical uptake by species i (L/g wet-d);
- C = the concentration of PCBs dissolved in the water ($\mu\text{g/L}$);
- K_i = the rate constant for excretion of chemical by species i ($1/\text{d}$);
- α_c = the efficiency at which ingested chemical is assimilated from prey;
- C_{ij} = the predation or consumption rate of species i on species j ($\text{g wet prey/g wet predator-d}$);
- G_i = the growth rate of species i (g wet/g wet-d); and
- n = the number of species (including different year classes of a single species) preyed upon by species i .

The first term of Equation 3-12 represents the direct uptake of PCBs by the animal from water. The second term represents the flux of PCBs into the animal through feeding. The third term represents the loss of chemical due to diffusion across the gill and the change in concentration due to growth. The fecal elimination rate for total PCBs is lower than both the gill depuration rate (Connolly et al. 1992; Gobas et al. 1989) and the growth rate and does not affect the overall PCB concentration to an important degree; it is not included in the model. The dynamic bioaccumulation model is applied to each fish species, accounting for species-specific differences in growth rate, consumption rate, and elimination rate.

Gill exchange involves diffusion between dissolved contaminant pools on either side of the gill membrane (e.g., Erickson and McKim 1990). Gill exchange (in units of $\mu\text{g/g wet-day}$) is given by:

$$\text{Gill exchange} = PK_u (c - v_B) \quad (3-13)$$

where the rate constant for respiratory chemical uptake (K_u , in units of L/g wet-day , without the subscript i denoting a specific species) is defined from the oxygen uptake rate and

the dissolved oxygen concentration (Connolly et al. 1992), P is a coefficient that is equal to the ratio of the transfer efficiencies of chemical and oxygen, and v_B is the concentration of contaminant dissolved in blood ($\mu\text{g/L}$). v_B is estimated by dividing the contaminant concentration in lipid by a lipid/blood partition coefficient, B_{LB} .

The exchange of organic chemicals across the gill surface is rapid (Connolly et al. 1992). The use of the lipid/blood partition coefficient assumes rapid equilibration between lipid stores and blood. However, the exchange between lipid stores and blood is relatively slow, and elimination rates in chronically exposed fish are probably controlled by transfer from storage tissue to blood (Nichols et al. 1990). Here, the relatively slow transfer between the deep compartments and blood is accounted for by reducing the parameter P .

The rate of consumption of food, $E_j(C_{ij})$, is calculated from the rate of energy usage for growth and metabolism. The model computes growth rates based upon a relationship between age and weight that is determined from data. The respiration model is:

$$R = \beta W^\gamma e^{\rho T} c_{act} \quad (3-14)$$

where:

R = the respiration rate (kJ/g wet-d);

T = the temperature ($^{\circ}\text{C}$);

c_{act} = a multiplier that accounts for the costs of swimming activity; and

β , γ , and ρ = coefficients determined by experiment.

The apparent specific dynamic action (ASDA), the energy required for absorption, digestion, transportation and deposition of food materials, is added to the respiration rate specified in Equation 3-14 to give the overall metabolic rate.

3.3.1.2.2 Application to the Site

Coefficients used in the bioaccumulation model were developed based upon site-specific data, current literature, and previous modeling experience, as summarized in Table 3-4.

Table 3-4. Bioaccumulation sub-model parameters.

Parameter	Site-Specific Data	Literature	Calibration
Lipid contents	✓	✓	
Growth rates	✓		
Bioenergetic coefficients (e.g., respiration, elimination, gill transfer)		✓	✓
Invertebrate trophic transfer coefficients		✓	
Partitioning coefficient	✓		
Fish diets		✓	✓

Species-specific growth rates were calculated using ages estimated from scales collected from fish in the study area. Growth curves for fish collected in Conard's Branch and Richland Creek are shown with the age data in Figure 3-39. Fish lipid contents were estimated from the data for creek chub in Conard's Branch and Richland Creek and longear sunfish in Richland Creek (Figure 3-40). Lipid contents in creek chub from the site vary seasonally to a considerable degree, thus, a seasonal cycle was represented in the model (Figure 3-40). Longear sunfish did not exhibit a strong cycle; a single average value was used.

Published laboratory measurements of standard metabolism were used (creek chub: values for dace reported by Hanson et al. 1997; longear sunfish: values for pumpkinseed as reported by Evans (1984). The ASDA was set equal to 17.5% of the total food consumption (Hanson et al. 1997).

The assimilation efficiency for PCBs was set equal to the food assimilation efficiency (Connolly 1991; Connolly et al. 1992; QEA 2002). K_{ow} was used as an estimate of the lipid/blood partition coefficient (B_{LB}) in the model, resulting in an inverse relationship between $\log(K_{ow})$ and $\log$ (elimination rate), as found by Erickson and McKim (1990). The value of $\log(K_{ow})$ appropriate for the total PCB model depends on the congener composition of the PCBs in the fish themselves. $\log(K_{ow})$ values were calculated using the congener composition measured in fish collected in 2003 from the study area (Figure 3-41). A $\log K_{ow}$ value of 6.0,

corresponding approximately to the median calculated value, was used in the bioaccumulation sub-model. The factor that accounts for the reduction in elimination rates due to the slow transfer from storage tissues (P) was estimated by calibration.

The bioenergetics parameters discussed above are influenced by water temperature. Stream temperatures during the year were estimated based on typical temperatures of spring-fed systems. A low of 0.5°C was used for mid-winter, a high of 20°C was used during mid-summer, and values between the two extremes were estimated by interpolation. Temperature measurements collected at CBVP in 2004 through 2006 are generally consistent with this specified range.

3.3.1.3 Parameterization – Invertebrates

The benthic and water column invertebrate models were developed so as to honor published information concerning the overall extent of accumulation, the body composition of the invertebrates, and the response time of the invertebrates to changes in their exposure levels.

3.3.1.3.1 Overall Extent of Accumulation

The most important criterion for the invertebrate models is that they produce a realistic estimate of the overall extent of bioaccumulation in the WCI and BMI. Estimates of the overall extent of bioaccumulation in aquatic invertebrates are available in the literature based upon field measurements of matched samples of invertebrates and their contaminant sources. These estimates are called biota/sediment accumulation factors (BSAFs; equal to the ratio of the lipid-based PCB concentration in the invertebrates and the carbon-based PCB concentration in the water) and water column bioaccumulation factors (BAFs; equal to the ratio of the lipid-based PCB concentration in the invertebrates and the dissolved PCB concentration in the water). The invertebrate model parameters were set so as to produce computed BSAF and BAF values that reflected published data.

An average BSAF value of 1.5 was calculated by Tracey and Hansen (1996) for total PCBs, based on an extensive literature review. This value was used in the Neal's Landfill bioaccumulation sub-model. It is similar to the value measured in matched sediment and invertebrate samples collected in the Hudson River (1.4 g OC/g lipid; USEPA 2000). The accumulation factor from water column particles to WCI was determined based upon PCB measurements in phytoplankton and zooplankton conducted in Green Bay as part of the Green Bay Mass Balance Study (Connolly et al. 1992; QEA 2002). This seminal data set includes a large number of paired phytoplankton and zooplankton samples collected over much of the year, providing what is probably the most extensive set of measured water column invertebrate accumulation factors available. The average ratio between the two ($[g \text{ PCB/g lipid}] / [g \text{ PCB/g organic carbon}]$) for each congener in Green Bay ranged from 2 to 4. A value of 3 was used in the Neal's Landfill bioaccumulation sub-model. This is two times the value of 1.5 used for the BMI. This difference likely reflects differences in the bioavailability of PCBs associated with recently generated water column particulate matter and aged sediments (e.g., QEA 1999).

3.3.1.3.2 Body Composition of the Invertebrates

Parameters that characterize the body composition of the invertebrates assure that the rate at which invertebrates are consumed by fish in order to meet the fish bioenergetic demands is realistic. A lipid content of 2% (Morrison et al. 1997, 1999; Zaranko 1994) and a protein content of 28% (Morrison et al. 1997, 1999) were used.

3.3.1.3.3 Rate at which Invertebrates Respond to Changes PCB Exposure

A half-life of about four days was used in the Neal's Landfill bioaccumulation sub-model. This lies within the range of 1 to 70 days reported by Hendriks (2001). The model is relatively insensitive to this characteristic of the invertebrates, because the PCB levels in the fish themselves represent an average over several months to years; since invertebrates respond relatively more quickly than fish to changes in exposure, variation in the response time of the invertebrates is unlikely to significantly affect PCB levels in fish.

3.3.1.4 Life Cycle Dynamics

The model computes the weight, lipid content, metabolic rate, and PCB concentration for each age class of each species on a daily basis.

3.3.2 Model Calibration

3.3.2.1 Approach

The bioaccumulation model was calibrated by adjusting two components of the model: the parameter P that controls the rate of elimination and uptake across the gill (Equation 3-13); and the fish diets, including the amount of terrestrial food and benthic and water column invertebrates. Parameters were constrained to reflect information available in the published literature, as well as experience using this model in other systems. The calibration strategy was designed to produce a model that provides a reasonable tool for projection into the future. Calibration was achieved by visual evaluation of the relationship between the model result and the data for the years 2001, 2003, 2004, and 2005.

Simulations from the PCB fate sub-model (Section 3.2.2.4) were used to provide daily PCB exposure levels for the water column and sediments, both particulate and dissolved phases, over the calibration period (January 1, 2001 to December 31, 2005).

3.3.2.2 Results

The value of the parameter P that resulted in the best model/data match was 0.15. This value is similar to values that have been used successfully in simulations of PCB bioaccumulation in Green Bay and the Fox River and the Hudson River (QEA 1999, 2002).

For Conard's Branch creek chub during winter, the calibrated diet consists of 60% terrestrial sources (25% from WCI and 15% from BMI), while in the summer 70% of the

calibrated diet was from terrestrial sources (20% from WCI and 10% from BMI; Table 3-5). In Richland Creek, longear sunfish was modeled with no terrestrial component to their feeding (40% WCI and 60% BMI), while creek chub diets were 10% terrestrial (60% WCI and 30% BMI).

Table 3-5. Calibrated diets in the bioaccumulation model.

Location	Species	Winter			Summer		
		WCI	BMI	Terrestrial	WCI	BMI	Terrestrial
Conard's Branch, Location B	Creek Chub	0.25	0.15	0.60	0.20	0.10	0.70
Richland Creek, Location D	Creek Chub	0.60	0.30	0.10	0.60	0.30	0.10
	Longear Sunfish	0.40	0.60	0.00	0.40	0.60	0.00

The patterns observed in these calibrated diet percentages are consistent with several lines of evidence from published literature:

- The terrestrial component is greater in Conard's Branch than in Richland Creek, which is consistent with literature studies which indicate decreasing percentage terrestrial invertebrates as stream size increases (Stair et al. 1984).
- The terrestrial component is greater in summer than in winter, also consistent with published information (Zaranko 1994).
- The contribution of terrestrial food to the creek chub is greater than for the longear sunfish (Lotrich 1973).

Calibration of the bioaccumulation sub-model involved a compromise between the various components of the data set, with the goal of providing the best overall fit. Computed PCB levels generally go through the scatter of the data (Figures 3-42 and 3-43). The model was not tuned on a point-by-point basis, so in some cases the model does not match data well (e.g., creek chub at Location B, lipid basis, fall 2003; Figure 3-42).

The left panels in Figures 3-42 and 3-43 present wet weight-based PCB concentrations, and the right panels present lipid-normalized results. The seasonal pattern of PCB concentrations observed in creek chub is captured by the model: wet weight-based

concentrations are generally higher in spring and lower in fall, while lipid-based concentrations show the opposite pattern. For longear sunfish, there is no apparent difference between seasonal patterns on a wet weight and lipid basis, both in the data and in the model. No clear relationship has been observed between PCB concentration and age in this data set, and, consistent with this, the model shows very little difference between age classes in computed PCB concentrations.

3.4 MODEL CALIBRATION SUMMARY

To summarize the model calibration results, a set of quantitative metrics has been developed. These metrics permit an assessment of bias and precision in the model calibration for water, sediment, and fish PCB concentrations.

3.4.1 Water Column PCBs

Scatter plots of model-predicted versus observed water column PCB concentrations, with lines indicating 1:1 (i.e., perfect agreement), were developed as the primary calibration metric. Bias is indicated by comparing the number of model-data comparisons above and below the 1:1 line. To aid in the evaluation of precision in the model calibration, lines indicating differences of a factor of two and a factor of five are indicated on the scatter plots. Scatter plots of the water column calibration results are shown separately for low flow and storm flow sampling data.

3.4.1.1 Low Flow (Non-Storm) Sampling Data

Scatter plots for model predictions of low flow water column PCBs are shown in Figure 1. The majority of the data were collected at CBVP (e.g., see Figures 3-29 through 3-33), which was the focus of calibration due to its proximity to fish sampling Location B. The CBVP predictions indicate little bias (i.e., roughly equal number of data points above and below the 1:1 line in the center panel of Figure 3-44), and all but one of the model-data comparisons are within a factor of two.

The comparisons for the upstream locations in Conard's Branch (i.e., NS and CBPL) suggest the model tends to be biased high there, but by less than a factor of two. This information is of limited value, since the data from these locations were collected on only three days of sampling in 2004; in comparison, the data for CBVP include ten sampling events between 2001 and 2004 and monthly sampling throughout 2005 (Table 2-1). This result may reflect uncertainty in the NSB loading, but is not considered significant to overall model performance, because of the lack of bias at the more intensively sampled downstream station at which the fish were collected. The model results for Richland Creek at Vernal Pike (RCVP) are well within a factor of two of the data, but the limited sample count does not provide a robust test of bias.

3.4.1.2 Storm Flow Sampling Data

Scatter plots of model-data comparisons for storm data are shown for individual samples in Figure 3-45. For samples that were reported as being less than the method detection limit (MDL), the data values are plotted at the MDL, and the model results are plotted at the MDL if the predicted concentration was less than the MDL. If the model prediction was above the MDL, the result is plotted at that predicted value. The storm data scatter plot comparisons indicate that the model calibration provides a good fit to the data at CBVP. The majority of the model-data comparisons at CBVP agree within a factor of two, and the similarity in the number of samples above and below the 1:1 line indicates a lack of overall bias. The storm data at the RCVP and RC43 locations are mostly non-detect, and the model is in general agreement with these results. For the limited number of samples with detectable PCBs at RCVP, the model predictions are mostly within a factor of two, and there is little evidence of bias.

A summary of the model-data comparisons for water column PCBs under storm conditions is provided by the scatter plot for event-mean concentrations (EMCs), which is shown in Figure 3-46. In this plot, model results and data from each location and sampling event are summarized into a single pair of EMCs (i.e., flow-weighted averages over the course of the storm), which provides a measure of the total PCB load passing a location during the storm. All sampling events/locations are plotted together in this figure. In general, the EMC scatter plot

indicates that although there is a slight tendency of the model to over-predict the data that are above the MDL, these values are well within a factor of two.

3.4.2 Sediment PCBs

As discussed previously, there are limited surface sediment PCB data with which to assess temporal trends; nonetheless, the available data provide little evidence of any temporal trend. Furthermore, sediment solids balances developed from the storm data suggest relatively small amounts of gross sediment deposition and erosion, which would suggest PCB concentrations would not be expected to change rapidly. For these reasons, the 1998-2004 sediment PCB data sets were combined and averaged spatially for developing the initial PCB concentrations used for the start of the 2001-2005 calibration period (see Section 3.2.1.2). Thus, the relevant calibration metric for surface sediment PCB concentrations is to compare the range of model results computed over the calibration period with the average of the data $\pm$ two standard errors of the mean (approximately equal to the 95% confidence interval). This comparison is plotted in Figure 3-47, and indicates that the model results change very little over the calibration period (as evidenced by the small error bars), and that the spatially-averaged model results are well within the variability of the spatial averages of the 1998-2004 data.

3.4.3 Fish Tissue PCBs

For fish tissue PCBs, the primary goal of the metrics was to evaluate whether significant bias exists in the calibration (based on the number of model values greater than and less than the data), and whether the model predictions were generally within a factor of two to five of the data. This range is consistent with model calibration metrics USEPA has used in PCB bioaccumulation modeling studies at other sites (e.g., WDNR and RETEC 2002; USEPA 2006). Thus, scatter plots of the same format presented for the water column PCB comparisons were developed for fish PCB concentrations, on both a wet-weight and lipid-normalized basis (Figure 3-48). The fish PCB scatter plots are presented in terms of averages for both data and model, which is the appropriate comparison because the model computes concentrations for the average fish. The data shown in Figure 3-48 are averaged by major sampling event using

congener-specific data only (i.e., no Aroclor data), and for the 2005 data, the means were computed using adjusted values (corrected extraction efficiency) when reported.

The fish tissue PCB scatter plots do not indicate an overall bias in the model calibration. For all combinations of species, location, and wet-weight vs. lipid normalized concentrations, 90% of the model-data comparisons lie within a factor of two, 7% lie between a factor of two and five, and only 3% (one data point) differ by more than a factor of five.

3.4.4 Summary

Bias and spread for the model-data comparisons are summarized in Table 3-6, which provides a listing of the number of model predictions that are greater than and less than the data, as well as the number of model predictions that are within a factor of two and a factor of five of the data.

Table 3-6. Summary of quantitative model metrics.

Media/Sample Type	Location(s)	Bias Evaluation ¹		Precision Evaluation ¹		
		# Above 1:1 Line	# Below 1:1 Line	# < 2X	# 2X-5X	# > 5X
Water Column PCBs at Low Flows (Figure 3-44) ²	CBNS/CBPL	6	0	6	0	0
	CBVP	10	11	19	2	0
	RCVP	1	2	3	0	0
	Total	17	13	28	2	0
Water Column PCBs at Storm Flows, Individual Samples (Figure 3-45) ²	CBVP	45	31	54	21	1
	RCVP	28	24	48	4	0
	RC43	24	20	42	2	0
	Total	97	75	144	27	1
Water Column PCBs at Storm Flows, Event Means (Figure 3-46) ²	CBVP, RCVP, RC43 combined	9	1	10	0	0
Fish Tissue PCBs, Wet Weight (Figure 3-47)	Location B, Creek Chub	2	3	5	0	0
	Location D, Creek Chub	2	3	3	1	1
	Location D, Longear Sunfish	4	1	5	0	0
	Total	8	7	13	1	1
Fish Tissue PCBs, Lipid-Normalized (Figure 3-47)	Location B, Creek Chub	2	3	5	0	0
	Location D, Creek Chub	2	3	4	1	0
	Location D, Longear Sunfish	4	1	5	0	0
	Total	8	7	14	1	0

Notes:

¹ Bias evaluation lists number of model-data comparisons that are above the 1:1 line (model over-predicts data) and below the 1:1 line (model under-predicts data), and precision evaluation lists number of model-data comparisons that differ by less than a factor of 2 (<2X), between a factor of 2 and 5 (2X-5X), and by more than a factor of 5 (>5X).

² Counts for water column samples in which the data and model were both less than the MDL were split equally for the above/below the 1:1 line counts in the bias evaluation.

Overall, the quantitative model metrics indicate that the model's predictions of water column and fish tissue PCB concentrations do not exhibit a consistent bias, and that the model provides a reasonable fit to the data, in that the model results generally lie within a factor of two of the observations.

SECTION 4 MODEL APPLICATIONS

The calibration results presented in Section 3 indicate that the model is able to reproduce the major spatial and temporal patterns in PCBs in sediments, water, and fish at the site. As such, the model provides a quantitative tool that links fish PCB bioaccumulation to the remaining sources of PCBs to the streams. This tool was applied in two ways to further evaluate the site. First, diagnostic calculations were used to quantify the extent to which the various sources of PCBs (springs, sediments, etc.) contribute to overall PCB bioaccumulation by the fish; these analyses are referred to as source assessments, and are presented in Section 4.1. These diagnostic results were then used to inform the development of potential remedial scenarios, which were simulated by the model in the second type of application. In these simulations, the model was used as a prognostic tool, in which long-term future projections of various remedial alternatives were developed as a means of evaluating options for achieving further reductions in fish PCB concentrations; these simulations are presented in Section 4.2.

4.1 PCB SOURCE ASSESSMENTS

The relative importance of PCB sources to fish in Conard's Branch and Richland Creek was assessed using model sensitivity analyses in which individual sources to the fish were changed to zero in the model inputs, and the results were then compared to the base calibration results². The difference in model-calculated fish PCB concentrations between the base calibration and the sensitivity simulation were then attributed to the source that was reduced to zero during that simulation. These source assessments were conducted in two groups: flow regime assessment and PCB source assessment. For both the flow regime and PCB source assessments, fish PCB concentrations of the three simulated species/location combinations

² These base calibration results for these model sensitivity analyses corresponded to years 2003-2005, which represent the current system operation, since the improvements to spring collection efficiency were completed in February 2003 (see Section 1.1). This three-year period was repeated twice for the simulations, so that the model results reached a steady-state condition.

(i.e., creek chub at Location B and creek chub and longear sunfish at Location D) were used to quantify the relative contributions from each source.

4.1.1 Flow Regime Assessment

The flow regime assessment was conducted to evaluate the relative importance of the PCB sources to fish in Conard's Branch and Richland Creek under varying flow conditions (e.g., storms versus base flow). Three different flow regimes were evaluated: low flow, high flow, and moderate flow. Flow conditions were defined by daily average flow rates at the CBW location. Daily average flows that did not exceed 10 gpm at CBW were considered low flow conditions. High flow conditions were defined as daily average flows that exceeded 500 gpm at CBW. Finally, moderate flows were defined as daily average flows between 10 and 500 gpm at CBW. Moderate flow days (10-500 gpm) often contain periods lasting several hours during which flows exceed the treatment system capacity of 500 gpm, and hence may contain sustained STF bypass conditions. Based on the 2003-2005 measured CBW flows, the fraction of days meeting the three flow criteria were: 71% low flow, 21% moderate flow, and 7% high flow.

The flow regime assessment was conducted by sequentially setting water column PCB exposure concentrations within the bioaccumulation model to zero during the targeted average daily flow rate. That is, water column exposure concentrations for days meeting the high flow criteria (i.e., >500 gpm) were set to zero and the bioaccumulation model was then run to compute fish PCB concentrations at Locations B and D. The differences between fish PCB concentrations for this high flow source assessment simulation and the base calibration were attributed to PCBs contained within high flow waters. The contributions of low flow and moderate flow water column PCBs to fish PCB concentrations were quantified in a similar fashion. To isolate only water column PCB sources, sediment PCB exposure concentrations were set to zero in both Conard's Branch and Richland Creek during these flow regime assessment runs.

The results of the flow regime assessment are contained in Table 4-1. The simulations indicate that low flow, moderate flow, and high flow conditions contribute approximately 67%,

22%, and 11% of the PCBs found in Conard's Branch creek chubs, respectively. Low flow periods represent the dominant water column source to Conard's Branch creek chubs since these conditions prevail during the summer periods when fish achieve much of their annual growth. Conversely, high flow conditions and, to a lesser extent, moderate flow conditions are generally infrequent and transitory, typically lasting no longer than several days. Hence, while water column PCB concentrations are generally higher during high and moderate flow conditions, they contribute considerably less to Conard's Branch fish PCB concentrations than the low flow water column conditions.

Table 4-1. Approximate contribution of water column sources to fish PCBs under different flow regimes (excludes uptake from sediments).

Location	Species	CBW Flow < 10 gpm ¹	CBW Flow 10-500 gpm ¹	CBW Flow > 500 gpm ¹
Conard's Branch Location B	Creek chub	67%	22%	11%
Richland Creek Location D	Creek chub	42%	27%	31%
	Longear sunfish	44%	27%	29%

¹ CBW flow criteria are applied on a daily average basis.

The flow regime assessment simulations indicate that low flow, moderate flow, and high flow conditions contribute approximately 42%, 27%, and 31% of the PCBs found in Location D creek chubs, respectively (Table 4-1). Similarly, approximately 44%, 27%, and 29% of the PCBs found in Richland Creek longear sunfish were attributable to low flow, moderate flow, and high flow conditions, respectively (Table 4-1). The reduced importance of low flow conditions to Richland Creek fish is due to differences in Richland Creek dilution between the different flow regimes. The dilution of PCBs within Richland Creek is attributable to Richland Creek flows originating upstream of the mouth of Conard's Branch. Based on the flow monitoring conducted in 2003-2005 (Table 2-1), flows in Richland Creek generally provide a five- to ten-fold dilution for PCBs entering the creek from Conard's Branch. Due to the higher base flows in the larger Richland Creek, these data indicate that this dilution is larger under low flow conditions. Hence, water column PCB concentrations within Richland Creek under low flow conditions are proportionately lower than under high flow conditions. This change in dilution as a function of flow regime reduces the relative importance of low flow water column PCB concentrations to Richland Creek fish.

4.1.2 Source Assessment

In a manner similar to the flow regime assessment, the PCB source assessment sequentially eliminated (i.e., set to zero in the model) individual PCB sources and calculated the resulting fish PCB levels in Conard's Branch and Richland Creek. The difference between the results and those under the base calibration were then compared. The PCB sources assessed using this procedure included PCBs within: 1) spring waters entering Conard's Branch at the weir (CBW); 2) STF effluent (STF); 3) the North Spring + Bypass (NSB); and 4) the sediments within the modeled stream sections (SED).

The results of the PCB source assessment are contained in Table 4-2. The simulations indicate that CBW, STF, NSB, and SED contribute approximately 24%, 11%, 37%, and 27% of the PCBs found in Conard's Branch creek chubs, respectively. That is, 72% of the PCBs found within Conard's Branch creek chubs originate from one of the water column PCB sources (CBW, STF, and NS). In contrast, sediment sources contribute only 27% of the PCBs found within Conard's Branch creek chubs. Among water column sources, NSB contributes the most and STF effluent contributes the least to Location B creek chub PCBs, due to the relatively lower PCB concentrations within STF effluent following treatment.

Table 4-2. Approximate contribution of sources to fish PCBs.

Location	Species	CBW	STF	NSB	Sediments
Conard's Branch Location B	Creek Chub	24%	11%	37%	27%
Richland Creek Location D	Creek Chub	36%	8%	21%	35%
	Longear Sunfish	24%	6%	14%	56%

The PCB source assessment simulations also indicate that CBW, STF, NSB, and SED contribute approximately 36%, 8%, 21%, and 35% of the PCBs found in Location D creek chubs, respectively (Table 4-2). Similarly, approximately 24%, 6%, 14% and 56% of the PCBs found in Location D longear sunfish were attributable to CBW, STF, NS, and SED, respectively (Table 4-2). The increased relative importance of sediment PCB contributions to Richland Creek

fish reflects the differences in food web structure between the two streams. Richland Creek is a higher order stream, and consequently, supports a larger benthic community available as prey for fish – this is reflected in the food web structure used to calibrate the bioaccumulation model (see Table 3-5). This is particularly true for Richland Creek longear sunfish, whose diet contains a slightly larger proportion of benthic invertebrates than the creek chubs in the model.

To further evaluate PCB sources, a water column PCB mass balance was developed for Location B within Conard's Branch (Figure 4-1). By summing mass fluxes computed internally by the PCB fate model for the various mechanisms (i.e., the same method used to develop the long-term mass balance shown in Figure 3-28), the relative contribution of individual PCB sources to water column PCB mass transport was developed. This mass balance was then qualitatively compared to the source assessment results for creek chubs at Location B (Figure 4-1). The PCB source contribution to creek chubs closely matches the water column load signature under low flow conditions, providing further evidence that PCBs within Conard's Branch creek chubs are controlled by low flow PCB sources.

4.2 SIMULATION OF REMEDIAL ALTERNATIVES

4.2.1 Development of Alternatives

Based, in part, on the results from the model source assessments described in Section 4.1, CBS and USEPA collectively identified a number of potential remedial action elements (termed “technologies” for this discussion) that could be used to reduce PCB concentrations in the fish of Conard's Branch and Richland Creek. These technologies are listed, along with the individual PCB source(s) that each would address, in Table 4-3.

Table 4-3. Remedial technologies identified to address PCB sources within the system.

Technologies	Details/Description	PCB Source(s) Addressed			
		Springs at Base Flow	Springs at Storm Flow	North Spring Bypass	Sediments
STF operation	- Operate at current 500 gpm capacity - Increase capacity from 500 to 1000 gpm	✓	✓		
Increase spring collection efficiency	- Increase % capture for higher STF capacity - Collect and treat large fraction of North Spring groundwater seepage	✓		✓	
Storage basin	2 Mgal off-line basin to collect storm flow when STF capacity is exceeded and then pass through STF after storm recedes and capacity is available		✓		
Settling basin(s)	Provide solids/PCB removal during storms and low flow through a series of 3 basins (13 Mgal total) constructed within Conard's Branch	✓	✓		
Sediment remediation	Remove sediments > 1 ppm				✓
Bank soil remediation	Remove bank soils > 1 ppm			✓	
Relocate STF discharge	Relocate 1000 ft. downstream			✓	

Technologies identified to address PCBs originating from the springs under base flow conditions include:

- STF operation, both at the current capacity as well as an increased capacity of 1000 gpm;
- improvement of the collection efficiency of spring water – at South Spring through expansion of the STF and its associated collection system and/or at North Spring through expanding the collection system to capture and treat bypass flows (i.e., groundwater seepage); and
- addition of a series of setting basins to provide some level of solids and PCB removal for untreated spring flows entering Conard's Branch.

The technologies identified to address PCBs originating from the springs under storm flow conditions include:

- STF operation at the increased capacity of 1000 gpm, which would provide only a small level of storm flow treatment as typical storms are well in excess of that flow (e.g., see Figure 3-29, bottom panel);
- addition of an off-line storage basin with a capacity of two million gallons that would hold excess storm water collected during the rising limb (after the STF capacity is exceeded) and would then discharge its water to the STF for treatment once flows recede and capacity is available (when full, flows in excess of the STF capacity would bypass the basin and enter Conard's Branch); and
- construction of a series of three settling basins with a combined capacity of 13 million gallons within the first 1,360 ft. of the Conard's Branch channel that would be operated at a constant volume and would receive spring flows not captured and treated by the STF and provide removal of solids and particulate phase PCBs during storms via settling.

A number of technologies to address the NSB PCB loads, which consist of PCBs from groundwater seepage as well as PCBs desorbed from the banks associated with STF cycling (see Section 3.2.1.1.4), have been identified:

- expanding the collection system at North Spring to capture groundwater seepage flows and route them to the STF for treatment;
- remediation of bank soils with PCB concentrations exceeding 1 ppm, which would significantly reduce the mass of PCBs available for desorption by cycling STF effluent waters; and
- relocation of the STF discharge 1,000 ft. downstream of its current location, which would bypass the most highly impacted bank soils, further reducing the potential for STF cycling to transport PCBs to Conard's Branch.

The remedial technologies described above and listed in Table 4-3 were combined into a series of alternatives that were further evaluated through model simulations. Seven such alternatives were identified by CBS and USEPA:

Alternative 1 – No action. Operation of the STF would cease under this alternative, and spring flows emerging from beneath the landfill would enter Conard's Branch untreated.

Alternative 2 – 500 gpm STF. This alternative would be identical to the current system configuration, where the STF is operated at a capacity of 500 gpm.

Alternative 3 – 500 gpm STF with source control. This alternative would include operation of the STF at its current configuration plus implementation of several measures to control low flow PCB sources to Conard's Branch. These include removal of sediment and bank soils with a PCB concentration exceeding 1 mg/kg, construction of additional collection systems to capture NSB flows and route them to the STF for treatment, and relocation of the STF discharge point.

Alternative 4 – 500 gpm STF with source control and 2-Mgal storage basin. This alternative would be the same as Alternative 3, with the addition of a two-million gallon storage basin to provide additional storm flow treatment.

Alternative 5 – 1000 gpm STF with source control. This alternative would be the same as Alternative 3, except the STF would be expanded to a capacity of 1,000 gpm. Associated with this expansion would be an improvement in the spring water collection efficiency in the South Spring area.

Alternative 6 – 1000 gpm STF with source control and 2-Mgal storage basin. This alternative would include a combination of elements from Alternatives 4 and 5, in which the STF and associated collection system would be expanded, and a 2 million gallon storage basin would be constructed.

Alternative 7 – 500 gpm STF with source control and series of 3 settling basins. This alternative would be the same as Alternative 3, with the addition of a series of three settling basins having a total capacity of 13 million gallons within Conard's Branch. Solids and associated sorbed PCBs, particularly during storms, would be removed by the basins. The geometry of the three basins is summarized in Table 4-4.

Table 4-4. Settling basin geometry for Alternative 7.

Basin #	Length (ft.)	Width (ft.)	Depth (ft.)	Volume (Mgal)
1	400	100	8	2.4
2	400	100	10	3.0
2	560	122	12	6.1

4.2.2 Model Setup

The general approach for simulating a given alternative consisted of making modifications to the model inputs to represent the remedial technologies included in the alternative, and then running the model for a 10-year projection period to predict the long-term response in water, sediment, and fish tissue PCB concentrations. The methods used to represent various aspects of the remedial alternatives in the model are described in the following subsections.

4.2.2.1 Hydrologic Conditions

Future simulations of the alternatives described in Section 4.2.1 with the model were conducted for a 10-year projection period. The hydrologic conditions used for these simulations were the same as those for the calibration period, which include relatively low flow and relatively high flow years, as well as several storm events of varying magnitude (e.g., Figure 3-7). The 2001-2005 inflows from the calibration period were repeated twice to define the 10-year flow record used in the model for the future simulations or remedial alternatives.

4.2.2.2 Spring/STF Flow Routing

The hourly flow data for CBW and STF from 2003-2005, a period that reflects current system operation, indicate that: 1) most of the spring flow is collected and routed to the STF at low system flow; 2) as system flow increases to above approximately 350 gpm, a smaller fraction of the flow is captured; and 3) once the total system flow increases to above approximately 550 gpm, the STF reaches its capacity and the remaining flow enters Conard's Branch untreated (Figure 4-2). For the model simulations, a mathematical representation of this characteristic was developed to provide a consistent method for specifying flows for all

alternatives, including those that include other treatment system configurations (e.g., increased STF capacity). Thus, in the model projections, the total system flow (i.e., CBW+STF from the historical record) was routed to either STF or CBW based on a spring capture efficiency, which represents the fraction of total system flow that is collected and treated by the STF. Based on the averages of the 2003-2005 data, the capture efficiency was specified to equal 97% for system flows less than 350 gpm, and to decrease to 70% for the portion of system flows that exceed 350 gpm, until the STF capacity is reached. This function is depicted by the line on Figure 4-2. The improved collection efficiency associated with expansion of the STF to a 1000 gpm capacity (Table 4-3) was represented in the model by specifying a higher capture efficiency of 98% for flows up to 425 gpm, with capture of 80% of the additional flows exceeding 425 gpm, until the higher STF capacity is reached.

Based on the spring capture efficiencies described above, the total system flow from the 10-year hydrograph was split between CBW and STF to specify the inflow boundary conditions for each remedial alternative simulated. The other flow inputs in the model were unchanged from the calibration, with the exception of the NSB flow. For the alternatives that included source control measures (i.e., Alternatives 3 through 7), collection and treatment by the STF of 90% of the NSB groundwater seepage flow was assumed. This was represented in the model by routing 90% of the original NSB flow (calculated using the method described in Section 3.1.1.1.3) to the STF, and specifying the remaining 10% to enter Conard's Branch at the NSB location. In cases where the system flows exceeded the STF capacity, the collected NSB flow was specified to be blended with the system flow and then bypass treatment and enter the model through the CBW boundary.

4.2.2.3 Spring PCBs

The PCB concentrations of spring water used in the boundary conditions for the model simulations of remedial alternatives were computed in a manner consistent with the calibration. For flows entering CBW untreated, the separate low flow and storm flow PCB relationships described in Section 3.2.1.1.2 were used in conjunction with the flows (computed according to the methods described in Section 4.2.2.2) to calculate the CBW boundary PCB concentrations.

The decline of PCB concentrations in spring water was assumed to continue at the same rate of 0.06 yr^{-1} throughout the 10-year simulation period. For alternatives that included capture of 90% of the North Spring groundwater seepage load (i.e., Alternatives 3 through 7), the CBW concentration was recomputed, by mass balance, based on the flows and concentrations of the individual components (i.e., CBW and the 90% of NSB).

Similar to CBW, the relationship described in Section 3.2.1.1.4 was used in conjunction with the modified system flows described in Section 4.2.2.2 for computing the NSB PCB boundary concentrations for the future simulations. However, two modifications were made to the NSB PCB concentrations to reflect source control measures (i.e., Alternatives 3 through 7). First, the seepage flows used in the calculation were reduced by 90% (to account for collection of that water – see above), and second, a modified value for the bank PCB loading term was used (described further in Section 4.2.2.6).

4.2.2.4 STF PCBs

Historically, the effluent PCB concentrations for the STF were largely non-detect, until about the 10th year of operation, at which time GAC breakthrough had begun, and the frequency of detectable PCB measurements rose sharply (Figure 4-3), with concentrations typically in the range of 0.1 to 0.2 $\mu\text{g/L}$ (Figure 3-18). Future simulations of the STF assumed a similar operation, in which the GAC would have a 10-year life and replenishment would occur once effluent concentrations reached 0.1 $\mu\text{g/L}$. Earlier replenishment of the GAC was simulated as an additional source control measure for the alternatives with source control but no storage or settling basins (i.e., Alternatives 3 and 5). This represented operationally changing the GAC often enough so that the STF effluent would never exceed 0.05 $\mu\text{g/L}$.

Thus, STF effluent PCB concentrations for the future projections of Alternatives 2, 4, 6, and 7 were specified to be 0.02 $\mu\text{g/L}$ for Years 1 through 9 of the model simulation, with a linear increase up to 0.1 $\mu\text{g/L}$ in Year 10. For Alternatives 3 and 5, earlier GAC replenishment was represented using the same PCB concentration time series, except once the concentration reached

0.05 µg/L halfway through Year 10, the concentrations were reduced back to 0.02 µg/L to simulate the GAC change-out.

4.2.2.5 Sediment Remediation

Removal of sediments exceeding 1 ppm (see Table 4-3) was represented in the model by setting the sediment PCB concentrations in the appropriate grid cells to zero at the start of the simulations, for those alternatives that included source control (i.e., Alternatives 3 through 7). Based on the PCB concentrations specified in the model inputs, this modification was made for all simulated sediments within the upper one-half mile of Conard's Branch (see Figure 3-19).

4.2.2.6 Bank Load Reduction

For the simulation of remedial alternatives, it was assumed that relocation of the STF outlet away from the most highly impacted bank soils in conjunction with remediation of bank soils with PCBs exceeding 1 ppm (see Table 4-3) would effectively eliminate the bank loading term in NSB PCB load (see Section 3.2.1.1.4; W_{bank} in Equation 3-6). Thus, for the alternatives that include source control (i.e., Alternatives 3 through 7), the PCB concentration of the NSB boundary was calculated using Equation 3-6 with $W_{bank} = 0$.

4.2.2.7 Storage Basin

To represent the operation of a 2 Mgal storage basin in the model simulations of remedial alternatives containing that technology (i.e., Alternatives 4 and 6), a flow routing algorithm was developed. This algorithm, which is depicted in the process diagram shown in Appendix C1, mathematically routes flows and recalculates model boundary conditions based on: the incoming flow to the STF/storage system (Q_o = captured spring flow plus the collected NSB seepage flow); the STF capacity for the given alternative (Q_{cap}); and a time-variable calculation of the water volume within the storage basin (V_o). This algorithm routes flow differently under four different conditions:

1. $Q_o \leq Q_{cap}$ and $V_o = 0$: This condition represents base flow, where all collected spring flow is routed to the STF and the storage basin remains empty.
2. $Q_o > Q_{cap}$ and $V_o < 2$ Mgal: This condition represents storm flow, where flow to the STF is at its capacity, and the remaining collected spring flow is routed to the storage basin, which is being filled.
3. $Q_o > Q_{cap}$ and $V_o = 2$ Mgal: This condition represents larger storms, where flow to the STF is at its capacity, the storage basin is full, and the remaining collected spring flow will enter Conard's Branch (along with the uncaptured flow).
4. $Q_o < Q_{cap}$ and $0 \leq V_o \leq 2$ Mgal: This condition represents the period following a storm, where all collected spring flow is routed to the STF, and the water within the storage basin is directed to the STF, until the basin is empty. While emptying, the storage basin outflow is specified, set equal to the maximum flow the STF can receive (i.e., $Q_{cap} - Q_o$), so that it drains as quickly as possible.

An example of the results from application of this algorithm to simulate operation of the storage basin in conjunction with a 1000 gpm STF capacity during an example storm is shown in Figure 4-4. For this storm, which peaked at 14,000 gpm, the basin filled within a few hours, the storm flows receded to less than 1,000 gpm after approximately three days, at which time, the storage basin emptied back to STF based on available capacity over approximately a day period.

This algorithm assumes no changes to the TSS or PCB concentrations occur within the storage basin. Thus the boundary concentrations computed using the methods described in Section 4.2.2.3 are used for the storage basin alternatives, but the boundary flows used in the model are modified based on the procedures described above.

4.2.2.8 Settling Basins

Model simulation of the series of settling basins for Alternative 7 included calculations of solids and PCB removal within the basins, which were based on site-specific data collected

during the June 2002 settling tests conducted at the site (Viacom 2002b). In these tests, time-series measurements of TSS and PCBs were measured two inches below the surface in a series of barrels that were filled with spring water collected under storm flow conditions. Two pairs of barrels were studied, one with and one without addition of flocculent. The settling test data were analyzed for the purposes of modeling to estimate settling characteristics (Figure 4-5). This analysis consisted of computing the change in TSS and PCB concentrations within the barrels over time based on particle settling and PCB partitioning. Particle settling was represented in this analysis through a representative settling speed and a fraction of solids that was non-settleable, and PCB sorption to the particles was computed using the site-specific partition coefficient developed for the PCB fate sub-model (see Section 3.2.1.3.6). These calculations indicated that the reductions in TSS and PCB concentrations within the barrels were consistent with a settling speed in the range of 1 to 3 m/d, and a fraction of non-settleable solids in the range of 5 to 10%. These results generally indicated improved TSS/PCB removal when flocculent was added. Based on this analysis, settling within the basins for model simulation of Alternative 7 was represented using a settling speed of 2.13 m/d (which corresponds to the Stokes setting speed for a 4 micron diameter silt particle) and 10% non-settleable solids (corresponding to the case of no flocculent addition).

Similar to the storage basins, a separate mass balance calculation was developed to compute flows, TSS, and PCB concentrations exiting the series of three basins to facilitate specification of the CBW boundary conditions in Alternative 7. A process diagram for this settling basin mass balance calculation is provided in Appendix C-2. In the settling basin mass balance, the flow entering the series of basins consists of uncollected spring flow plus flow collected from both South and North Springs that exceeds the STF capacity. The basins maintain a constant volume (Table 4-4), and as such, the outflow equals the inflow for each. The effluent from the third basin enters Conard's Branch, and the PCB and TSS concentrations of that water are used to set the CBW boundary condition for the model simulation. Within each basin, a time-variable mass balance for TSS and PCBs is used to compute effluent concentrations:

- the TSS/PCB mass entering a given basin is based on the time-variable inflow rate and influent concentrations;

- based on the settling test data analyses described above, TSS is divided into 90% settleable and 10% non-settleable classes, and removal of settleable solids within the basin is computed according to the site-specific settling speed of 2.13 m/d;
- dissolved and particulate phase PCBs within the basin are calculated based on TSS and model partition coefficients, and the mass of PCBs removed from the basin by settling is calculated based on the fraction of PCBs sorbed to settleable solids and the settling flux of those solids.

An example of the results from application of this mass to simulate operation of the three settling basins in series during an example storm is shown in Figure 4-6. For this storm, which peaked over 10,000 gpm, the settling basins reduced peak TSS concentrations by approximately a factor of two and peak PCB concentrations by approximately a factor of four. The broader-shaped peak in effluent concentrations and sustained period of concentrations higher than the influent at the conclusion of the storm result from the slow flushing of the relatively large basins (13 Mgal). Comparison of influent and effluent TSS and PCB masses computed using the method described above for the 10-year projection period indicates that the simulated basins achieve 71% removal of solids and 62% removal of PCBs.

4.2.3 Results from Simulation of Remedial Alternatives

Model results for the simulated remedial alternatives are presented in Figures 4-7 through 4-13. Figures 4-7 through 4-9 display temporal plots of water column PCBs at CBVP and RCVP, for three alternatives per figure. Similar figures showing fish tissue concentrations for creek chubs at Location B and creek chub and longear sunfish at Location D are provided in Figures 4-10 through 4-12. Figure 4-13 provides a comparison of average Year 10 fish tissue PCB concentrations among all seven alternatives. The results shown in these figures are discussed in the following subsections.

4.2.3.1 Water Column PCBs

Figure 4-7 shows a comparison of model-simulated water column PCBs for Alternatives 1, 2, and 3 to evaluate the benefits of STF operation and source control. A sharp increase in water column PCB concentrations at the beginning of the projection period occurs for Alternative 1, as a result of shutting down the STF operation. This response is observed in both Conard's Branch (top panel) and Richland Creek (bottom panel), but is more noticeable in Conard's Branch due to its closer proximity to the spring PCB sources and lesser amount of dilution from tributaries and runoff. Following this increase, predicted water column PCB concentrations for Alternative 1 decline slowly over the 10-year projection period as a result of the 0.06 yr^{-1} decay of PCBs in the spring system. Model-predicted water column PCB concentrations for Alternative 2 demonstrate a similar temporal trend between the calibration and projection periods, as the STF operation is identical for these two periods. As with Alternative 1, a slight decreasing trend over time in Alternative 2 water column PCB concentrations results from the decline of PCBs in the springs. Predicted PCB concentrations for Alternative 2 are much lower than those from Alternative 1 (by a factor of five or more) for low flow periods, due to operation of the STF. Differences between these two alternatives at high flows are smaller, since untreated flows entering CBW are much larger than STF flows during storms. Relative to Alternative 2 (continued operation of the 500 gpm STF); an approximate five-fold reduction in water column PCBs is predicted during low flows for Alternative 3. This reduction is a result of the combination of capturing of 90% of NSB flow, elimination of the bank PCB load at NSB, and the remediation of PCBs in sediments of Conard's Branch. However, during storms, PCB concentrations for Alternative 3 are similar to those shown in Alternative 2 due to the large volume of flow that bypasses treatment.

An evaluation of the benefit of increasing STF capacity is provided by comparing results for Alternatives 3 and 5 in Figure 4-8. Doubling the STF capacity from 500 to 1000 gpm results in slightly lower water column PCB concentrations under storm flow conditions (due to the higher fraction of spring flow treated), as well as low flow conditions, which is primarily due to the improved capture efficiency associated with the expanded STF/collection system. The benefits of adding a 2-Mgal storage basin to the 1000 gpm STF can be evaluated by comparing predicted water column PCB concentrations for Alternatives 5 and 6 in Figure 4-8. Alternative 6

provides a further reduction in PCB concentrations during high flows, as the storage basin allows for more storm water to be treated by the STF. Comparing results between Alternatives 5 and 6 indicates that the storage basin has no impact on PCBs during low flow periods, since the basin does not operate.

Figure 4-9 provides a means of evaluating the benefits of adding the storage basin or the series of three settling basins to the 500 gpm STF (i.e., Alternatives 3, 4, and 7). Similar to the 1000 gpm STF alternatives described above, predicted water column PCB concentrations for Alternative 4 are only slightly lower than those for Alternative 3 during storms (due to storage basin operation), with no differences during low flow periods. Relative to Alternative 3, the model results from Alternative 7 show greater reductions in water column PCBs compared with those from Alternative 4 during high flows, indicating that the removal of solids and associated PCBs in the settling basins is more effective than the simulated storage. Model-predicted water column PCB concentrations for Alternative 7 during low flows are reduced relative to the no settling basin case (i.e., Alternative 3), however, to a lesser extent. The differences in water column PCBs among these alternatives under low flows is less pronounced in Richland Creek than in Conard's Branch due to the differing importance of low flow versus high flow PCB sources in those streams (see Section 4.1.1).

There are some observable differences in water column PCB concentrations in Year 10 of the projection period in Figures 4-7, 4-8, and 4-9. These result from the differences in timing of the STF GAC regeneration discussed in Section 4.2.2.4. While these differences are observable in water column concentrations, the effects are short-term, and do not impact the fish tissue results described below.

4.2.3.2 Fish Tissue PCBs

Model predictions of long-term trends in fish tissue PCB concentrations for Alternatives 1, 2, and 3 are shown in Figure 4-10. In general, the predicted fish concentrations track the water column results described above, but exhibit much less temporal variability due to the integrating nature of PCB uptake by fish. The strong seasonal variation in creek chub

concentrations is a result of the seasonality in lipid contents simulated by the model (see Section 3.3.1.2.2).

Model-predicted fish PCB concentrations for Alternative 1 increased over the first four years of the projection as the fish equilibrated to the large increase in water concentrations that resulted from ceasing STF operation (Figure 4-10). Conard's Branch creek chub concentrations increased fivefold during this period. Following this initial increase, fish levels decreased over the remainder of the projection period in response to the 0.06 yr^{-1} decline in spring PCBs. Simulated fish PCB concentrations for Alternative 2 are much lower than Alternative 1, due to STF operation. Over the 10-year projection period, Alternative 2 fish concentrations are characterized by a steady decrease due to the decline in spring PCB concentrations. The rate of decline in fish concentrations for continued operation of the current system is approximately 3 to 4% per year (Appendix B), which is lower than the rate for the springs because sediment sources, which also contribute to the fish, respond at a much slower rate and therefore mute the fish response to changes in water column exposures. Alternative 3 provides an approximate two-fold decrease in Conard's Branch creek chub concentrations relative to Alternative 2, due to the reduction in low flow PCB inputs associated with source control measures (i.e., sediments, NSB, and banks). This difference is less pronounced for Richland Creek fish, because the source control measures address low flow sources (Table 4-3), and the PCB source assessments indicated that storms account for a higher fraction of fish PCB uptake in Richland Creek than in Conard's Branch (Section 4.1.2).

Comparison of model-predicted fish PCB concentrations for Alternatives 3 and 5 indicates that increasing the STF capacity from 500 to 1000 gpm provides a small reduction in Locations B and D creek chub concentrations (Figure 4-11). This difference is less pronounced in Richland Creek longear sunfish because those fish are more influenced by sediment sources (see Table 4-2), which do not respond to the additional storm treatment provided by the simulated STF expansion. Comparison of model results for Alternatives 5 and 6 indicates that adding a 2-Mgal storage basin to the 1000 gpm STF produces no observable change in fish tissue PCB concentrations (Figure 4-11).

The fish tissue PCB concentrations simulated by the model for Alternatives 3 and 4 are nearly identical, which indicates that operation of the storage basin in conjunction with the 500 gpm STF provides little added benefit (Figure 4-12). The reason for this is because the storage basin addresses only a portion of the storm flows (e.g., for a sustained 10,000 gpm storm, the 2-Mgal storage basin would be filled in a little over 3 hours), and the model source assessments indicate that storms are less important than low flow conditions for fish PCB uptake (Table 4-1). The model predictions for Alternative 7 indicate that addition of the series of settling basins does provide some reduction in fish PCB concentrations beyond that of the 500 gpm STF with source control (i.e., Alternative 3). This reduction is greatest for creek chubs in Richland Creek because: 1) the settling basins have the greatest impact under storm conditions, to which Richland Creek fish respond more than Conard's Branch fish (Table 4-1), and 2) creek chubs respond more to water column-based sources than do longear sunfish, for the reasons discussed above.

4.2.4 Comparative Analysis

As a means of summarizing the fish PCB results from the model simulations, the average concentrations from the last year of the projection (i.e., Year 10) are compared among the alternatives each for of the simulated species/location combinations in Figure 4-13. For comparison purposes, the model results from the last year of the calibration period (i.e., 2005) are shown on the plots as well. This summary plot illustrates that for Conard's Branch creek chub: 1) turning off the STF under Alternative 1 results in an approximate two-fold increase in concentrations relative to current conditions; 2) continued operation of the current STF under Alternative 2 will reduce concentrations from approximately 4 to just under 3 ppm; 3) implementation of the source control measures under Alternative 3 will achieve a further reduction to approximately 1.5 ppm; and 4) expanding the STF through added capacity, storage basins, or settling basins under Alternatives 4 through 7 provides little reduction beyond that achieved by Alternative 3. The model summary results for Richland Creek fish are similar, with the exception that the decrease in concentrations achieved by Alternative 3 relative to Alternative 2 is lower than in Conard's Branch. Thus, in Richland Creek fish, the model results

suggest that Alternatives 3 through 7 do not provide a significant reduction beyond that of Alternative 2 (e.g., reduction from 0.5 to 0.4 ppm).

The Year 10 endpoint concentrations for Conard's Branch creek chub are plotted in terms of the percent reduction relative to no action (i.e., Alternative 1) in Figure 4-14. This plot further illustrates the incremental benefit associated with the various alternatives. STF operation alone (i.e., Alternative 2) reduces fish concentrations by 69%, and an additional 14% reduction is realized by implementing the source control measures in Alternative 3. Figure 4-14 indicates that at most an additional 3% reduction in Year 10 Conard's Branch creek chub concentrations results from increasing the STF capacity to 1000 gpm, construction of a 2-Mgal storage basin, or installation of three settling basins in series.

To facilitate further comparisons among the alternative simulated with the model, percent reductions in Year 10 fish concentrations for all three species/location combinations were compared with two additional metrics that quantify the amount of spring water treatment provided by a given alternative: 1) the fraction of total spring flow over the 10-year projection period that receives treatment by the STF; and 2) the percent reduction in total PCB mass entering Conard's Branch over the 10-year projection period, relative to that entering under no action (i.e., Alternative 1). The model-calculated values for these comparison metrics are listed in Table 4-5.

Table 4-5. Comparison of spring flow treatment, mass removal, and fish reductions for model-simulated remedial alternatives.

Alternative	Description of Alternative	Fraction of Spring Flow Treated	Reduction in PCB Mass ¹	% Reduction Year 10 Average Conard's Branch Creek Chub (Location B) ²	% Reduction Year 10 Average Richland Creek Chub (Location D) ²	% Reduction Year 10 Average Richland Creek Longear Sunfish (Location D) ²
1	No Action	0%	0%	0%	0%	0%
2	500 gpm Treatment System	47%	38%	69%	63%	51%
3	Source Control + 500 gpm Treatment System	51%	39%	83%	69%	56%
4	Source Control + 500 gpm Treatment System + 2 Mgal Storage	59%	48%	83%	71%	57%
5	Source Control + 1000 gpm Treatment System	66%	50%	86%	74%	60%
6	Source Control + 1000 gpm Treatment System + 2 Mgal Storage	74%	64%	86%	75%	60%
7	Source Control + 500 gpm treatment System + 3 Settling Basins	51 % (STF), 100% (STF + basins) ³	75%	85%	74%	60%

Notes:

¹ Reduction in PCB Mass is relative to No Action (i.e., Alternative 1).

² Reductions in Year 10 fish PCB concentrations are relative to No Action (i.e., Alternative 1).

³ Fraction of spring flow treated by the STF for Alternative 7 is 51%; the remaining 49% of flow receives some treatment by the settling basins (i.e., removal of solids) since they would be constructed within Conard's Branch.

Comparison of the fraction of spring flow receiving treatment indicates that the current system would treat 47% of the total flow, NSB flow collected through source control only amounts to an additional 4% of treated flow, increasing the STF capacity provides treatment for an additional 15% of the flow, and operation of the storage basin allows for treatment of an additional 8% of the flow. The amount of flow treated by the STF for Alternative 7 is not increased by the settling basins, although the uncollected flow does receive some treatment in the basins through settling. The reduction in PCB mass entering Conard's Branch achieved by these alternatives closely tracks the percent of treated flow. Relative to Alternative 1, operation of the

500 gpm STF, with or without implementing source control (Alternatives 2 and 3), reduces the PCB load to the streams by approximately 40%. Doubling the plant capacity or adding a storage basin under Alternatives 4 or 5 increases that PCB mass reduction to approximately 50%. Doubling the plant capacity in conjunction with construction of the storage basin increases the mass reduction further, to 64%, while the greatest mass reduction of 75% is achieved by installing the series of settling basins. The large increases in mass reduction associated with Alternatives 6 and 7 arise entirely from PCB removal under storm flow conditions.

The Conard's Branch creek chub Year 10 average PCB concentrations that result from simulation of these seven alternatives are compared to the percent reduction in the 10-year total PCB mass entering Conard's Branch in Figure 4-15. This comparison again shows that the largest decreases in fish concentration are associated with continued operation of the current STF and implementing source control to reduce PCB inputs from North Spring Bypass, sediments, and bank soils. Furthermore, the plot demonstrates that the additional levels of storm treatment provided by the storage basin, increased STF capacity, and series of settling basins can approximately double the amount of mass removed relative to no action, but that these measures provide little incremental benefit with respect to reductions in fish PCB concentrations. This result is consistent with the model source assessments described in Section 4.1.2, which indicated that the low flow sources account for a majority of the PCB uptake by creek chubs in Conard's Branch.

SECTION 5 SUMMARY

A mechanistic mathematical model was developed to quantitatively evaluate potential future remedial actions to reduce PCB levels within the fish of Conard's Branch and the upper portion of Richland Creek. The model framework consists of three sub-models:

1. A two-dimensional vertically-averaged hydrodynamic sub-model that computes temporal and spatial variations in flow rate, water depth, current velocity, horizontal dispersion (i.e., mixing), and bed shear stress.
2. A sediment and PCB fate and transport sub-model that computes advective and dispersive transport of PCBs and suspended sediments within the water column, sediment deposition and erosion at the bed/water interface, partitioning of PCBs between the dissolved and particulate phases, and volatilization of PCBs at the air-water interface. This sub-model also simulates PCB transport processes within the sediment bed, including molecular diffusion within sediment pore water, and particle mixing (i.e., bioturbation).
3. A bioenergetics-based bioaccumulation sub-model that computes the transfer of PCBs within the food web to fish species of interest. This sub-model simulates the uptake of PCBs by diffusion across the gill surface and from food sources and PCB loss by diffusion across the gill and the change in concentration due to growth.

This framework has a long history of successful application to numerous sites that have been documented in a number of peer reviewed technical publications and reviewed and accepted by regulatory agencies.

A variety of site-specific data were used for development of these sub-models. In the absence of data, model parameterization was based upon literature, experience with modeling other systems, professional judgment, and calibration. The sub-models were calibrated and validated independently:

- The hydrodynamic sub-model was calibrated to match travel times, dilution, and dispersion measured during two dye tests, and was validated against a two-year record of hourly water surface elevation data from three locations. The sub-model provides a good representation of the system's hydrodynamics, under a range of flow conditions.
- The sediment transport and PCB fate sub-models were calibrated over multiple time scales. Model-predicted concentrations of TSS and PCBs compare well with high frequency data collected at four locations over storm events having peak flows that ranged from 500 to 10,000 gpm, indicating the model captures the deposition/erosion patterns within the system. The sub-models also reproduce the spatial pattern in PCB concentrations within the streams at low flow conditions. Overall, the model provides a good representation of PCB dynamics within the system.
- The bioaccumulation sub-model provides a good match for tissue PCB concentrations in creek chub and longear sunfish at both simulated locations, including capturing differences among fish age classes as well as seasonal changes associated with variations in lipid levels.

The calibrated model provides a quantitative tool to evaluate the site, under both current and projected future conditions. Mass balances and sensitivity simulations were conducted with the model to quantify the relative importance of the various PCB sources to fish (i.e., base and storm flows from the springs, STF discharges, in-stream sediments, and groundwater seeps along Conard's Branch). Such model source assessments provide important insights into the PCB sources, sinks, and processes that drive site dynamics. For example, these analyses indicated that while springs from upstream account for a majority of the annual PCB load to Conard's Branch (which is dominated by storm flows), they account for less than a quarter of the PCBs bioaccumulated by creek chubs in that stream. This result is consistent with past modeling studies and bioaccumulation theory, which indicate that most of the PCB uptake by fish in streams typically occurs under lower flow conditions rather than under storms because 1) fish bioaccumulation is a integration of longer term exposures, whereas storms are transient events; and 2) low flows are associated with summertime, when the majority of fish growth and associated PCB uptake occurs. The model sensitivity analyses also indicate that although

sediments contribute little to the annual PCB load to the Conard's Branch water column, they are important to fish uptake, both directly through feeding in the benthic food web and indirectly through diffusive flux of PCBs to the water column. Results from such source assessments were used to develop remedial strategies assessed with the model.

The relative effectiveness of various management alternatives for reducing PCB concentrations in fish tissue was assessed through 10-year future projections with the model. The model was configured to represent a range of potential remedial strategies, consisting of various source control measures as well as varying levels of increased STF treatment, including addition of storage capacity and settling basins. The future projections indicate that, at the current rate of decline in spring PCBs, fish tissue PCB concentrations in Conard's Branch creek chubs will decrease by approximately one third over 10 years. The model indicates that instituting additional source control measures, which include collection and treatment of the North Spring bypass groundwater seepage as well as remediation of sediment and bank soils within Conard's Branch, will achieve a reduction in fish PCB concentrations of an additional one third. Finally, the model results indicate that doubling the STF capacity and/or installing a storage basin or series of settling basins for increased treatment of PCBs during storm conditions provides less incremental benefit beyond the source control measures. Large increases in spring treatment capacity provide relatively less benefit than the source control measures because the additional capacity largely addresses storm flows, and, as shown by the model source assessments, PCBs entering from Conard's Branch during storms account for less of the PCB uptake by fish than do base flow sources, which are addressed by the past and planned source control measures and current STF capacity.

SECTION 6 REFERENCES

- Alcoa, Inc., 2001. *Comprehensive Characterization of the Lower Grasse River, Grasse River Study Area, Massena, New York*. April 2001.
- Alcoa, Inc., 2002. *Analysis of Alternatives Report, Grasse River Study Area, Massena, New York*. June 2002.
- Alcoa, Inc., 2003. *Update to the Cap Modeling Studies Presented in the June 2002 Analysis of Alternatives Report*.
- Avnimelech, Y., G. Ritvo, L.E. Meijer, and M. Kochba, 2001. Water content, organic carbon and dry bulk density in flooded sediments. *Aquacultural Engineering* 25:25-33.
- Blasland, Bouck & Lee, Inc. and Quantitative Environmental Analysis, LLC, 2003. *Housatonic River – Rest of River RCRA Facility Investigation Report*. Prepared for General Electric Company, Pittsfield, MA. September 2003.
- Brunner, S., E. Hornung, H. Santi, E. Wolff, O.G. Piringer, J. Altschuh, and R. Brüggemann, 1990. Henry's Law constants for polychlorinated biphenyls: experimental determination and structure-property relationships. *Environ. Sci. Technol.* 24:1751-1754.
- Burban, P.Y., Y.J. Xu, J. McNeil, and W. Lick, 1990. Settling speeds of flocs in fresh water and seawater. *J. Geophys. Res.* 95(C10):18, 213-18, 220.
- CBS, 1998. Letter from D. Alke to the CD party project managers dated June 25, 1998. *Transmitting Summary Report for Sampling Performed Under Bloomington Sites QAPjP Volume XI, Neal's Landfill Boring Program Sampling Plan Dated March 18, 1998*.
- Connolly, J.P., 1991. Application of a food chain model to polychlorinated biphenyl contamination of the lobster and winter flounder food chains in New Bedford Harbor. *Environ. Sci. Technol.* 25:760-770.

- Connolly, J.P., T.F. Parkerton, J.D. Quadrini, S.T. Taylor, and A.J. Thuman, 1992. *Development and application of a model of PCBs in the Green Bay, Lake Michigan Walleye and Brown Trout and their food webs*. USEPA, Grosse Ile, MI.
- Connolly, J.P. and R. Tonelli, 1985. A Model of Kepone in the Striped Bass Food Chain of the James River Estuary. *Estuarine, Coastal & Shelf Science* 20:349-366.
- Connolly, J.P. and D. Glaser, 2002. p,p'DDE Bioaccumulation in Female Sea Lions of the California Channel Islands. *Continental Shelf Research* 22:1059-1078.
- Connolly, J.P., H.A. Zahakos, J. Benaman, C.K. Ziegler, J. Rhea, and K. Russell, 2000. A model of PCB fate in the Upper Hudson River. *Environ. Sci. Technol.* 34(19):4076-4087.
- Das, B.M., 1990. *Principles of Geotechnical Engineering*, 2nd edition. PWS-KENT Publishing, 1990.
- Erickson, R.J. and J.M. McKim, 1990. A model for exchange of organic chemicals at fish gills: flow and diffusion limitations. *Aquatic Toxicology* 18:175-198.
- Evans, D.O., 1984. Temperature independence of the annual cycle of standard metabolism in the pumpkinseed. *Trans. Amer. Fish. Soc.* 113:494-512.
- Ferguson, R.I., 1986. River loads underestimated by rating curves. *Water Resour. Res.* 22(1):74-76.
- Gailani, J., C.K. Ziegler, and W. Lick, 1991. Transport of suspended solids in the Lower Fox River. *J. Great Lakes Res.* 17(4):479-494.
- Gailani, J., W. Lick, C.K. Ziegler and D. Endicott, 1996. Development and Calibration of a Fine-Grained Sediment Transport Model for the Buffalo River. *J. Great Lakes Res.* 22(3):765-778.
- Glaser, D. and J.P. Connolly, 2002. A Model of p,p'DDE and Total PCB Bioaccumulation in Birds from the Southern California Bight. *Cont. Shelf Res.* 22:1079-1100.

- Gobas, F.A.P.C., K.E. Clark, W.Y. Shiu, and D. Mackay, 1989. Bioconcentration of polybrominated benzenes and biphenyls and related superhydrophobic chemicals in fish: role of bioavailability and elimination into the feces. *Environ. Tox. Chem.* 8:231-245.
- Hamrick, J.M., 1992. *A Three-Dimensional Environmental Fluid Dynamics Computer Code: Theoretical and Computational Aspects*. The College of William and Mary, Virginia Institute of Marine Science. Special Report 317.
- Hanson, P.C., T.B. Johnson, D.E. Schindler, and J.F. Kitchell, 1997. *Fish Bioenergetics 3.0*. University of Wisconsin – Madison Center for Limnology and University of Wisconsin Sea Grant Institute. <http://www.seagrant.wisc.edu/fish.html>.
- Hayduk, W. and H. Laudie, 1974. Prediction of diffusion coefficients for non-electrolytes in dilute aqueous solutions. *AIChE, J.* 20:611-615.
- Hendriks, A.J., A. van der Linde, G. Cornelissen, and D.T.H.M. Sijm, 2001. The power of size. 1. Rate constants and equilibrium ratios for accumulation of organic substances related to octanol-water partition ratio and species weight. *Environ. Tox. Chem.* 20:1399-1420.
- HydroQual, 1998. *Development and Application of a Modeling Framework to Evaluate Hurricane Impacts on Surficial Mercury Concentrations in Lavaca Bay*. Prepared for Alcoa. April 1998.
- Imhoff, J.C., A. Stoddard, and E.M. Buchak, 2003. *Evaluation of Contaminated Sediment Fate and Transport Models. Final Report*. USEPA, National Exposure Research Laboratory, Athens, GA.
- Karickhoff, S.W., 1984. Organic pollutant sorption in aquatic system. *J. Hydr. Engrg.* 110:707-735.
- Kawaguchi, Y. and S. Nakano, 2001. Contribution of terrestrial invertebrates to the annual resource budget for salmonids in forest and grassland reaches of a headwater stream. *Freshwater Biology* 46:303-316.

- Lerman, A., 1978. Chemical exchange across sediment-water interface. *Ann. Rev. Earth Planet* 6:281-303.
- Lotrich, V.A., 1973. Growth, production, and community composition of fishes inhabiting a first-, second-, and third-order stream of eastern Kentucky. *Ecological Monographs* 43:377-397.
- Mackay, D., W.Y. Shiu, and K.C. Ma, 1992. *Illustrated handbook of physical-chemical properties and environmental fate for organic chemicals: Volume 1, monoaromatic hydrocarbons, chlorobenzenes and PCBs*. Chelsea: Lewis Publishers.
- Morrison, H.A., F.A.P.C. Gobas, R. Lazar, D.M. Whittle, and G.D. Haffner, 1997. Development and verification of a benthic/pelagic food web bioaccumulation model for PCB congeners in Western Lake Erie. *Environ. Sci. Technol.* 31:3267-3273.
- Morrison, H.A., D.M. Whittle, C.D. Metcalfe, and A.J. Niimi, 1999. Application of a food web bioaccumulation model for the prediction of polychlorinated biphenyl, dioxin, and furan congener concentrations in Lake Ontario aquatic biota. *Can. J. Fish And Aquatic. Sci.* 56:1389-1400.
- Nichols, J.W., J.M. McKim, M.E. Andersen, M.L. Gargas, H.J. Clewell, III, and R.J. Erickson, 1990. A physiologically-based toxicokinetic model for the uptake and disposition of waterborne organic chemicals in fish. *Toxicol. Appl. Pharmacol.* 106:433-447.
- O'Connor, D.J. and W.E. Dobbins, 1958. Mechanisms of reaeration in natural streams. *Trans. Am. Soc. Civ. Eng.* 123:641-684.
- O'Connor, D.J., 1983. The effect of wind on the gas-liquid transfer coefficients. *J. Environ. Eng.* 109:731-752.
- O'Connor, D.J., 1984. *The significance of gas exchange in water quality assessment and planning*. Gas Transfer at Water Surfaces. Eds. W. Brutsaert, and G.H. Jirka. D. Reidel Publishing Company.

- Partheniades, E., 1992. Estuarine sediment dynamics and shoaling processes. *In: Handbook of Coastal and Ocean Engineering*, Volume 3. Ed. J. Herbick.
- Quantitative Environmental Analysis, LLC, 1999. *PCBs in the Upper Hudson River, Volume 2, A Model of PCB Fate, Transport and Bioaccumulation*. Prepared for General Electric Company, May 1999.
- Quantitative Environmental Analysis, LLC, 2002. Food Web Model Report. *In: Feasibility Study: Lower Fox River and Green Bay, Wisconsin Department of Natural Resources*. www.dnr.state.wi.us.
- Quantitative Environmental Analysis, LLC, 2005a. *Dredge Resuspension Modeling: Attachment E to the Phase 1 Intermediate Design Report, Hudson River PCBs Superfund Site*. Prepared for General Electric Company.
- Quantitative Environmental Analysis, LLC, 2005b. *Development and Calibration of a Mathematical Model of Surface Water PCB Fate, Transport, and Bioaccumulation at the Neal's Landfill Site, Bloomington, IN*. Prepared for Viacom, Inc., December 2005.
- Stair, D.M., V.R. Tolbert, and G.L. Vaughan, 1984. Comparison of growth, population structure, and food of the creek chub *Semotilus atromaculatus* in undisturbed and surface mining disturbed streams in Tennessee. *Environmental Pollution* (Series A) 35:331-343.
- TetraTech, 2003. *Final Technical Memorandum Regarding Stream Conditions and Fish Sampling, Neal's Landfill Site, Bloomington, Monroe County, Indiana*. <http://www.copa.org/2003/neals/fish-tech/fishtech.html>.
- Thibodeaux, L.J. and V.J. Bierman, 2003. The bioturbation-driven chemical release process. *Environ. Sci. Technol.* 37(13):252A-258A.
- Thibodeaux, L.J., T.V. Kalliat, and D.D. Reible, 2001. Bioturbation-driven transport of hydrophobic organic chemicals from bed sediment. *Environmental Engineering Science* 18(4):215-223.

- Thomann, R.V. and J.P. Connolly, 1984. Model of PCB in the Lake Michigan lake trout food chain. *Environ. Sci. Technol.* 18:65-71.
- Thomann, R.V., J.P. Connolly, and T.F. Parkerton, 1992. An Equilibrium Model of Organic Chemical Accumulation in Aquatic Food Webs with Sediment Interaction, *Environ. Toxl. Chem.* 11:615-629.
- Thoms, S.R., G. Matisoff, P.L. McCall, and X. Wang, 1995. *Models for alteration of sediments by benthic organisms*. Water Environmental Research Foundation Project 92-NPS-2, Alexandria, VA.
- Tracey, G.A. and D.J. Hansen, 1996. Use of biota-sediment accumulation factors to assess similarity of nonionic organic chemical exposure to benthically-coupled organisms of differing trophic mode. *Arch. Environ. Contam. Toxicol.* 30:467-475.
- U.S. Environmental Protection Agency, 2000. *Revised Baseline Modeling Report. Hudson River PCBs Reassessment RI/F*. Limno-Tech, Inc., Menzie-Cura & Assoc., Inc., and TetraTech, Inc.
- U.S. Environmental Protection Agency, 2003. *Conard's Branch/Richland Creek Sediment Profile*. Prepared by FIELDS Team, Region 5 Superfund Division, December 2003.
- U.S. Environmental Protection Agency, 2006. *Final Model Documentation Report: Modeling Study of PCB Contamination in the Housatonic River*. Prepared by Weston Solutions, Inc., West Chester, PA, for the U.S. Army Corps of Engineers, New England District, and the U.S. Environmental Protection Agency, New England Region, November 2006.
- Viacom Inc., 2005a. *Conard's Branch and Richland Creek Sediment Sampling and Analysis Report. QAPjP Volume XXXVI*. January 2005.
- Viacom Inc., 2005b. Email from D. Alke to the CD party project managers dated 8/25/05. Subject: "Unified Modeling Trend Assessment."
- Viacom Inc., 2004a. *Final Report for the Groundwater Investigation at Neal's Landfill. QAPjP Volume XXX*. July 2004.

- Viacom Inc., 2004b. Email from D. Alke to the CD party project managers dated 12/16/04.
Subject: *Scope of work for North Spring and related seepage bypass tests.*
- Viacom Inc., 2003. Letter from D. Alke to Mr. Steve Roush dated July 18, 2003. Subject:
NPDES Per. No. IN0045918 Neal's Landfill Spring Treatment Facility Bloomington, IN.
- Viacom Inc., 2002a. *Long-Term Groundwater Monitoring Plan for Neal's Landfill. QAPjP Volume XXXI.* April 2002.
- Viacom Inc., 2002b. *Test Report for Neal's Landfill Settling Test Conducted June 5, 2002.* September 2002.
- Viacom Inc., 2002c. Letter from D. Alke to the CD party project managers dated 11/13/02.
Subject: *New Spring Collection System at Conard's Branch-Additional Investigation under the Neal's Landfill Groundwater Investigation Plan.*
- Wisconsin Department of Natural Resources and The RETEC Group, Inc., 2002. *Final Model Documentation Report. Lower Fox River and Green Bay, Wisconsin Remedial Investigation and Feasibility Study.* December 2002.
- Zaranko, D.T., 1994. *Polychlorinated biphenyls (PCBs) in an urban creek: application of a food web model.* Master Thesis, University of Guelph, Canada.
- Ziegler, C.K. and W. Lick, 1986. *A numerical model of the resuspension, deposition, and transport of fine-grained sediments in shallow water.* UCSB Report ME-86-3.
- Ziegler, C.K. and B.S. Nisbet, 1994. Fine-grained sediment transport in Pawtuxet River, Rhode Island. *J. Hydr. Engr.* 120(5):561-576.
- Ziegler, C.K. and B.S. Nisbet, 1995. Long-Term Simulation of Fine-Grained Sediment Transport in a Large Reservoir. *J. Hydr. Engrg.* 121(11): 773-781.
- Ziegler, C., P. Israelsson, and J. Connolly, 2000. Modeling Sediment Transport Dynamics in Thompson Island Pool, Upper Hudson River. *Water Quality and Ecosystem Modeling* 1:193-222.

FIGURES

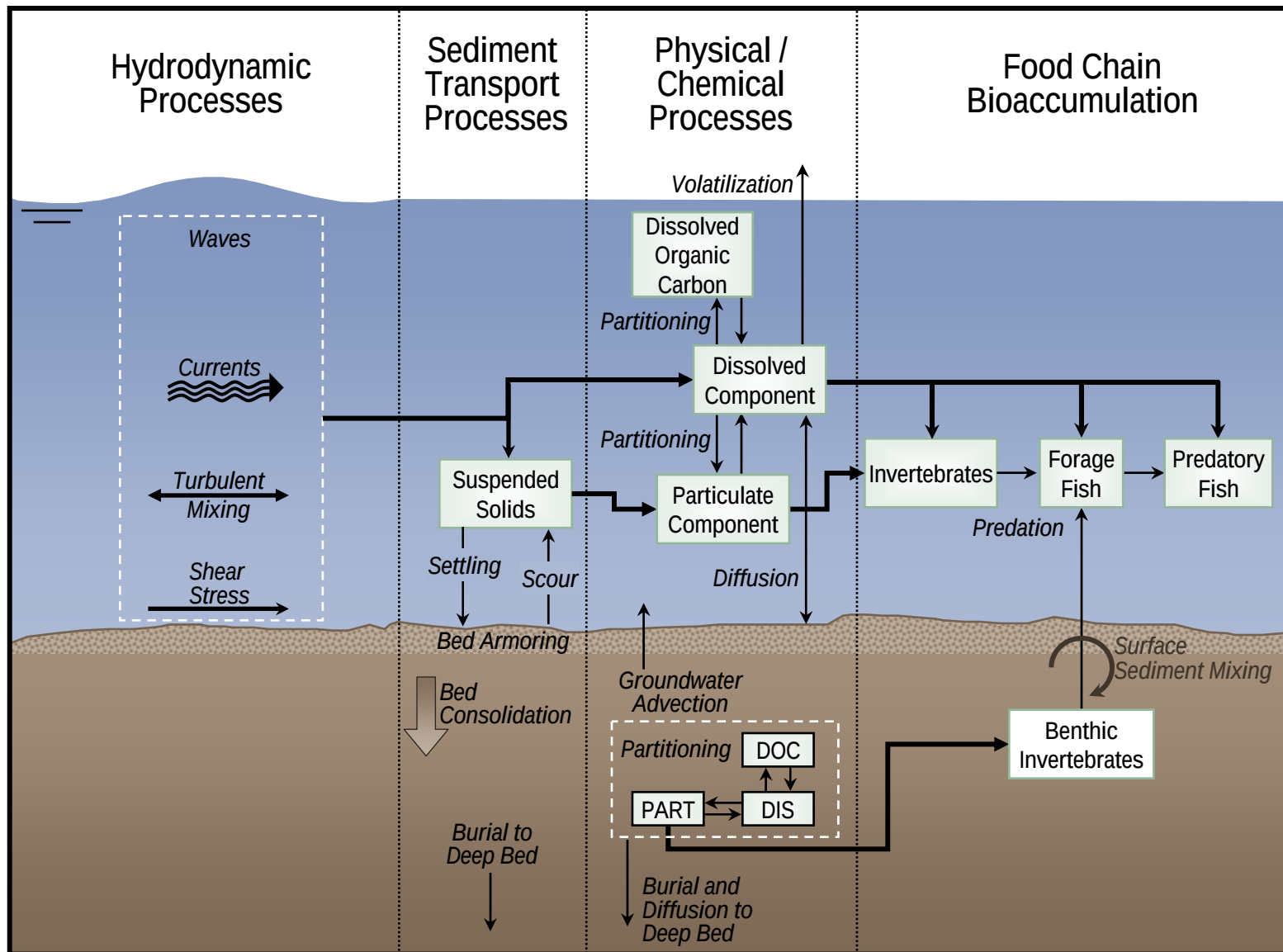
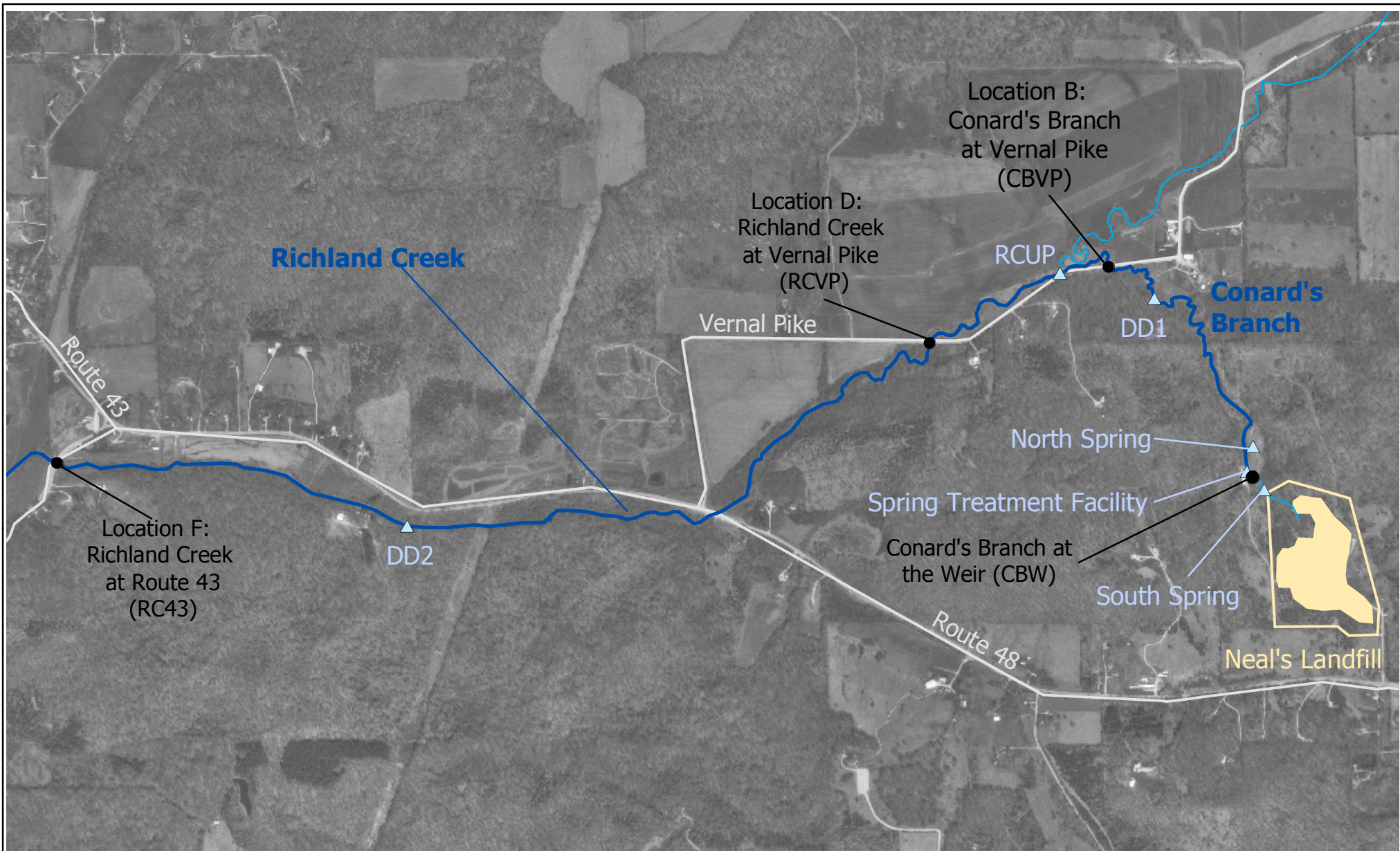
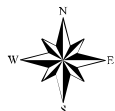


Figure 2-1. Model framework: submodels and processes.



LOCATOR



0 0.1 0.2 Miles

LEGEND

- Neal's Landfill
- Inflows / Tribes
- Primary Sample Locations
- Model Domain
- Roads
- Shoreline

Figure 2-2.
Map of Conard's Branch and
Richland Creek with model domain.

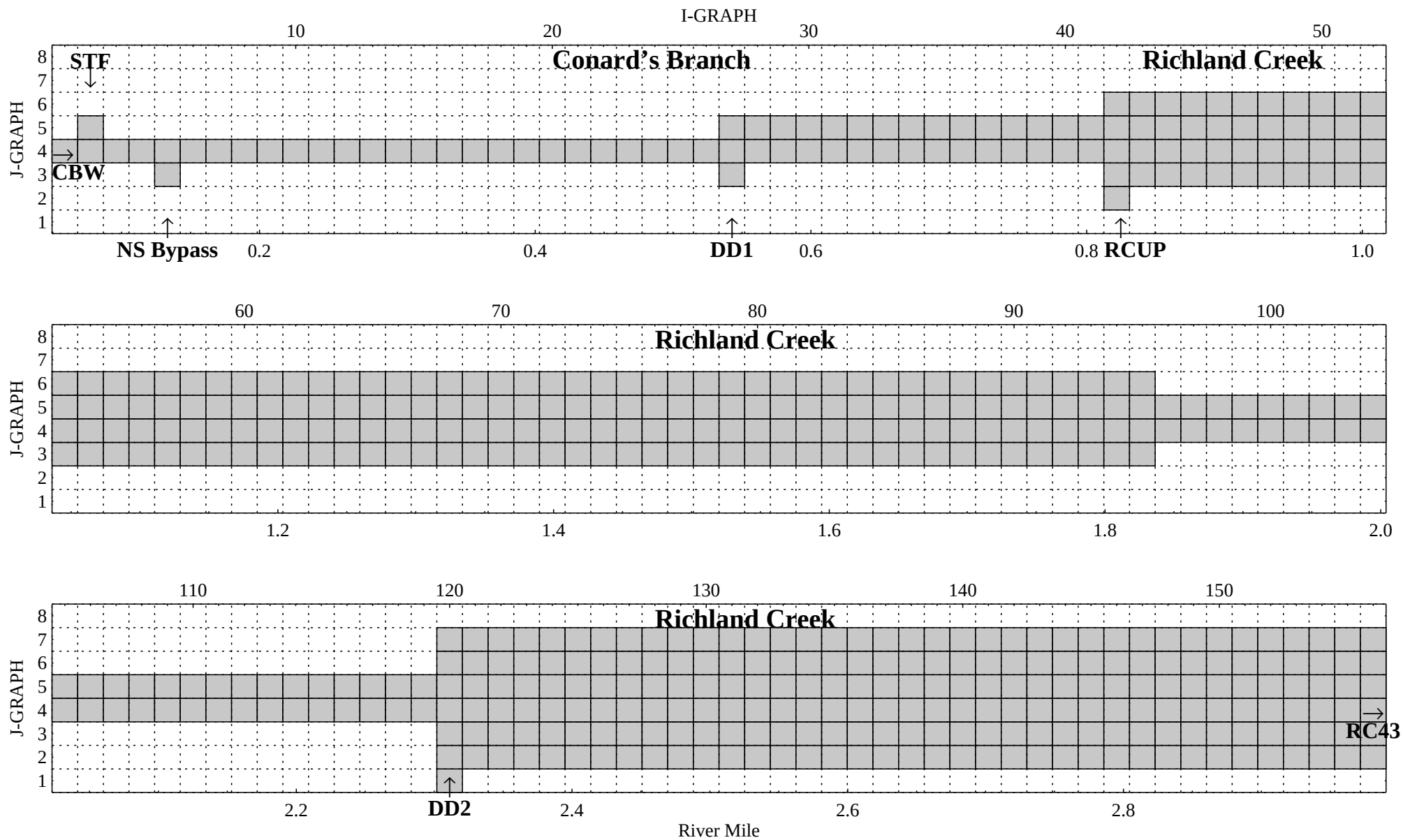


Figure 2-3. Model grid.

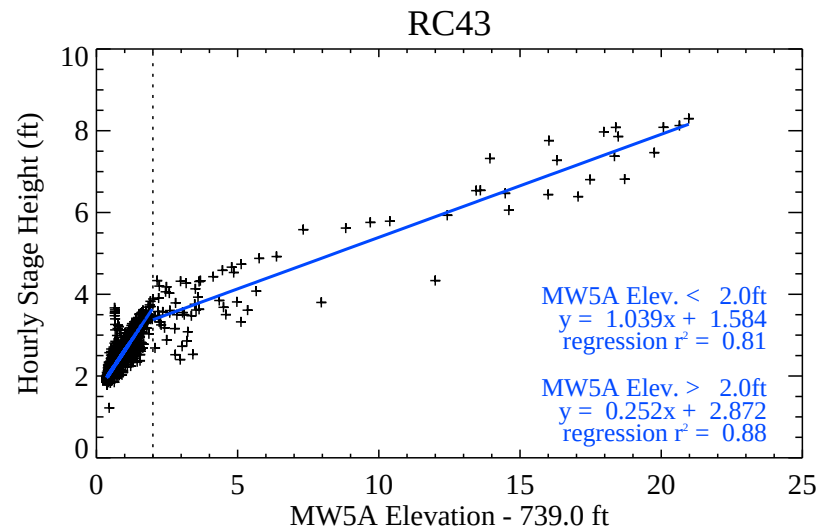
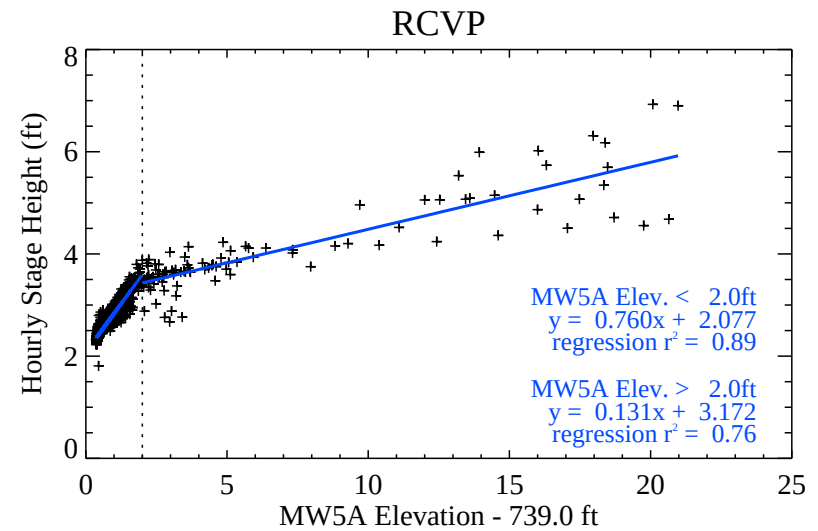
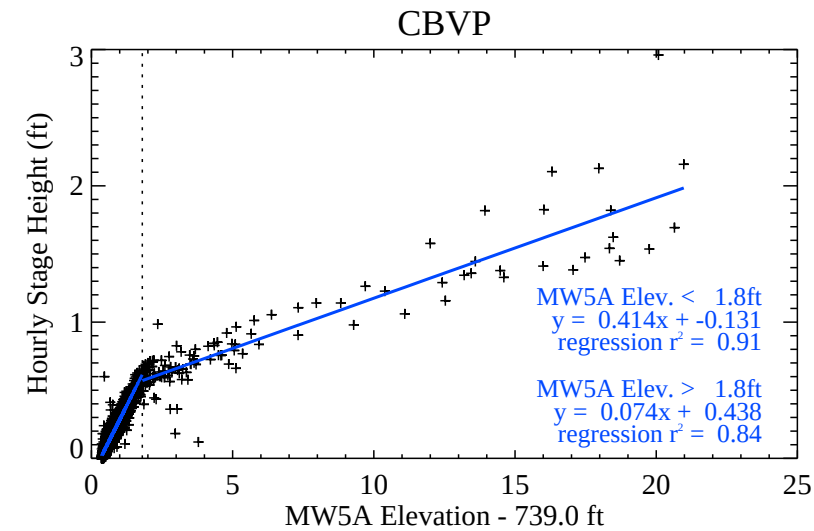


Figure 3-1. Relationships between hourly stage heights at CBVP, RCVP, and RC43 and MW5A in 2003 and 2004.

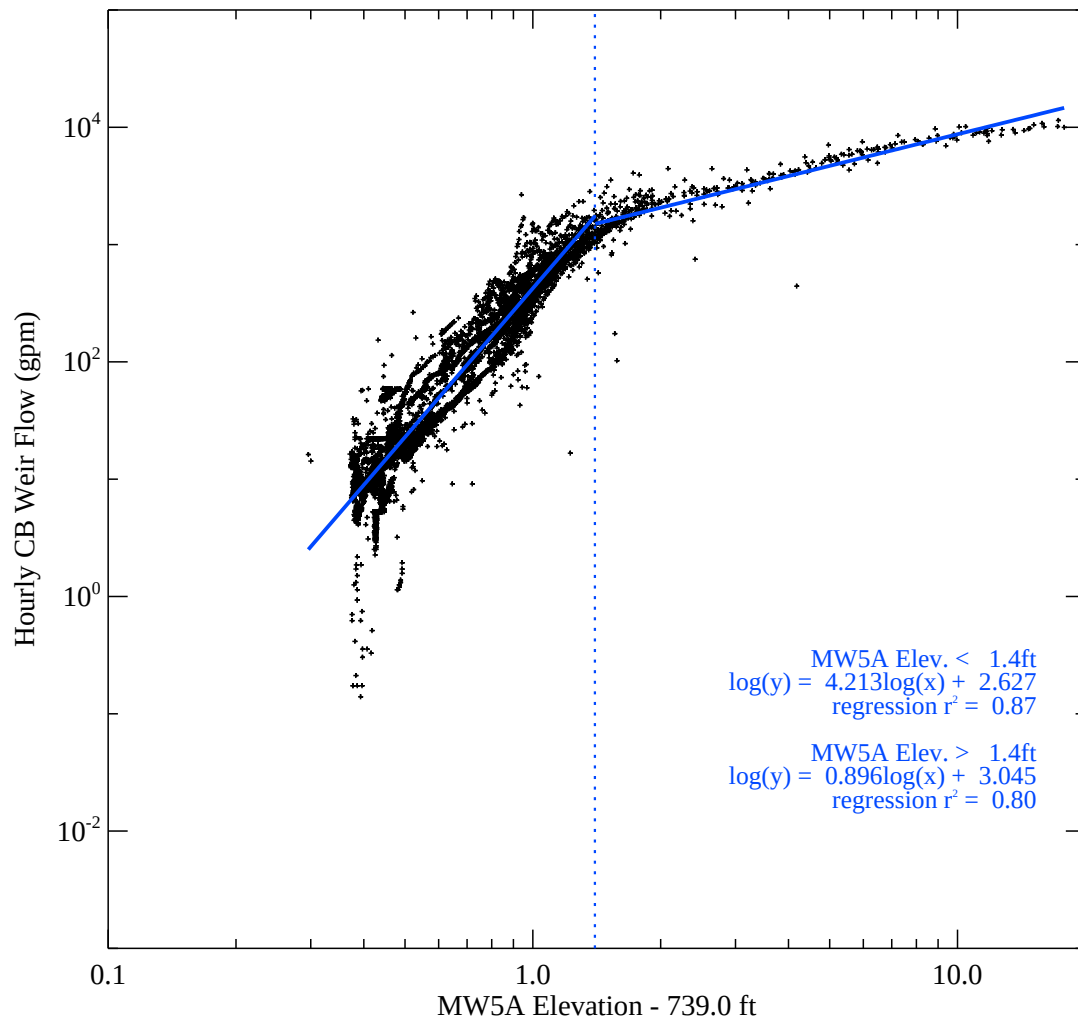


Figure 3-2. Relationship between CB Weir flow and MW5A elevation in 2002.

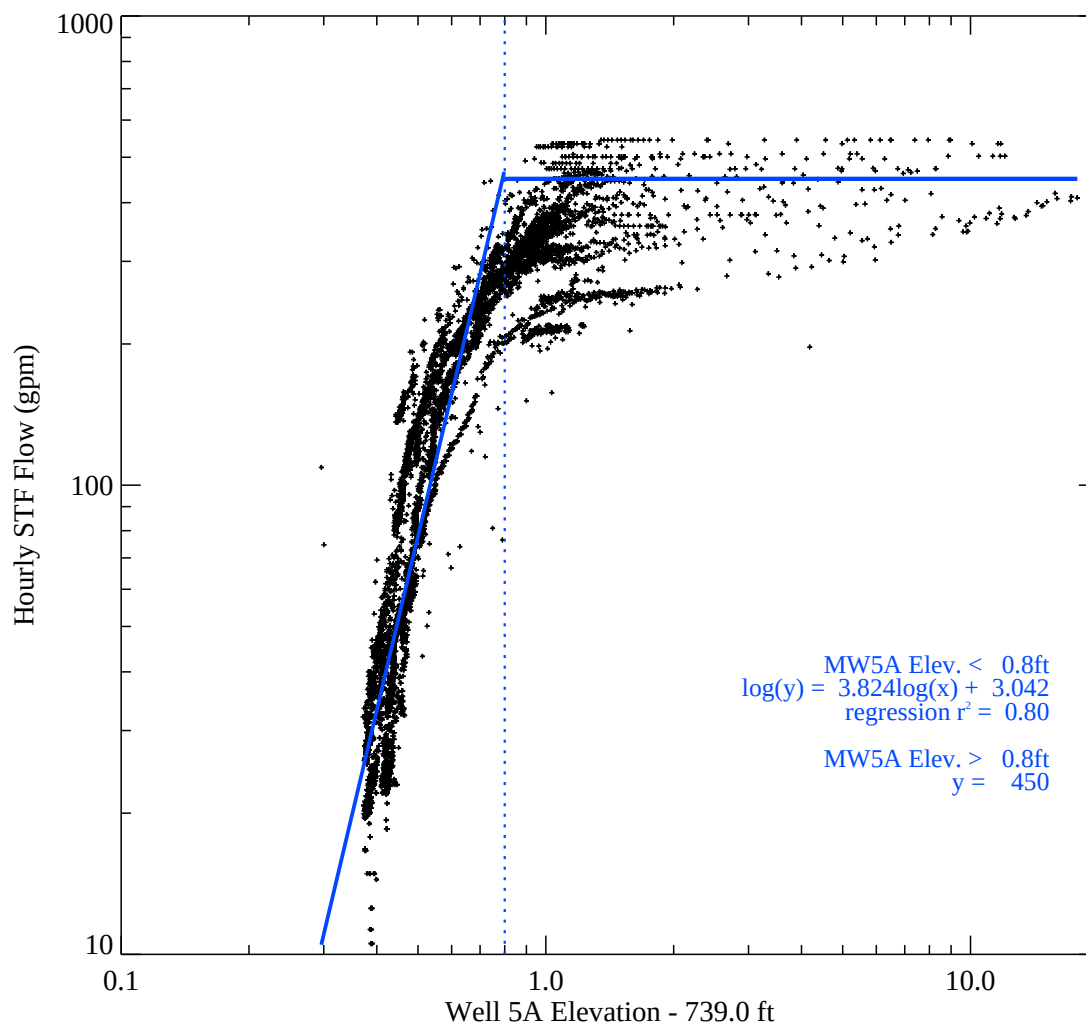


Figure 3-3. Relationship between STF flow and MW5A elevation in 2002.

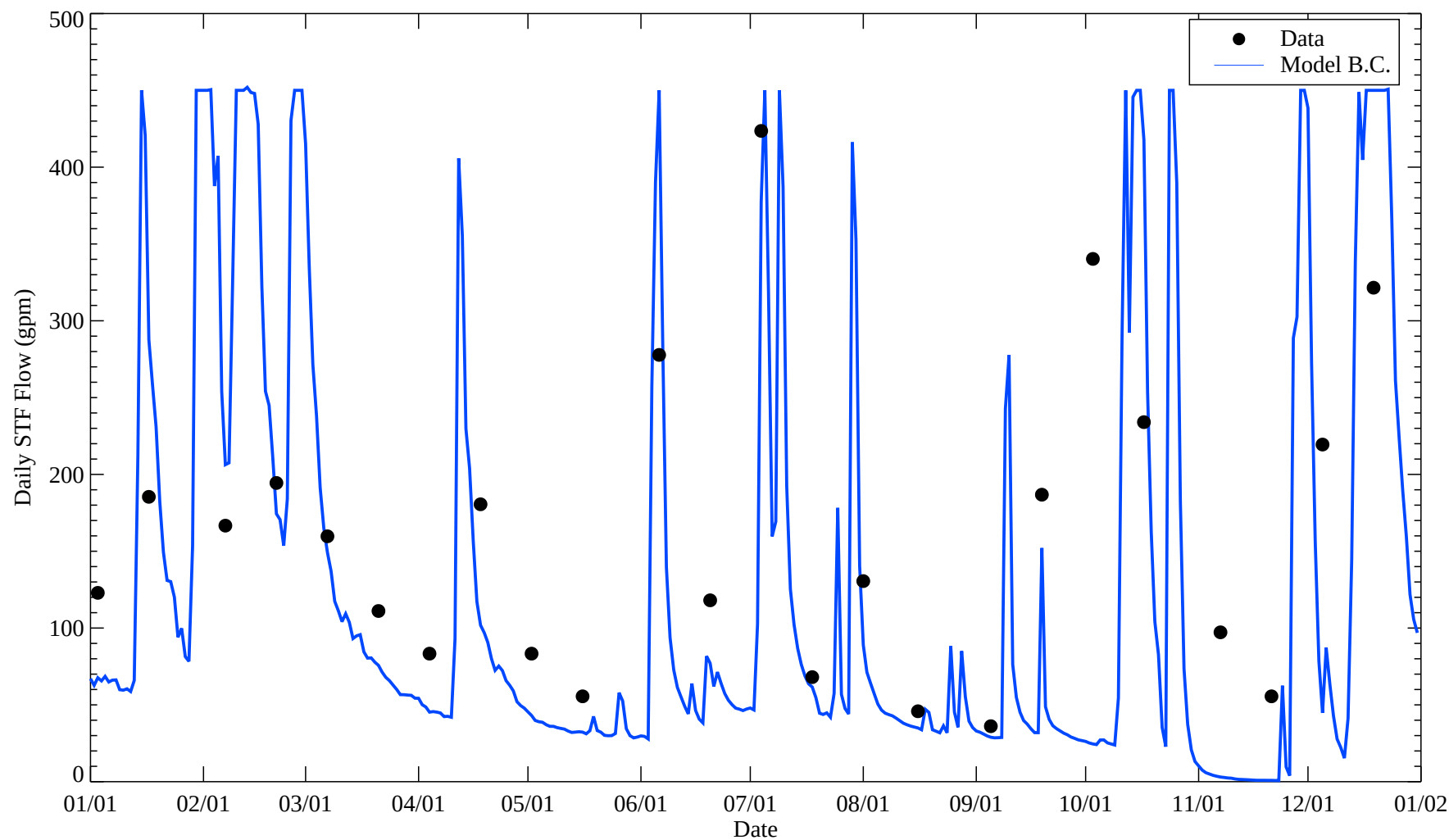


Figure 3-4. Comparison of estimated STF flows with biweekly flow measurement at STF influent in 2001.

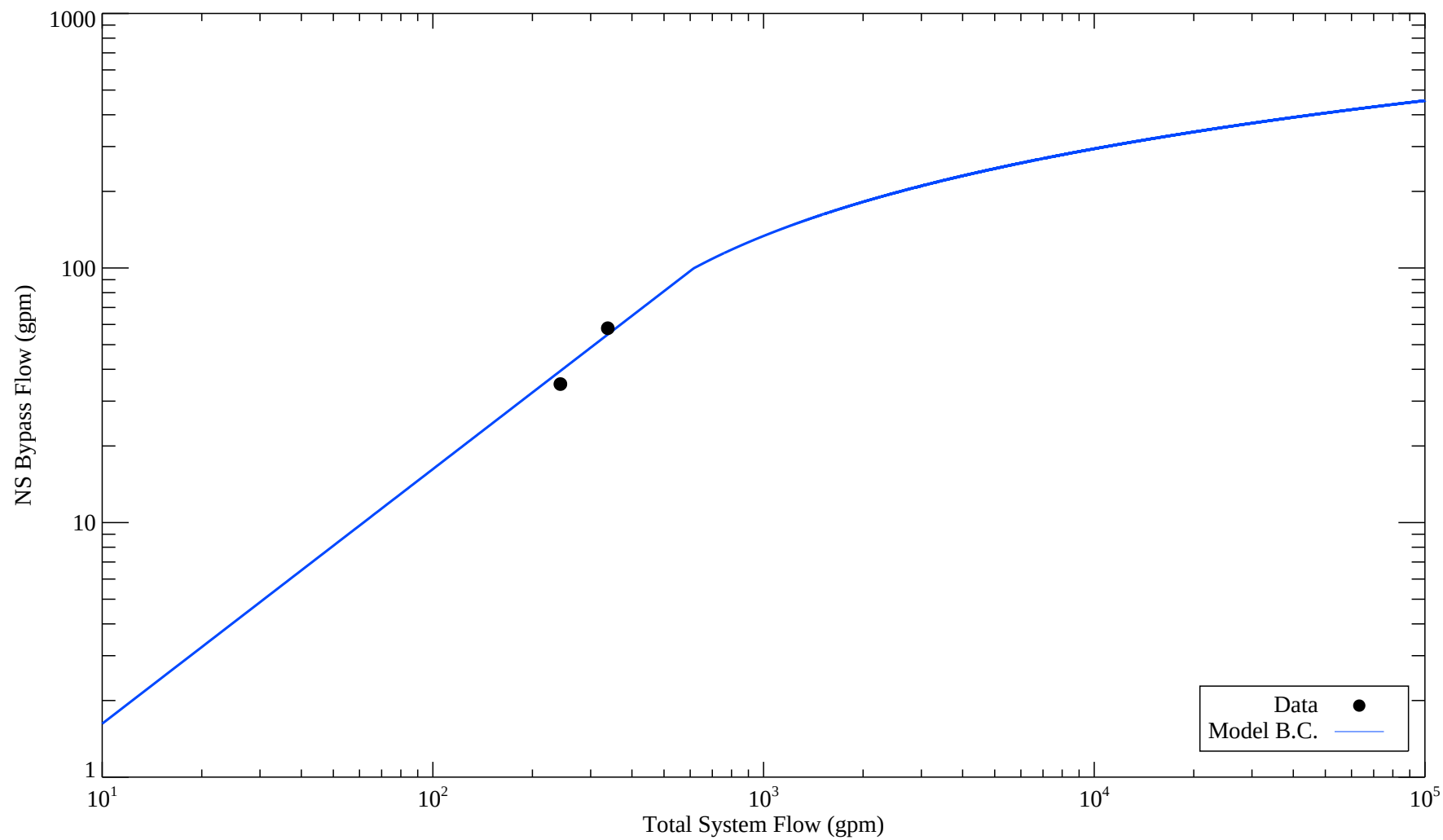


Figure 3-5. Relationship of North Spring bypass flow with total system flow.

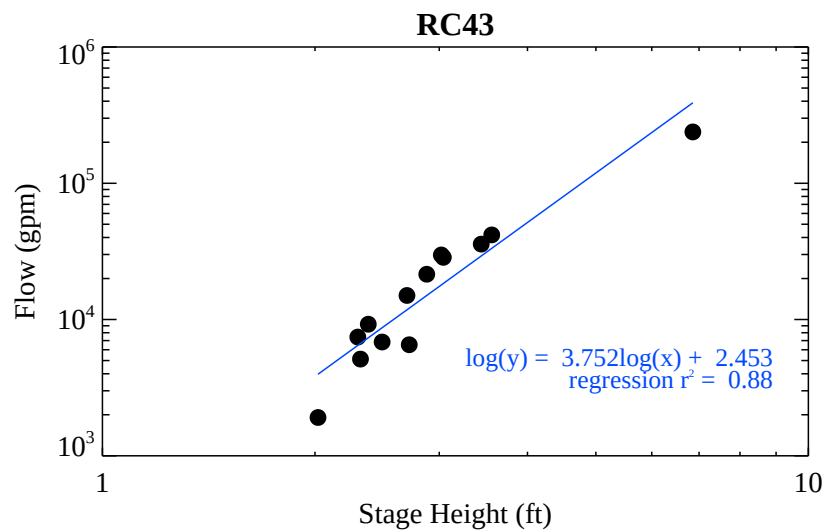
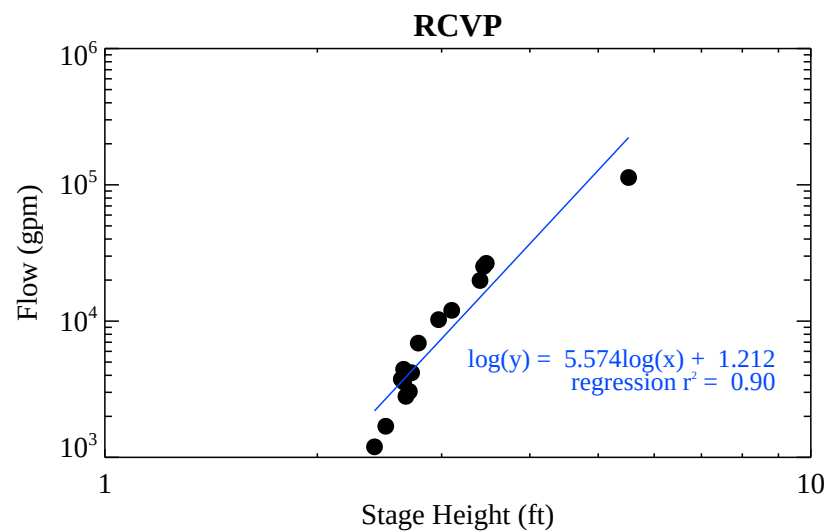
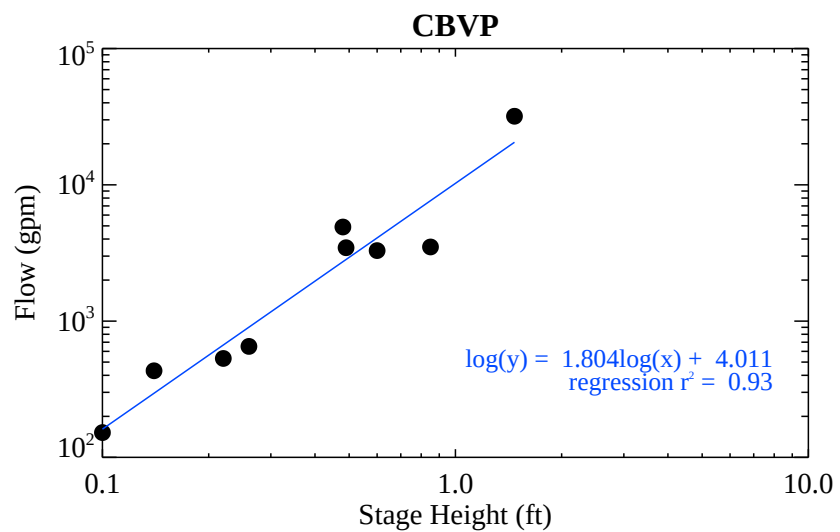


Figure 3-6. Stage height rating curves for CBVP, RCVP, and RC43.

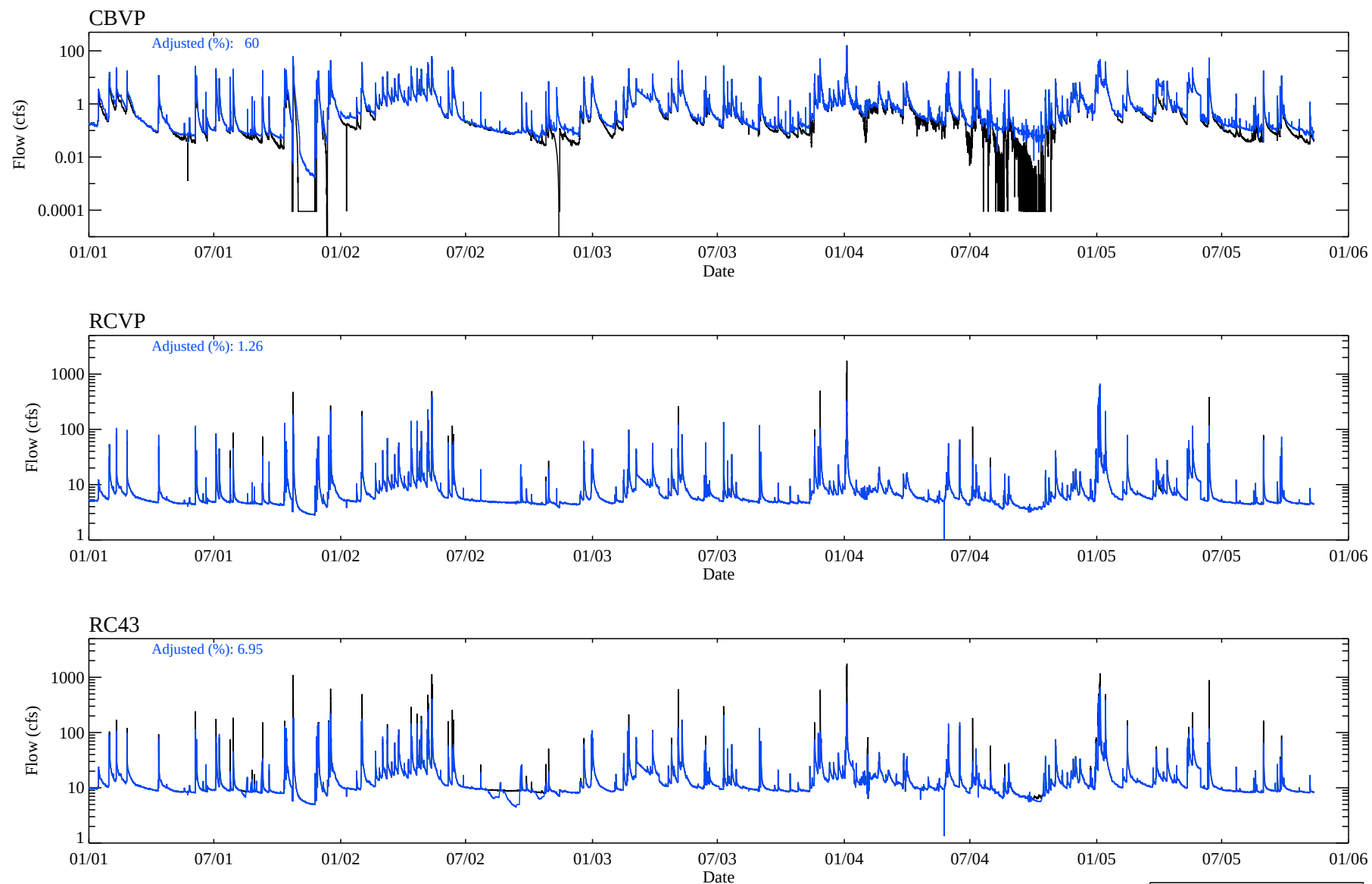
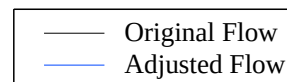


Figure 3-7. Comparison of flows at CBVP, RCV, and RC43 before and after the flow adjustments.



Note: MW5A elevation data was not available after 11/12/2005

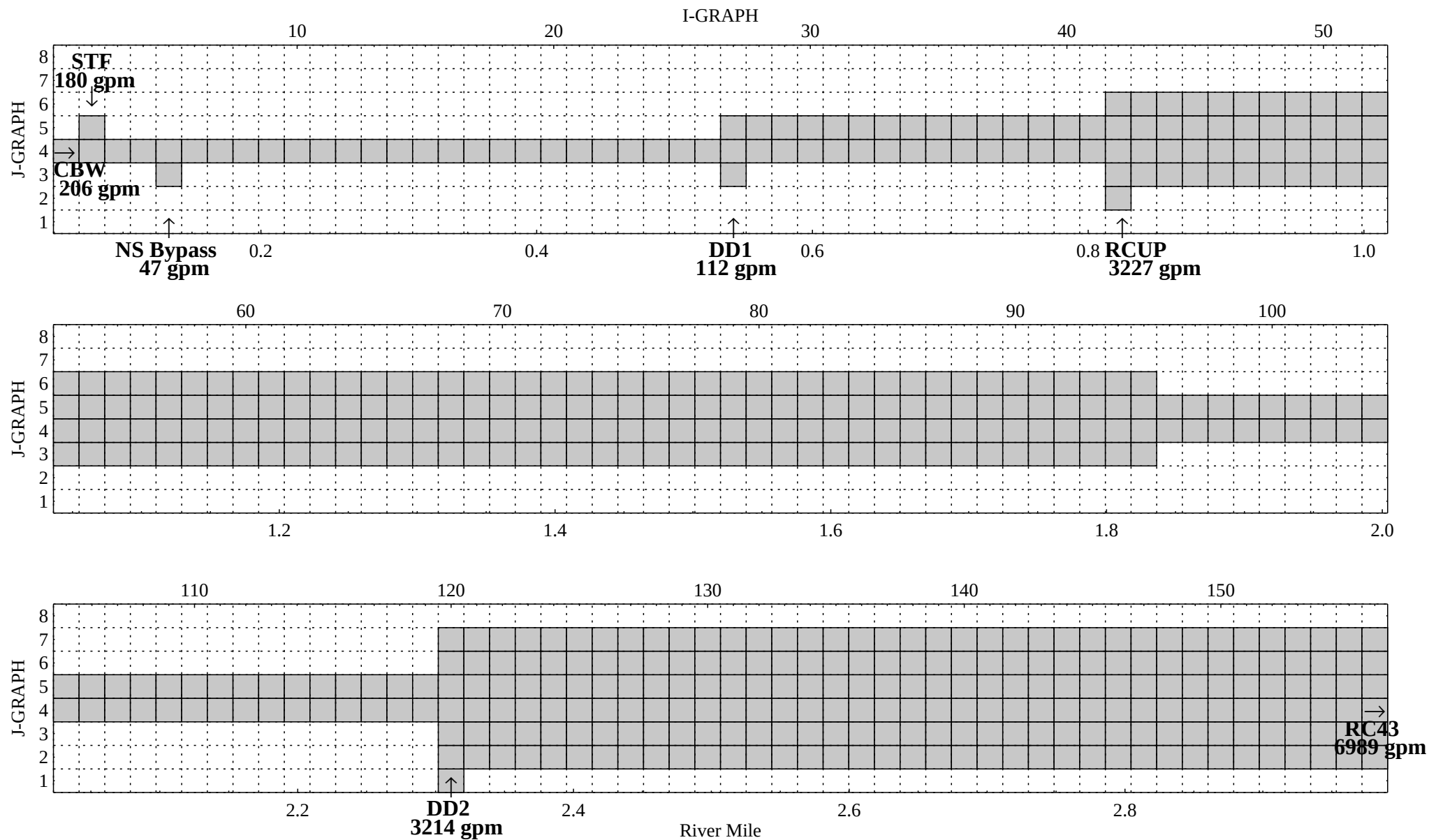


Figure 3-8. Long-term average flow rates at model boundaries over the 2001-2005 calibration period.

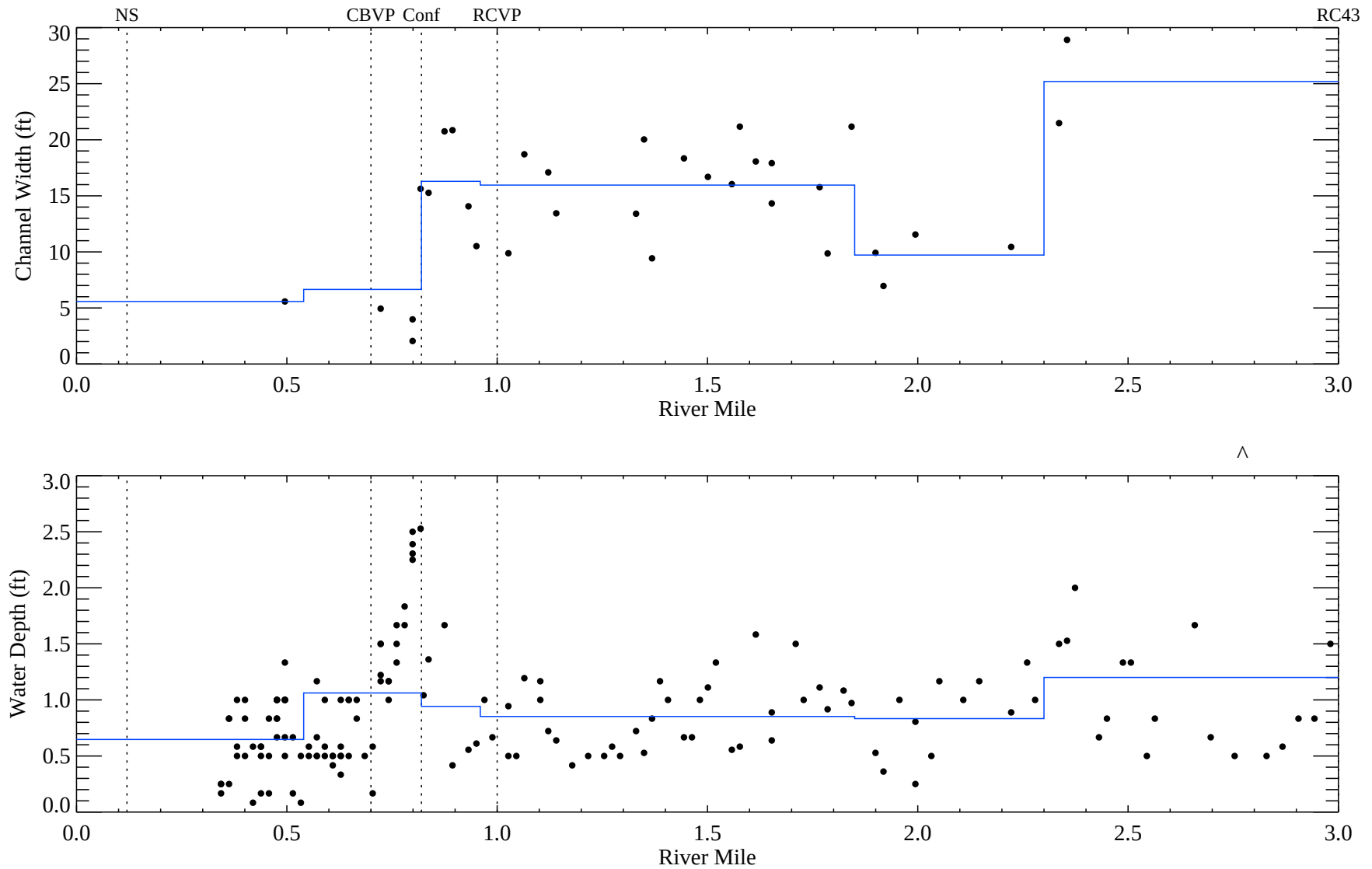


Figure 3-9. Spatial profiles of channel width and water depth collected by USEPA in November 2003.

Notes: Zero water depth data removed; water depth for the same transect averaged.



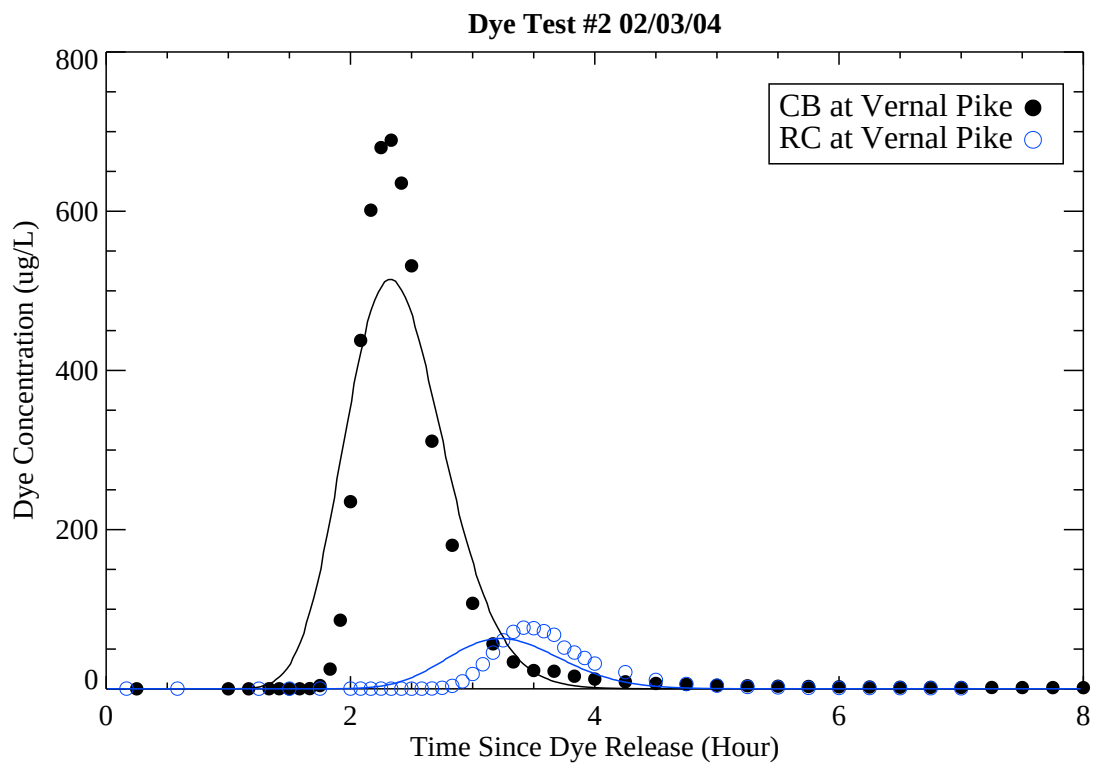
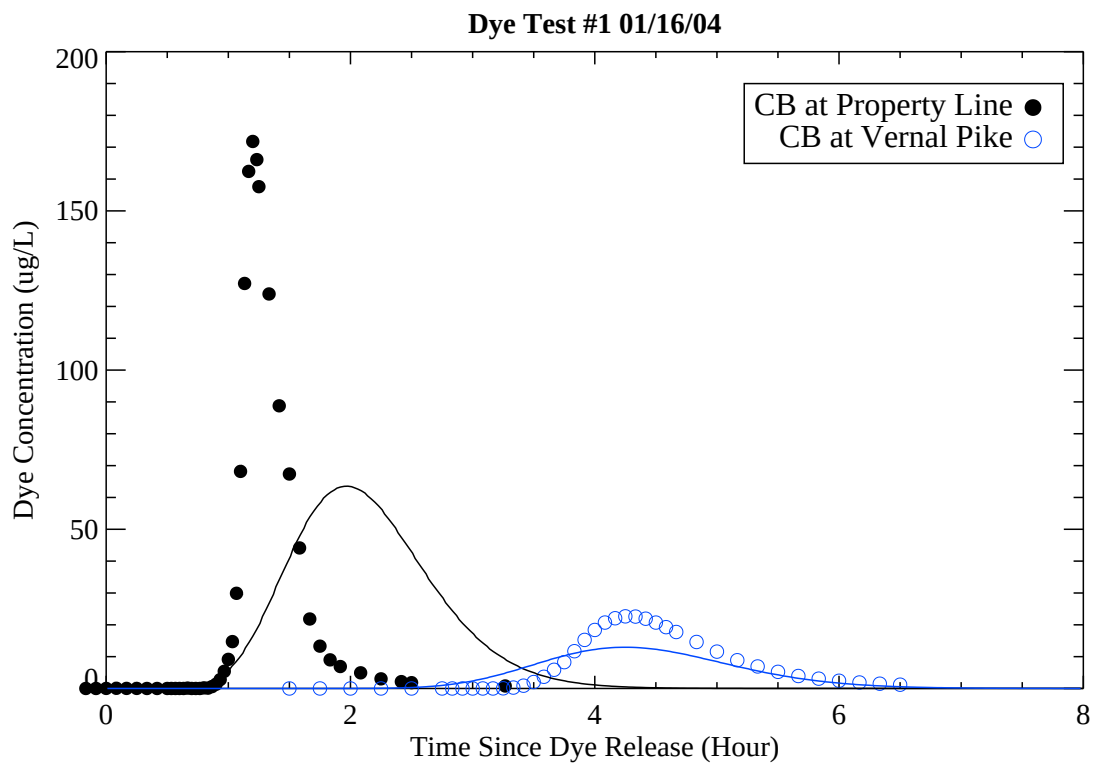


Figure 3-10. Comparison of measured and predicted dye concentrations at two different stations during dye tests.

Note: Lines represent model results.

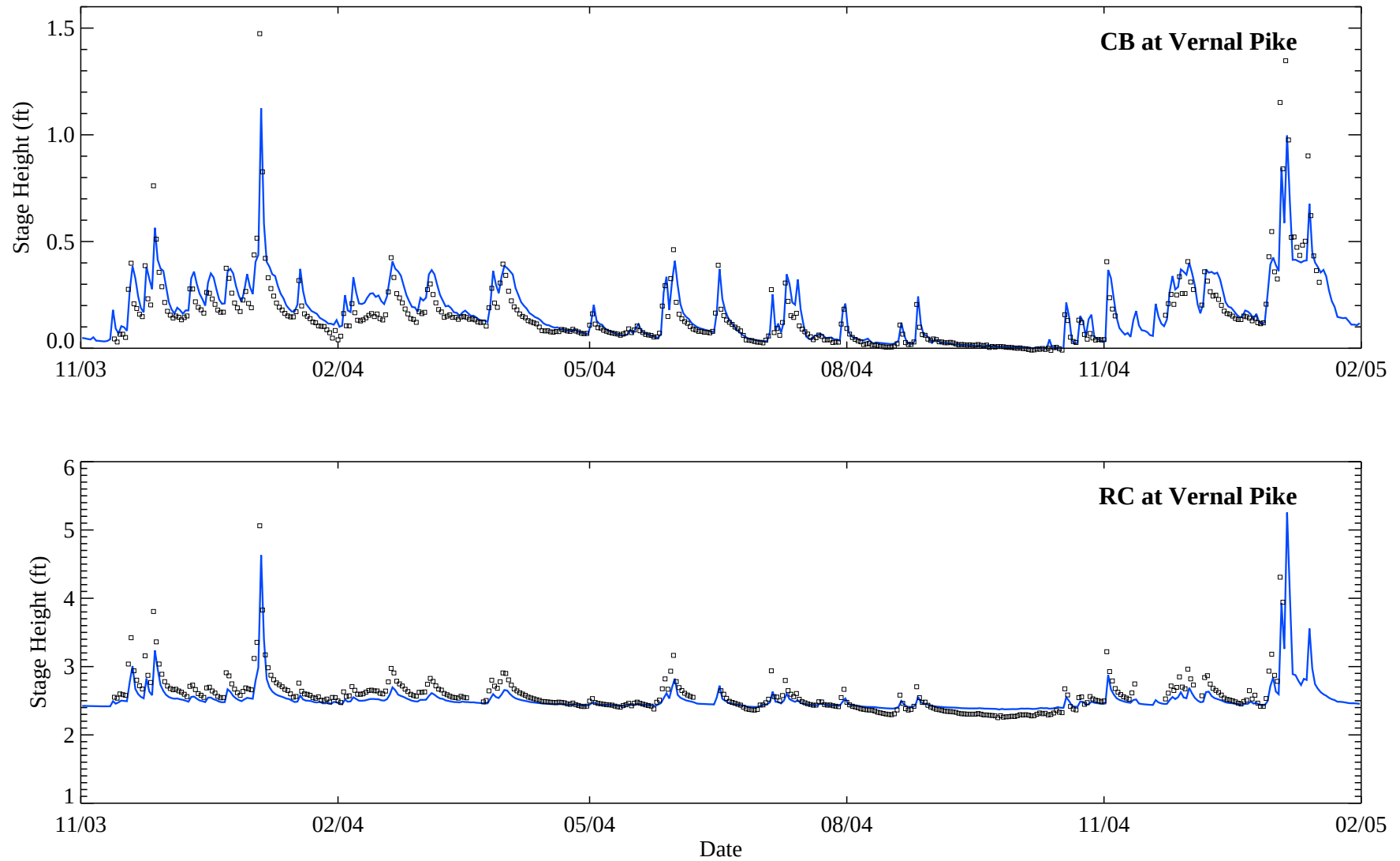


Figure 3-11. Comparison of predicted and measured stage height at CBVP and RCV.



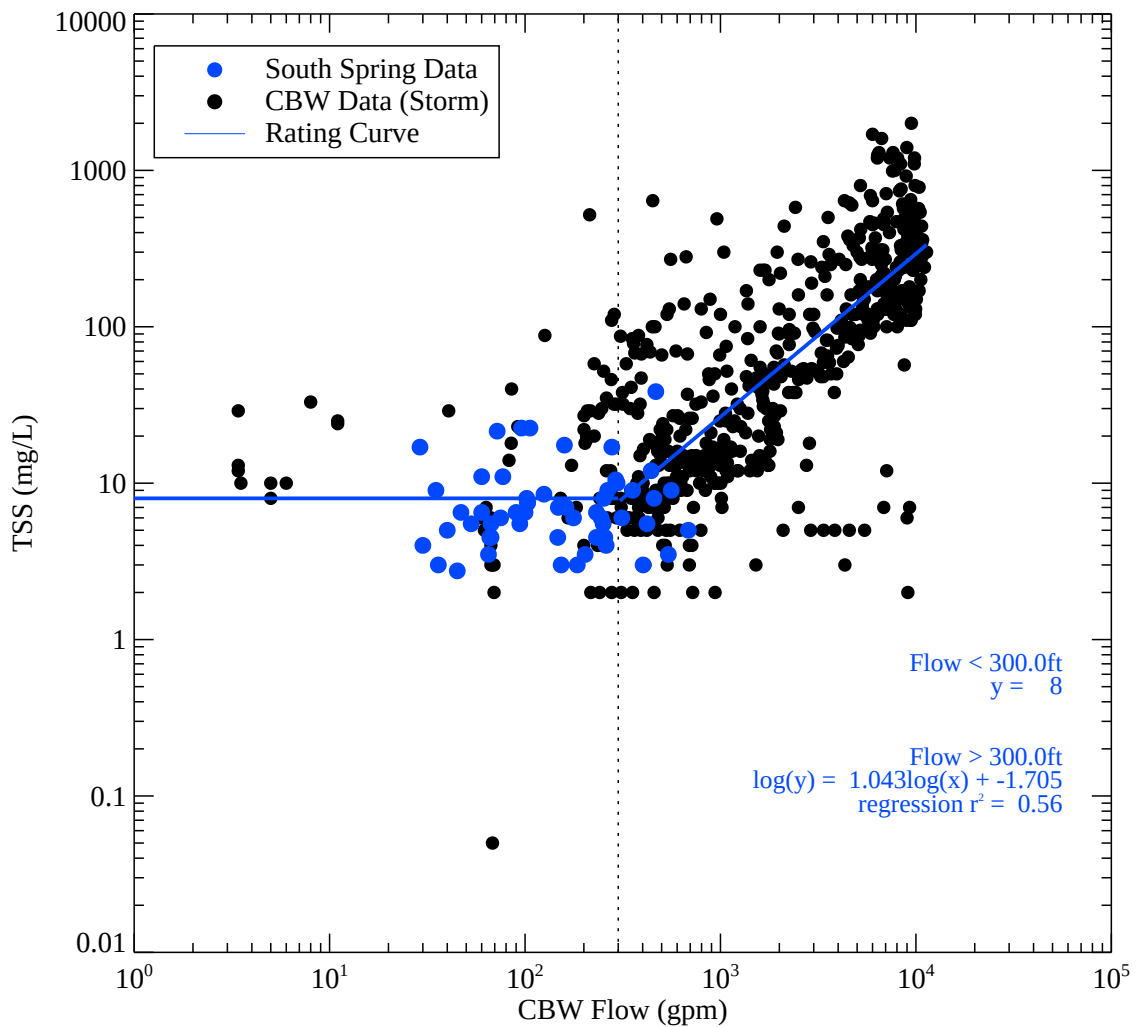


Figure 3-12. Sediment rating curve for CBW.

Data source: storm data collected between 1998 and 2005; South Spring data between 2001 and August 2005.

Note: Non-detect TSS set to 1/2 MDL.

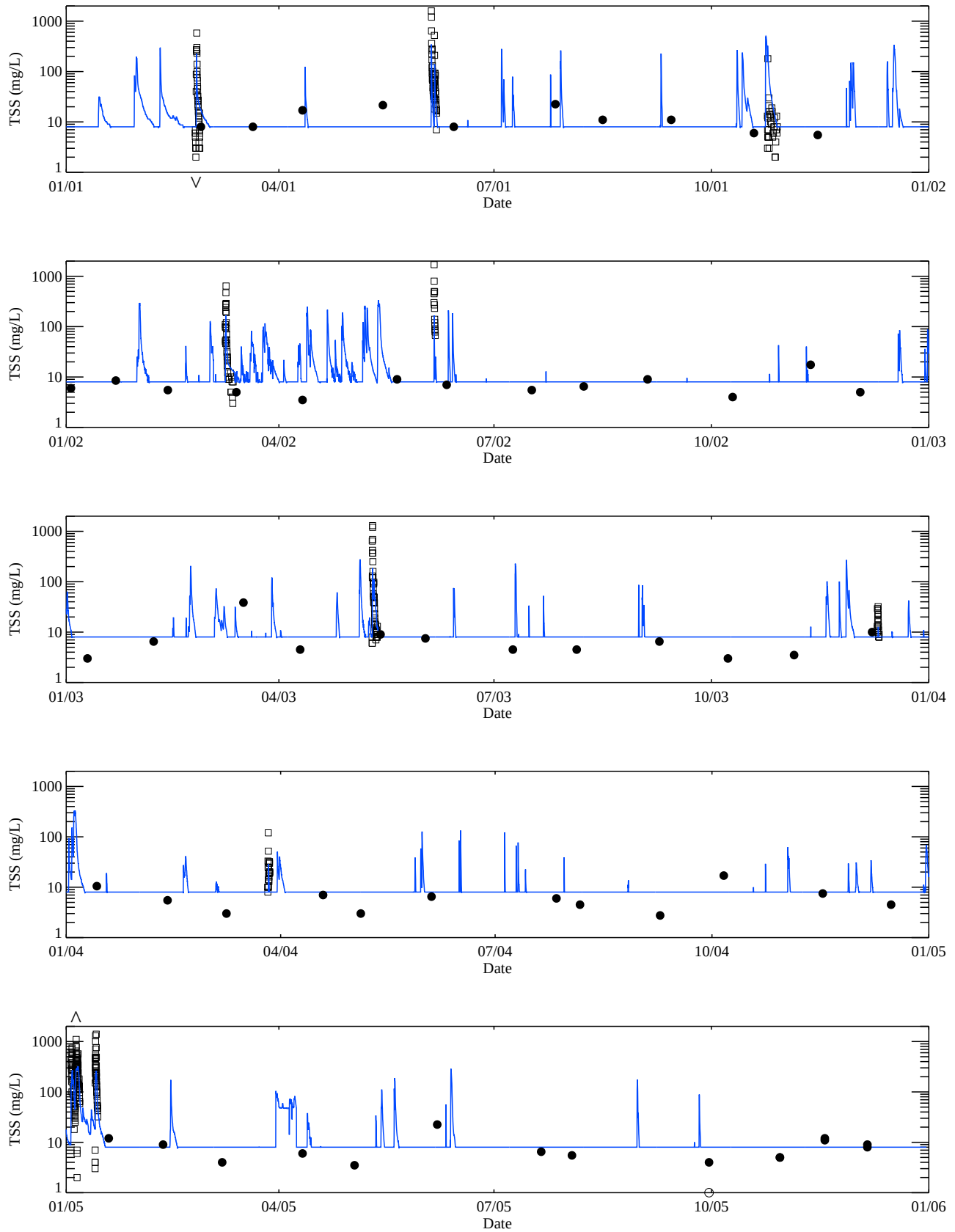
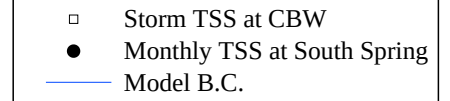


Figure 3-13. Comparison of measured TSS with estimated TSS at CBW.

Notes: Model boundary condition after 11/12/05 is set to a constant value equal to the last value; non-detect TSS are plotted as open symbols.



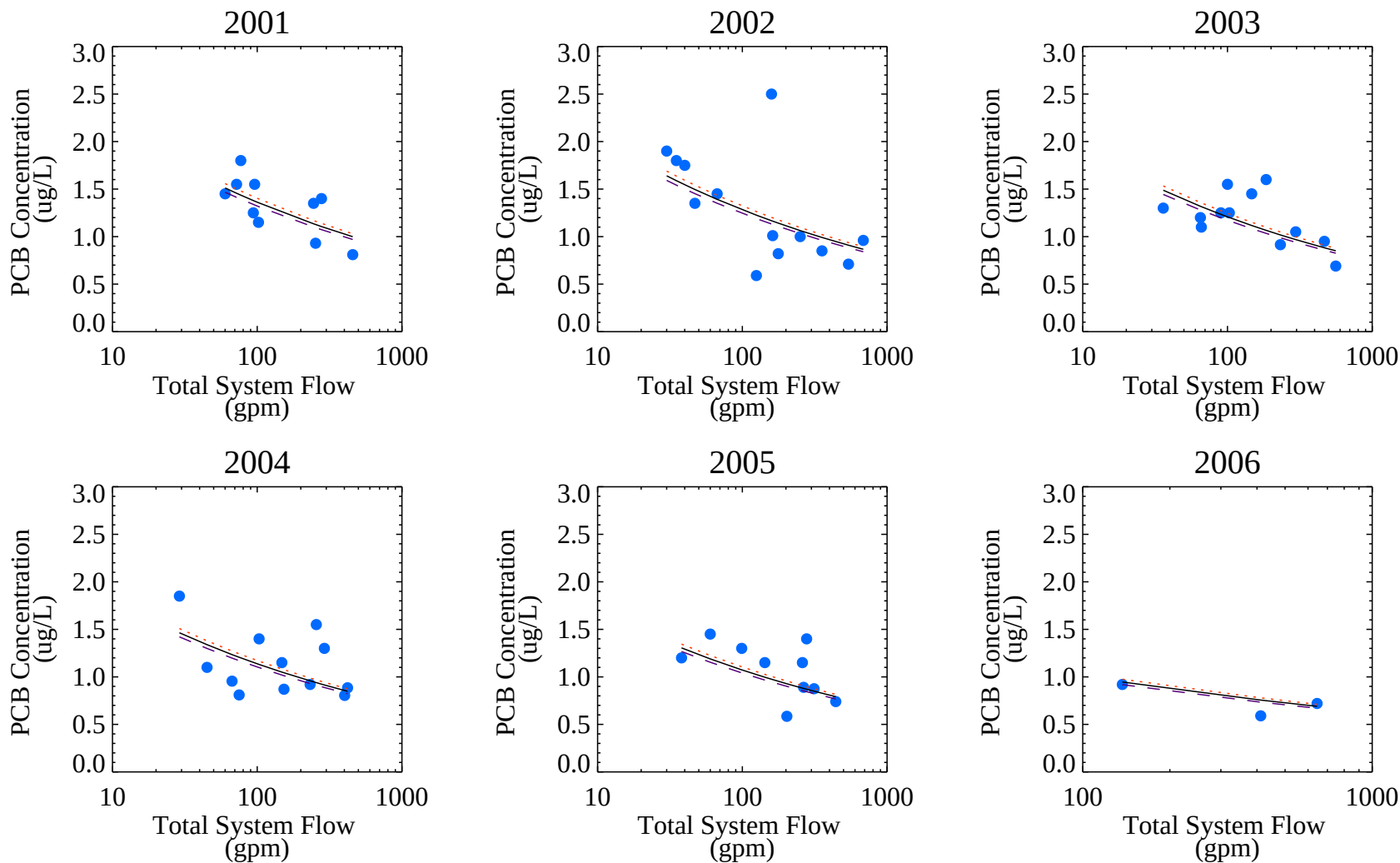


Figure 3-14. PCB - flow relationship used for low flow CBW boundary condition.

Notes: Data measured between 1/1/2001 and 3/15/2006.

Blue dots represent measured data. Fits shown here were obtained using the value of elapsed time at Jan-1 (dotted-red line), mid-year (solid-black line), and Dec-31 (dashed-purple line) every year. Open circles represent non-detects.

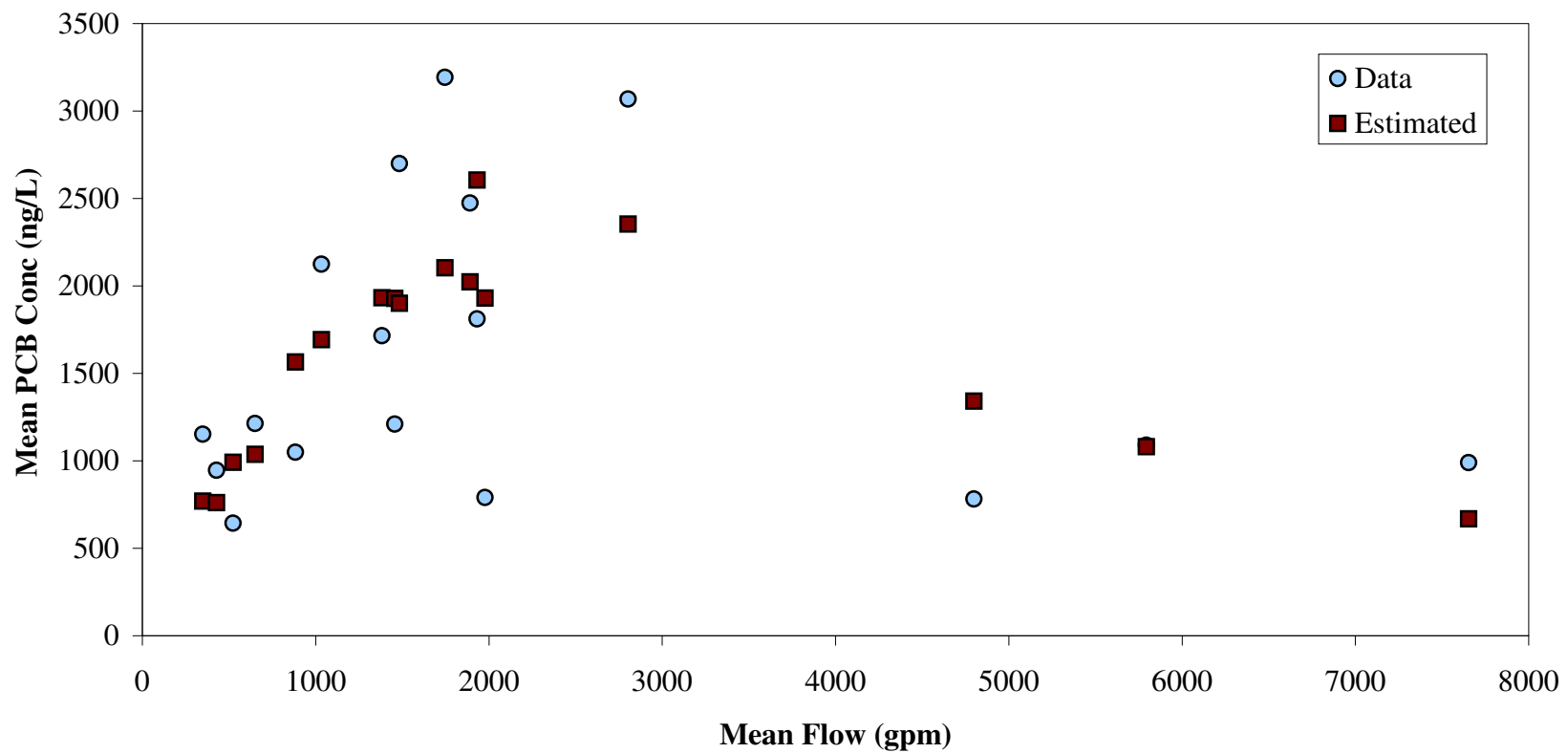


Figure 3-15. Comparison of measured and calculated CBW event-mean PCB concentration vs. flow for Conard's Branch storm events from 1998 to 2005.

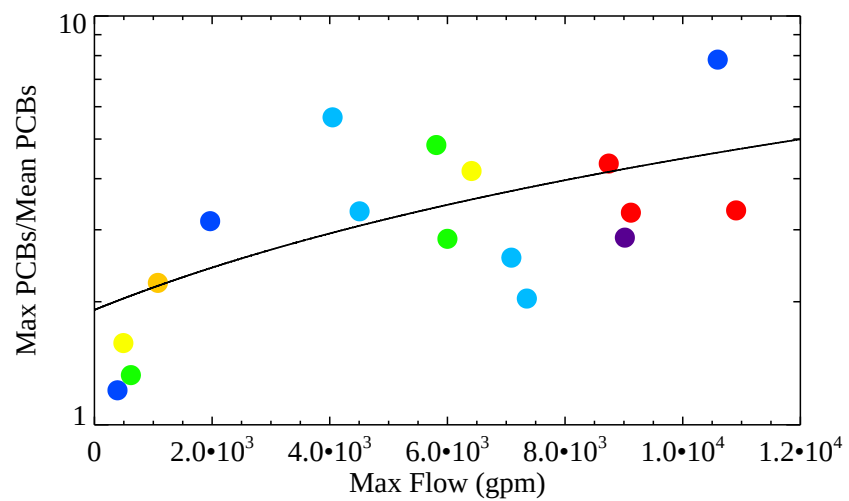
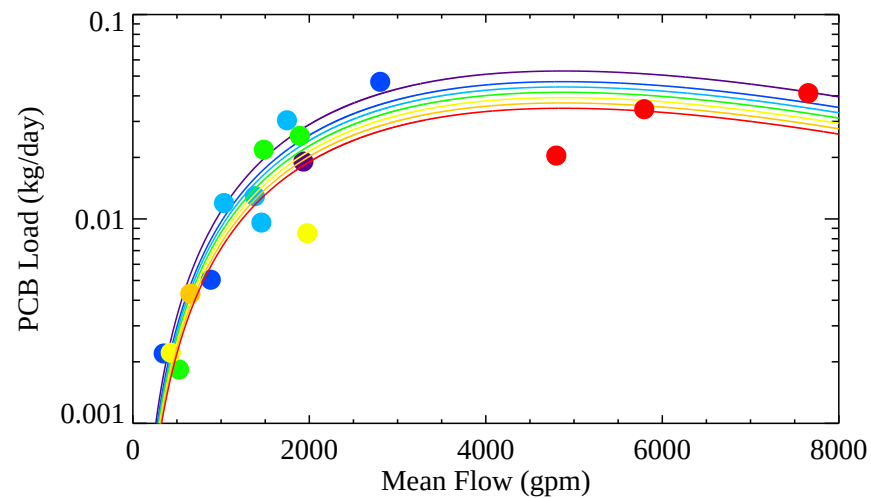
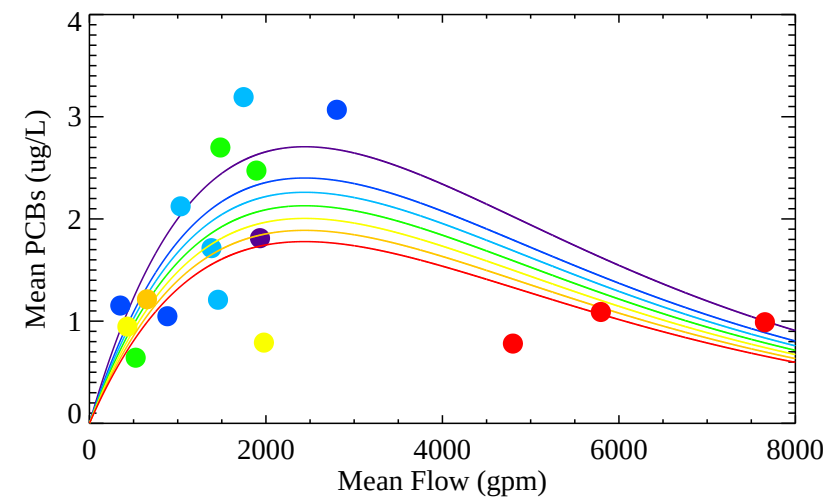
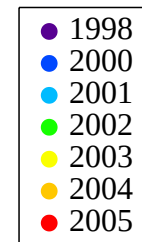


Figure 3-16. Model representation of PCB concentration at CBW during storms.



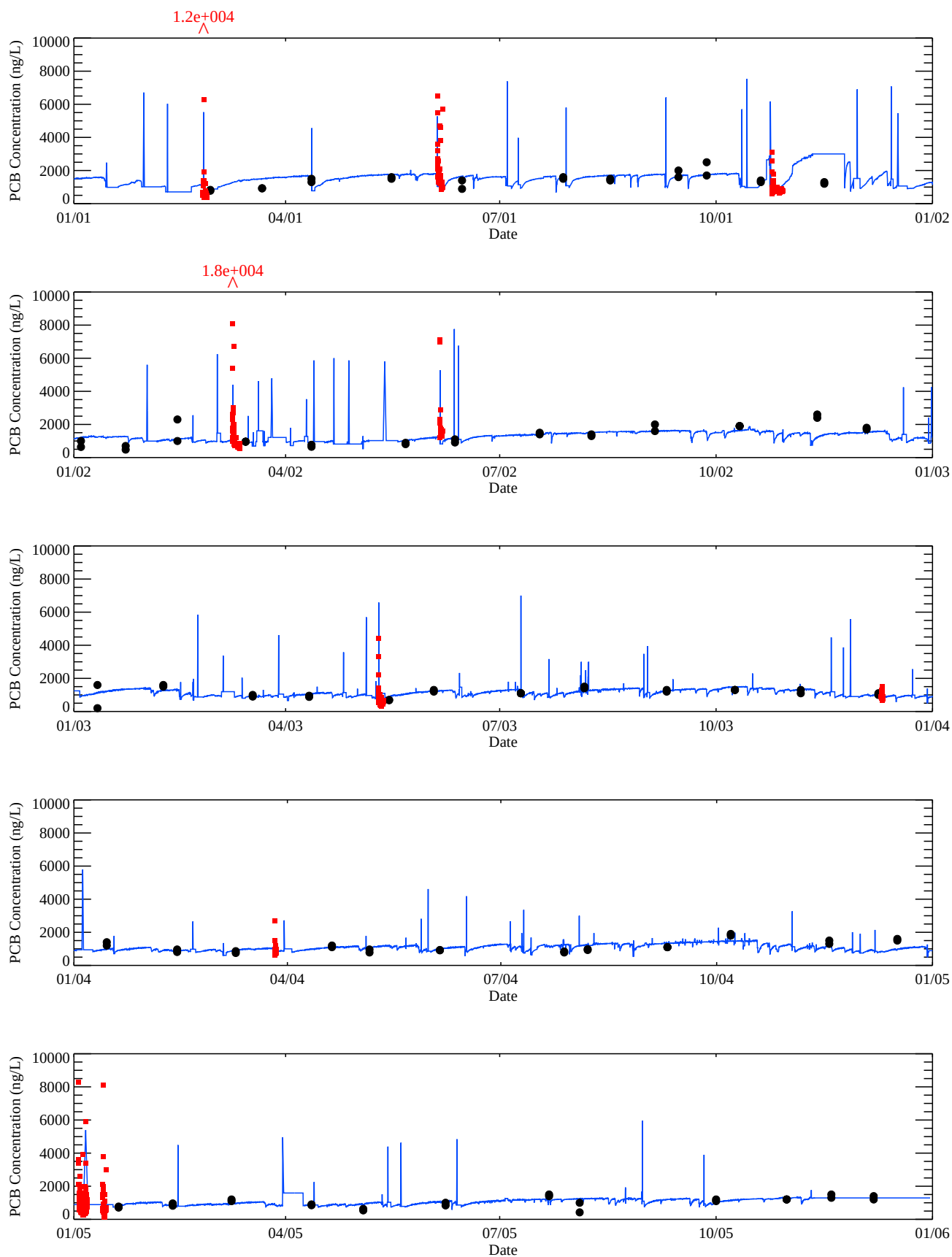
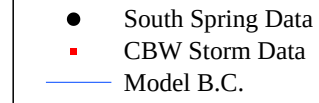


Figure 3-17. Comparison of PCB concentrations at CBW used as model boundary conditions with data collected at South Spring and at CBW.

Note: Model boundary condition after 11/12/05 is set to a constant value equal to the last value.



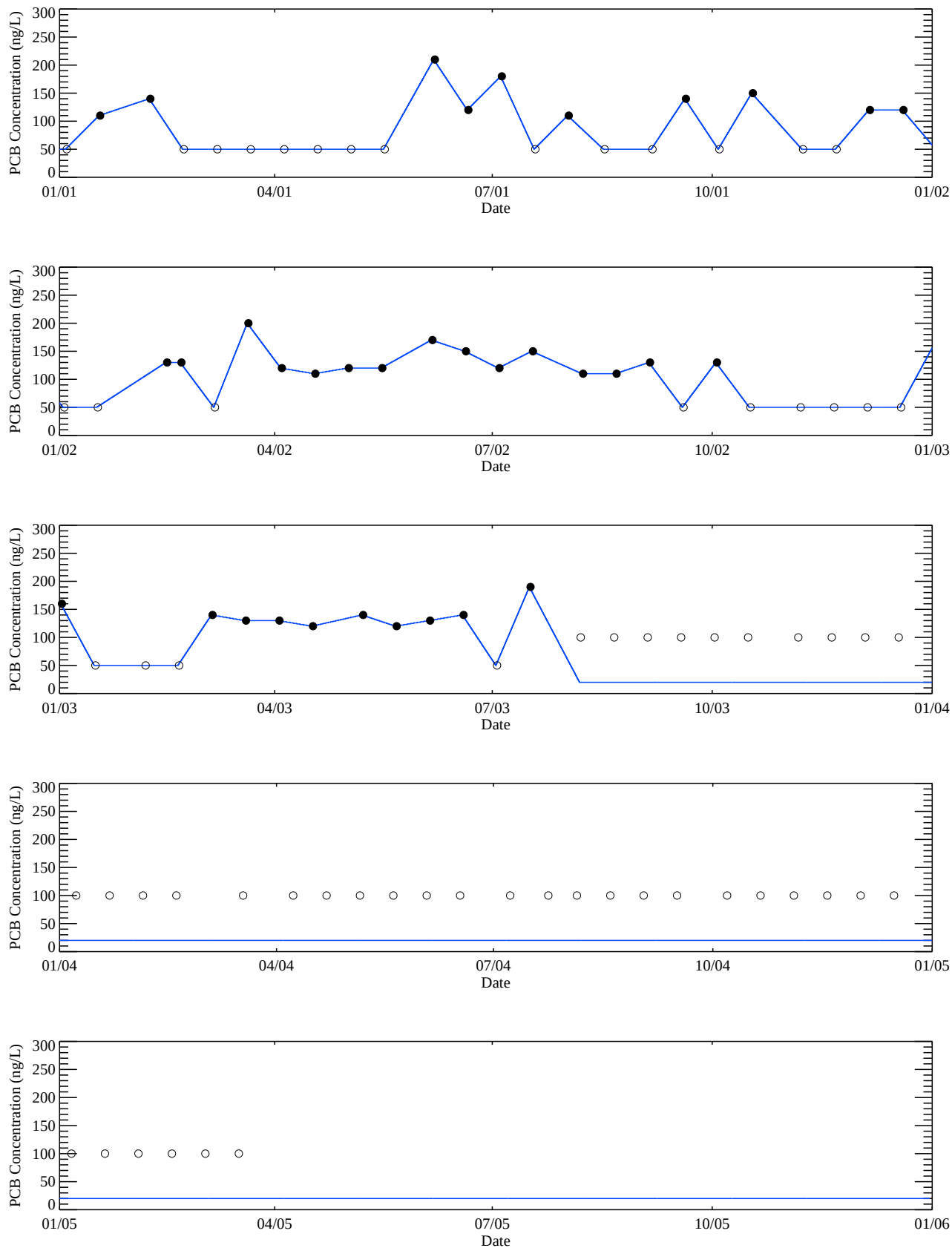
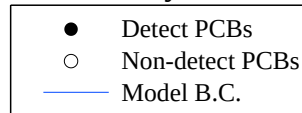


Figure 3-18. Comparison of PCB concentrations at STF used as model boundary conditions with data collected at STF effluent.

Notes: Non-detect PCB plotted as open symbol at 1/2 MDL; model boundary condition was set to 20 ng/L after August 2003 to reflect GAC replacement in STF; model boundary condition after 11/12/05 is set to a constant value equal to the last value.



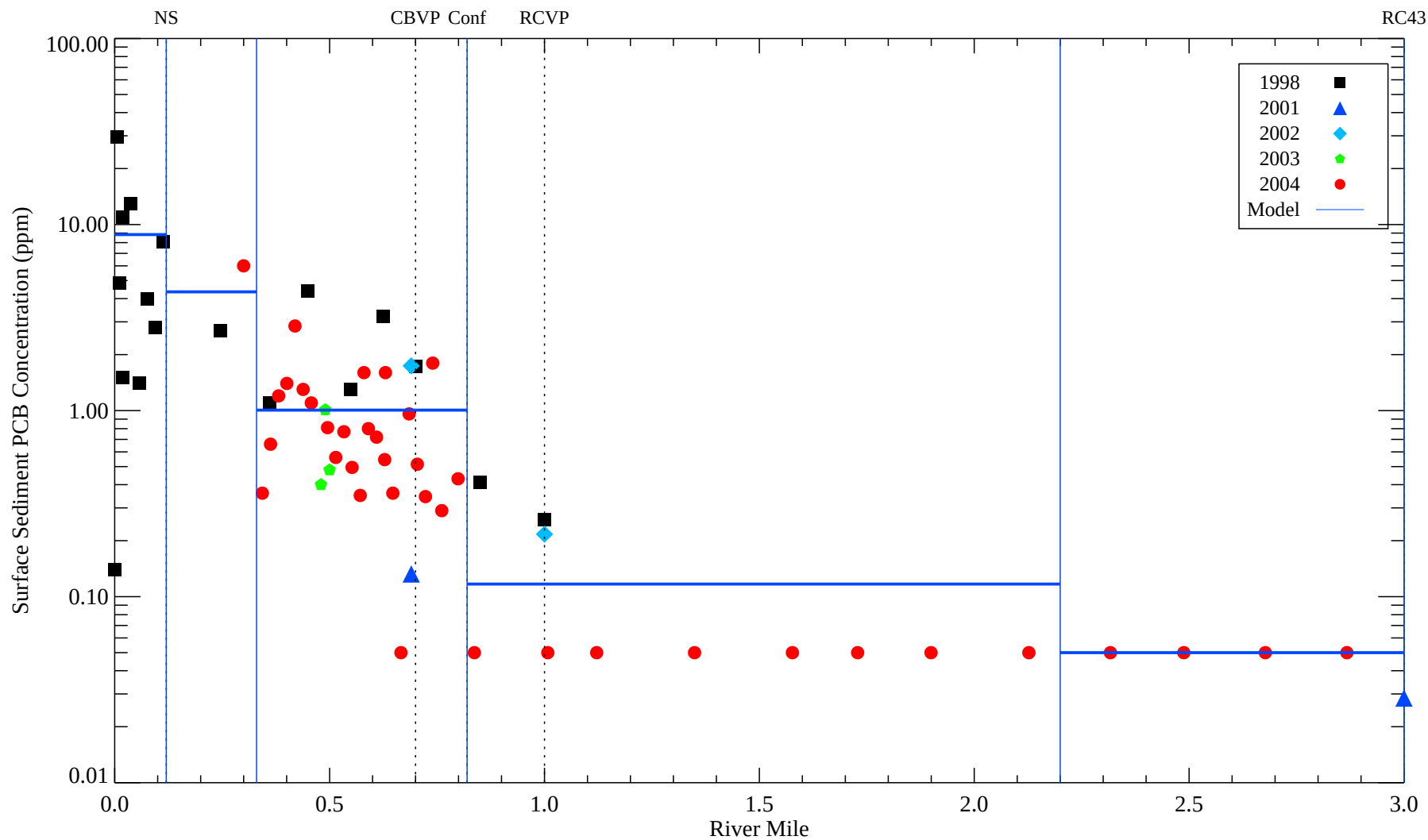


Figure 3-19. Spatial profile of surface sediment PCB concentrations collected in Conard's Branch and Richland Creek between 1998 and 2004.

Note: Horizontal lines represent average of PCB concentrations within segments.

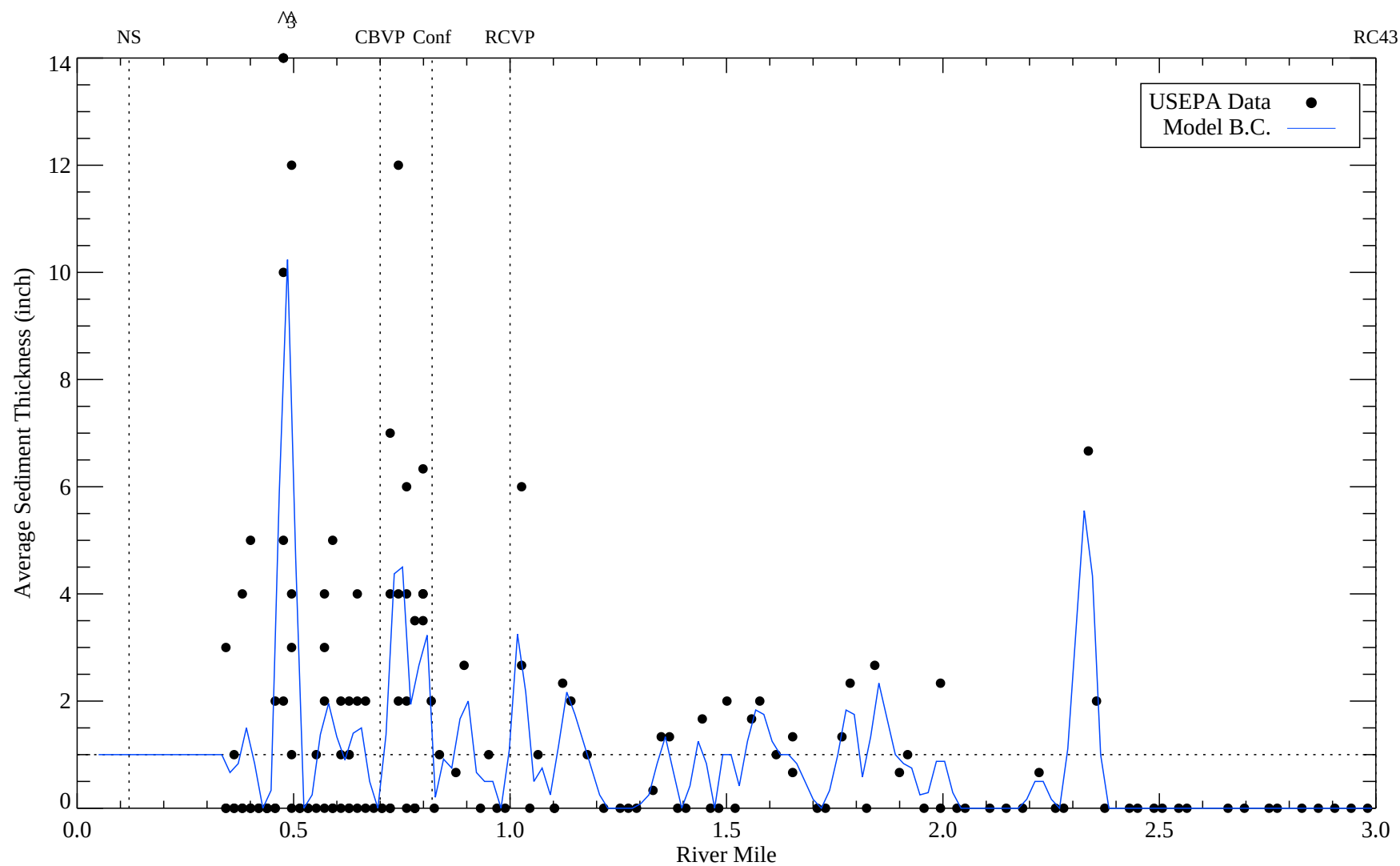


Figure 3-20. Spatial distribution of sediment thickness collected by USEPA in November 2003.

Note: Cohesive sediment bed assigned to locations where sediment thickness > 1 inch.

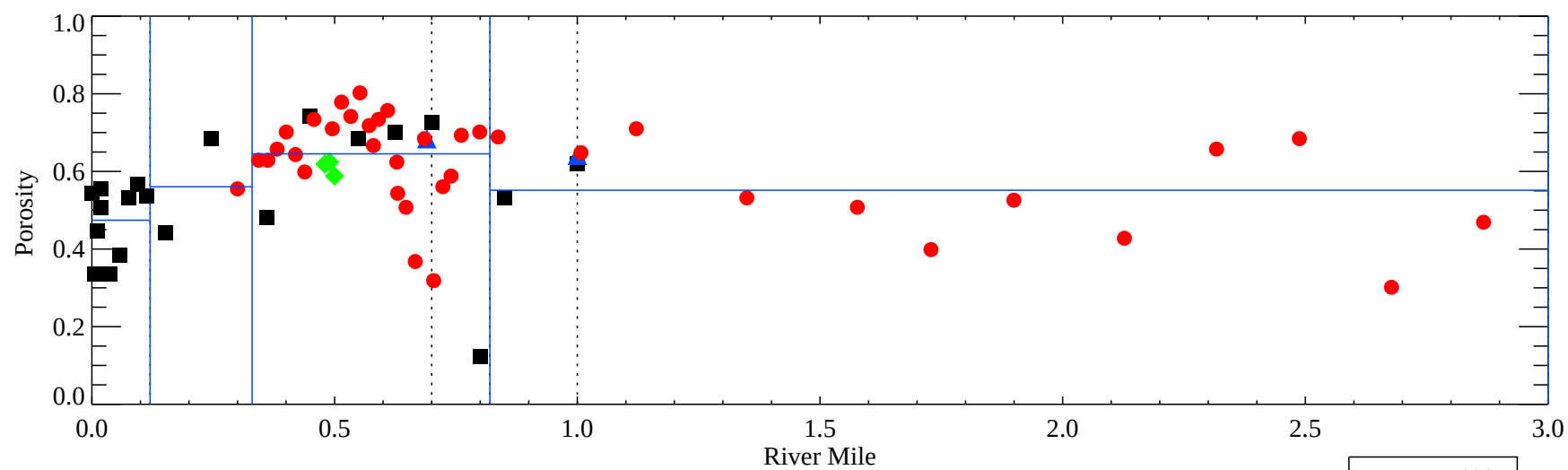
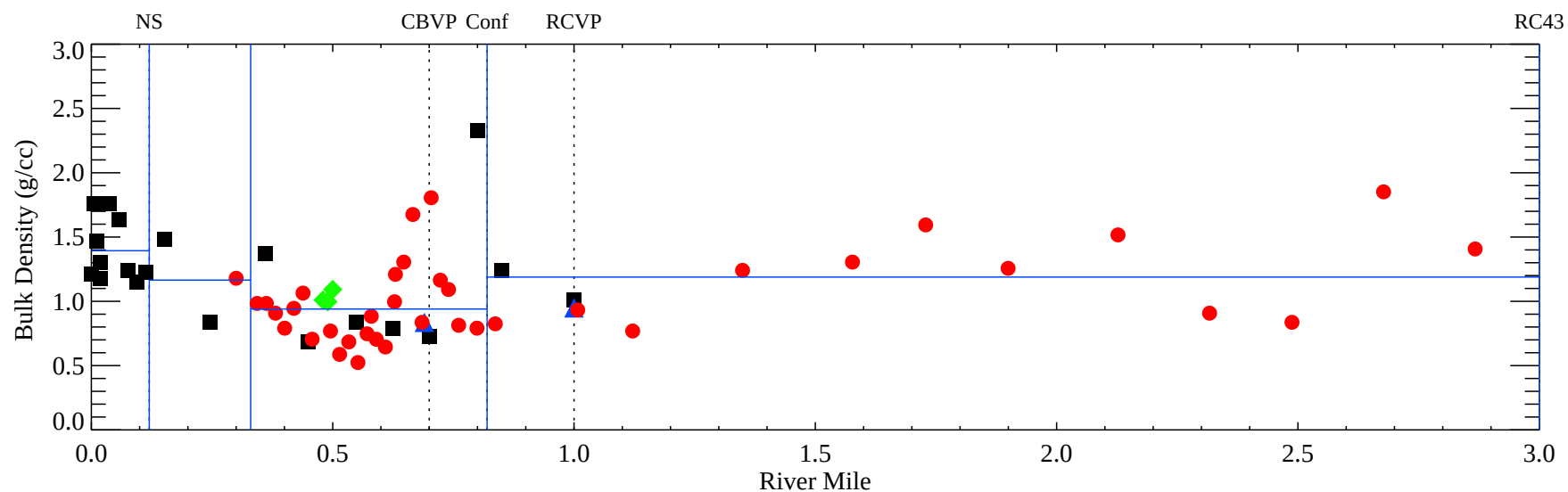
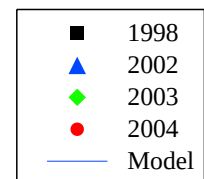


Figure 3-21. Spatial distributions of bulk density and porosity in surface sediment.

Notes: Horizontal lines represent average values within segments; bulk density and porosity were calculated from percent solids data; one high percent solids sample near the confluence was not included in the model.



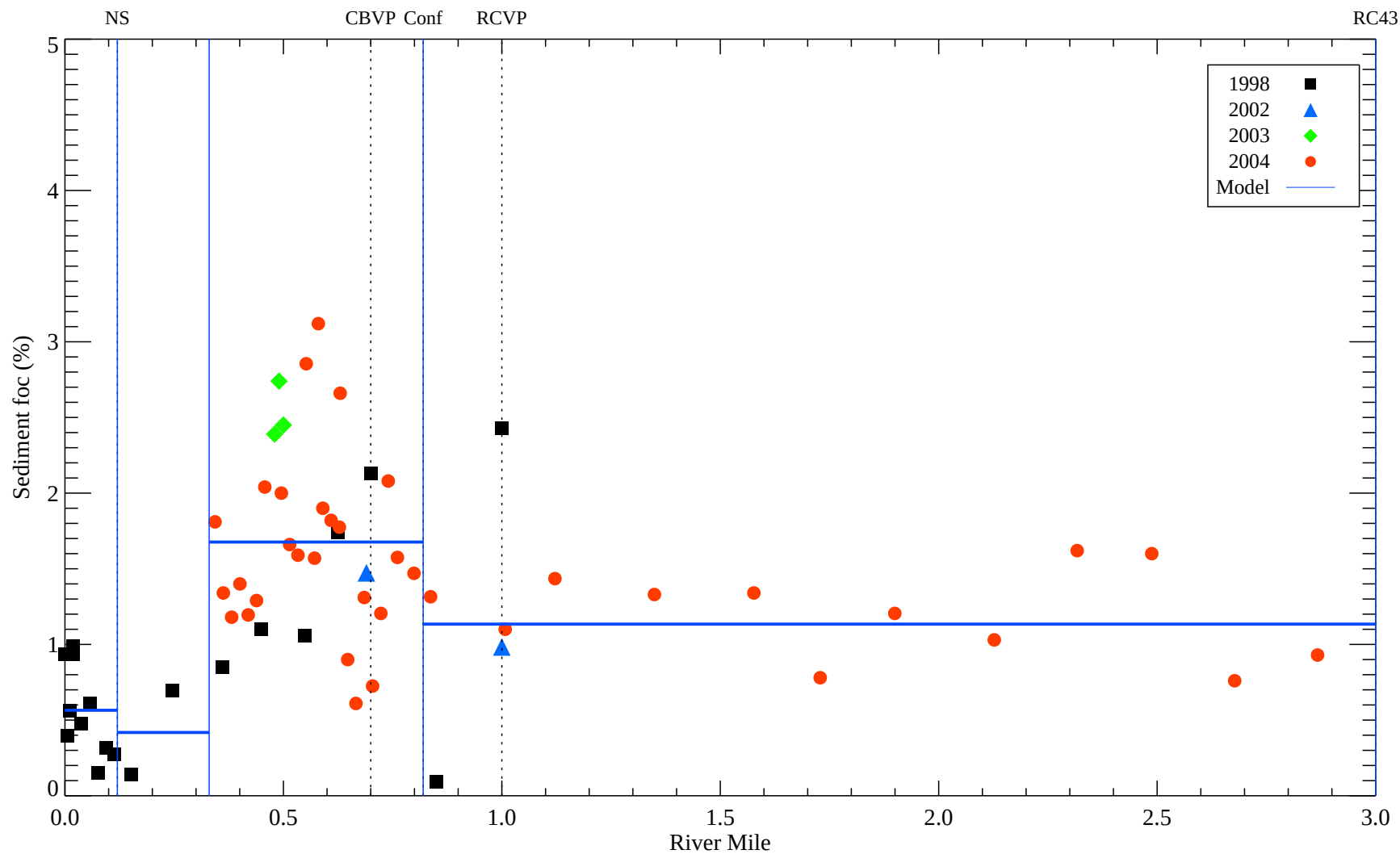


Figure 3-22. Spatial profile of total organic carbon in surface sediment.

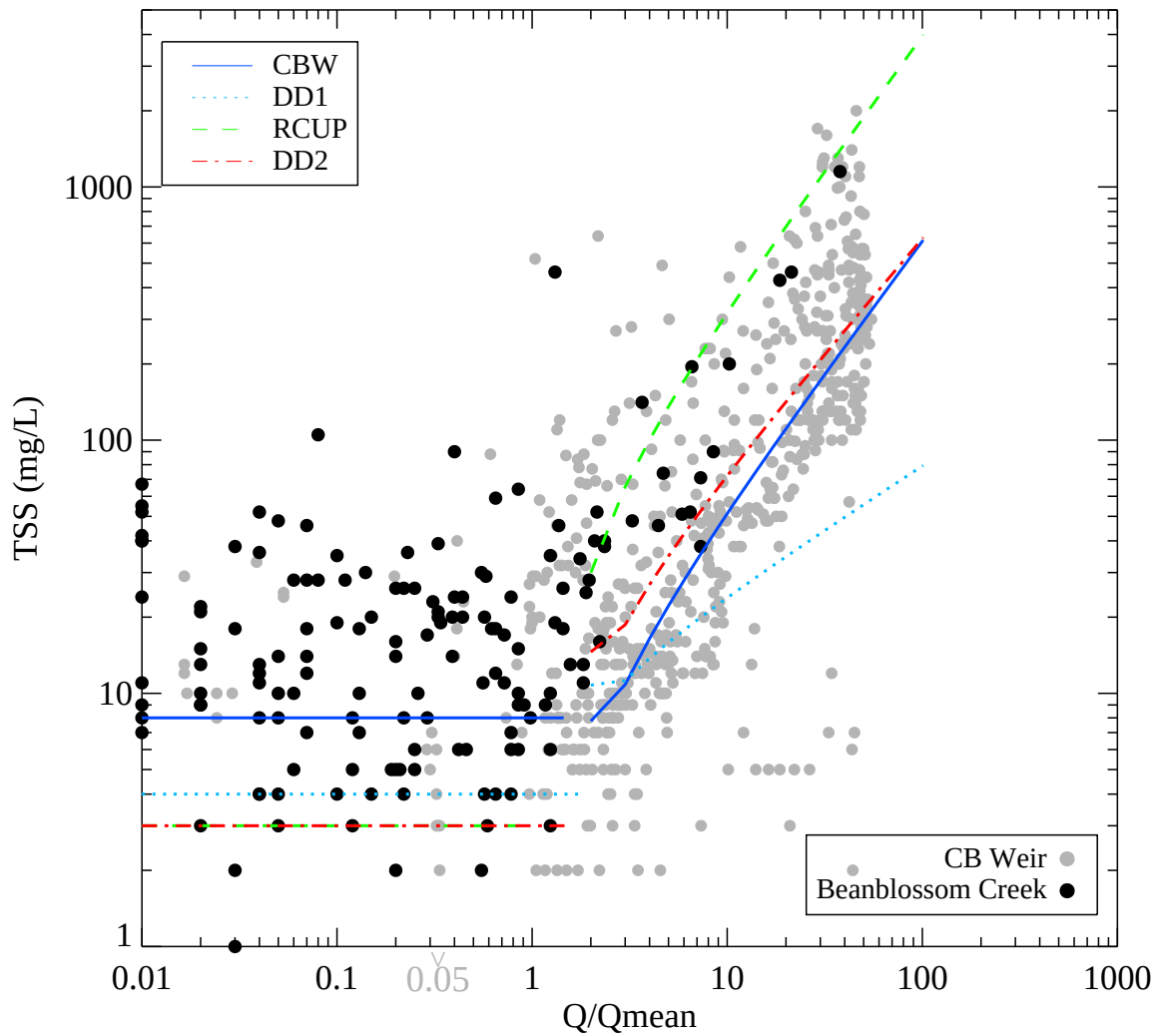


Figure 3-23. Calibrated sediment rating curves for DD1, RCUP, and DD2.

Note: Points present data from USGS station 03354500 Beanblossom Creek at Blossom, IN.

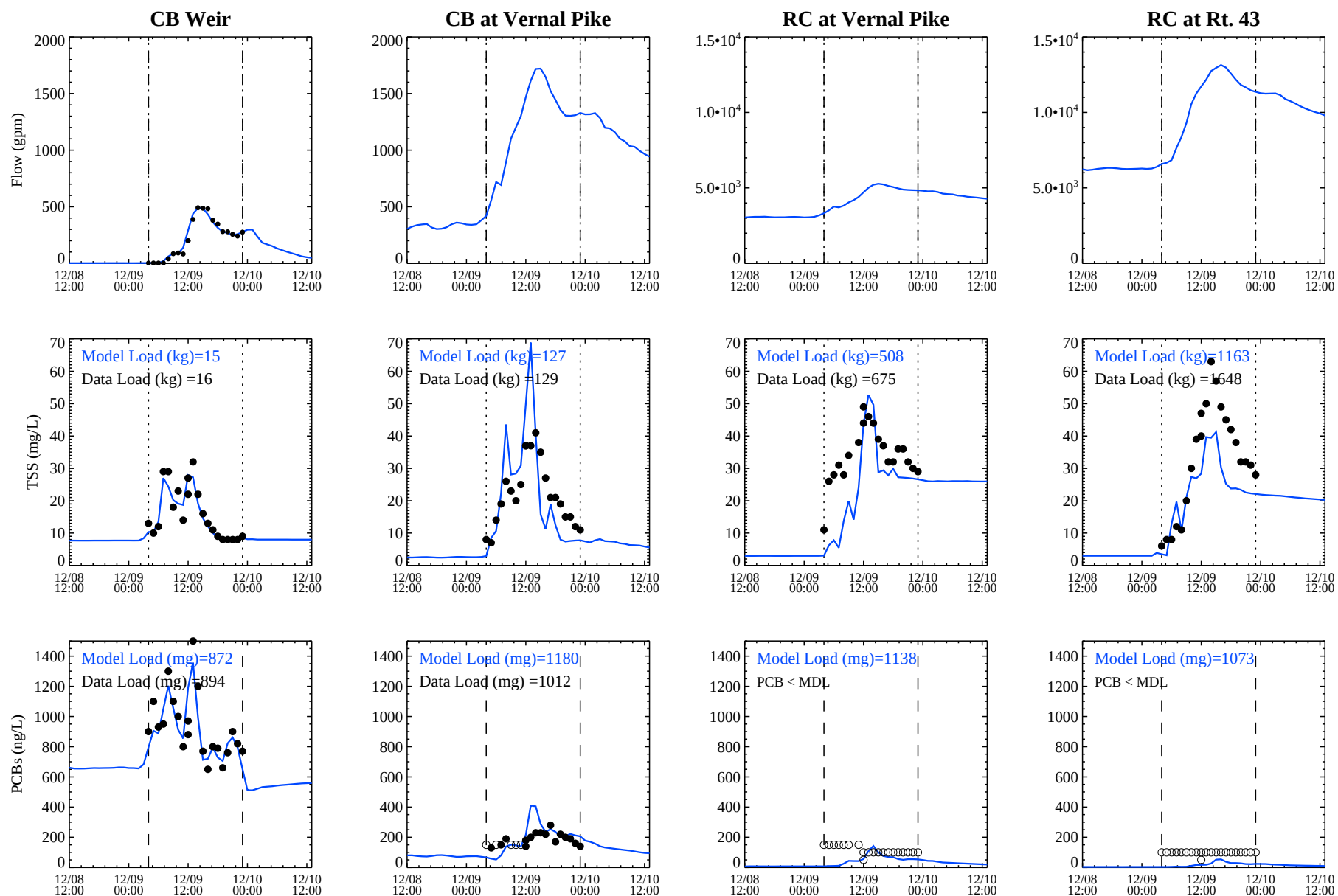


Figure 3-24. Temporal profiles of water column TSS and PCB concentrations at CB Weir (boundary), CBVP, RCVP, and RC43 during DEC 2003 event.

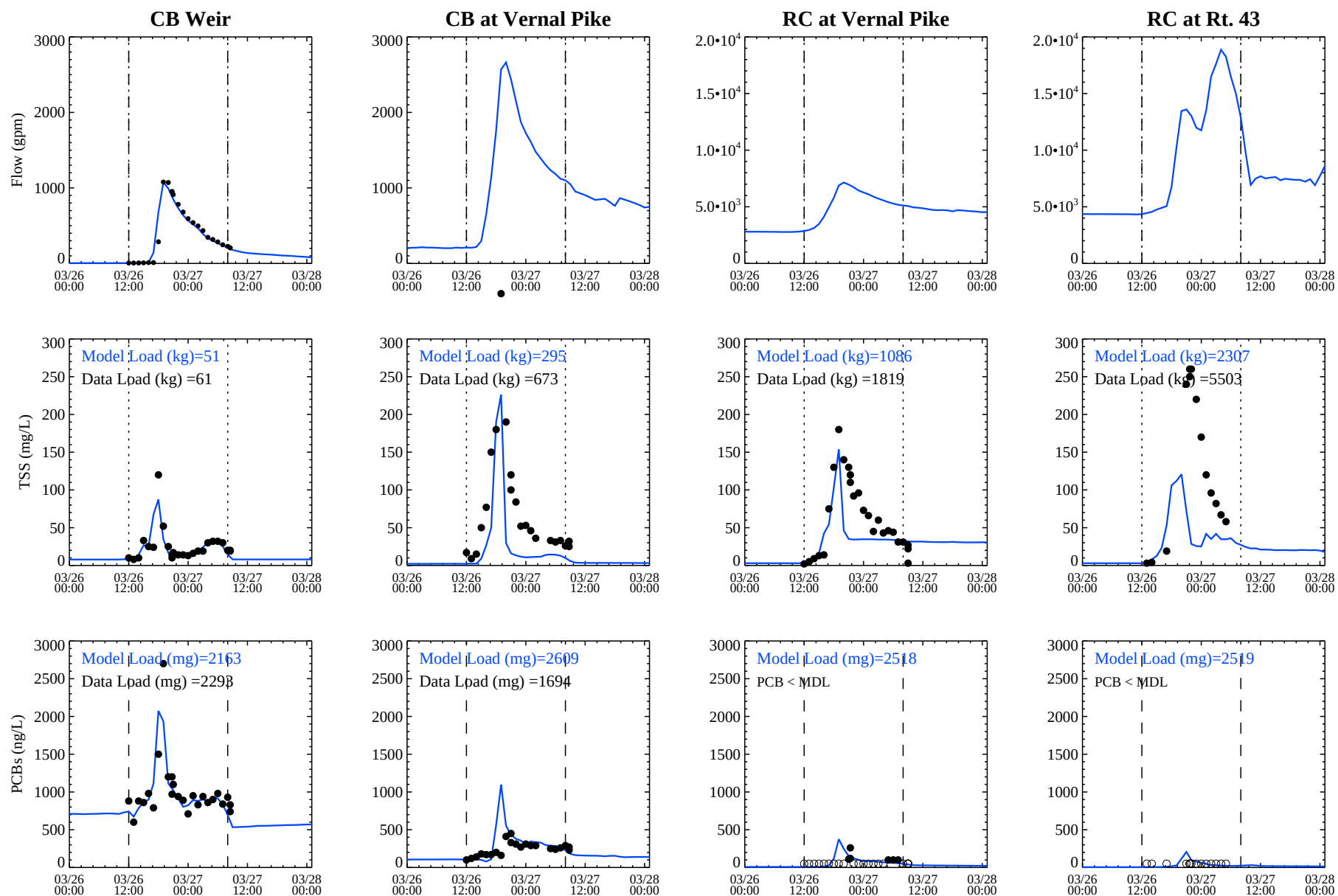


Figure 3-25. Temporal profiles of water column TSS and PCB concentrations at CB Weir (boundary), CBVP, RCPV, and RC43 during MAR 2004 event.

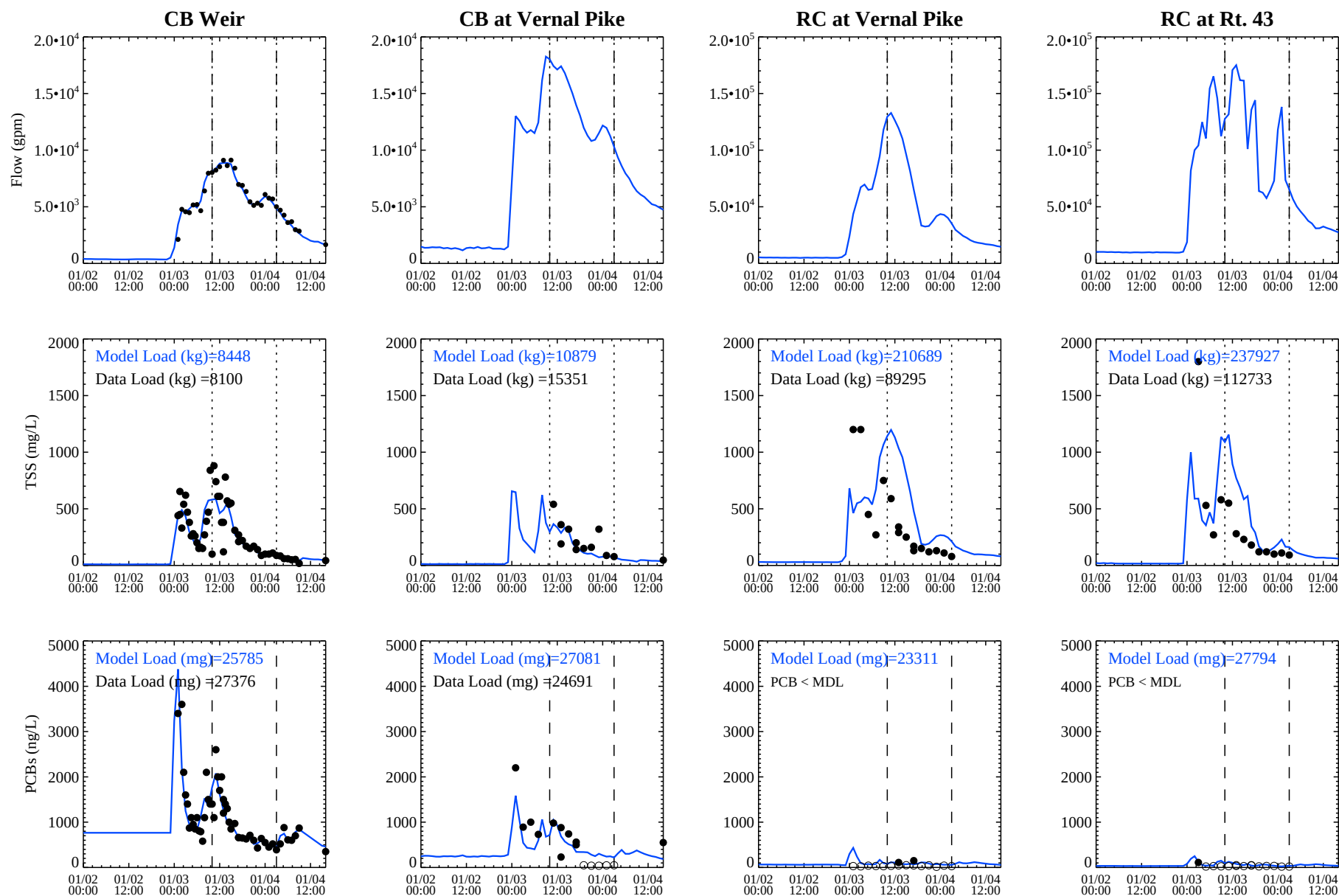


Figure 3-26. Temporal profiles of water column TSS and PCB concentrations at CB Weir (boundary), CBVP, RCVP, and RC43 during JAN 2005 (1st) event.

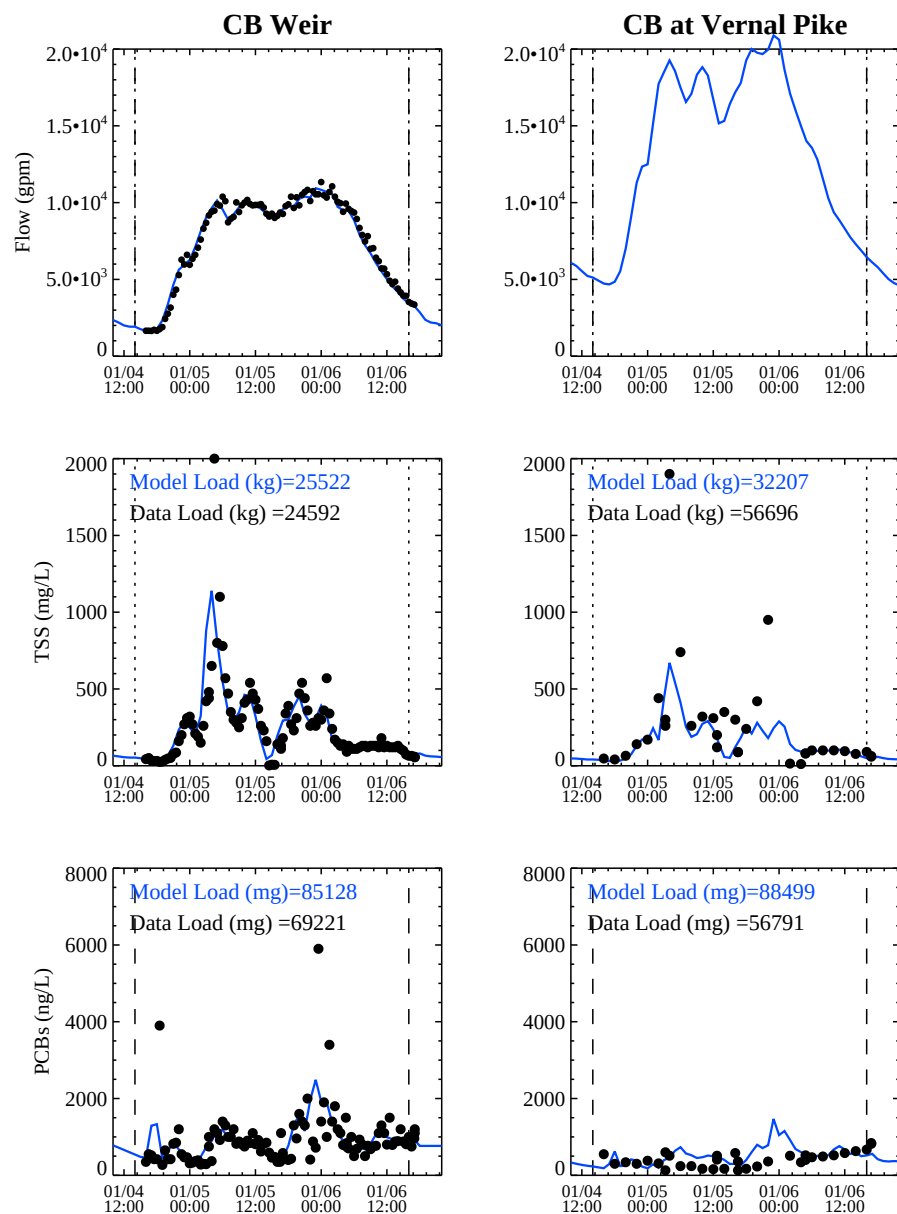


Figure 3-27. Temporal profiles of water column TSS and PCB concentrations at CB Weir (boundary), CBVP, RCVP, and RC43 during JAN 2005 (2nd) event.

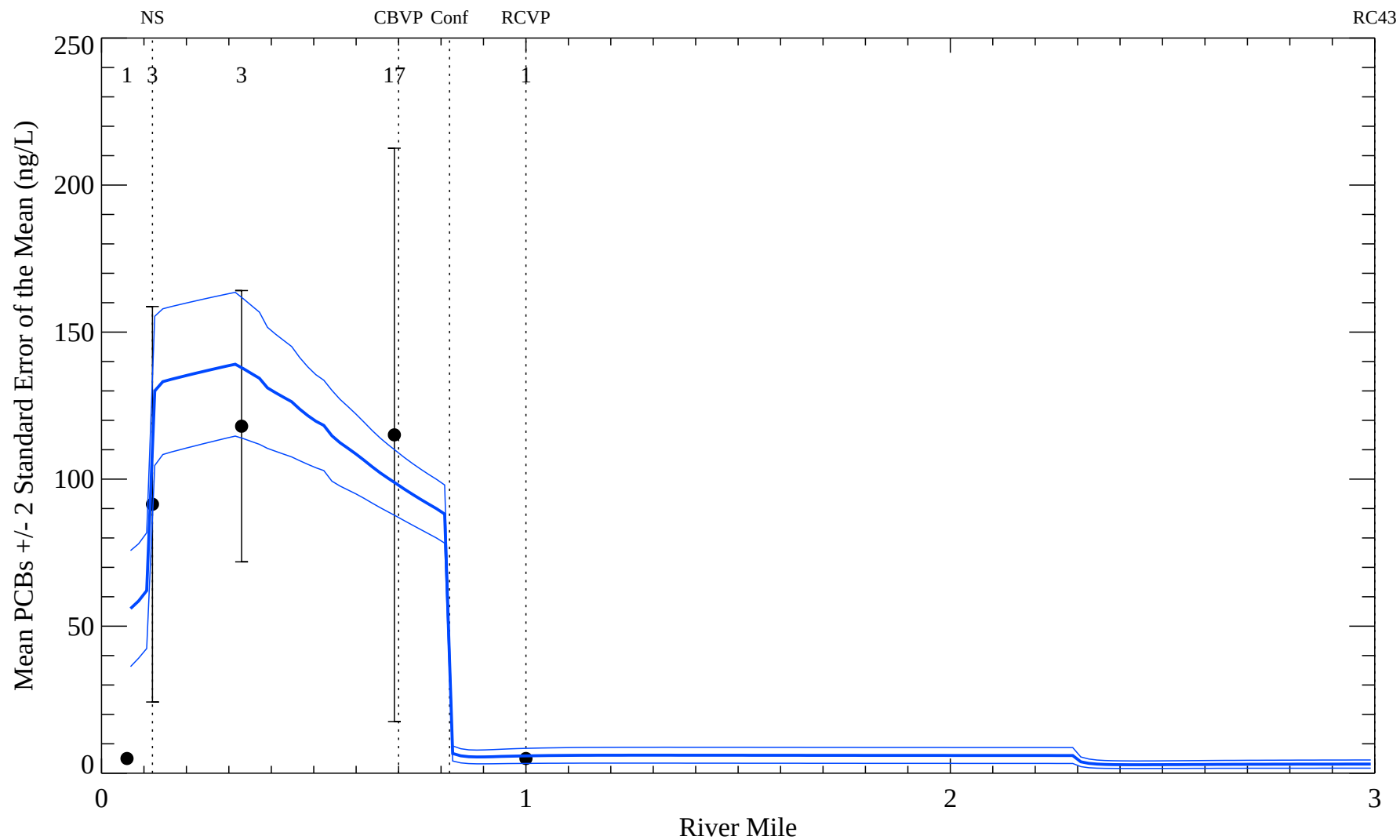


Figure 3-28. Spatial profiles of low flow water column PCB concentrations collected by Viacom between 2004 and 2005.

Notes: Non-detect PCBs set to 1/2 MDL; number of sampling events posted; data collected on 5/4/05 were not included in the data average due to the change of STF discharge location to evaluate North Spring bypass.

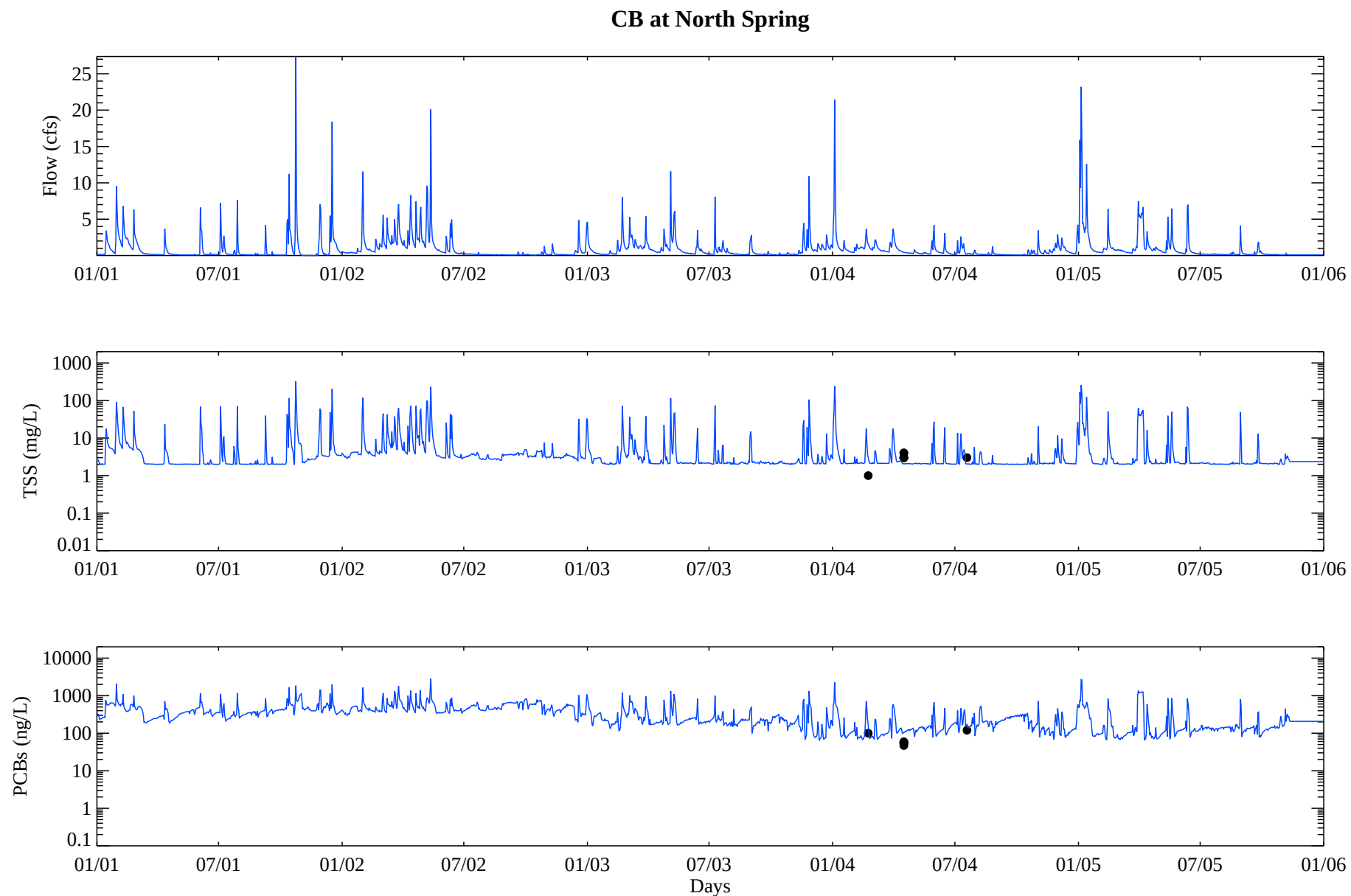
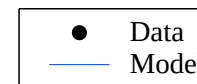


Figure 3-29. Comparison of predicted and observed water column TSS and PCB concentrations in CB at North Spring.

Note: Non-detect PCBs plotted as open symbol at 1/2 MDL.



CB at Property Line

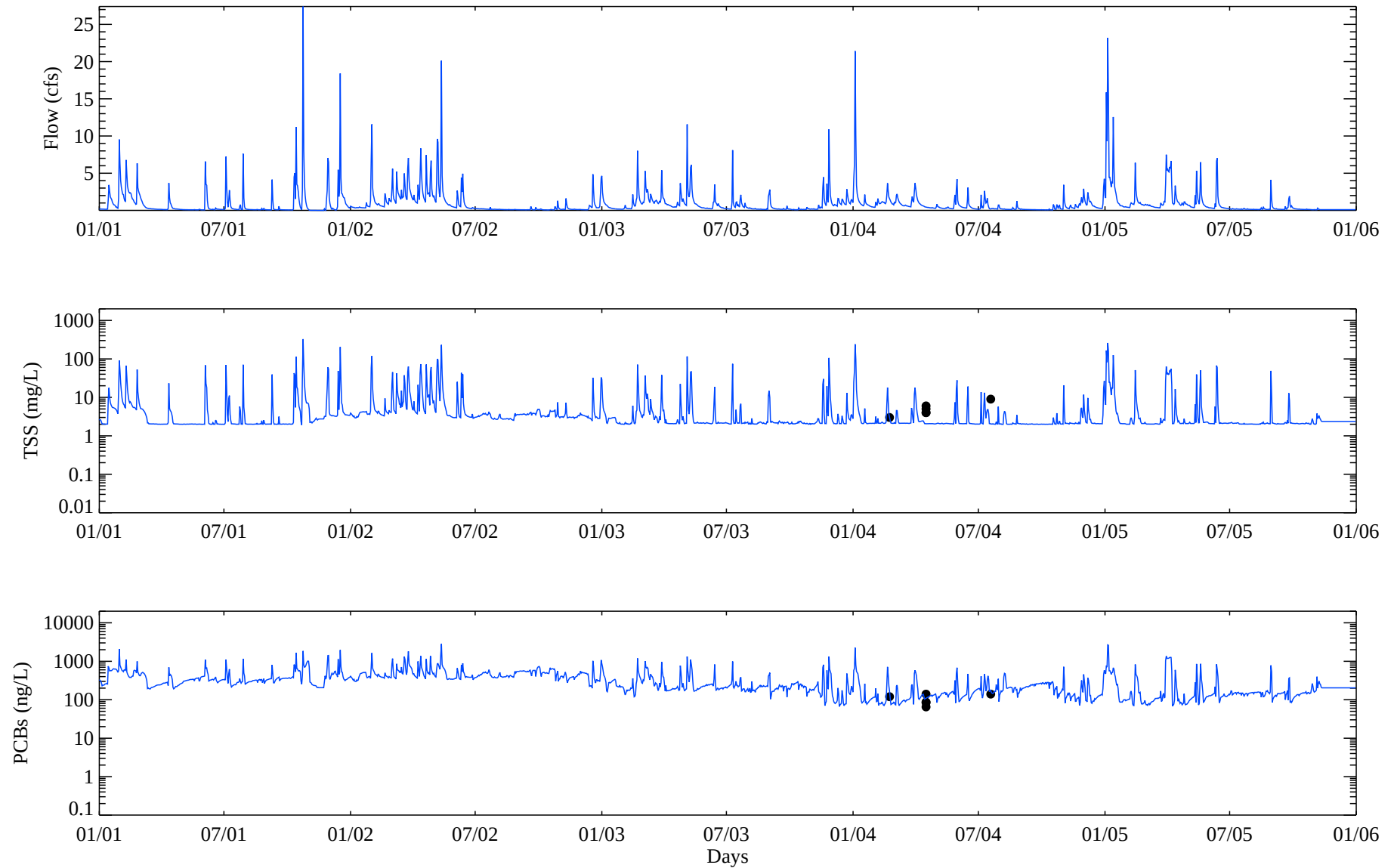


Figure 3-30. Comparison of predicted and observed water column TSS and PCB concentrations in CB at Property Line.

Note: Non-detect PCBs plotted as open symbol at 1/2 MDL.



CB at Vernal Pike

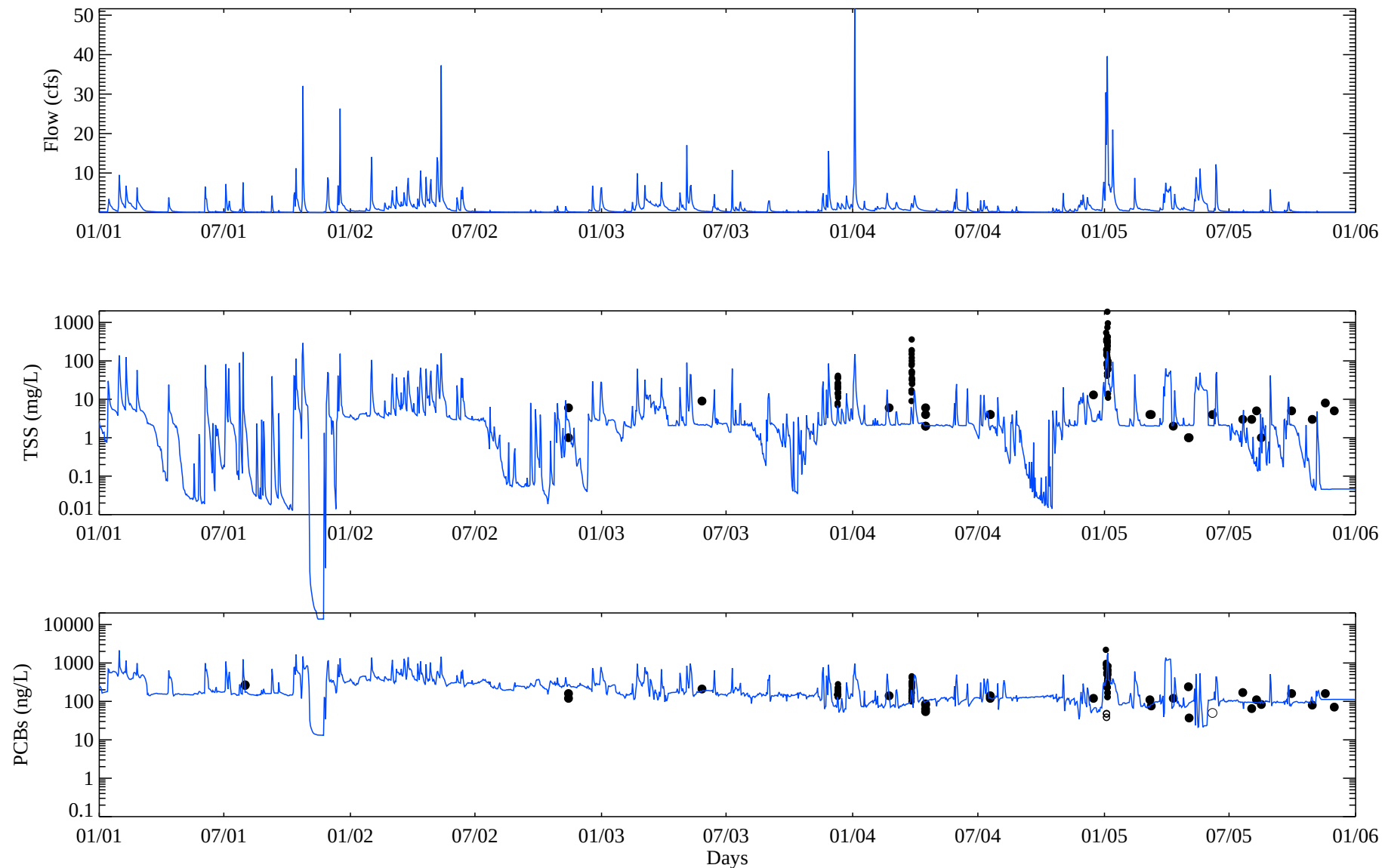
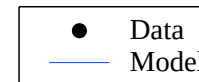


Figure 3-31. Comparison of predicted and observed water column TSS and PCB concentrations in CB at Vernal Pike.

Note: Non-detect PCBs plotted as open symbol at 1/2 MDL.



RC at Vernal Pike

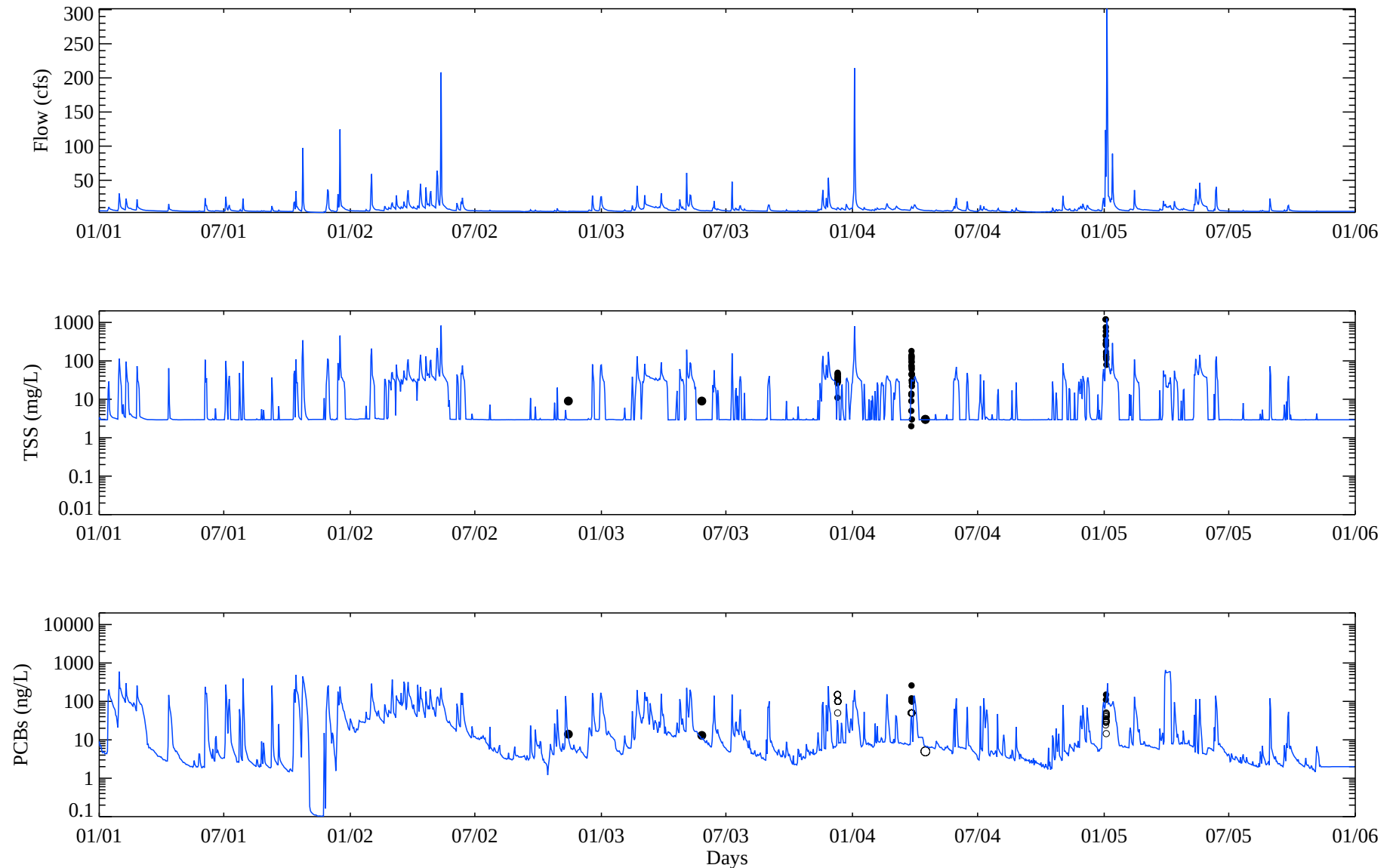


Figure 3-32. Comparison of predicted and observed water column TSS and PCB concentrations in RC at Vernal Pike.

Note: Non-detect PCBs plotted as open symbol at 1/2 MDL.



RC at Rt. 43

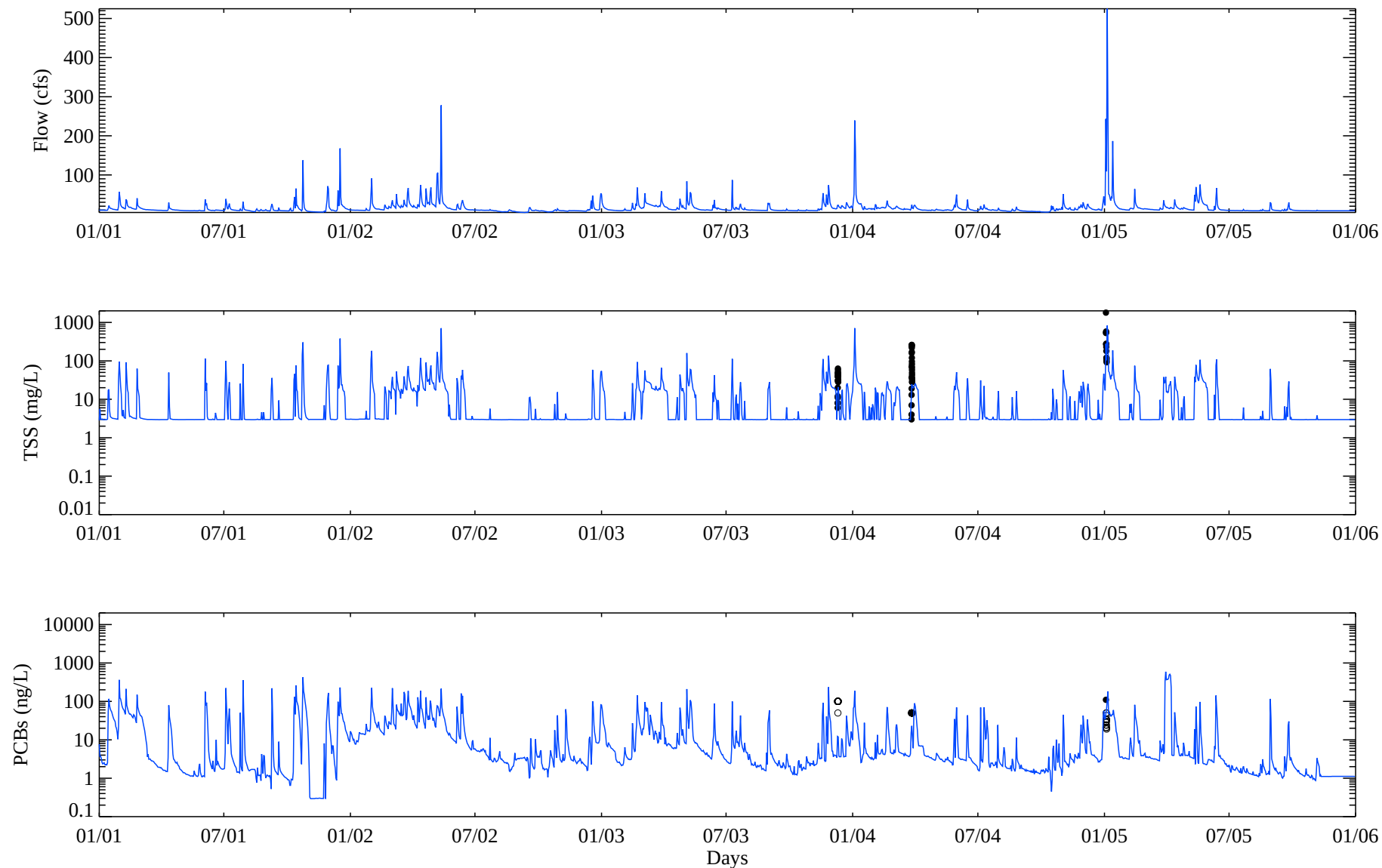
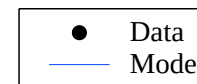


Figure 3-33. Comparison of predicted and observed water column TSS and PCB concentrations in RC at Rt. 43.

Note: Non-detect PCBs plotted as open symbol at 1/2 MDL.



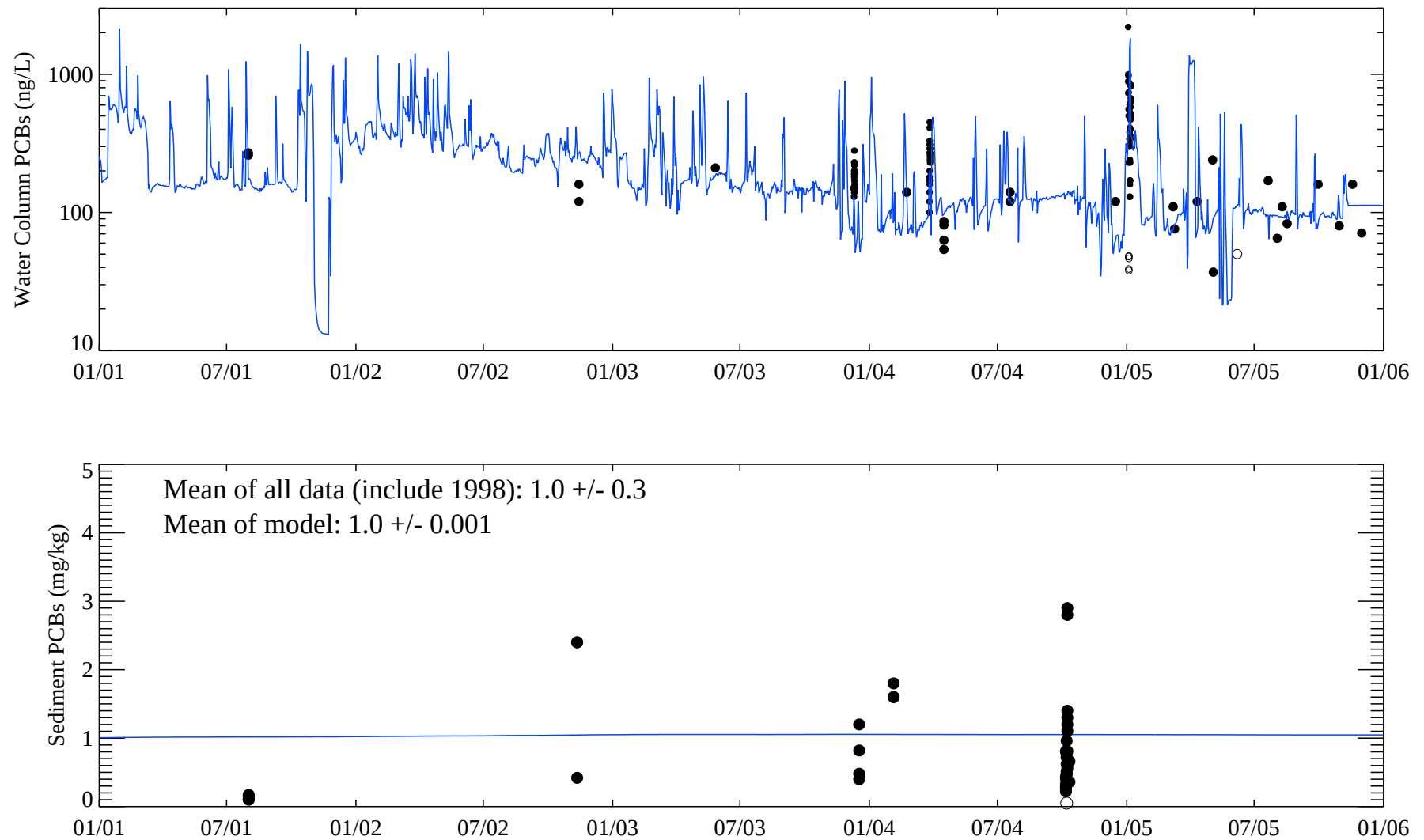


Figure 3-34. Comparison of predicted and observed water column and sediment PCB concentrations in Conard's Branch at Vernal Pike.

Runs: run60a

Note: Non-detect PCBs plotted as open symbol at 1/2 MDL.

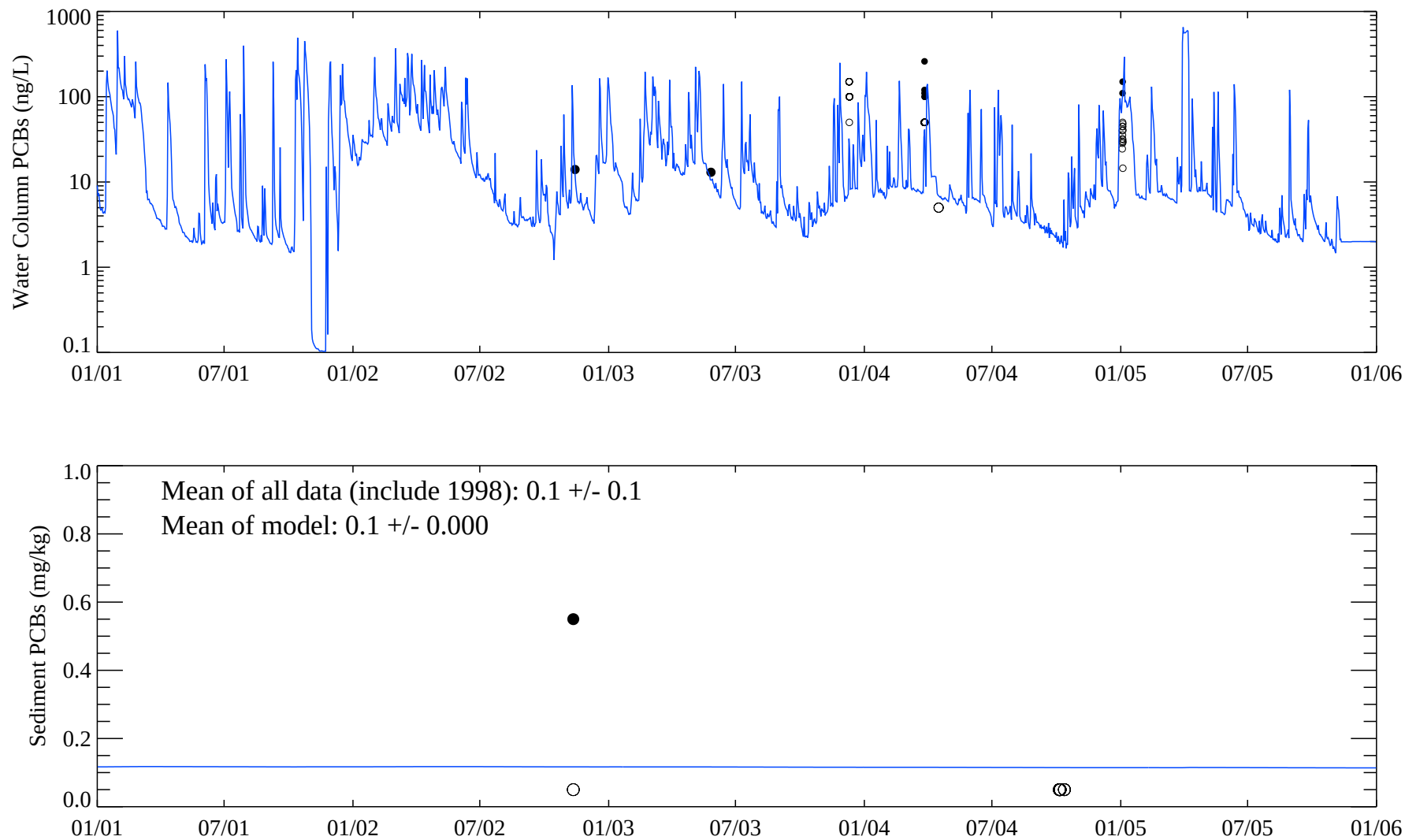


Figure 3-35. Comparison of predicted and observed water column and sediment PCB concentrations in Richland Creek at Vernal Pike.

Runs: run60a

Note: Non-detect PCBs plotted as open symbol at 1/2 MDL.



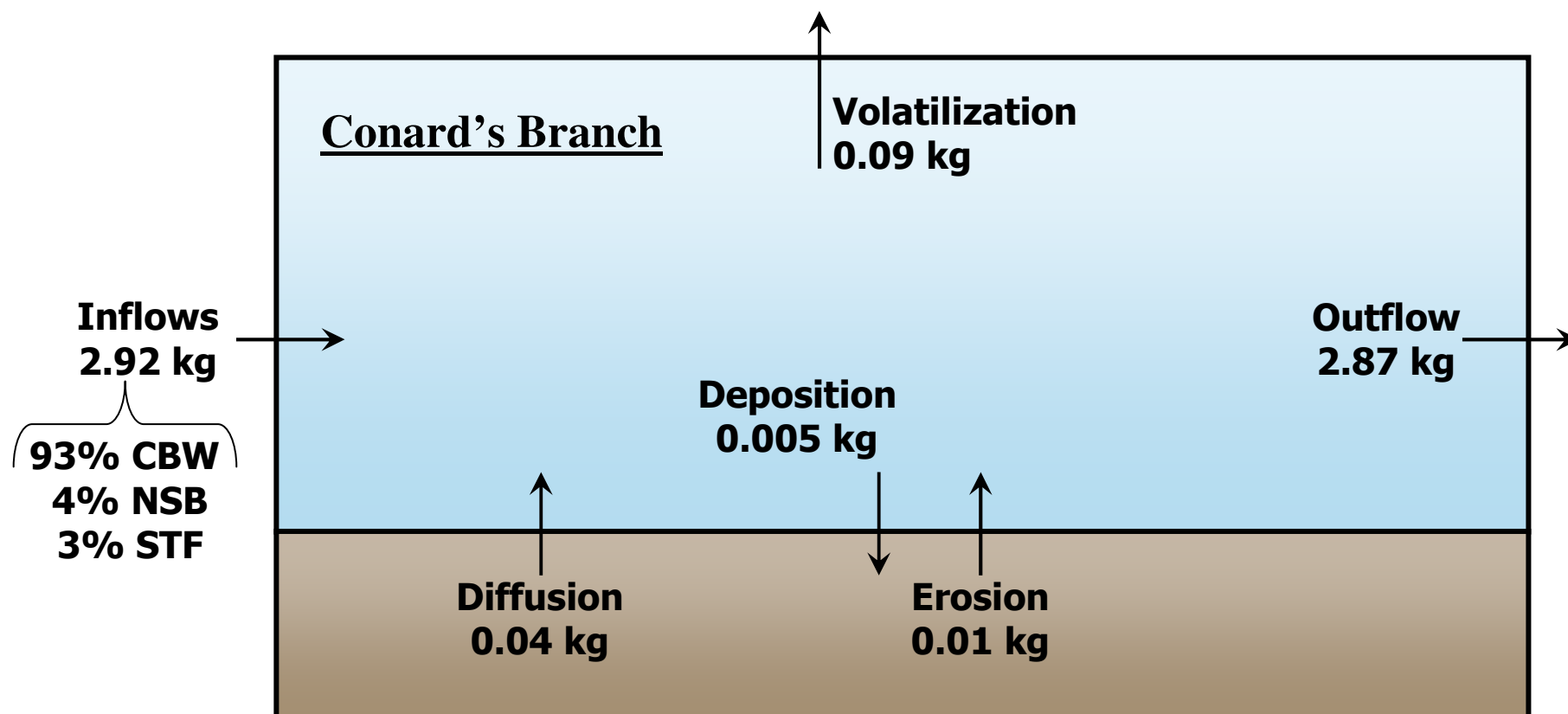


Figure 3-36. PCB mass balance: 2001-2005.

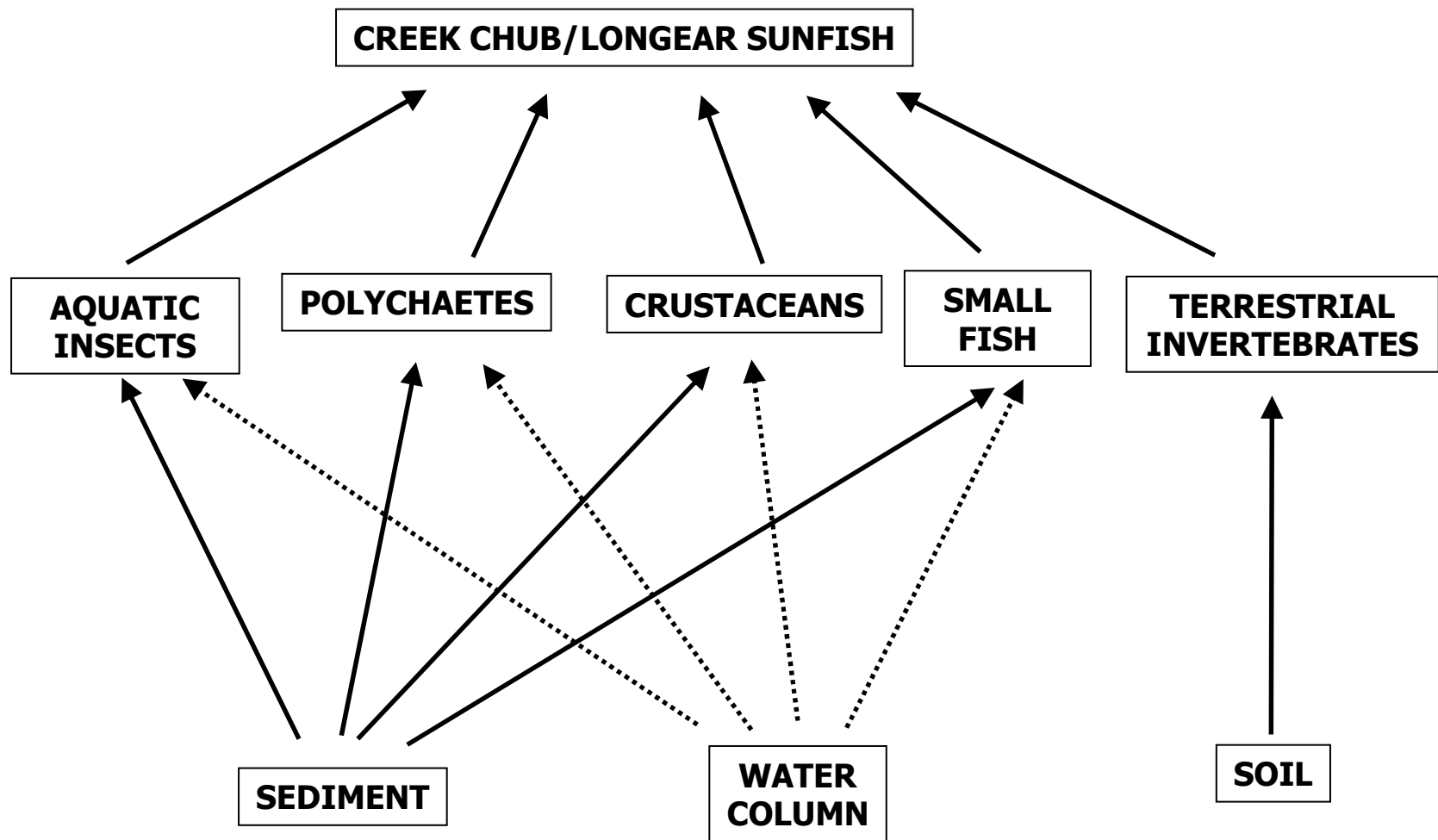


Figure 3-37. Food web structure in Conard's Branch and Richland Creek.

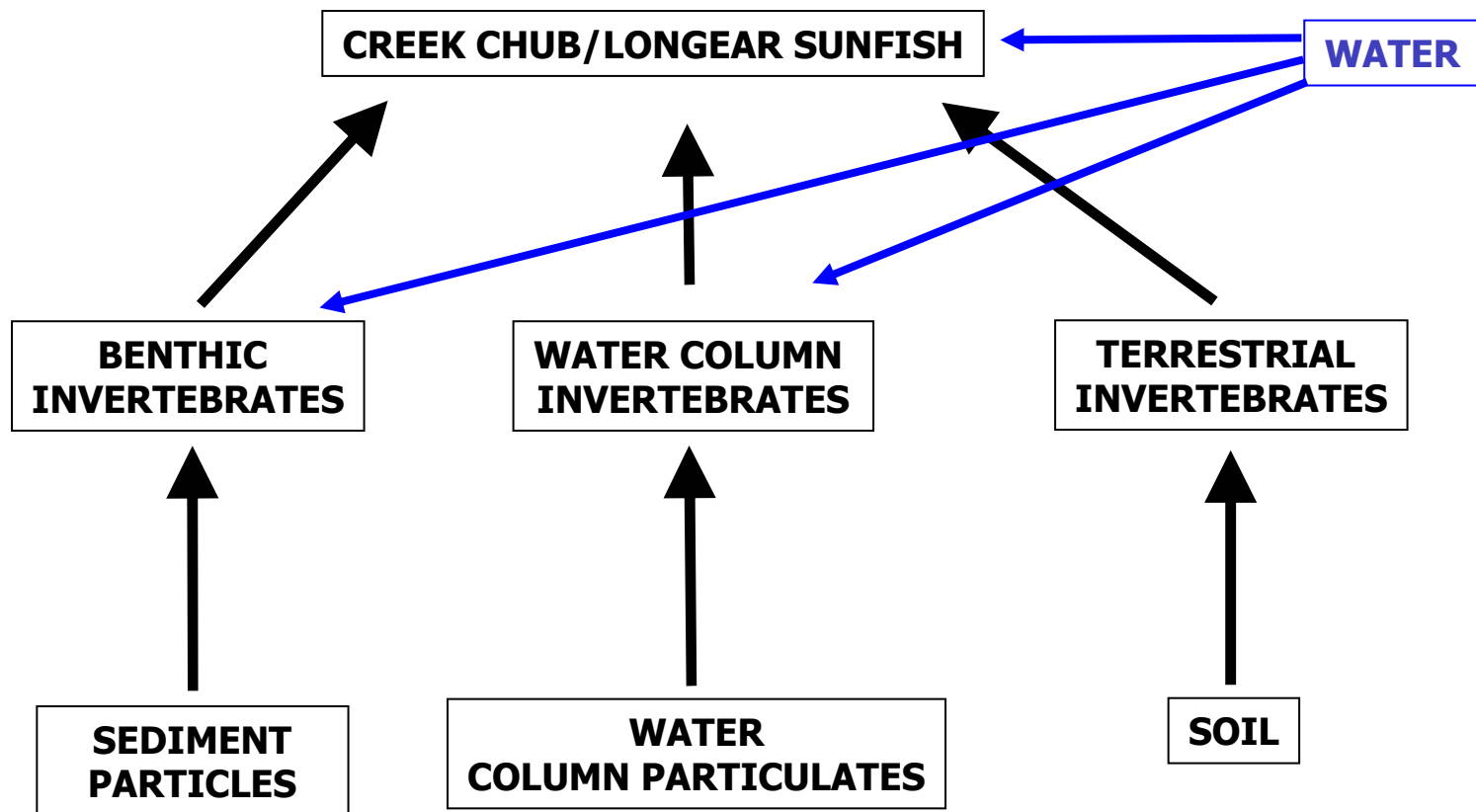


Figure 3-38. Model food web structure.

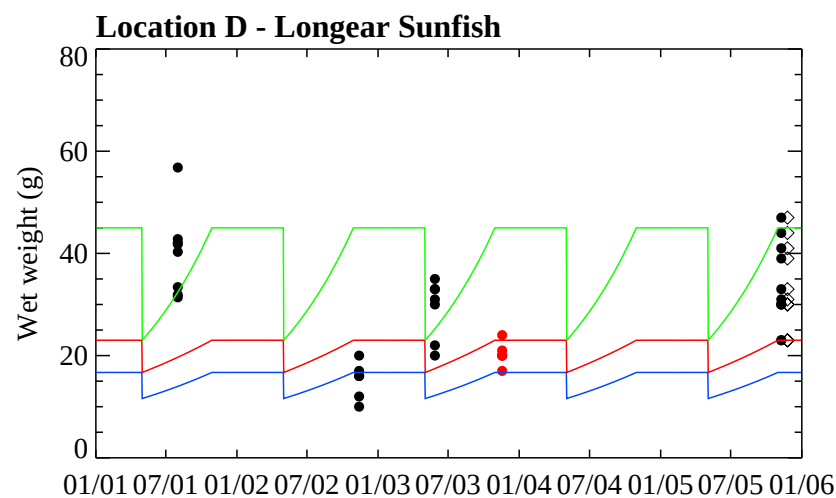
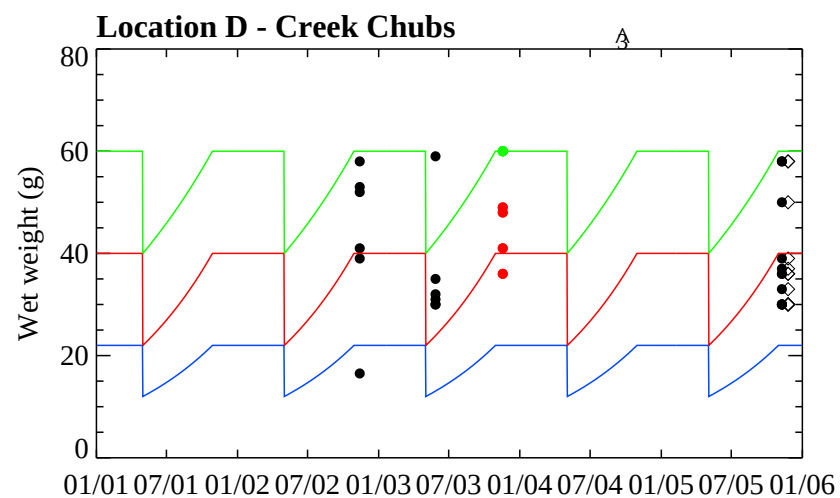
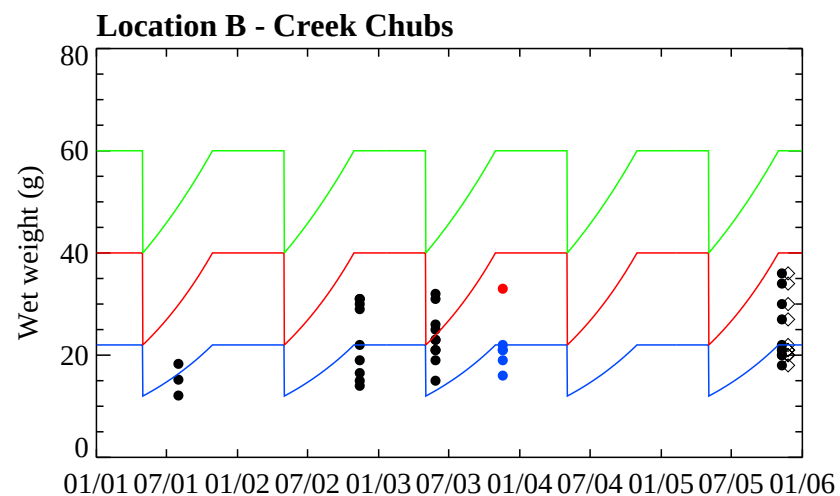
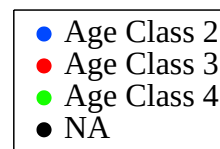


Figure 3-39. Comparison of model and measured growth rate for creek chubs and longear sunfish at Locations B and D.

Model Source: \\Legolas\d_drive\VIAnea\model\FDCHN\output\runD90
Open diamonds represent 2005 ES Recovery adjusted values (offset to view)



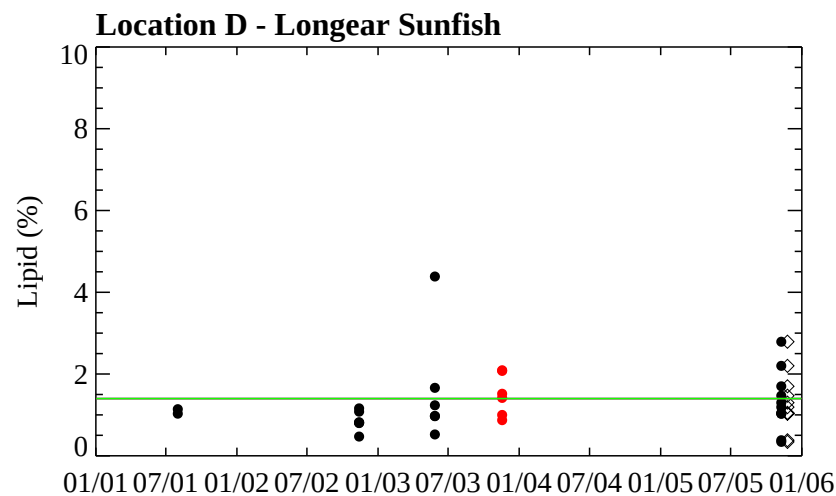
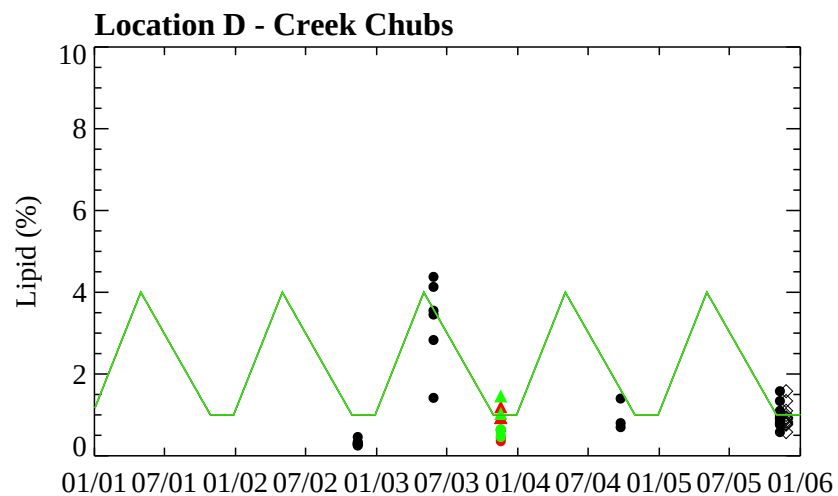
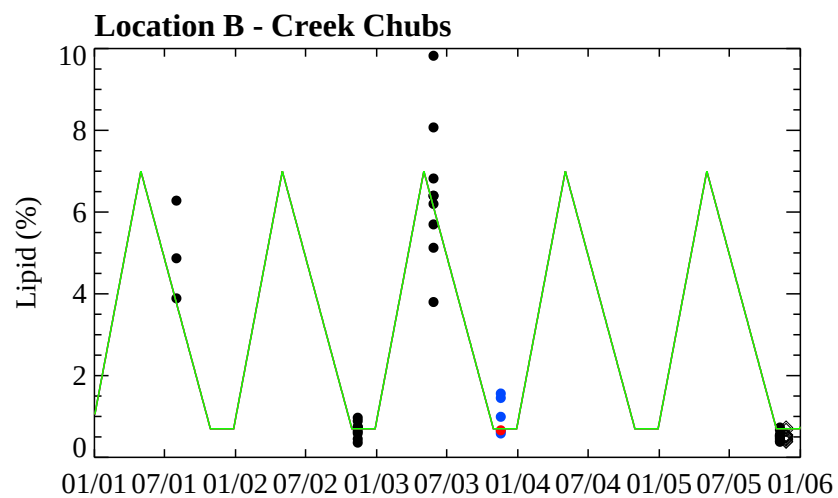
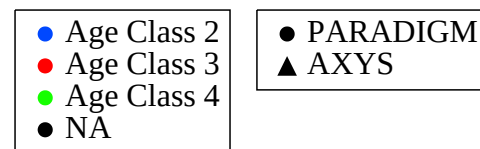


Figure 3-40. Measured and model lipid contents for creek chubs and longear sunfish at Locations B and D.

Model Source: \\Legolas\d_drive\VIAnea\model\FDCHN\output\runD90
Open diamonds represent 2005 ES Recovery adjusted values (offset to view)



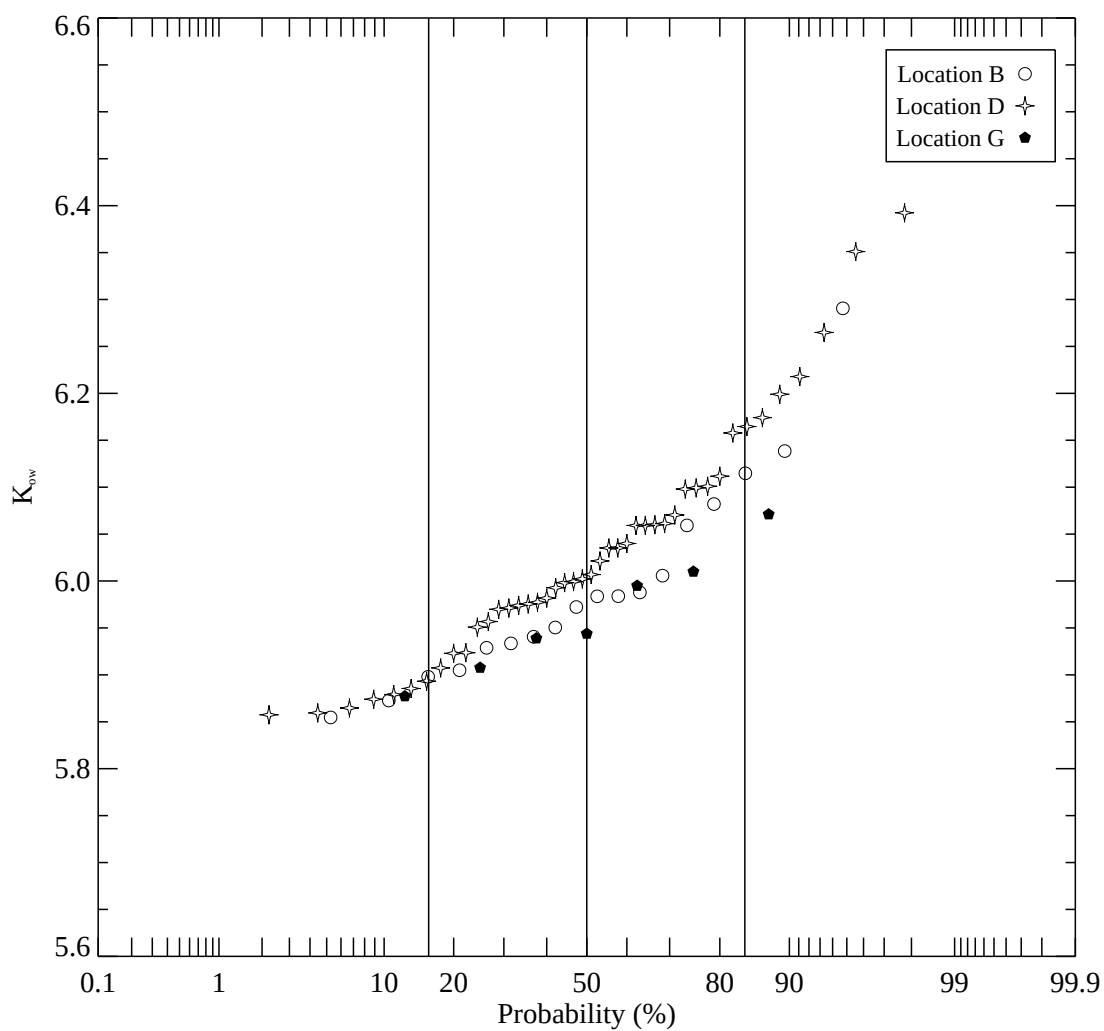


Figure 3-41. Probability plot of K_{ow} of PCB congeners in aquatic fauna in Conard's Branch and Richland Creek during 2003.

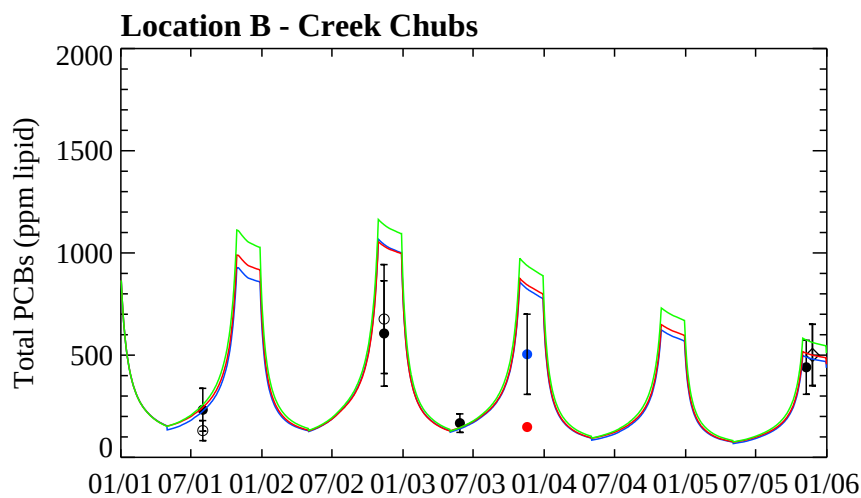
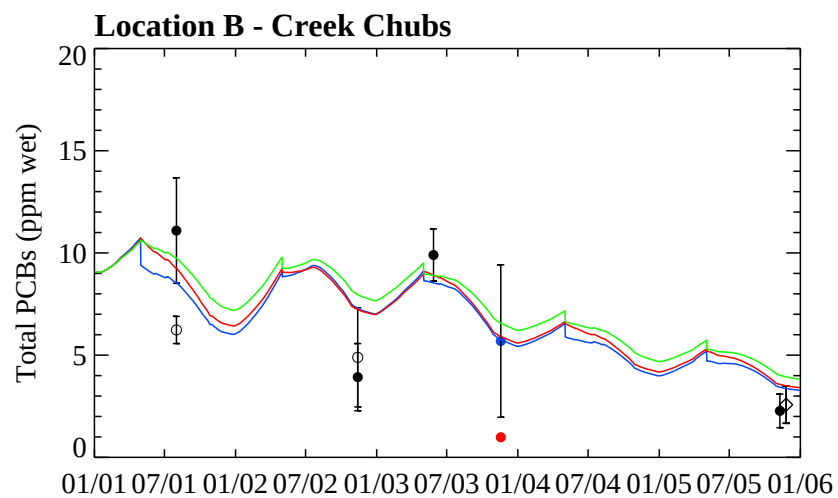
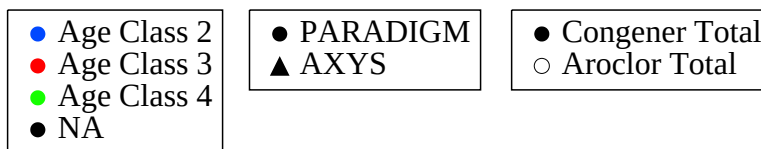


Figure 3-42. Comparison of predicted and measured PCB concentrations for creek chubs at Location B.

Model Source: \\Legolas\d_drive\VIAnea\model\FDCHN\output\runD90
 Open diamonds represent 2005 ES Recovery adjusted values (offset to view).
 Data shown are means $\pm$ 2 standard errors.



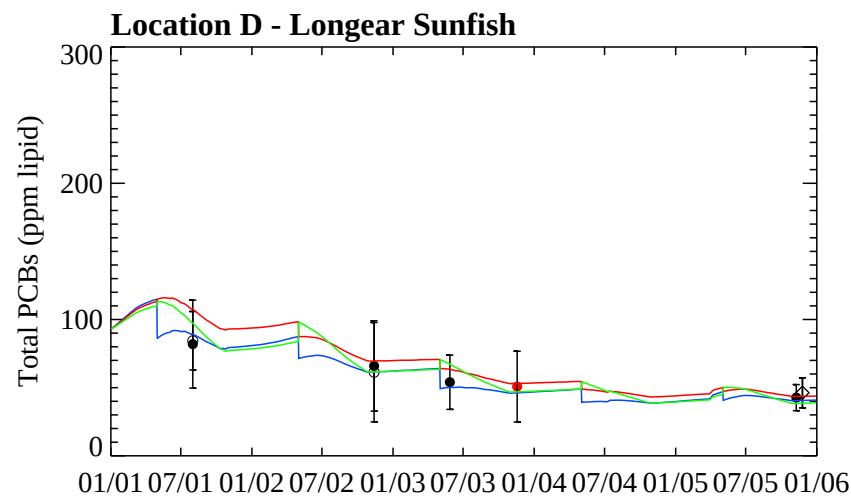
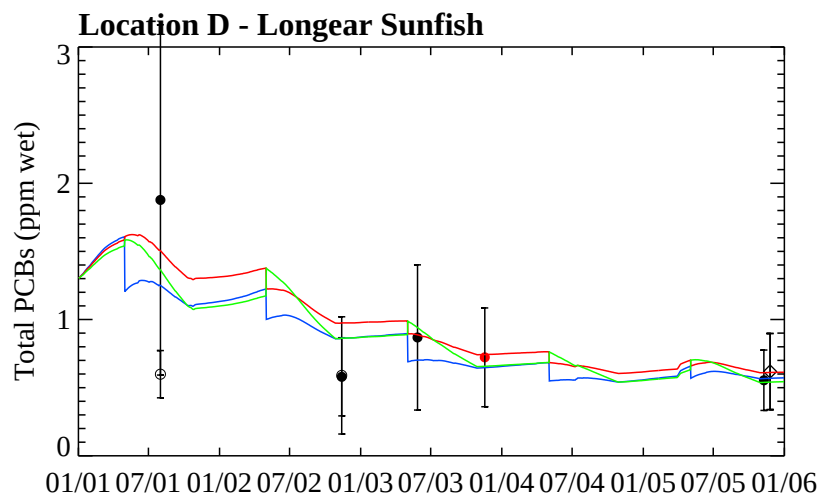
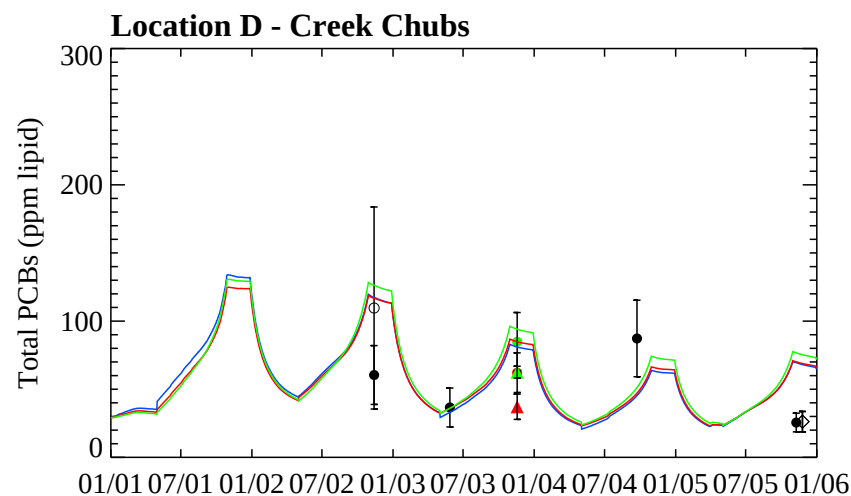
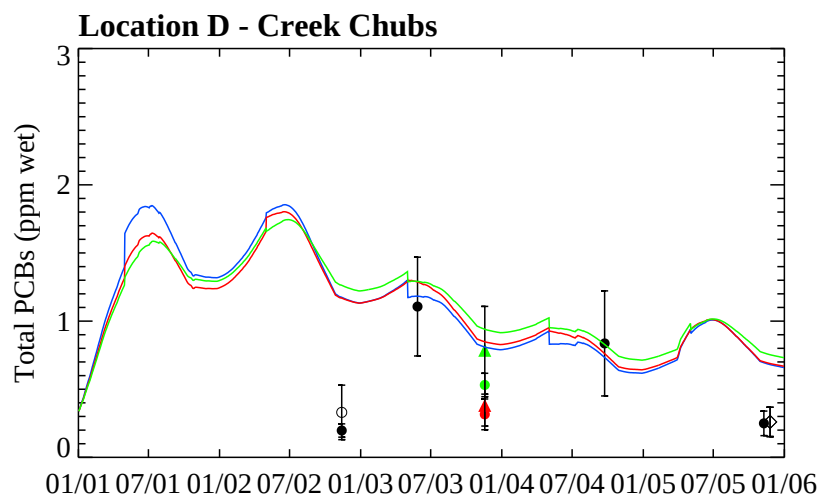
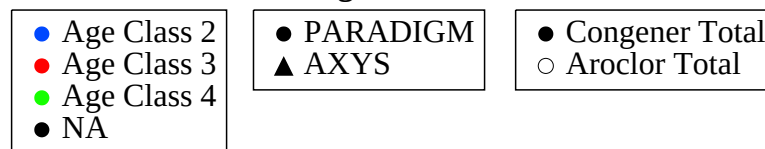


Figure 3-43. Comparison of predicted and measured PCB concentrations for creek chubs and longear sunfish at Location D.

Model Source: \\Legolas\d_drive\VIAnea\model\FDCHN\output\runD90
 Open diamonds represent 2005 ES Recovery adjusted values (offset to view).
 Data shown are means $\pm$ 2 standard errors.



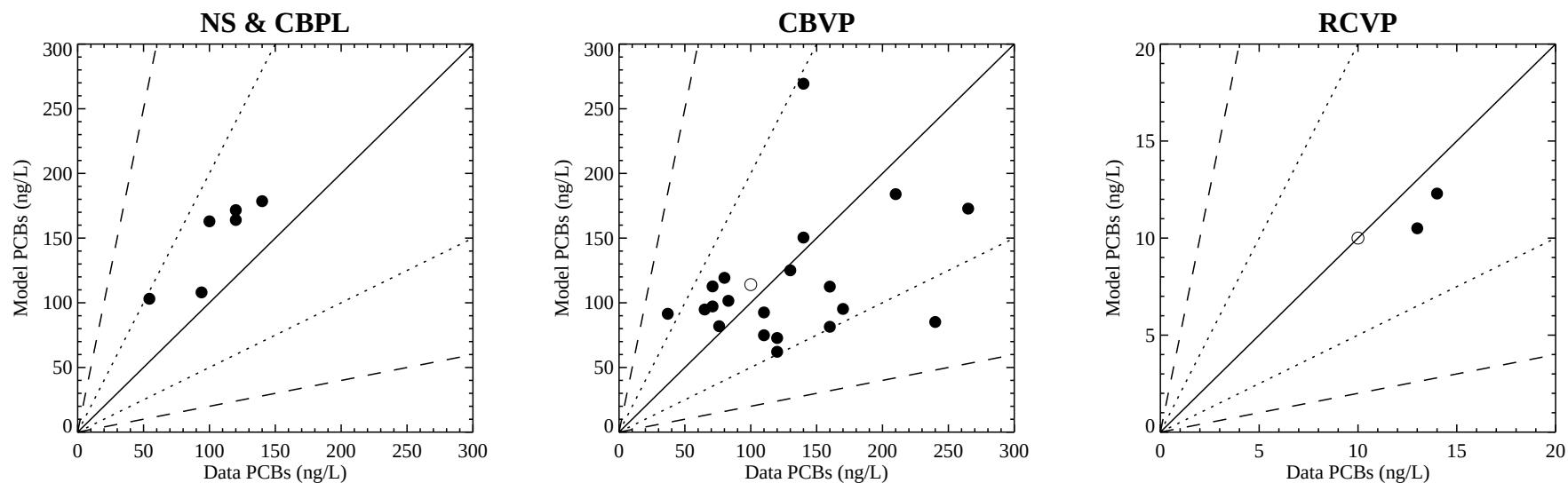


Figure 3-44. Comparison of model calculated water column daily average PCBs with data during low flow surveys.

Notes: Non-detect PCBs shown at MDL. Duplicate data averaged.

Source: \\legolas\d_drive\VIAnea\model\outputs\calibrate\runs\run60\run60a

● Detected Data
○ Non-detect Data

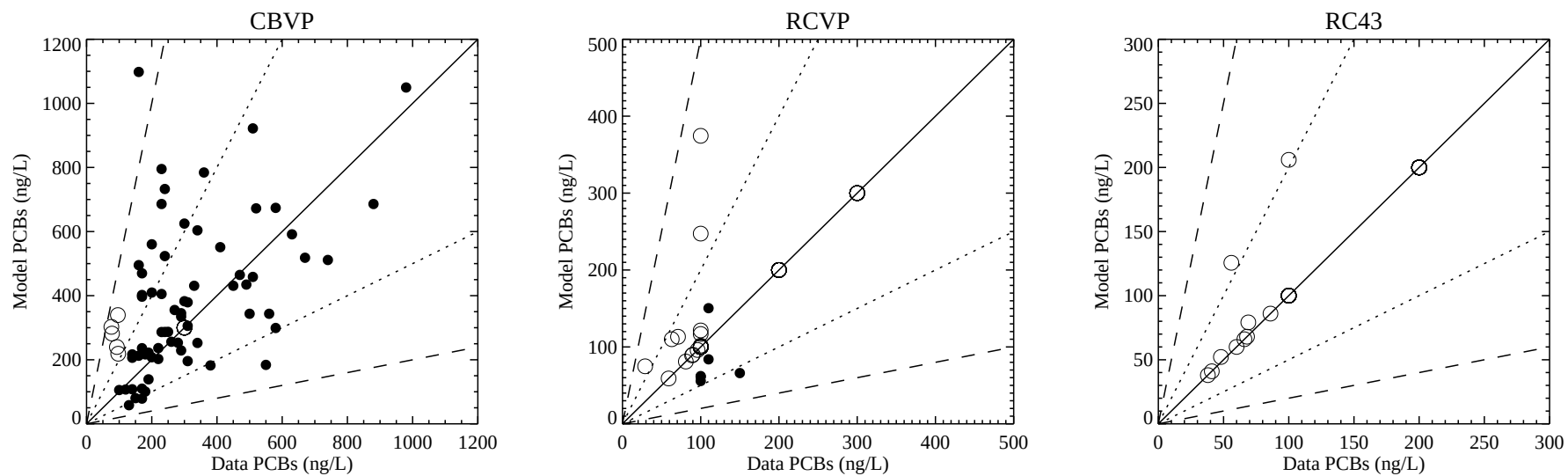


Figure 3-45. Comparison of model calculated water column PCB concentrations with data during storm events.

Note: Non-detect PCBs shown as open symbols at MDL.



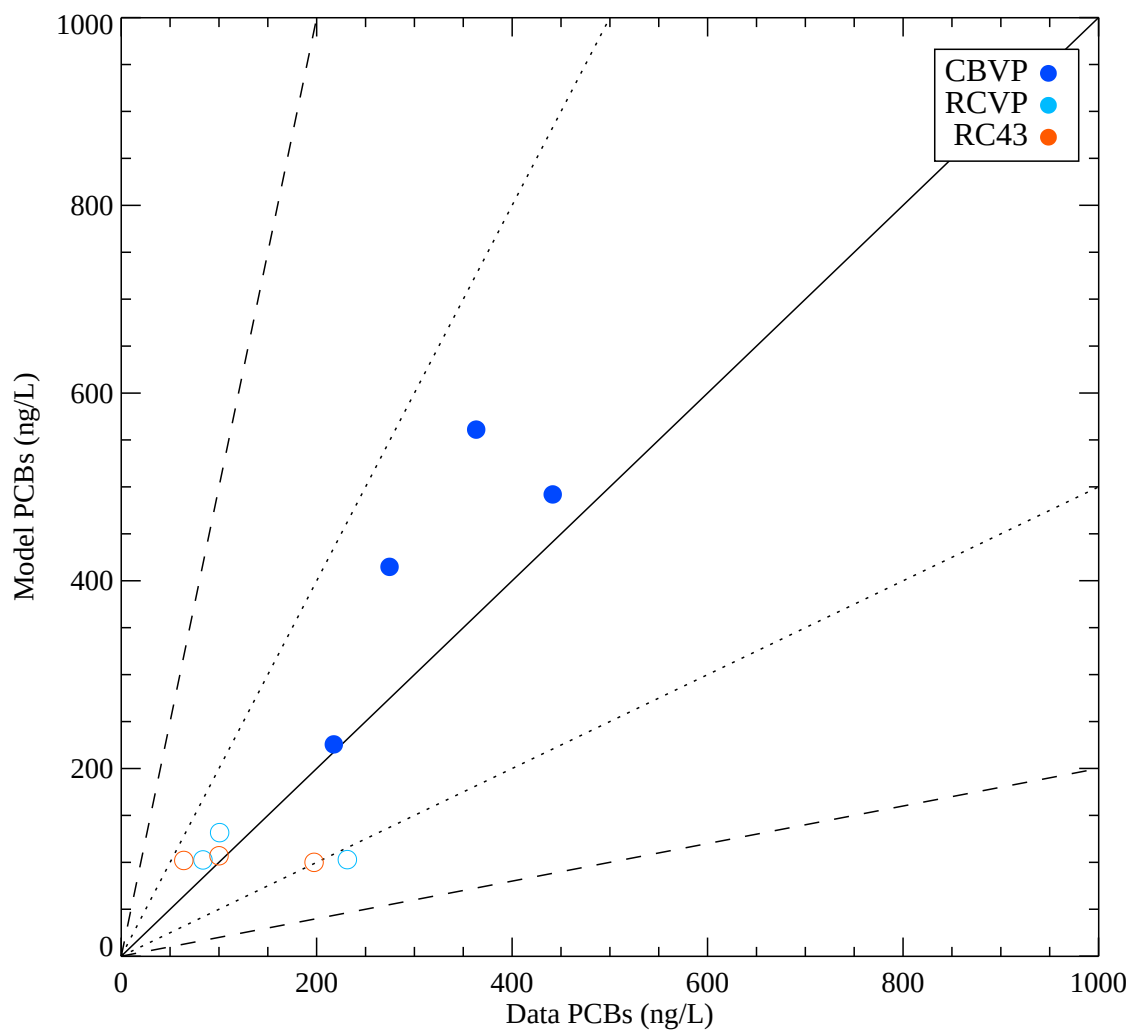


Figure 3-46. Comparison of event mean PCB concentrations calculated from model and data at CBVP, RCV, and RC43 during storms.

Notes: Open symbols represent events in which a majority of the PCB samples collected during the storm were non-detect; non-detect PCBs set to MDL.

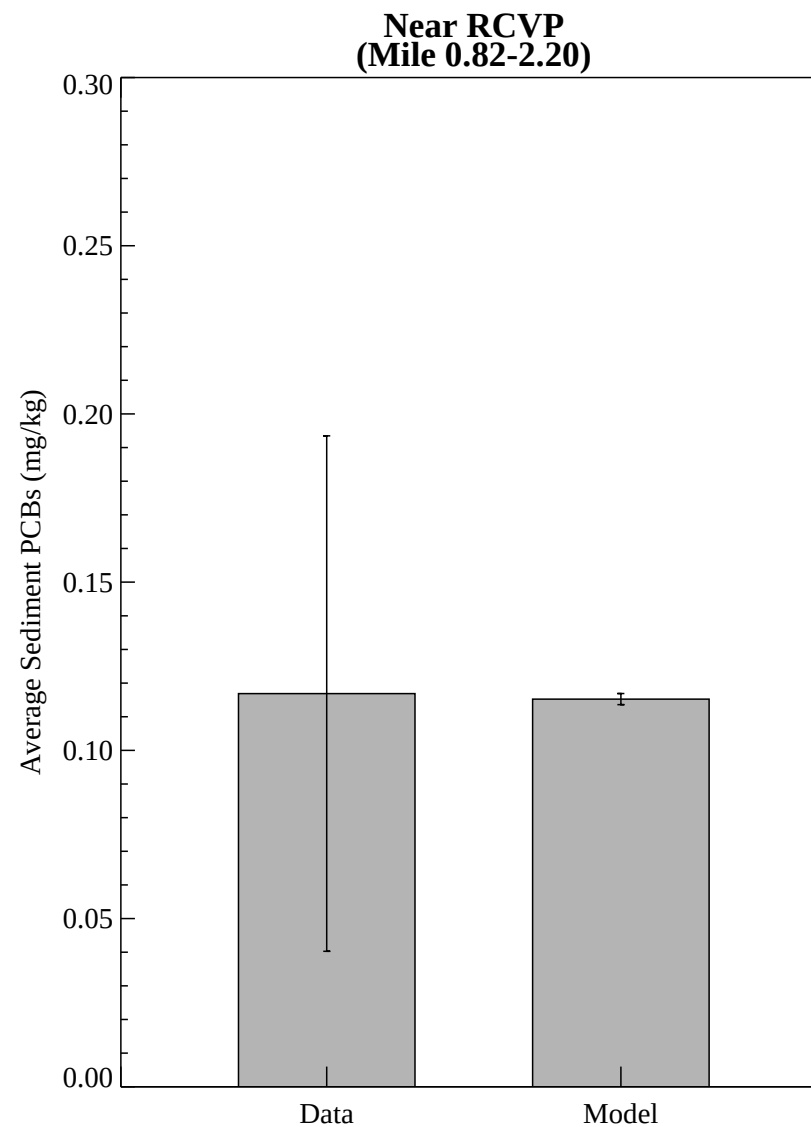
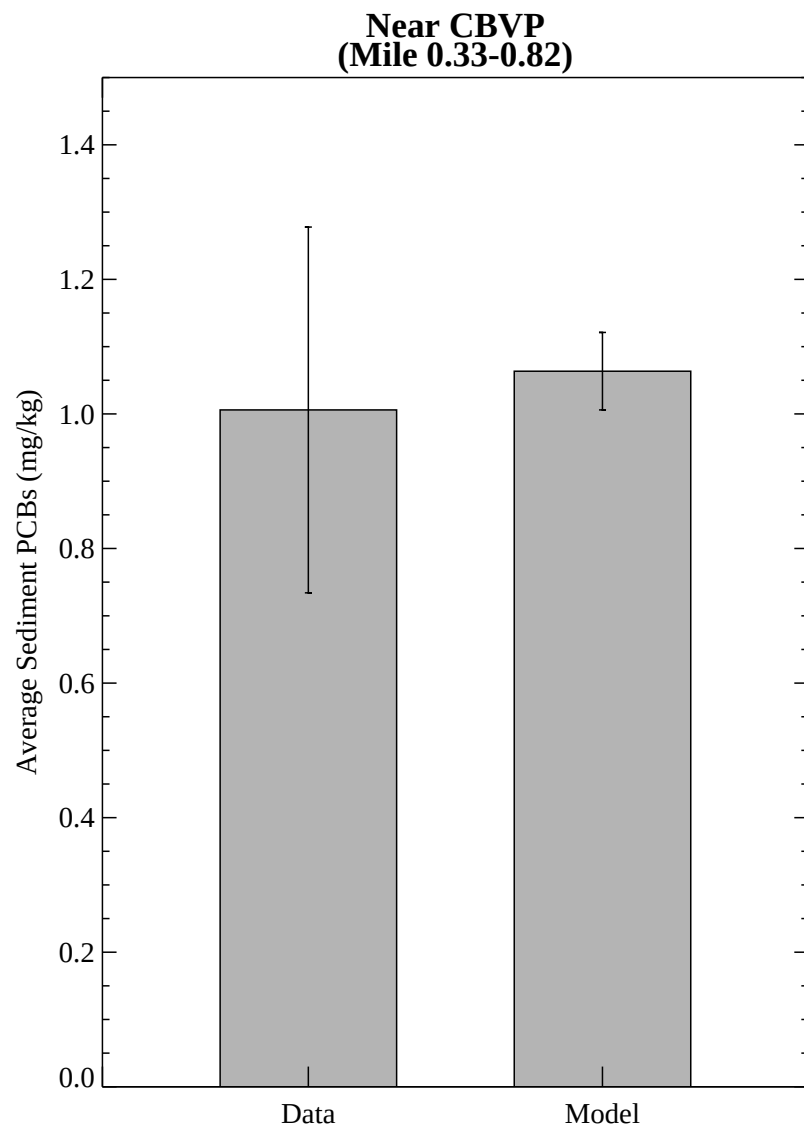


Figure 3-47. Comparison of model calculated surface sediment PCBs with data near CBVP and RCVP.

Data: Average data during 1998-2004 +/- 2*SEM; Model: Average 2001-2005 results +/- range.

Notes: Non-detect PCBs set to 1/2 method detection limit.

Source: \\legolas\d_drive\VIAnea\model\outputs\calibrate\runs\run60\run60a

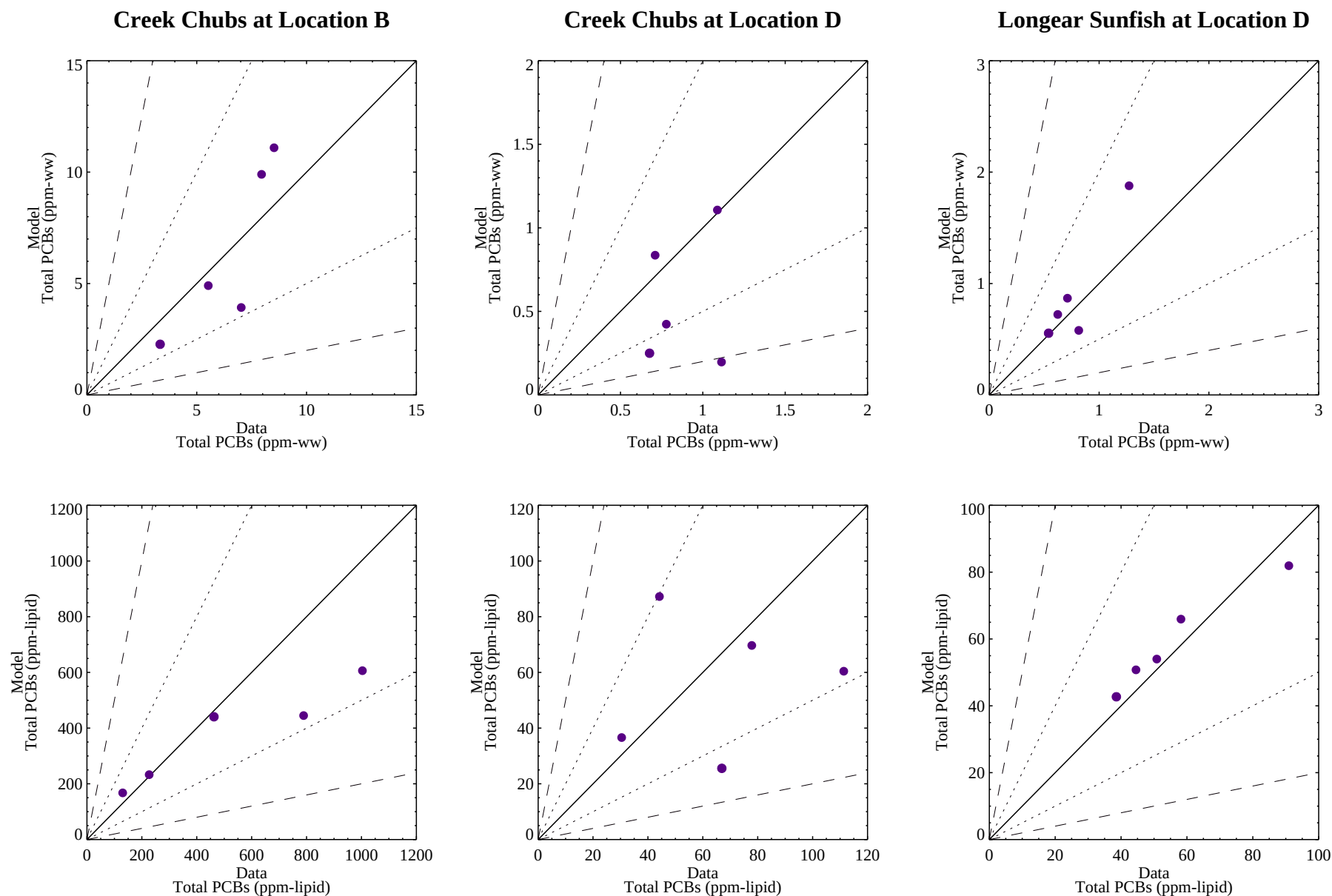
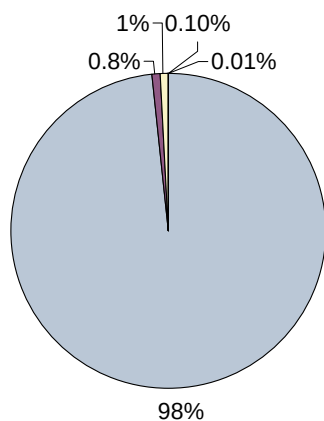


Figure 3-48. Comparison of model calculated fish tissue PCB concentrations with data for creek chub and longear sunfish in Conard's Branch and Richland Creek.

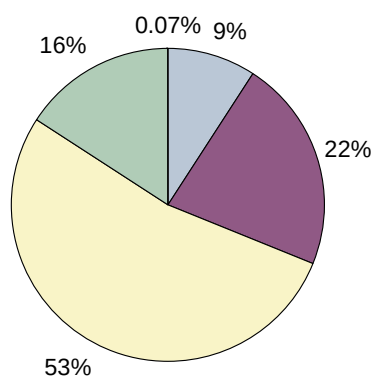
Notes: Congener PCB data shown; 2005 data plotted on 11/9/2005; model output is average of age class 2, 3, and 4.

Sources to Water at Location B

**Storm
Flows**



**Low
Flows**



Sources to Creek Chub at Location B

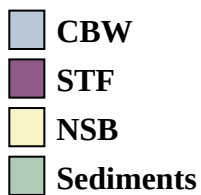
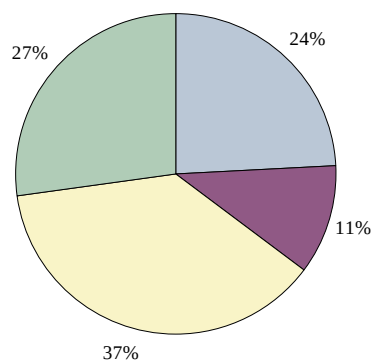


Figure 4-1. Comparison of PCB sources to the water column under storm and low flow conditions to PCB sources to creek chubs in Conard's Branch.

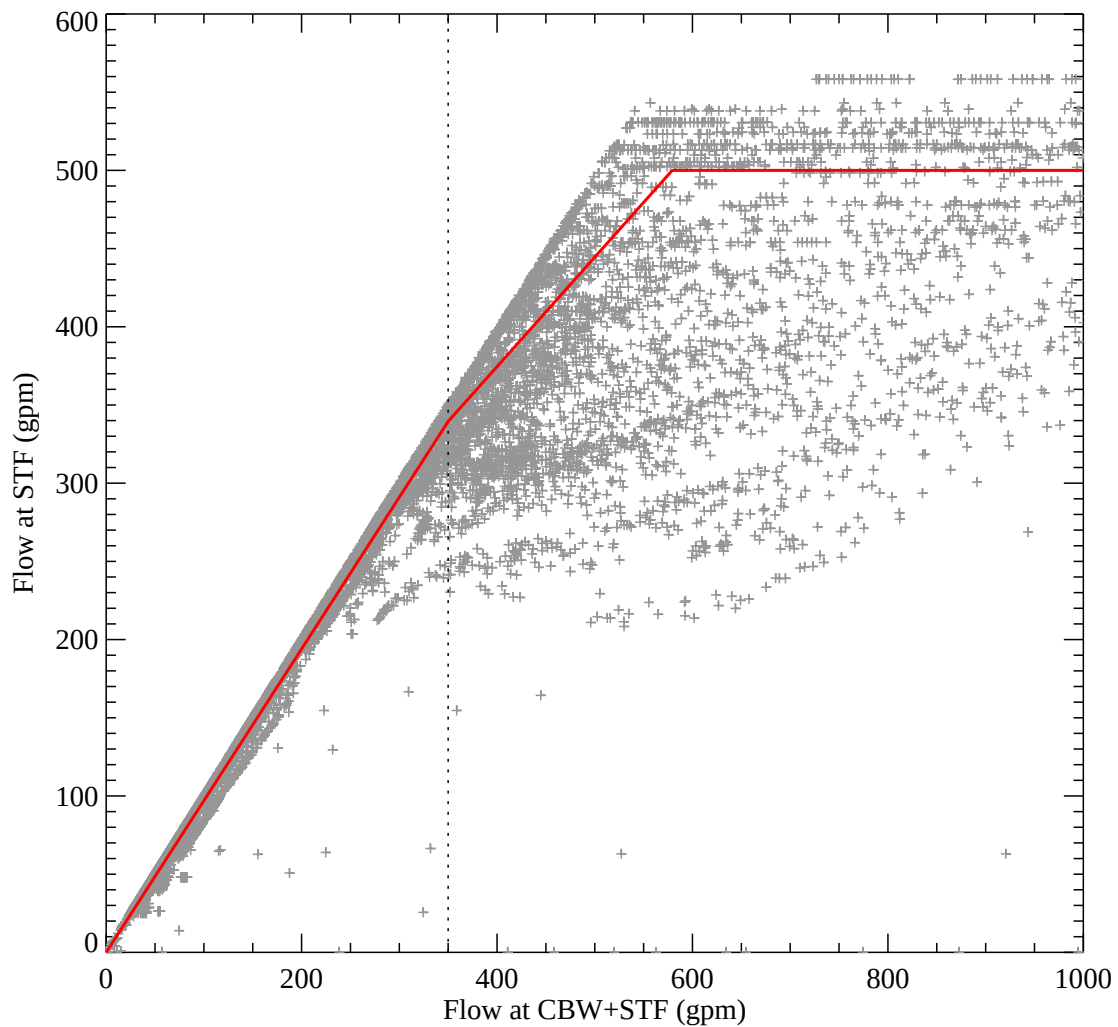


Figure 4-2. Estimated spring water collection: comparison of flow routed to STF with untreated flow entering Conard's Branch in 2003-2005.

Notes: STF capacity = 500 gpm; flow at CBW+STF > 1000 gpm not shown.

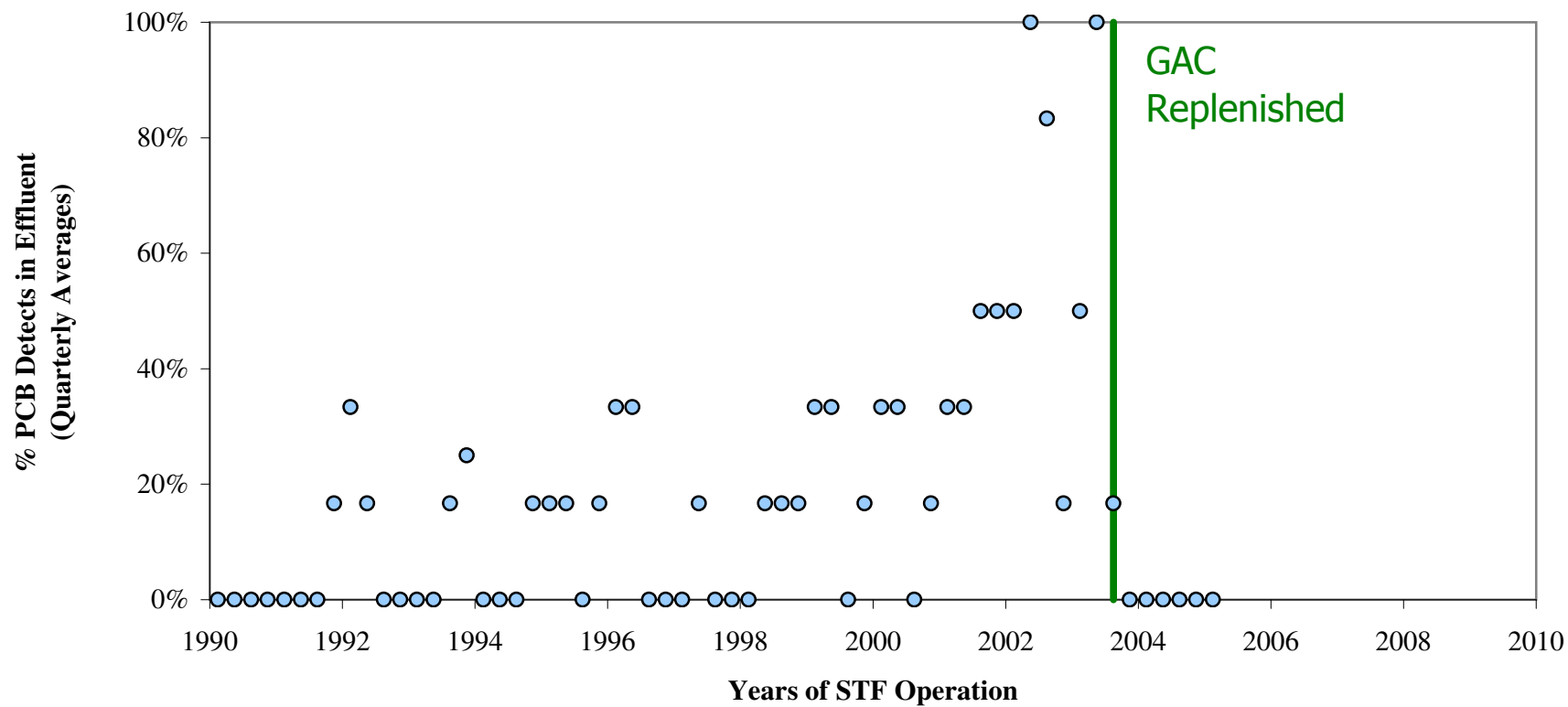


Figure 4-3. Temporal plot of PCB detections in STF effluent.

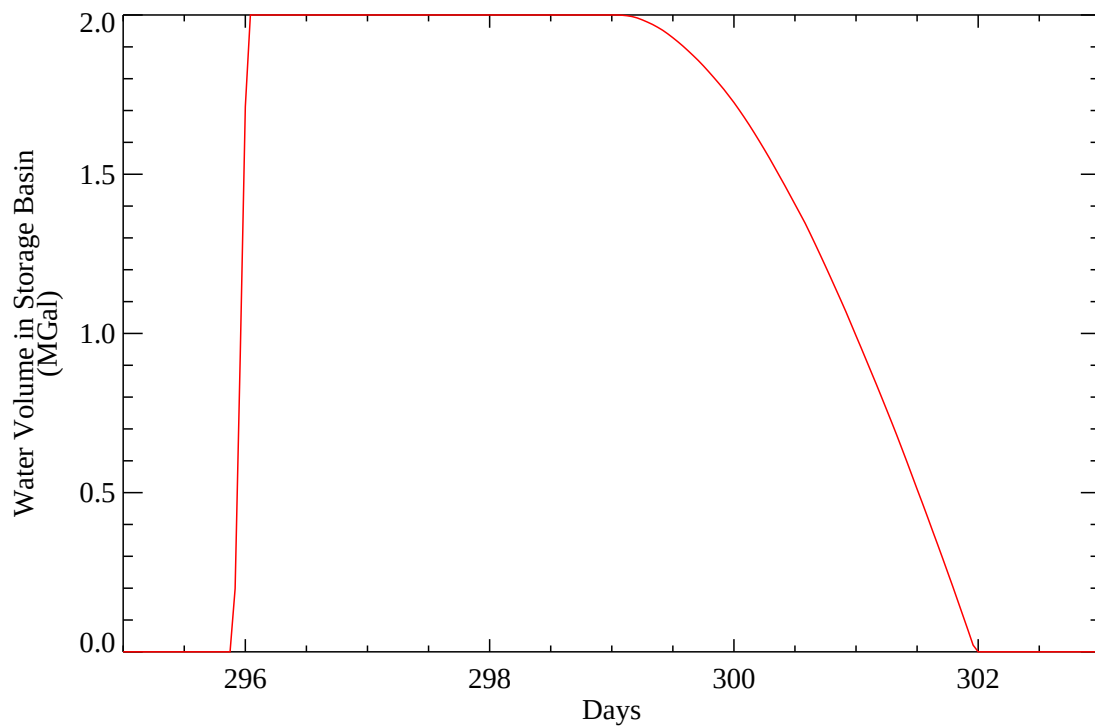
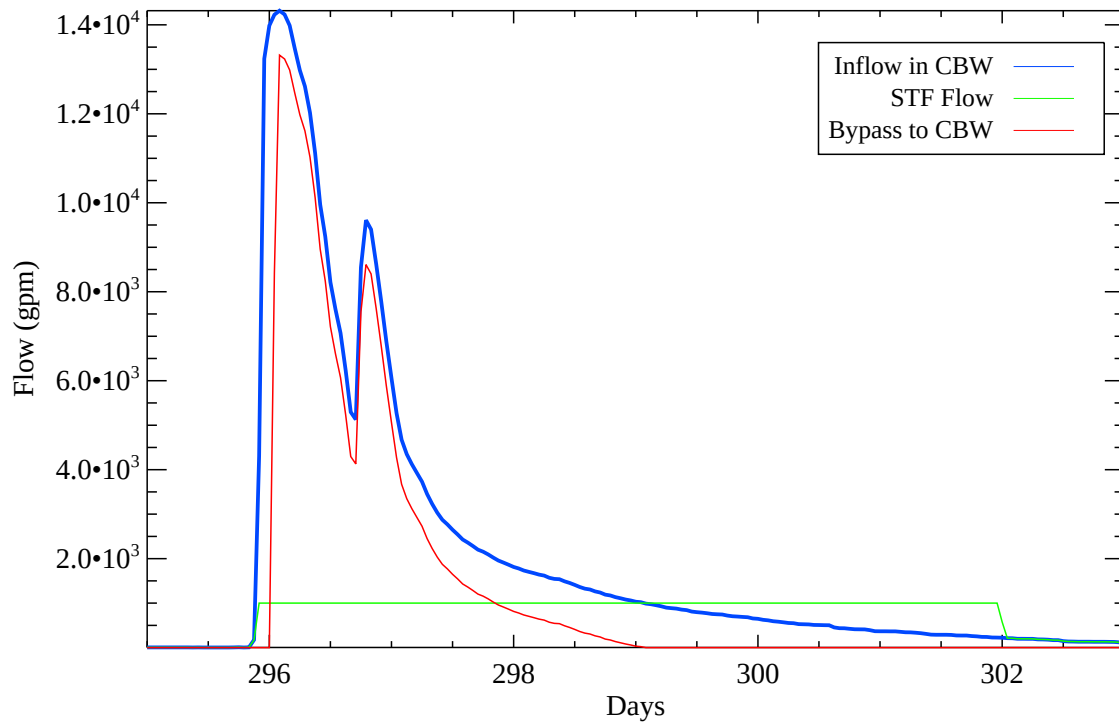


Figure 4-4. Example operation of model-simulated storage basin during October 2001 storm.

Note: Storage basin capacity = 2 MGal; STF capacity = 1000 gpm.

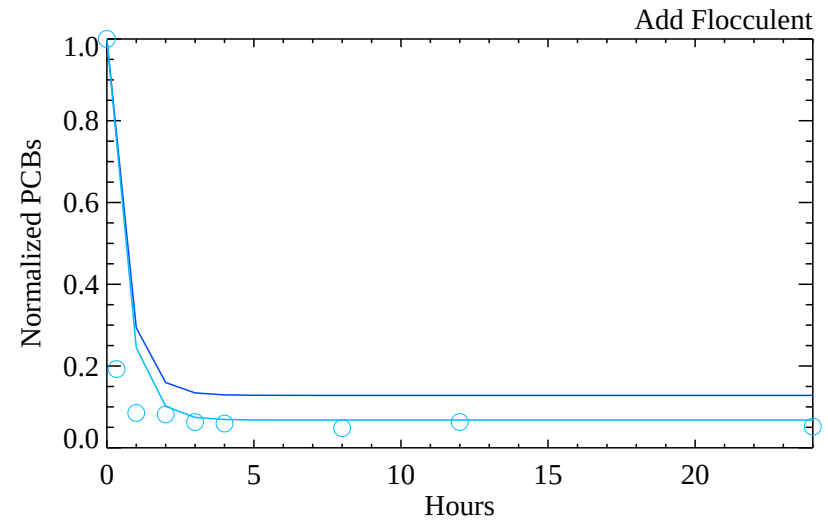
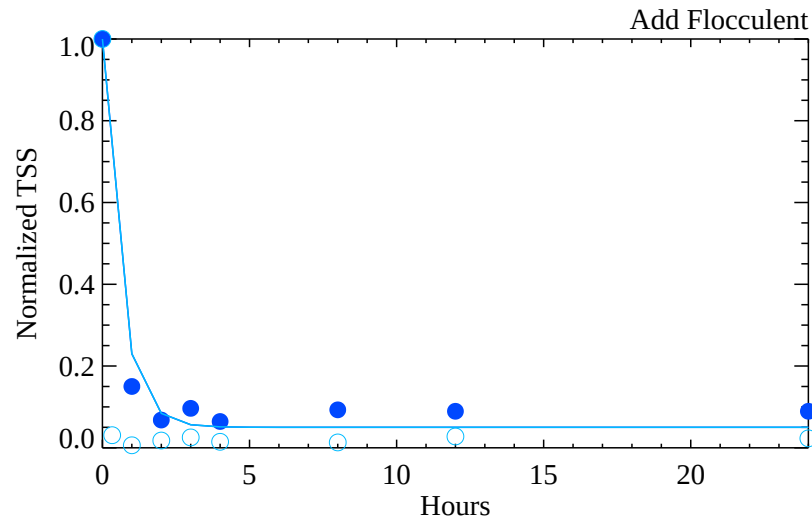
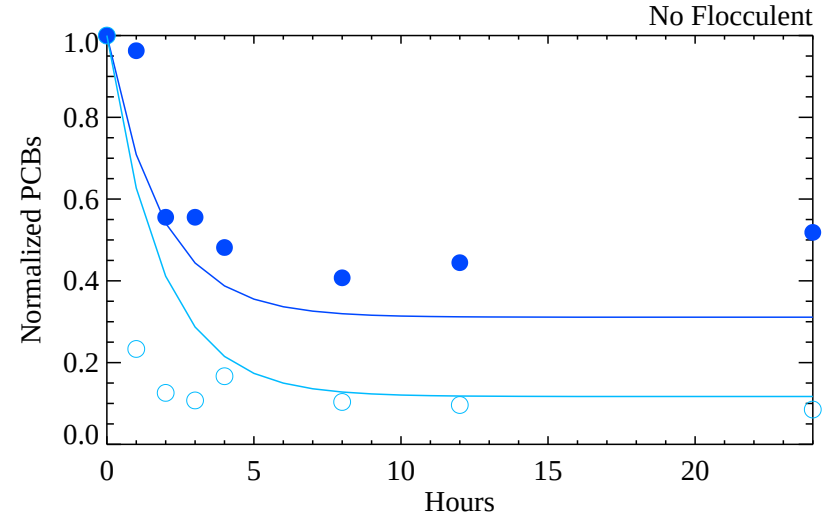
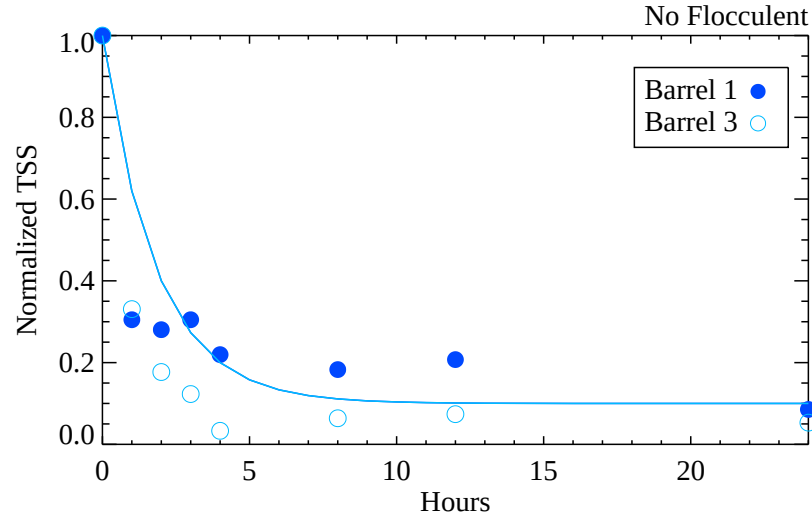


Figure 4-5. Comparison of calculated TSS and PCB concentrations with data collected from the June 2002 barrel study.

Notes: PCBs for Barrel 1 with flocculent not shown due to uncertainty in initial concentration.
 Simulation of barrels without flocculent: $V_s = 1$ m/day; non-settleable solids = 10%
 Simulation of barrels with flocculent: $V_s = 3$ m/day; non-settleable solids = 5%

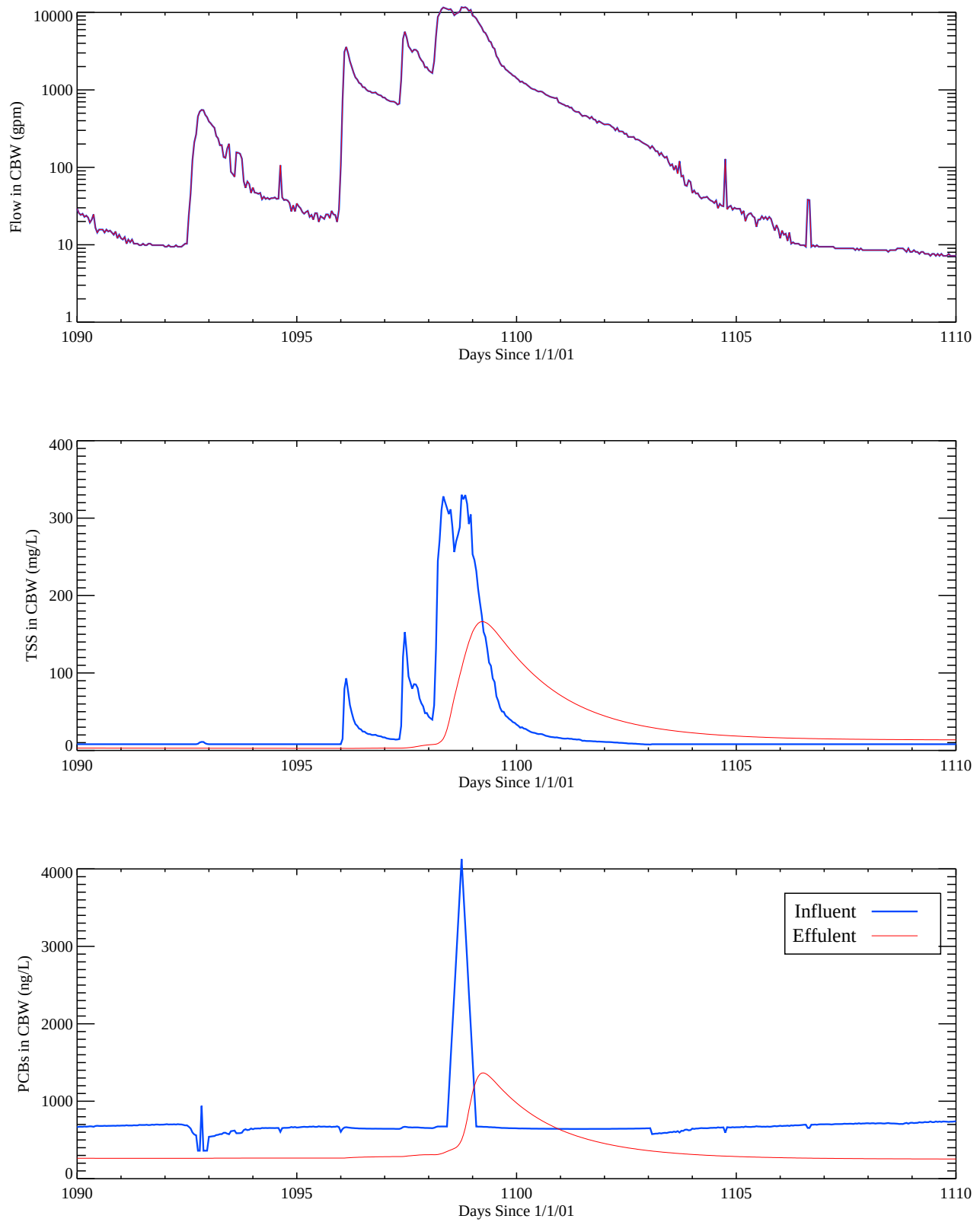


Figure 4-6. Example operation of model-simulated settling basins during the January 2003 storm.

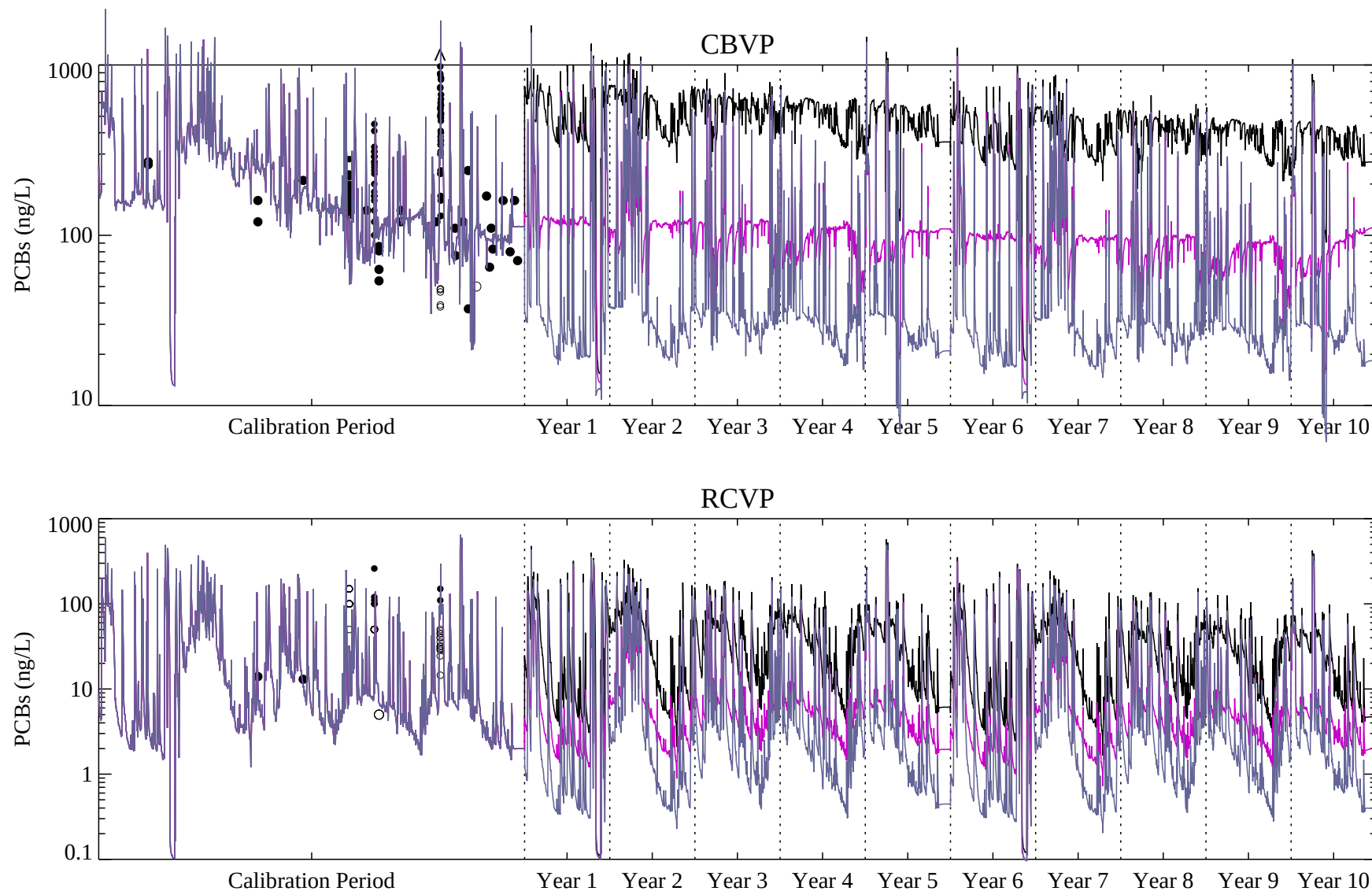
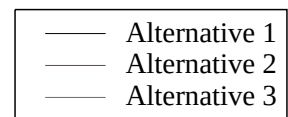


Figure 4-7. Temporal trend of water column PCBs during 10-year projection period for Alternative 1, Alternative 2, and Alternative 3.

Note: Non-detect PCBs plotted as open symbols at 1/2 MDL.



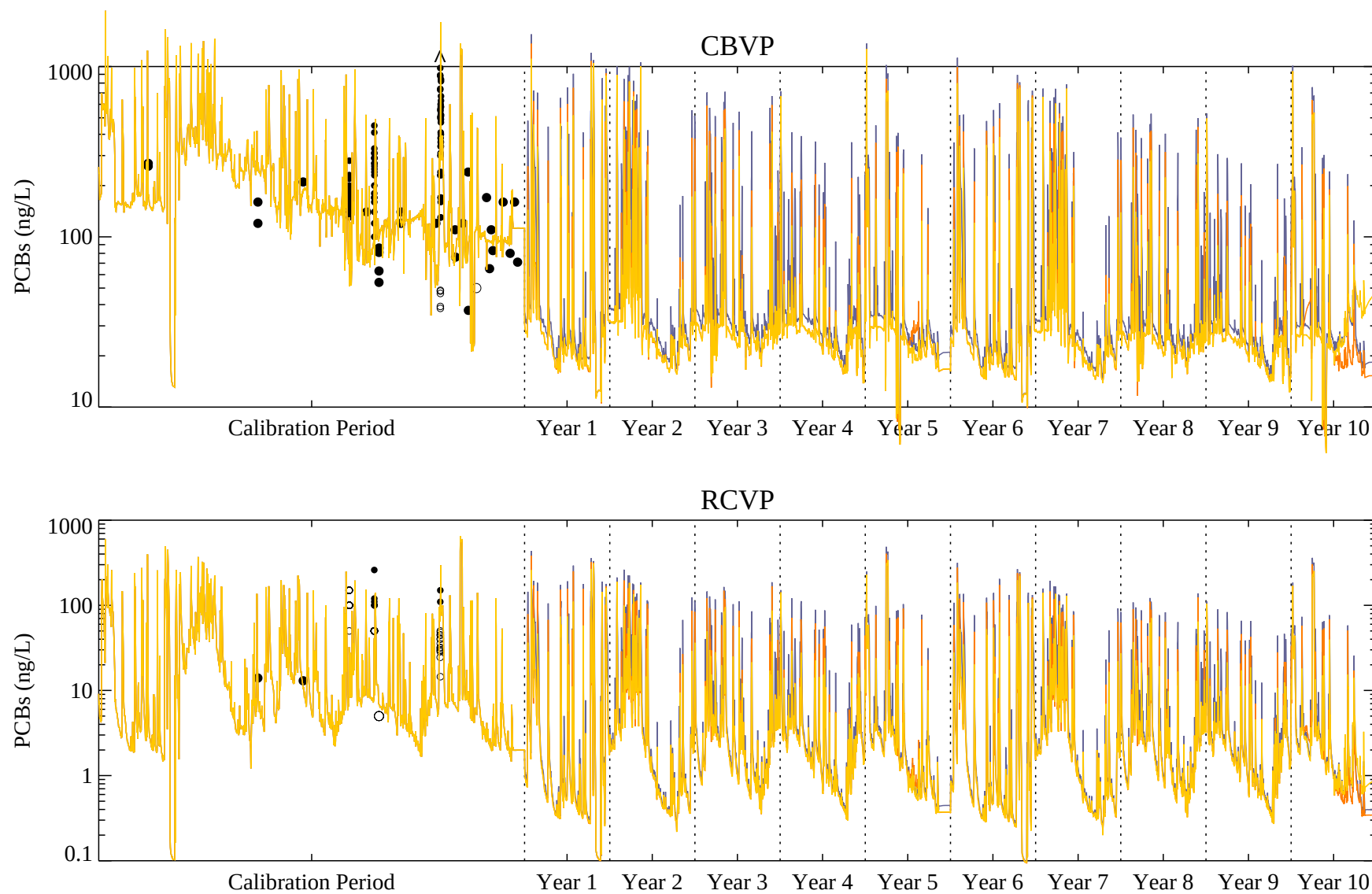


Figure 4-8. Temporal trend of water column PCBs during 10-year projection period for Alternative 3, Alternative 5, and Alternative 6.

Note: Non-detect PCBs plotted as open symbols at 1/2 MDL.



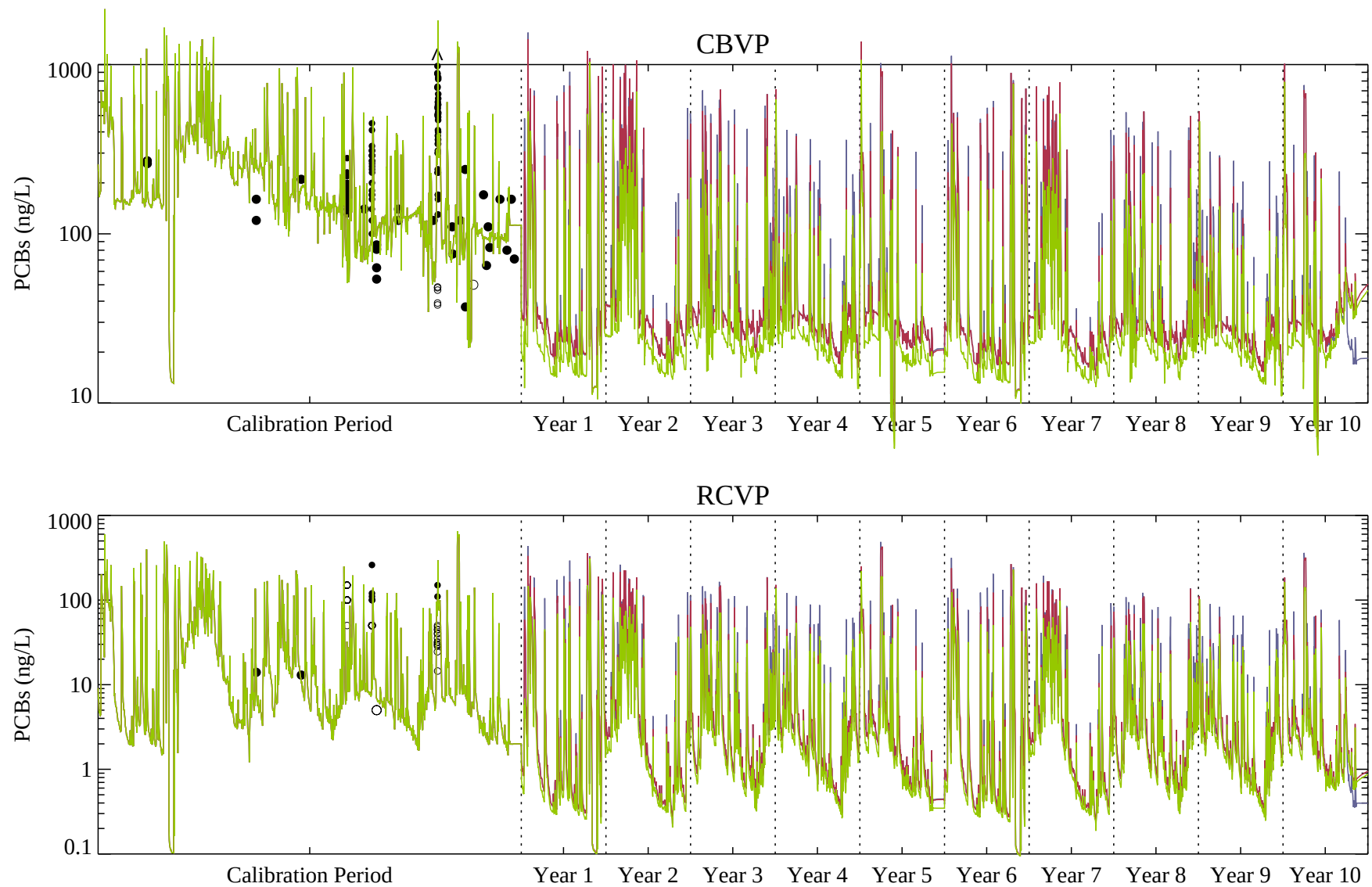
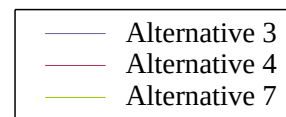


Figure 4-9. Temporal trend of water column PCBs during 10-year projection period for Alternative 3, Alternative 4, and Alternative 7.

Note: Non-detect PCBs plotted as open symbols at 1/2 MDL.



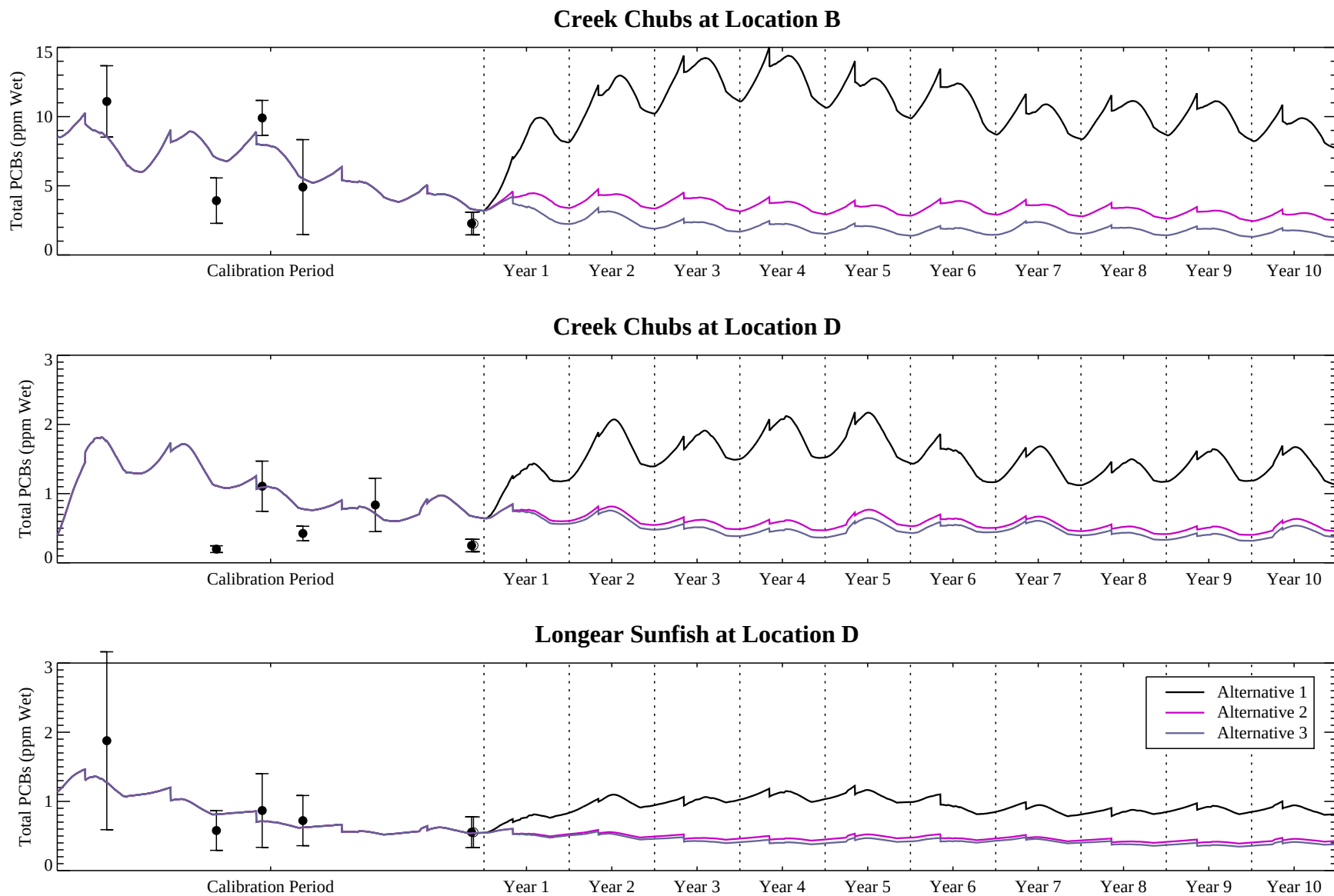


Figure 4-10. Temporal profiles of model PCB concentrations in fish tissue during during 10-year projection period for Alternative 1, Alternative 2, and Alternative 3.

Notes: 2005 data plotted on 11/9/2005; open symbols represent ES Recovery adjusted values (offset to view); data plotted as mean $\pm$ 2SE; model output is average of age class 2, 3, and 4.

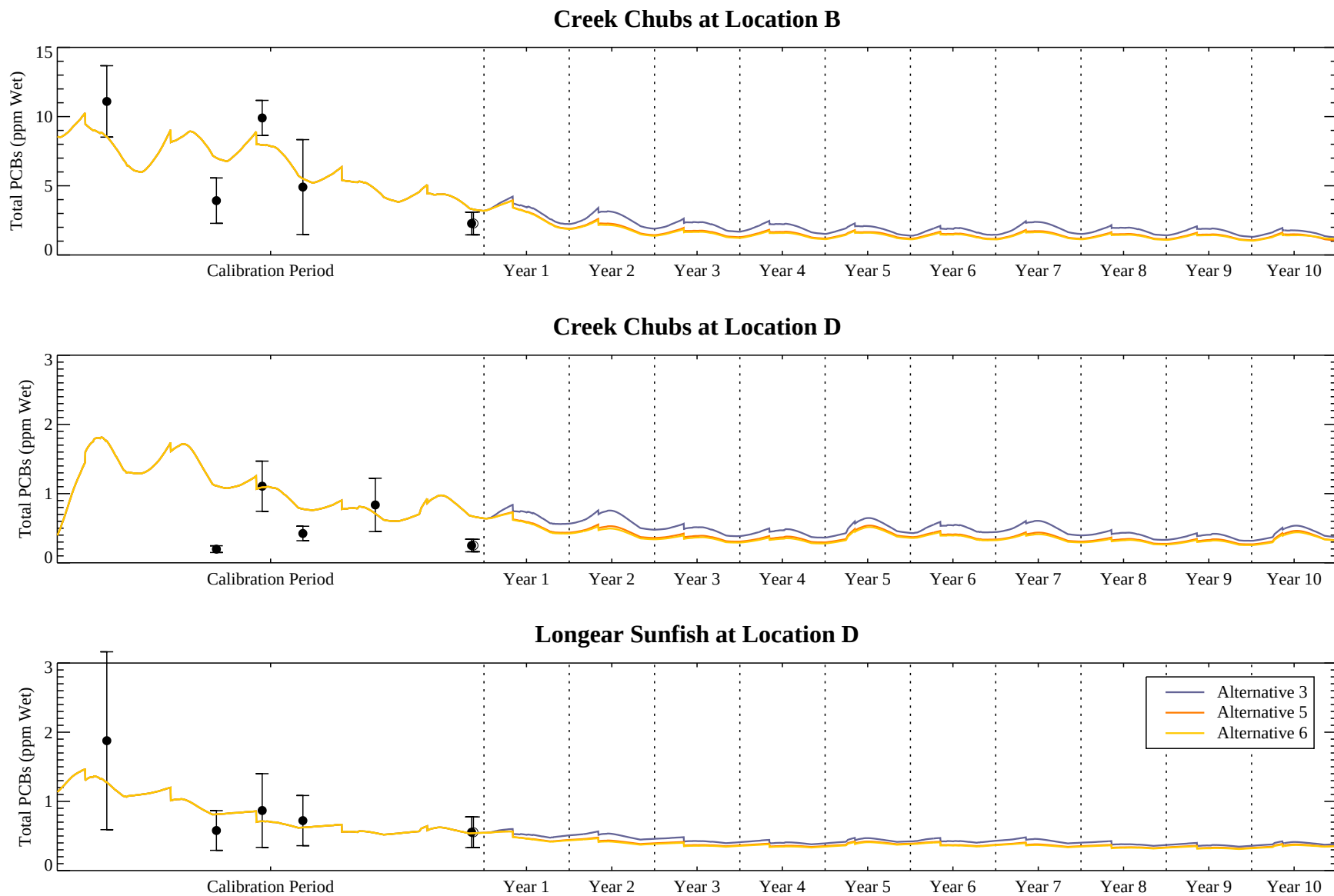


Figure 4-11. Temporal profiles of model PCB concentrations in fish tissue during during 10-year projection period for Alternative 3, Alternative 5, and Alternative 6.

Notes: 2005 data plotted on 11/9/2005; open symbols represent ES Recovery adjusted values (offset to view); data plotted as mean $\pm$ 2SE; model output is average of age class 2, 3, and 4.

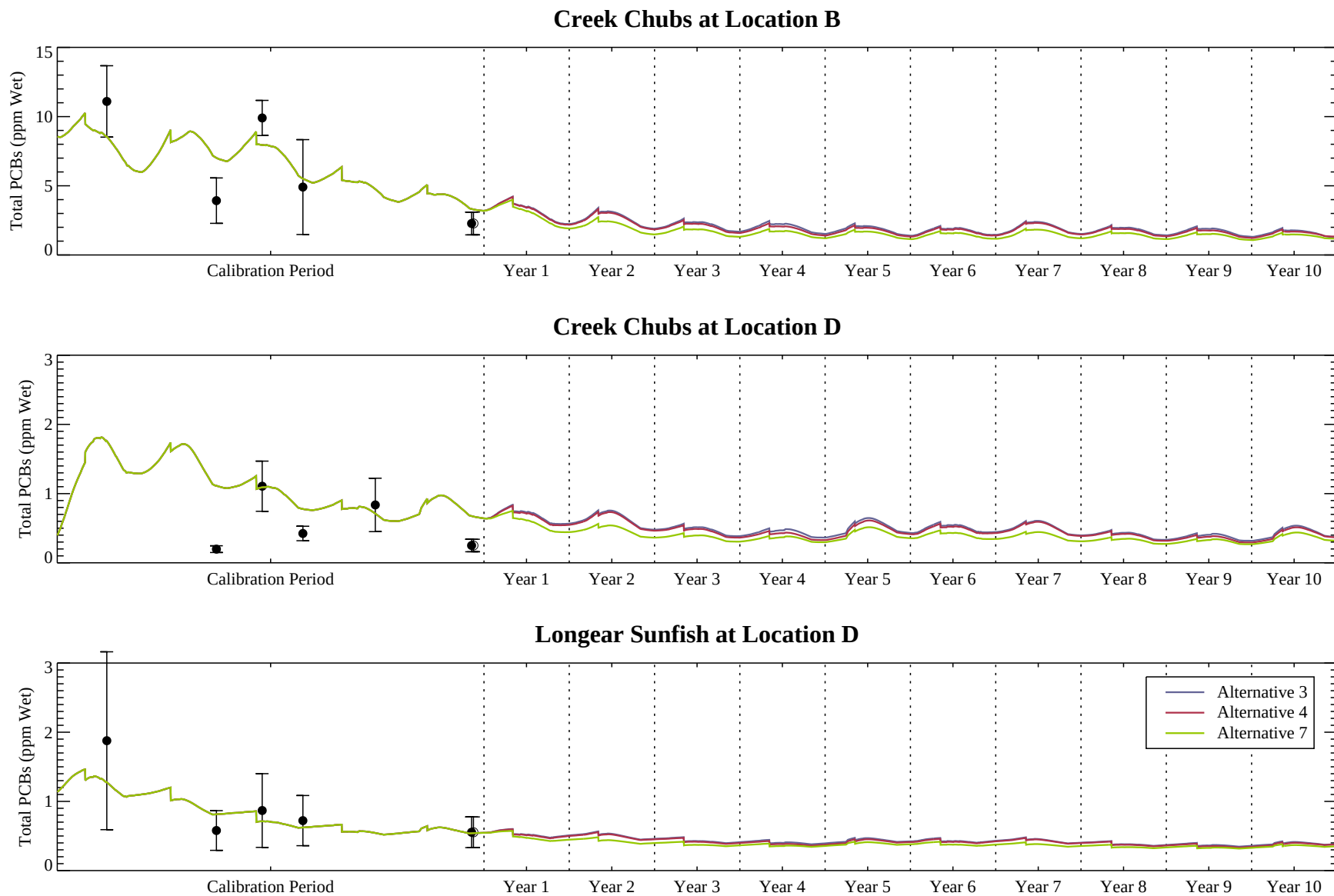


Figure 4-12. Temporal profiles of model PCB concentrations in fish tissue during during 10-year projection period for Alternative 3, Alternative 4, and Alternative 7.

Notes: 2005 data plotted on 11/9/2005; open symbols represent ES Recovery adjusted values (offset to view); data plotted as mean +/- 2SE; model output is average of age class 2, 3, and 4.

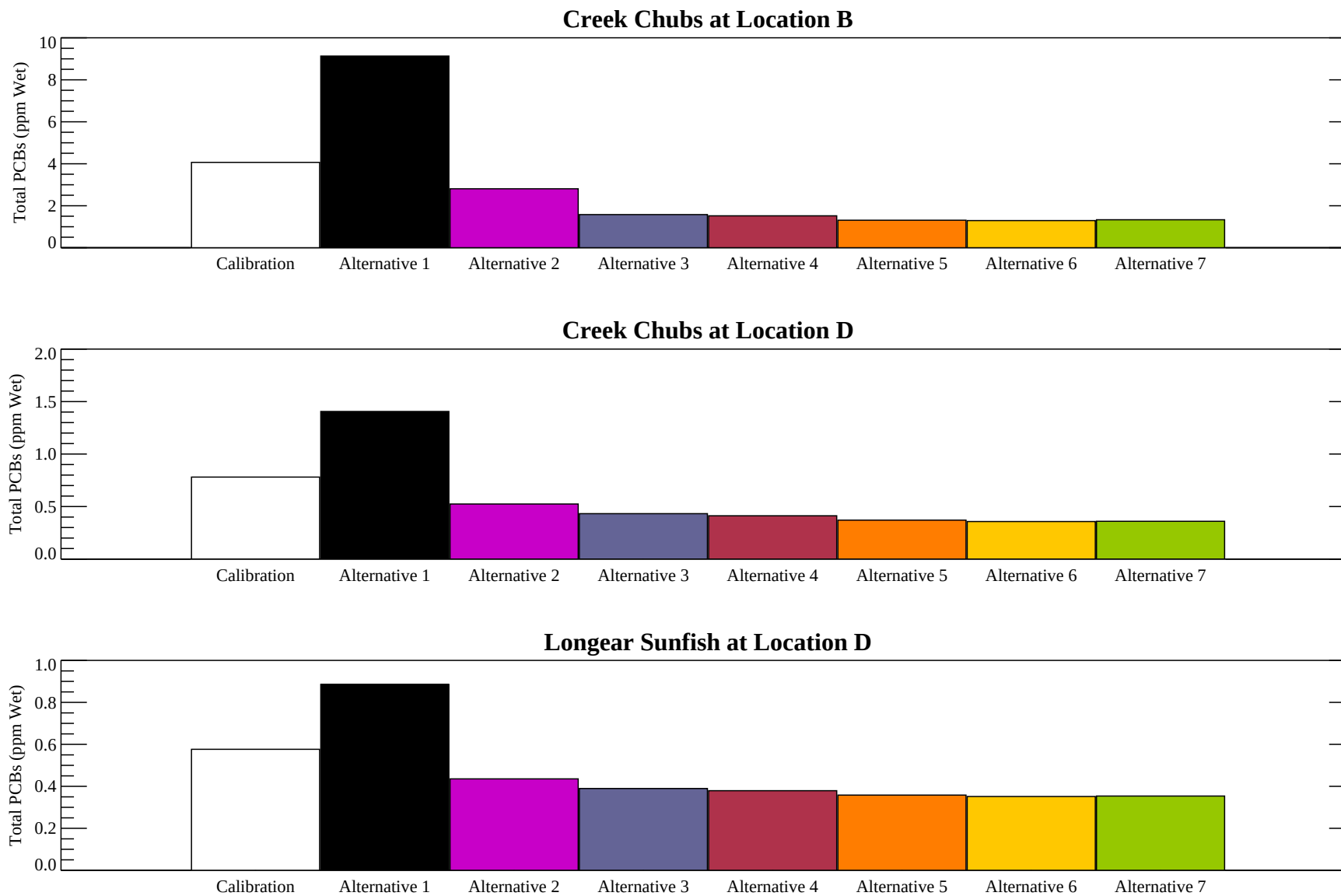


Figure 4-13. Average PCB concentrations in fish tissue from Year 10 of the model projection.

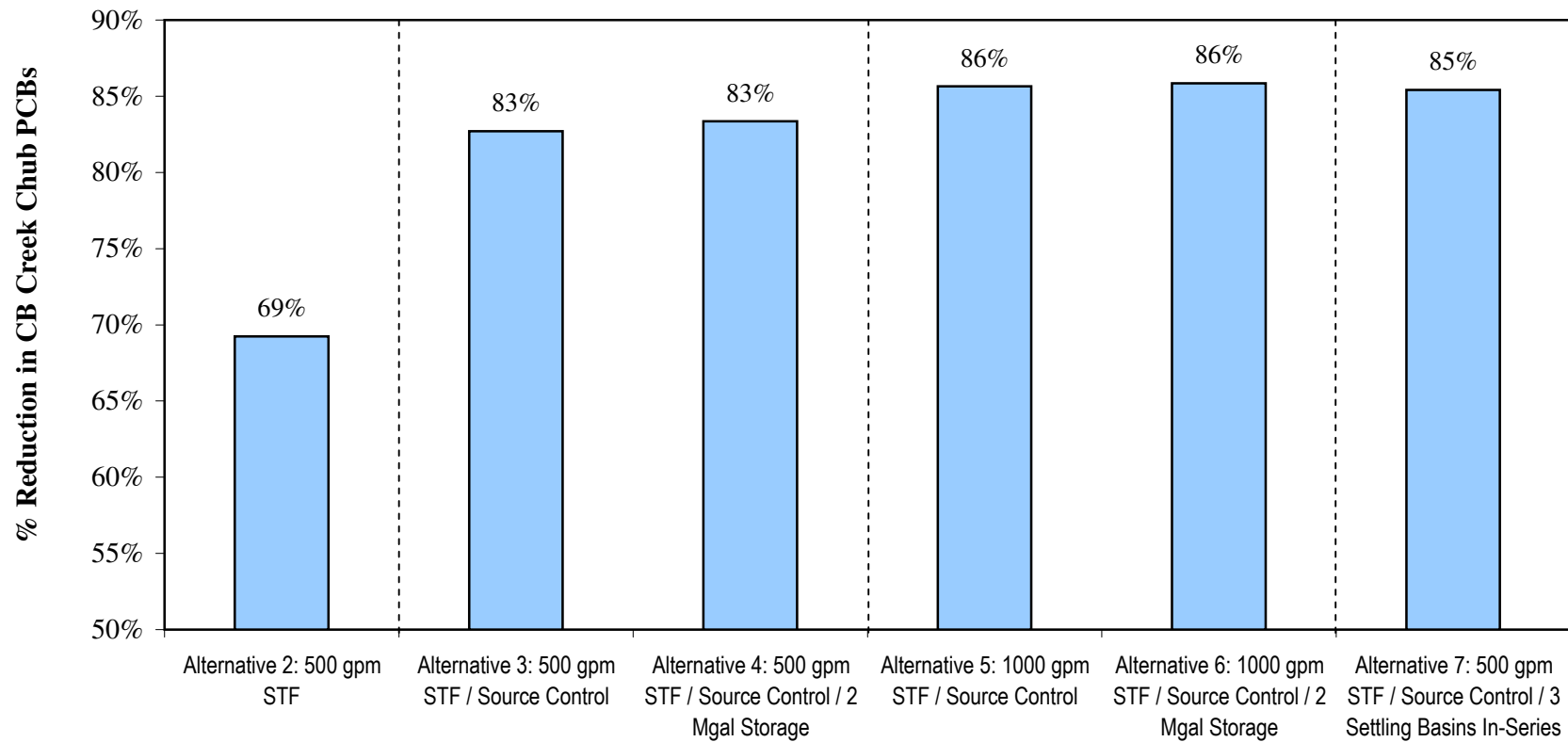


Figure 4-14. Percent reduction (relative to No Action) in Year 10 average Conard's Branch creek chub PCB concentrations for Alternatives 2 through 7.

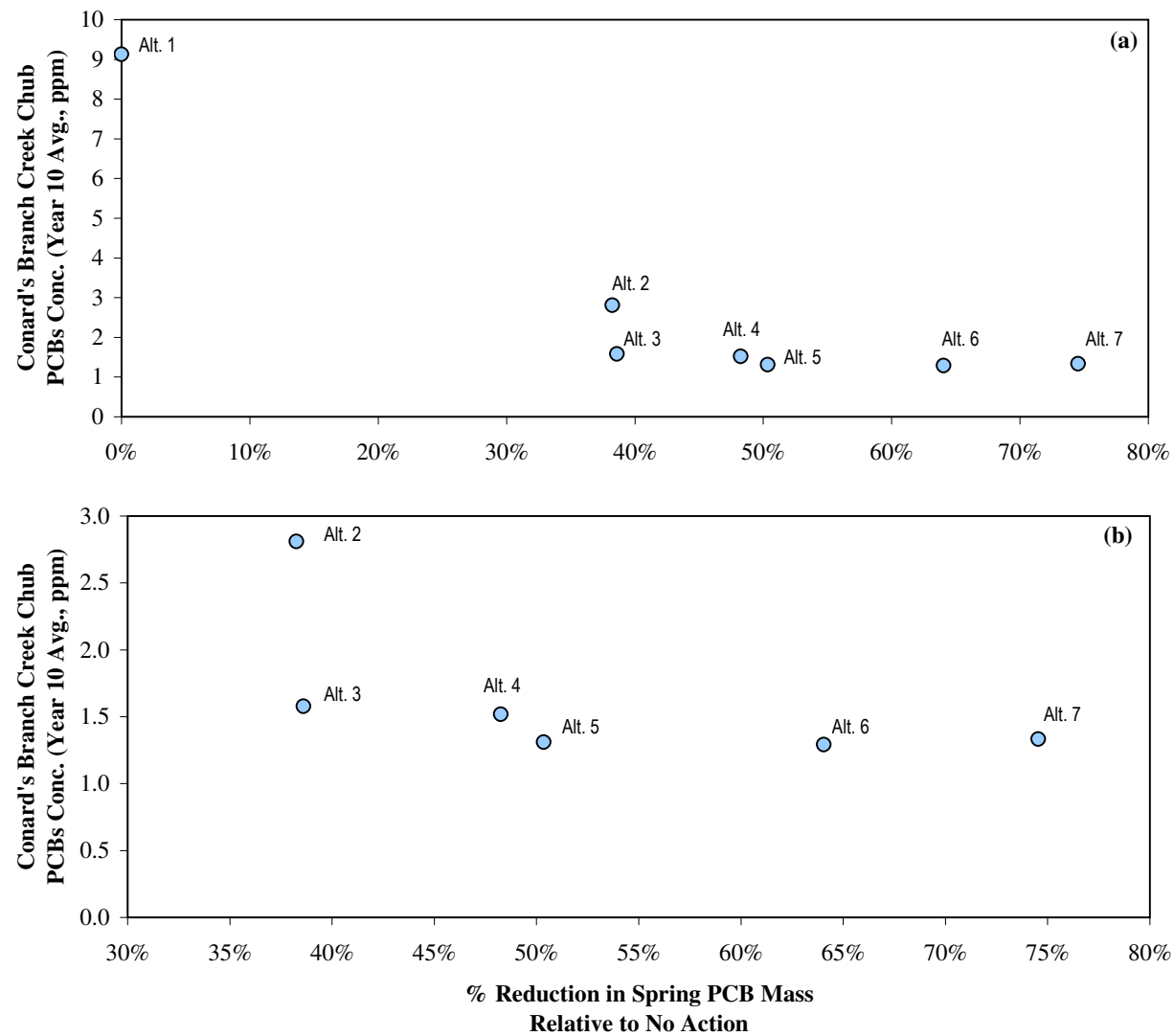


Figure 4-15. Year 10 average Conard's Branch creek chub PCB concentrations versus spring mass reduction (relative to No Action) for Alternatives 2 through 7: (a) All Alternatives; (b) Alternatives 2-7.

APPENDICES

Appendix A

Technical Memorandum

To: Russ Cepko, Viacom

From: Pradeep Mugunthan and David Glaser, QEA

April 18, 2006

**RE: Analysis of PCB Trends at the Neal's Landfill Site:
Spring Model**

TECHNICAL MEMORANDUM

TO: Russ Cepko **DATE:** April 18, 2006
FROM: Pradeep Mugunthan and David Glaser **RE:** Analysis of PCB Trends at the
Neal's Landfill Site: Spring
Model
CC: Kevin Russell, Jim Rhea, Paul Switzer **JOB#:** VIAtre:110

Introduction

Understanding the rate of natural recovery of PCB contamination in Conard's Branch and Richland Creek is essential to developing a management plan for the Neal's Landfill Site. As discussed with USEPA¹, a statistical data analysis has been undertaken focusing on the direct statistical estimation of the projected rate of change in PCB concentrations, along with its associated confidence interval. To make the best use of all of the data and to account for the important confounding co-factors, we are using a unified modeling approach, one that incorporates both statistical analysis as well as scientific understanding of the underlying physical, chemical, and biological processes through which PCBs are transferred from spring water entering Conard's Branch to fish tissue. Such understanding is provided by the mechanistic simulation model that includes hydrodynamic, sediment transport, chemical fate and bioaccumulation components.

The first step in the analysis involves a statistical modeling of trends in PCB concentrations in the spring water entering the system. The goal of this memo is to provide a brief description of the development and results of this model of time trends in PCB levels in the spring system at Neal's Landfill.

¹ Viacom presented USEPA with a technical memorandum describing the method on August 25, 2005. This was followed by a conference call with USEPA and their consulting statistician on September 26, 2005. On October 12, 2005, Viacom provided USEPA with a series of slides describing the method in greater detail. A technical memorandum was transmitted to EPA on December 5, 2005 summarizing the statistical modeling work performed, using data collected through September 2004. EPA provided Viacom with comments on this memo developed by Neptune and Co. on January 9, 2006, and Indiana Department of Environmental Management provided comments on February 9. The present memo is a modified version of the December 5 memo with changes addressing these comments.

The spring system is depicted in Figure 1. Waters from both North Spring (NS) and South Spring (SS) are conveyed to the Spring Treatment Facility (STF), where they are treated. The effluent from the STF is directed into Conard's Branch.

The initial model included data through September 2004² (QEA, 2005). While data through August 2005 was available at that time, data collected after September 2004 were not used in the analyses, because it was suspected that cave excavation activity in fall 2004 and summer 2005 might have affected the PCB concentrations in the spring water. Subsequently, data through March 2006 became available for analysis. This memo summarizes the results of the updated modeling analysis using all of the data. Efforts to refine the model (by exploring the potential for improvement of the model by including temperature and TSS, as well as other modifications) are discussed. This memo is responsive to comments received on the 12/5/05 memo (QEA, 2005) and presents the results of an additional estimate performed with an expanded data set.

Data Visualization

A temporal plot of the data is shown in Figure 2. A seasonal trend in PCB levels is evident. Flow rates in the spring system are seasonal, so, as might be expected, PCB concentrations are strongly correlated with flow. In Figure 3, the relationship between PCB concentrations measured at each of the three locations and the total North West (NW) Spring flow is shown for each year. The total NW Spring flow is the total STF flow rate, which represents the combined flows from North and South Springs, summed with the Conard's Branch weir flow (which records flows which bypass collection/treatment). The PCB levels exhibit a clear negative relationship with flow.

To further explore time trends in the data, additional scatter plots of the data are presented in Figure 4. These figures show the relationship between PCB concentration and time for three different flow ranges for the North Spring (NS; Figure 4a), South Spring (SS; Figure 4b) and the spring treatment facility (STF; Figure 4c). A time series of all concentrations is plotted in the bottom right hand panels of Figures 4a to 4c, along with flow data for those days on which PCB data were collected. The flow cutoffs used in this figure ("low": <110; "moderate": 110 – 270; "high": >270 GPM) are operational definitions developed for this analysis, based upon a visual examination of the flow data in the bottom right-hand panel of Figure 4c.

From the bottom right hand panel in each figure it becomes clear that low flows in late summer to fall are associated with higher PCB concentrations, and high flows observed in spring are associated with lower PCB levels. There is a perceptible downward trend under low flow conditions for all three sites. Contaminant trends under moderate- and high-flow conditions are evident in some cases; in other cases, no trend is visible.

² QEA, 2005. *Analysis of PCB Trends at the Neal's Landfill Site: Spring Model*, Technical Memorandum, QEA, LLC, Montvale NJ.

Statistical Modeling of Trends in PCB Concentrations

In this trend analysis, PCB concentrations and flows measured between 1/1/2001 and 3/15/2006 were considered. The expanded data set is shown in the appendix, Tables A1 and A2.

The PCB levels in the spring waters and the spring treatment plant influent were considered to be related to the combined system flow of the spring system by Equation (1). Combined system flow, equal to the sum of the flow at the STF and the flow going over the weir at Conard's Branch, was used, because daily flow data are not available for the individual springs. The power relationship with flow provides a model of dilution in which the strength of the relationship (the exponent) is estimated directly from the data. The exponential relationship used for the change over time represents simple first-order process.

$$C_i(Q, t) = a_i Q^{b_i} e^{-k_i t} \quad (1)$$

where

C_i is the concentration of PCB at location i (ppb)

Q is the combined flow (GPM)

a_i and b_i are unknown constants to be determined for location i

k_i is the decay rate (y^{-1}) for location i

t is the time elapsed in years from the beginning of the period of interest (1/1/2001)

$i = \{1, 2, 3\}$ is an index representing respectively the North and South springs and the spring treatment facility.

Comparison of Decay Rates Among Locations

The decay rate will likely be similar at all three locations. This is reasonable given the fact that the PCBs in the North and South Springs likely originate from the same source, and both springs contribute to the STF. To verify whether the decay rates are similar across the sites, the parameters a_i , b_i and k_i were first estimated independently for each site.

Equation (1) can be log-transformed and expressed as the following statistical model:

$$\log[C_{i,j}(Q_j, t_j)] = \log(a_i) + b_i \log(Q_j) - k_i t_j + \varepsilon_{i,j} \quad (2)$$

where

$C_{i,j}(Q_j, t_j)$ is the measured concentration of PCB at location i and time t_j

j is an index over measured data

$\varepsilon_{i,j}$ is the error between the modeled and observed log-concentration of PCB.

The errors are assumed to be independent and normally distributed with mean 0 and variance σ_i^2 . The parameters a_i , b_i and k_i were estimated by least squares regression. The estimates of these parameters are shown in Table 1.

Table 1. Estimated parameters for the Neal's Landfill Site Spring Model, considering different decay rates at each location.

Location	Parameter				Standard Error			Lower Bound For k	Upper Bound For k	Sample Size
	log(a)	a	b	k (y ⁻¹)	log(a)	b	k			
North Spring	2.47	11.88	-0.60	0.06	0.22	0.04	0.02	0.01	0.10	61
South Spring	1.25	3.50	-0.20	0.05	0.21	0.04	0.02	0.01	0.10	62
STF	0.99	2.69	-0.20	0.08	0.15	0.03	0.02	0.04	0.12	126

Note: Upper and lower bounds represent the 95% confidence limits.

Log(a) was estimated by least squares and is reported here with its associated standard error. We also report the value of a, for convenience.

Comparison of the confidence intervals of the decay rates estimated independently for the three sites indicated no statistically significant difference in the value of k , the time trend parameter (Table 1). Therefore, a global decay rate was assumed to be representative of all three sites. Using a global decay rate also gives a more parsimonious parameterization for the spring system.

Estimation of the Global Decay Rate

The subscript for k in Equation (2) can now be dropped, and the equation can be rearranged in terms of the errors ($\varepsilon_{i,j}$) as follows:

$$\varepsilon_{i,j} = \log C_{i,j} - (\log a_i + b_i \log Q_j - kt_j) \quad (3)$$

The errors are assumed to be independent and normal as before. Under this assumption, the likelihood for the i^{th} location is given by the following equation:

$$L_i = \prod_{j=1}^{n_i} \frac{1}{\sigma_i \sqrt{2\pi}} \cdot e^{-\frac{1}{2\sigma_i^2} \{ \log C_{i,j} - (\log a_i + b_i \log Q_j - kt_j) \}^2}$$

$$= \left(\frac{1}{2\pi \cdot \sigma_i^2} \right)^{\frac{n_i}{2}} \cdot e^{-\frac{1}{2\sigma_i^2} \sum_{j=1}^{n_i} \{ \log C_{i,j} - (\log a_i + b_i \log Q_j - kt_j) \}^2} \quad (4)$$

where

L_i is the likelihood of observing the data $C_{i,j}$ given the parameters a_i and b_i

n_i is the number of data points at location i .

The parameters σ_i^2 , k , a_i and b_i were estimated by iteratively maximizing the sum of the log-likelihoods for the three sites as a function of k , i.e., the following equation was maximized for k :

$$\sum_{i=1}^3 l_i(k) = \sum_{i=1}^3 \left[-\frac{n_i}{2} (\log 2\pi + \log \hat{\sigma}_i^2) - \frac{1}{2\hat{\sigma}_i^2} \sum_{j=1}^{n_i} \{ \log C_{ij} - (\log \hat{a}_i + \hat{b}_i \log Q_j - kt_j) \}^2 \right] \quad (5)$$

where l_i is the log-likelihood of location i and $\hat{a}_i$ and $\hat{b}_i$ are least squares estimates of the following linear model:

$$\log C_{i,j} + kt = \log a_i + b_i \log Q_j + \delta_{i,j} \quad (6)$$

where

$\delta_{i,j}$ is independent and normally distributed (since we assume the same for the $\epsilon_{i,j}$'s)

and:

$$\hat{\sigma}_i^2 = \frac{1}{n_i} \sum_{j=1}^{n_i} \{ \log C_{i,j} - (\log \hat{a}_i + \hat{b}_i \log Q_j - kt_j) \}^2 \quad (7)$$

The relationship between the sum of log-likelihoods and k is shown in Figure 5³. A value of 0.06 per year maximized the sum of the log-likelihood functions for the three sites. This was chosen as the conditional maximum likelihood estimate of k , that is, our best estimate of the rate of natural recovery in the springs. The estimated parameters for a , b , and σ for each spring system at the Neal's Landfill Site are presented in Table 2.

³ Note that Figure 5 does not provide an indication of how confident we are that the true decay rate is equal to the modeled decay rate. It is used purely in optimization: the parameters exhibiting the maximum value of the cumulative log-likelihood is likely to provide the best representation of the data. Uncertainty is dealt with in the bootstrap analysis.

Table 2. Estimated parameters for the Neal's landfill site spring model.

Location	Parameter			
	a	b	k (y ⁻¹)	σ
North Spring	12.03	-0.60	0.06	0.27
South Spring	3.59	-0.20	0.06	0.26
STF	2.57	-0.20	0.06	0.34
<i>Note: The value of k represents the value for which the sum of log-likelihoods for the three sites was maximized. See figure 5.</i>				

Analysis of Diagnostics

The residuals (equal to the difference between the data and the model) were analyzed to determine if the assumptions for regression were met (Figure 6). Plots of residuals versus modeled PCB concentration values showed no correlation (top left panel). Plots of residuals against flow and time showed no consistent patterns. This means that the variance is stable, i.e., that the residuals do not vary with flow or time. The normal probability plots in Figure 6 do not show any substantial deviation from linearity, which indicates that the errors are approximately normally distributed. Thus, these assumptions of the regression model are met, thereby supporting the validity of the regression model.

The relationships between PCB levels and flow are shown for each year of record in Figure 7. This figure is the same as Figure 3 with the addition of model results. The goal of this figure is to highlight the relationship between PCB concentration and flow. The impact of time within the year is not substantial: in each panel, three curves (solid, dashed and dotted), representing PCB concentrations computed for January 1, mid-year and December 31 of the specified year, lie close together. In general, the fitted model appears to capture the relationship with flow.

Figure 8 presents the relationship between measured values and the model estimate for each data value. In general, the model exhibits no overall bias: values are scattered above and below the 1:1 line (solid line in Figure 8).⁴ Nearly all estimated values lie within 25% of the data for NS and SS, and within 50% of the data for STF (dotted lines in Figure 8).

Several potential refinements to the model were explored:

- A term for seasonality was introduced by considering the time elapsed since the spring peak.
- 2-day and 3-day moving averages of the daily average flows were considered in lieu of the actual daily average flows.

⁴ The slope of the scatter in Figure 8 is shallower than the 1:1 line. This is the regression effect and is not an indication of model inadequacy.

- Weighted least squares (WLS) was performed. The residuals were regressed against the natural log of observed PCB levels, and the weights for WLS were estimated as the inverse of the squared estimated residual.
- Temperature was considered as an additional regressor to incorporate seasonal effects that are not accounted by flow.
- The relationship between TSS and PCBs was studied by examining scatter plots of PCBs vs. TSS, and residuals (using the current model) vs. TSS. Neither of these plots indicated a perceptible relationship between TSS and PCB.
- Cave excavation activity in fall 2004 and summer 2005 was suspected to mobilize additional PCBs into the stream. The impact of cave activity was studied by selectively excluding data that were suspected to have been impacted by cave activity, based on the dates of this activity and the dates of sampling⁵.

None of these refinements changed the conditional MLE of the decay rate, with the exception of the last case, exclusion of some data based on cave activity. Thus, the inclusion of the above-mentioned factors (except the last) did not improve the model. When select data based on cave activity was excluded, the conditional MLE decay rate changed slightly from 6.25% to 6.58%, which round to 6% and 7%, respectively. However, since it is unclear what the real impact of cave activities may be, the 6% decay rate based on the total expanded data set is at this time considered to be the most reasonable estimate of the rate of natural recovery in the springs, since it is based on the largest data set.

A Confidence Interval for the Global Decay Rate

The bootstrap method was used to obtain the uncertainty in the estimated decay rate. Computation of a 95% bootstrap confidence interval for the global decay rate was accomplished by obtaining 1000 bootstrap resamples of the data, estimating k for each resample (using the maximization process), and then finding the 25th and 975th values of the ordered estimates. A bootstrap resample consisted of random samples with replacement from the data set for each location. The size of a random sample was the same as the size of the original location data set.

The histogram of the 1000 bootstrap estimates of k is shown in Figure 9. The 25th and 975th of the sorted results were used to estimate the 95% confidence interval for the estimated value of k . The median value (500th of the sorted results) was 0.06, the same as the conditional maximum likelihood estimate. The 95% confidence interval ranged from 0.04 to 0.09. Thus, the 95% confidence interval does not include a value of 0 (i.e., no recovery), indicating that, given these data, it is unlikely that PCB levels in the Neal's Landfill springs are not recovering.

⁵ The excluded dates were: 9/30/05, 8/3/05, 7/21/05, 11/17/04, and 10/6/04 for NS and SS; 9/8/05, 8/3/05, 7/20/05, 11/17/04 and 10/6/04 for STF

Uncertainty in the Model Estimates

The 1000 bootstrap estimates of the model parameters were used to provide 1000 model estimates of PCB concentrations for each data value (that is, 1000 model predictions were made using the flow and date of collection associated with each PCB measurement). The 95% confidence intervals of the model estimates for each value in the data set are represented by the red bars shown in Figure 10. The model clearly reflects the seasonal patterns in the data and represents the central tendency of the data for each year realistically. While it tends to underestimate the highest values and overestimate the lowest values at SS and STF, the ability of the model to capture the average is the essential requirement, and in this the model succeeds at all three locations.

Model Projections

Projected PCB concentrations from 2001 through 2020, in NS, SS and STF for the average flow rate of 455 gallons per minute (GPM), are illustrated in Figure 11. These projections are meant to be illustrative of future trends under average conditions. The three lines in Figure 11 for each of the spring were calculated by setting the decay rate to the lower bounds, median and upper bound bootstrap estimates (0.04, 0.06, and 0.09 per year). The least squares estimates of a and b appropriate for each value of k were used in the projections.

Conclusions

The best estimate of rate of natural recovery of PCB concentrations in the spring system of Neal's Landfill is 0.06 per year. The uncertainty analysis demonstrates that a value of $k = 0$ lies outside of the 95% confidence interval (0.04 to 0.09 per year), and thus it is unlikely that there is no recovery in the system. While there is some uncertainty as to what is the most representative data set, due to cave exploration activities, it is reasonable to assume that the conditional MLE would be at least 6% had cave activities not occurred and thus this estimate is likely conservative.

The next step in the analysis is to quantify the relationship between trends in PCB concentrations in the spring system and trends in PCB concentrations in the sediments, water and fish of Conard's Branch and Richland Creek. This will be performed using the mechanistic simulation model that has been developed for this system.

Appendix

Tables A1 and A2 include the data used in the analyses discussed herein. These data were collected by Viacom during the period from January 1, 2001 to March 15, 2006. These data are provided on the attached spreadsheet.

Table A1. Data used in the analysis: North and South Springs

Total NW spring flow (GPM)	Sampling Date	PCB Concentration (ppb)	
		North Spring	South Spring [#]
457	2/27/2001	0.23	0.81
253	3/21/2001	0.31	0.93
278	4/11/2001	0.63	1.4
72	5/15/2001	1.1	1.55
102	6/14/2001	-	1.15
96	7/27/2001	0.89	1.55
60	8/16/2001	0.79	1.45
77	9/14/2001	1.1	1.8
245	10/19/2001	0.57	1.35
94	11/15/2001	0.78	1.25
177	1/3/2002	0.56	0.82
125	1/22/2002	0.39	0.59
251	2/13/2002	0.42	1
685	3/14/2002	0.22	0.96
541	4/11/2002	0.2	0.71
355	5/21/2002	0.3	0.85
162	6/11/2002	0.54	1.01
67	7/17/2002	0.71	1.45
47	8/8/2002	1.2	1.35
35	9/4/2002	1.1	1.8
30	10/10/2002	1.6	1.9
159	11/12/2002	0.82	2.5
40	12/3/2002	1.3	1.75
185	1/10/2003	0.58	1.6
100	2/7/2003	0.63	1.55
467	3/17/2003	0.24	0.95
232	4/10/2003	0.36	0.92
560	5/14/2003	0.18 ⁺	0.69
103	6/2/2003	0.66	1.25
66	7/9/2003	0.68	1.1
147	8/5/2003	0.75	1.45
90	9/9/2003	0.67	1.25
36	10/8/2003	1.2	1.3

65	11/5/2003	0.86	1.2
296	12/8/2003	0.35	1.05
291	1/14/2004	0.42	1.3
421	2/13/2004	0.34	0.89
402	3/9/2004	0.2	0.81
148	4/19/2004	0.35	1.15
153	5/5/2004	0.26	0.87
232	6/4/2004	0.43	0.92
75	7/16/2004	0.43	0.81
67	8/6/2004	0.56	0.96
45	9/9/2004	0.88	1.1
29	10/6/2004	1.4	1.85
103	11/17/2004	0.82	1.4
256	12/16/2004	0.45	1.55
442	1/19/2005	0.16	0.74
265	2/11/2005	0.32	0.89
260	3/8/2005	0.41	1.15
313	4/11/2005	0.26	0.875
203	5/3/2005	0.24	0.585
106	6/7/2005	0.46	0.92 ⁺
67	7/21/2005	0.92	1.45
53	8/3/2005	0.78	0.71 ⁺
143	9/30/2005	0.78	1.15
38	10/30/2005	0.83	1.2
278	11/18/2005	0.68	1.4
99	12/6/2005	0.74	1.3
645	1/16/2006	0.17	0.72
412	2/8/2006	0.27	0.59
137	3/6/2006	0.4	0.92

[#] Replicates were available for South spring. The values presented here are average of replicates.

⁺ Represents estimated value.

Table A2. Data for spring treatment facility used in the analyses

Total NW Flow (GPM)	Sampling Date	PCB Concentration (ppb)
160	1/3/2001	0.92
374	1/17/2001	0.62
336	2/7/2001	0.74
293	2/21/2001	0.59
272	3/7/2001	0.64
171	3/21/2001	0.47

108	4/4/2001	1
218	4/18/2001	0.75
98	5/2/2001	0.93
71	5/16/2001	1.4
584	6/6/2001	1.1
136	6/20/2001	1.3
987	7/4/2001	0.8
144	7/18/2001	0.79
186	8/1/2001	0.85
82	8/15/2001	1.2
58	9/5/2001	1.5
71	9/19/2001	1.4
40	10/3/2001	1.3
450	10/17/2001	1
145	11/7/2001	0.87
84	11/21/2001	1.1
131	12/5/2001	1
587	12/19/2001	0.5
196	1/2/2002	0.59
148	1/16/2002	0.74
230	2/14/2002	0.86
2065	2/20/2002	1.4
524	3/6/2002	0.71
2113	3/20/2002	0.59
722	4/3/2002	0.42
798	4/17/2002	0.42
641	5/1/2002	0.32
961	5/15/2002	0.51
5608	6/5/2002	1.2
167	6/19/2002	0.48
79	7/3/2002	0.97
67	7/17/2002	1.2
47	8/7/2002	1.4
38	8/21/2002	1.1
34	9/4/2002	1.3
34	9/18/2002	1.1
46	10/2/2002	1.6
24	10/16/2002	1.8
61	11/6/2002	1.6
52	11/20/2002	1.1
34	12/4/2002	1.6
138	12/18/2002	1.7
2568	1/1/2003	0.45
112	1/15/2003	1.2

120	2/5/2003	0.2
300	2/19/2003	1
2204	3/5/2003	0.28
436	3/19/2003	0.73
419	4/2/2003	0.76
166	4/16/2003	0.61
818	5/7/2003	0.49
228	5/21/2003	0.57
103	6/4/2003	0.84
218	6/18/2003	0.6
87	7/2/2003	0.89
346	7/16/2003	1.1
159	8/6/2003	0.83
57	8/20/2003	0.8
286	9/3/2003	1.4
59	9/17/2003	0.88
59	10/1/2003	0.77
115	10/15/2003	1.4
62	11/5/2003	0.83
1202	11/19/2003	0.55
257	12/3/2003	0.56
507	12/17/2003	0.63
833	1/7/2004	0.63
317	1/21/2004	0.66
269	2/4/2004	0.58
375	2/18/2004	0.75
537	3/3/2004	0.57
274	3/17/2004	0.46
342	4/7/2004	0.52
143	4/21/2004	0.7
161	5/5/2004	0.53
127	5/19/2004	0.7
327	6/2/2004	0.66
935	6/16/2004	0.31
192	7/7/2004	0.93
92	7/23/2004	0.7
79	8/4/2004	0.98
50	8/18/2004	1
59	9/1/2004	0.77
34.89	9/15/2004	1
28.04	10/6/2004	1.2
64.26	10/20/2004	1.3
454.8	11/3/2004	0.97
102.75	11/17/2004	1.1

1077.93	12/1/2004	0.54
220.24	12/15/2004	0.79
10583	1/5/2005	0.23
437	1/19/2005	0.53
160	2/2/2005	0.6
629	2/16/2005	0.38
274	3/2/2005	0.4
157	3/16/2005	0.47
350	4/6/2005	0.4
220	4/20/2005	0.48
254	5/4/2005	0.45
271	5/18/2005	0.52
122	6/1/2005	0.75
369	6/15/2005	0.64
71	7/6/2005	0.73
55	7/20/2005	0.72
53	8/3/2005	0.62
60	8/17/2005	0.52
64	9/7/2005	0.49
73	9/21/2005	0.95
78	10/5/2005	0.79
47	10/19/2005	0.83
46	11/2/2005	1.1
901	11/16/2005	0.85
87	12/7/2005	1.1
124	12/21/2005	0.74
612	1/4/2006	0.67
877	1/18/2006	0.39
348	2/1/2006	0.68
196	2/15/2006	0.67
156	3/1/2006	0.74
1066	3/15/2006	0.59

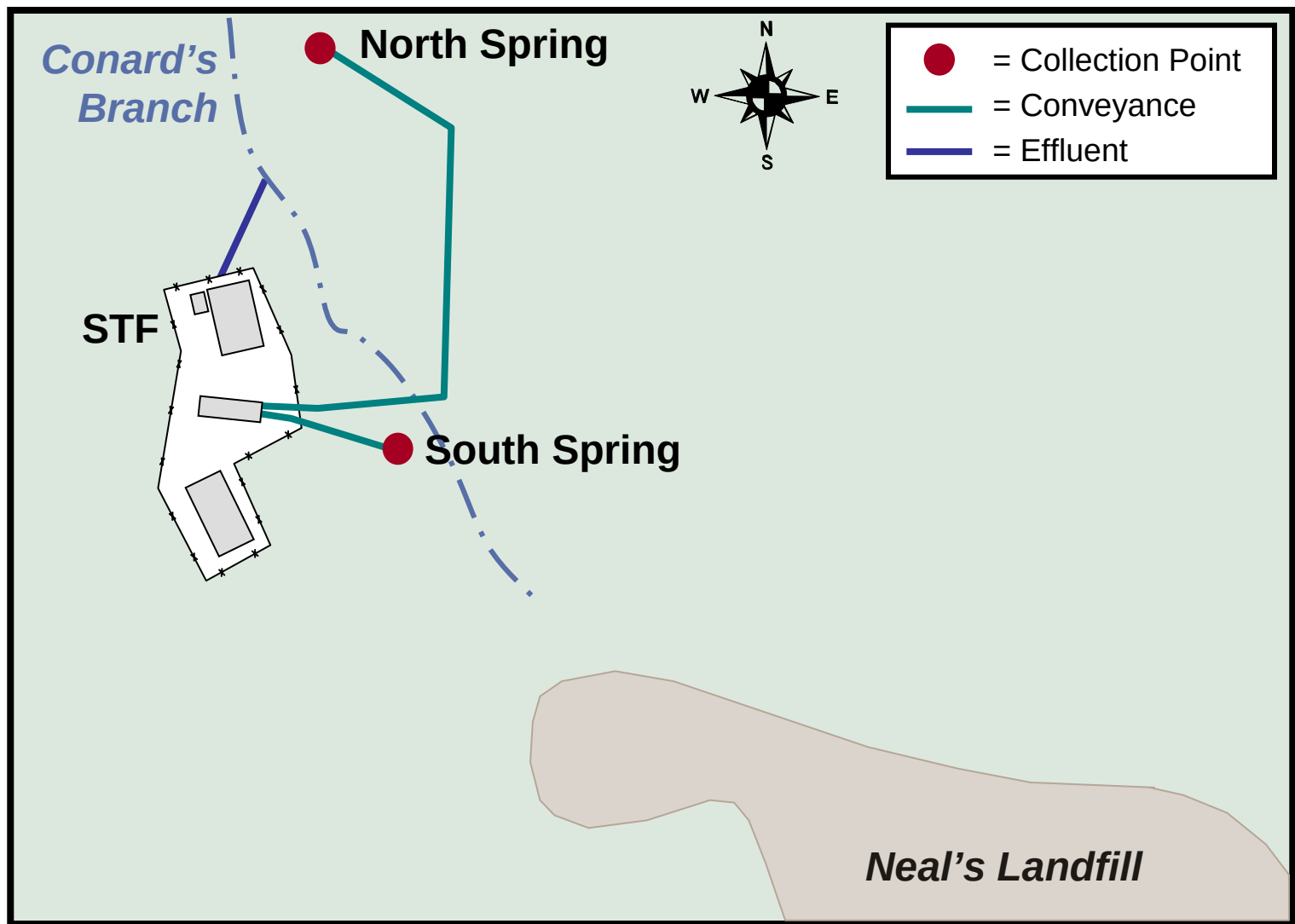


Figure 1. Site map.

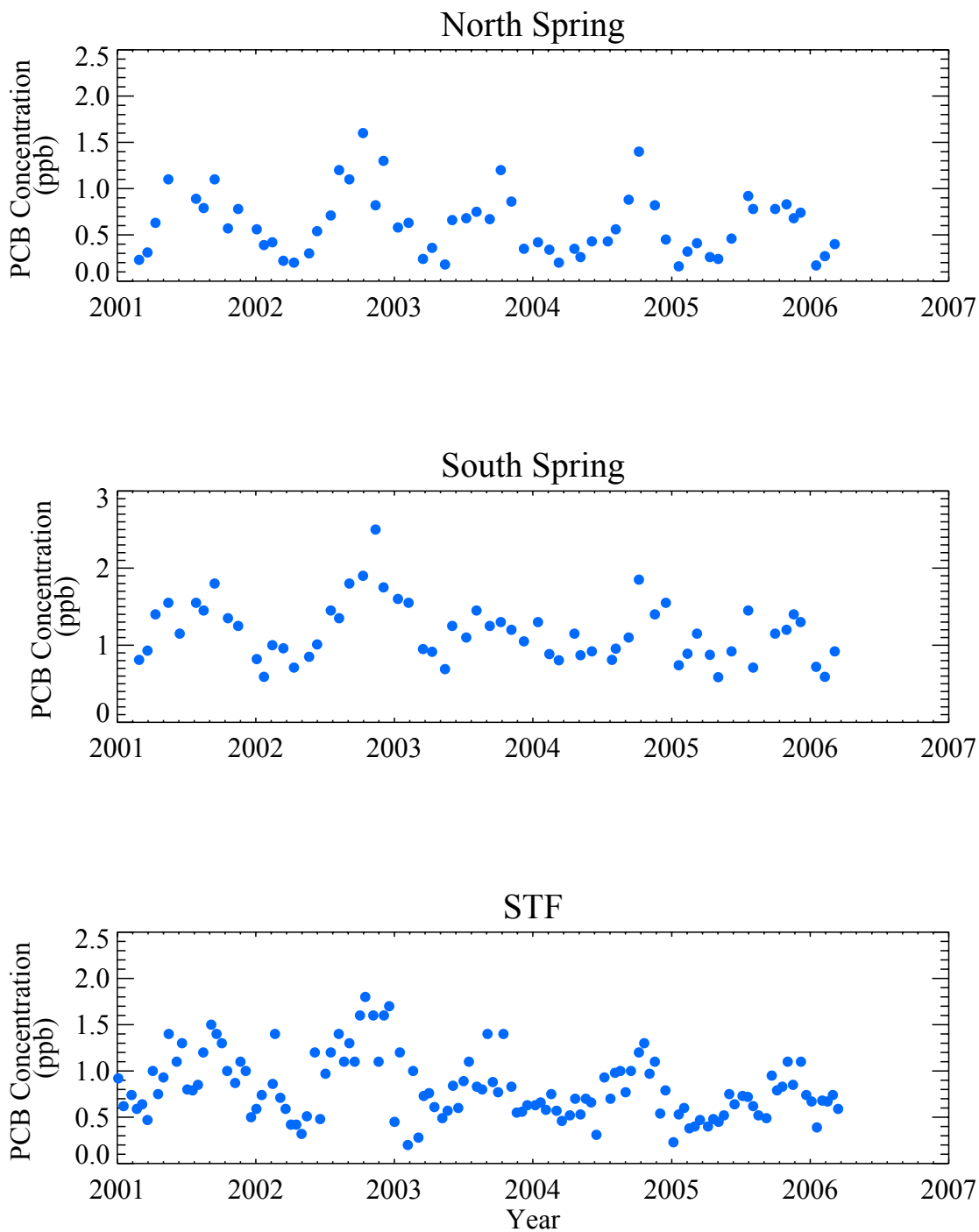


Figure 2. Measured PCB concentrations in the springs of the Neal's landfill site.

Data measured between 1/ 1/2001 and 3/15/2006.

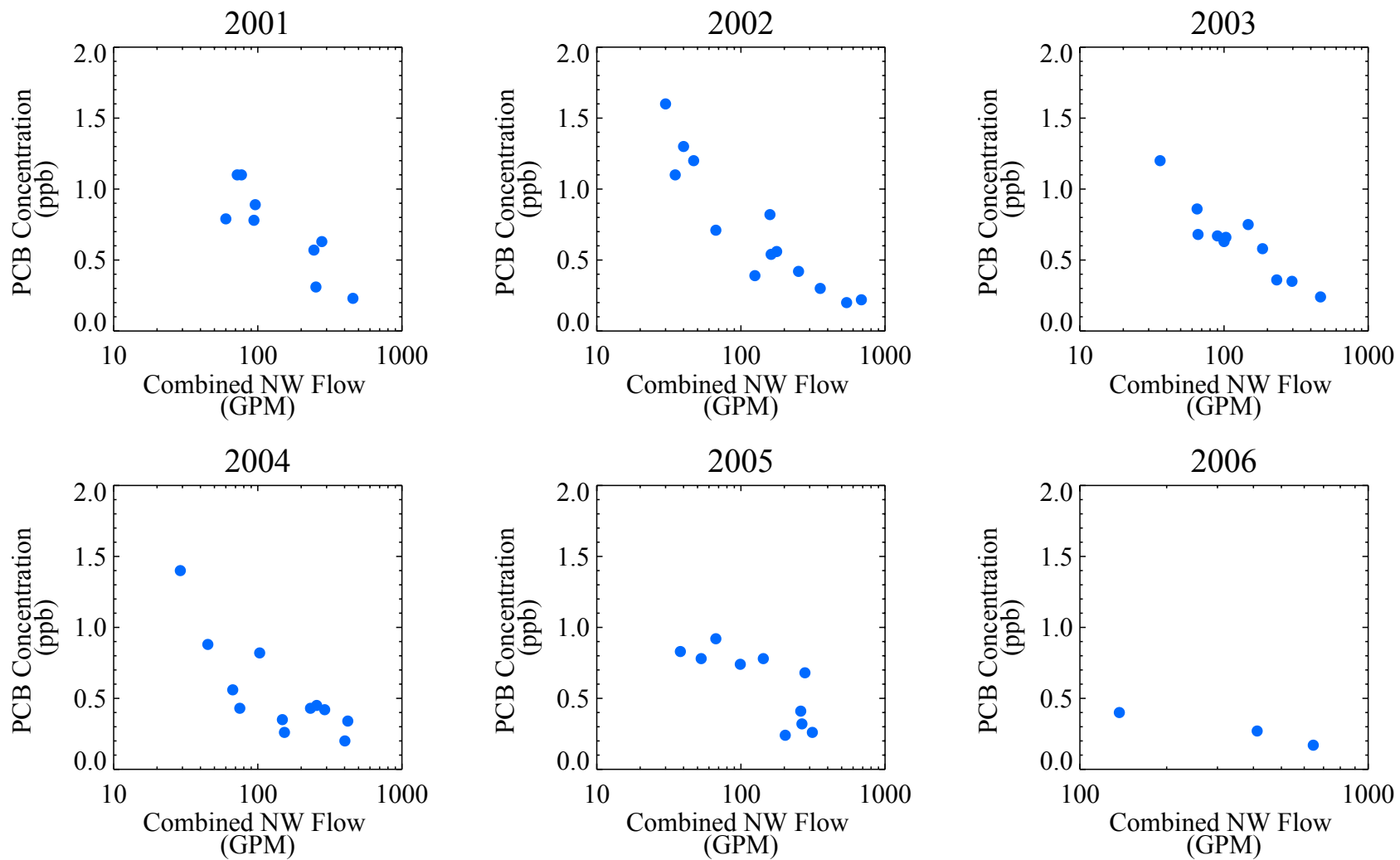


Figure 3a. Annual plots of PCB levels vs. combined NW flow for North spring

Data measured between 1/1/2001 and 3/15/2006

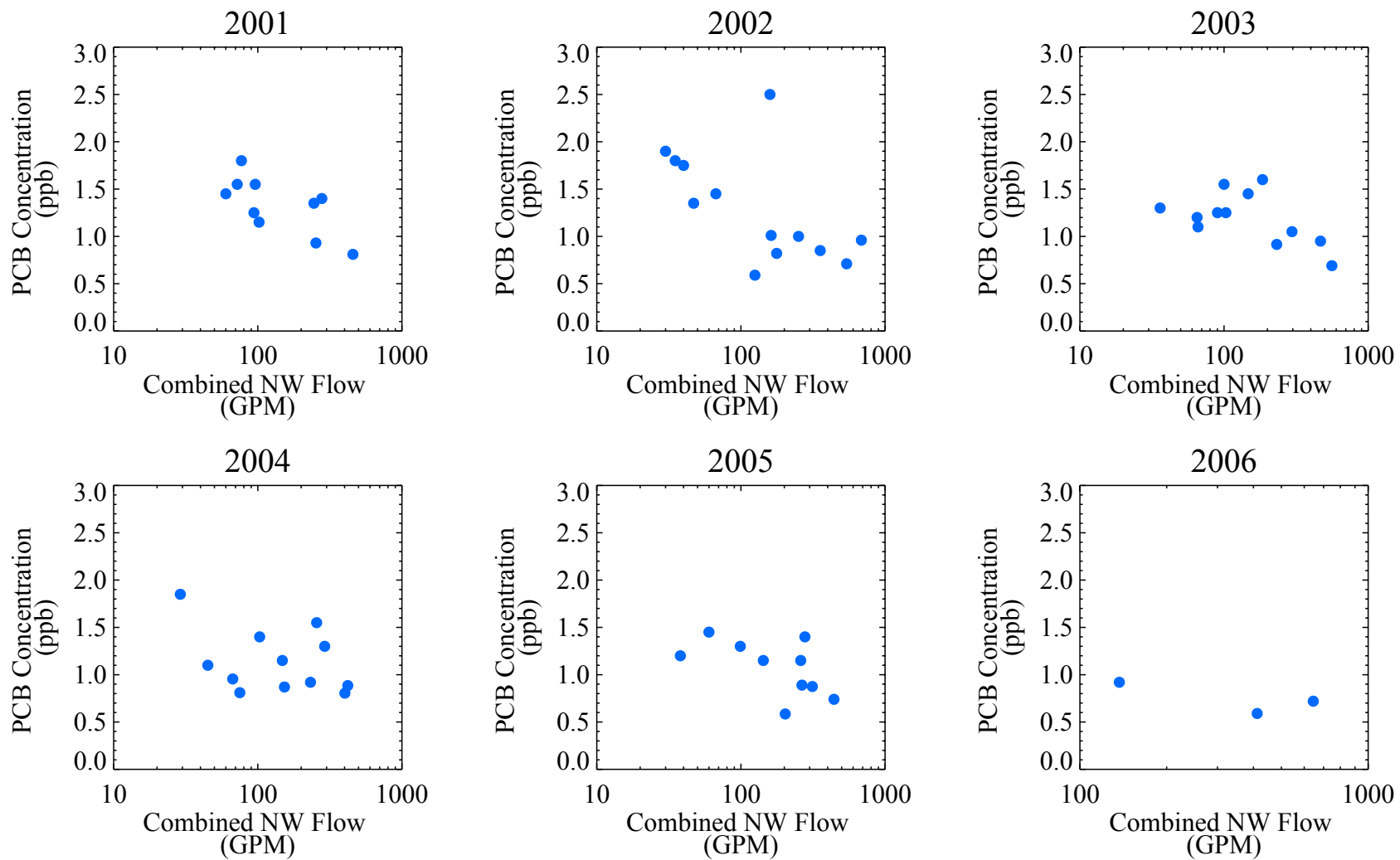


Figure 3b. Annual plots of PCB levels vs. combined NW flow for South spring

Data measured between 1/1/2001 and 3/15/2006

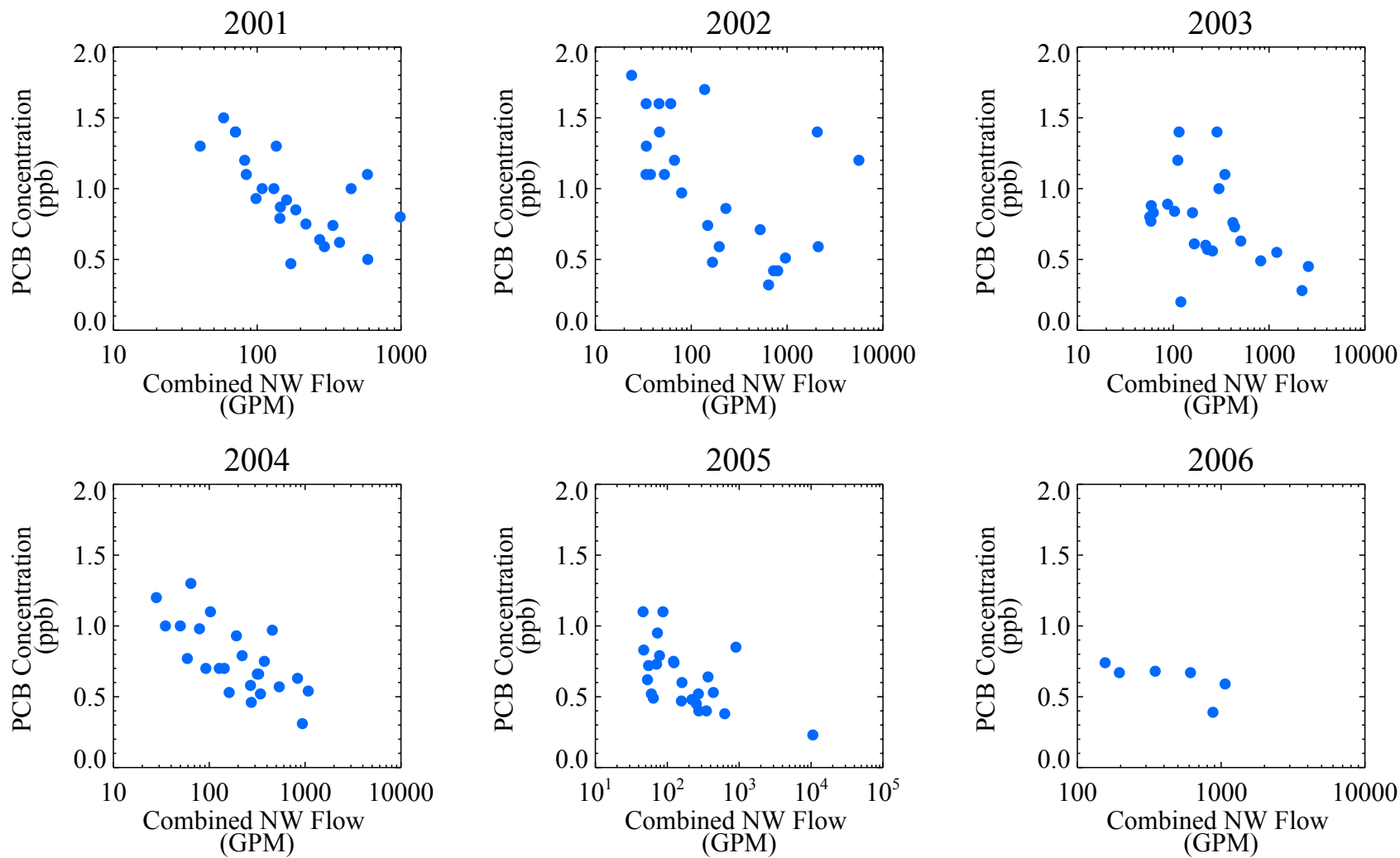
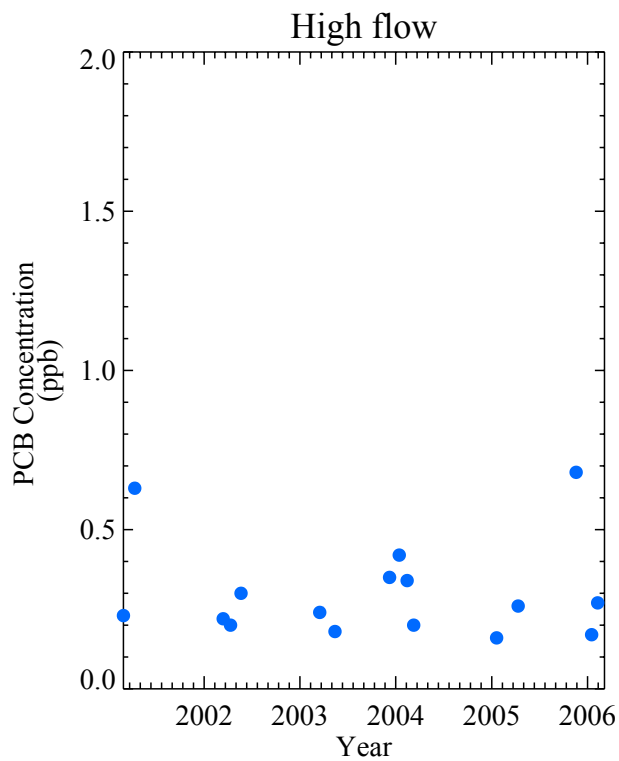
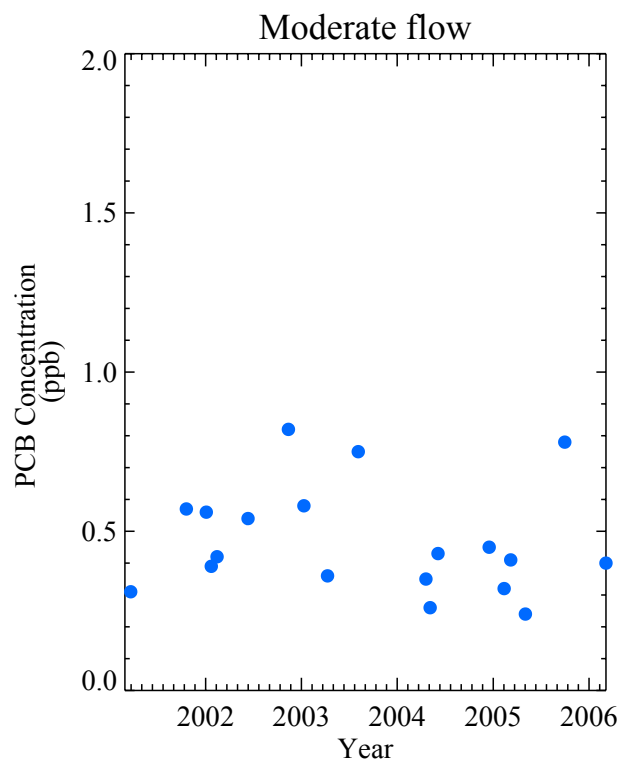
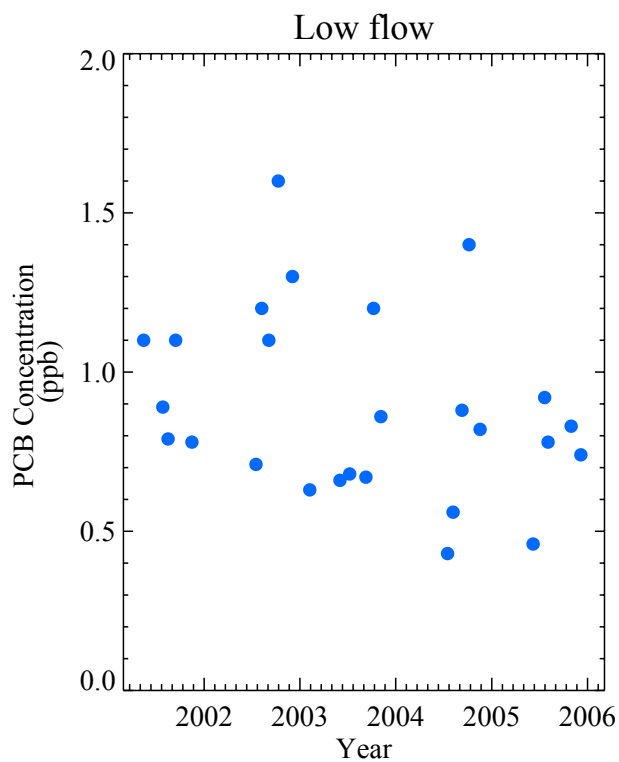


Figure 3c. Annual plots of PCB levels vs. combined NW flow for STF

Data measured between 1/1/2001 and 3/15/2006



Time Series Plots of Flow and PCB Levels

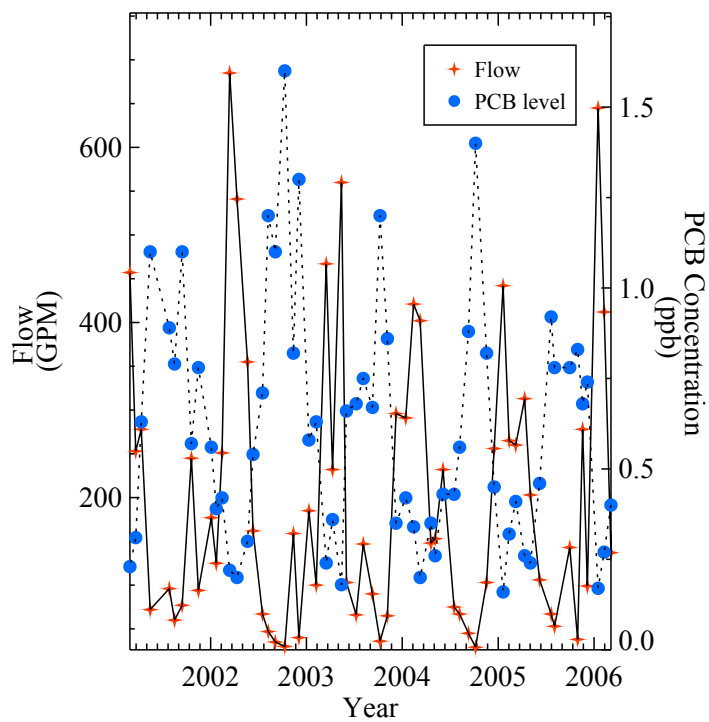
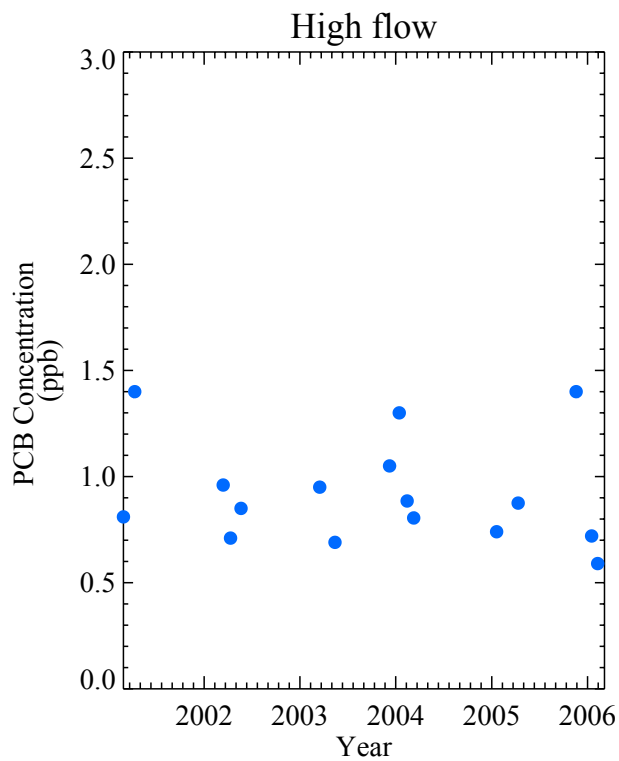
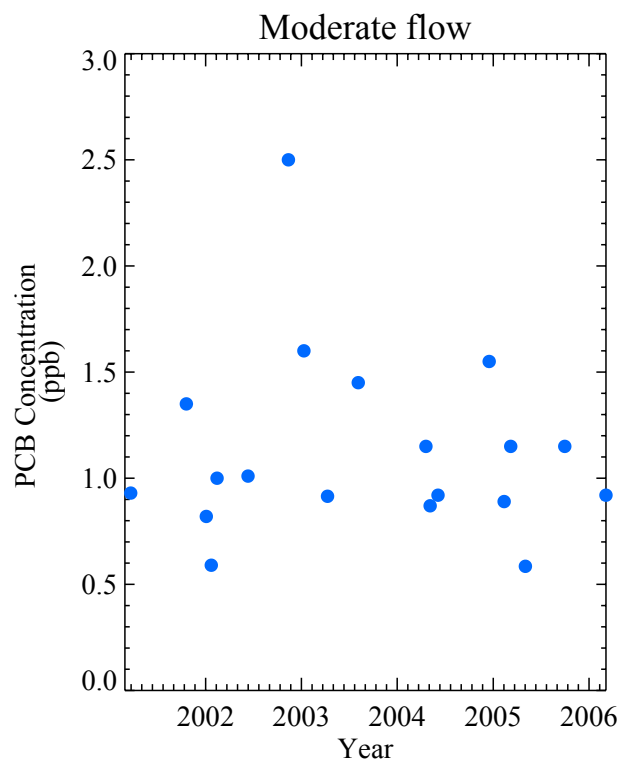
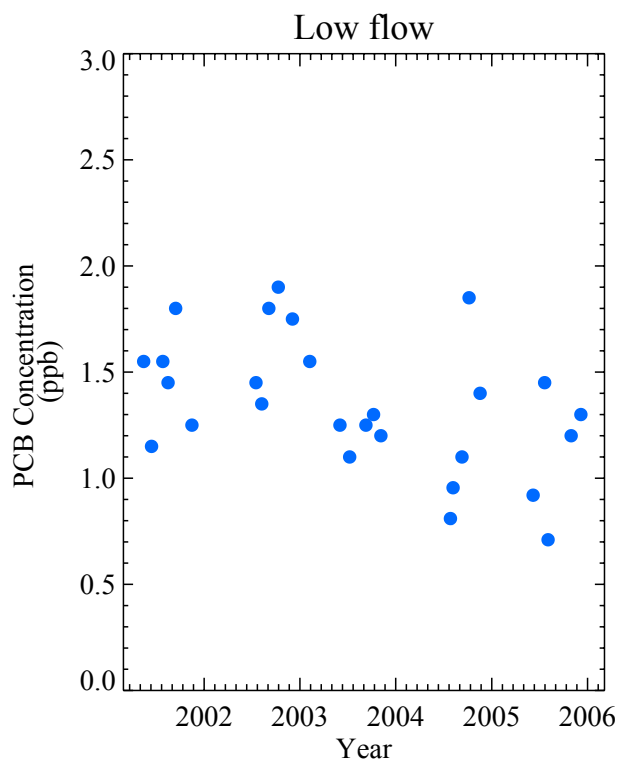


Figure 4a. Scatter plots of data for North spring

Data measured between 1/1/2001 and 3/15/2006

Low flows lie below 110 GPM, high flows lie above 270 GPM and moderate flows lie within this range.



Time Series Plots of Flow and PCB Levels

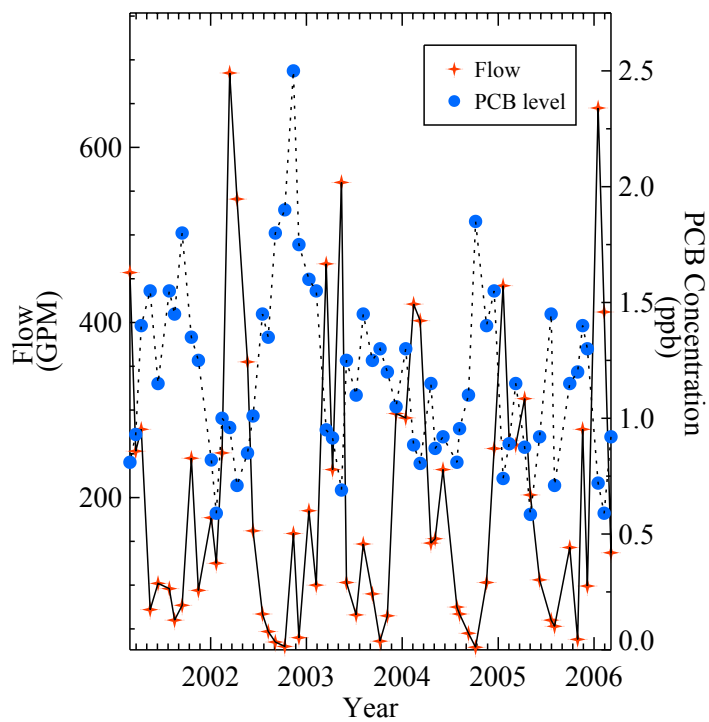


Figure 4b. Scatter plots of data for South spring

Data measured between 1/1/2001 and 3/15/2006

Low flows lie below 110 GPM, high flows lie above 270 GPM and moderate flows lie within this range.

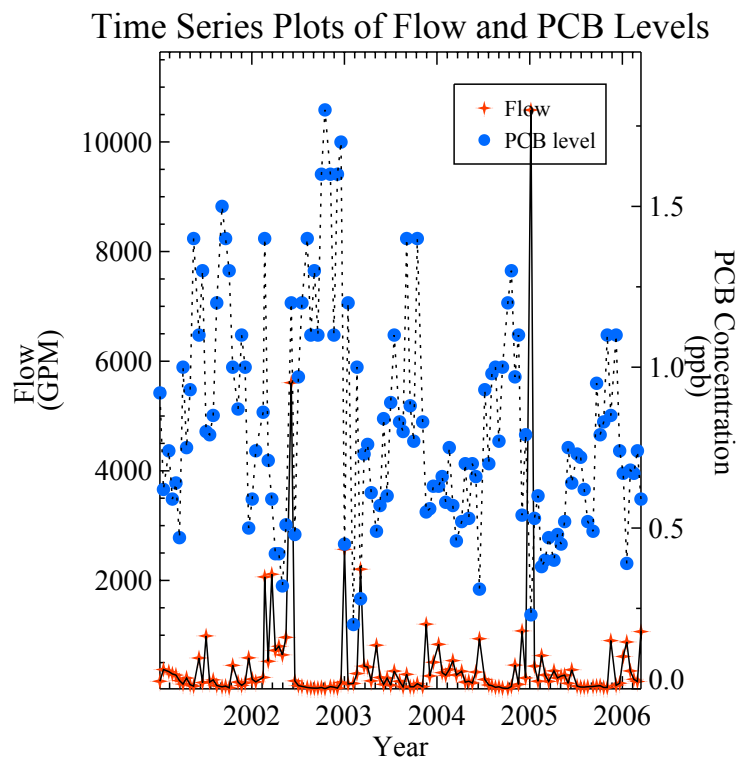
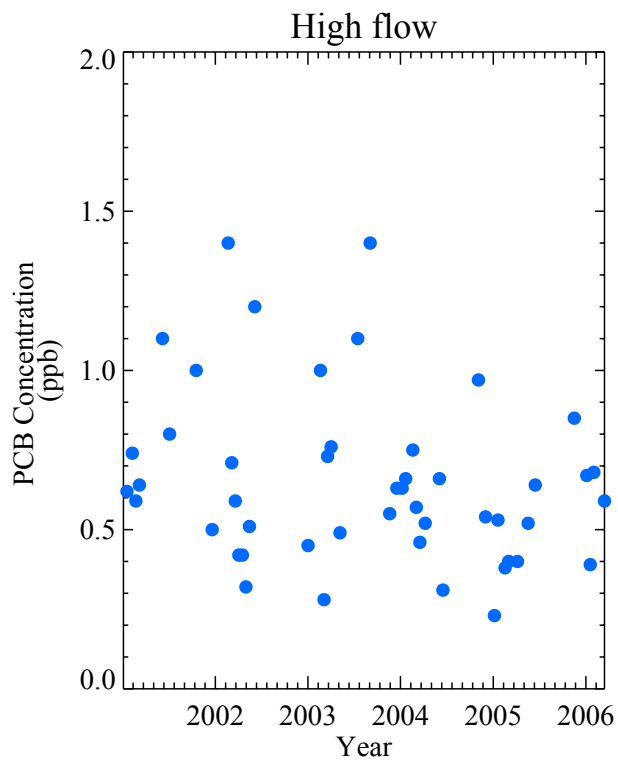
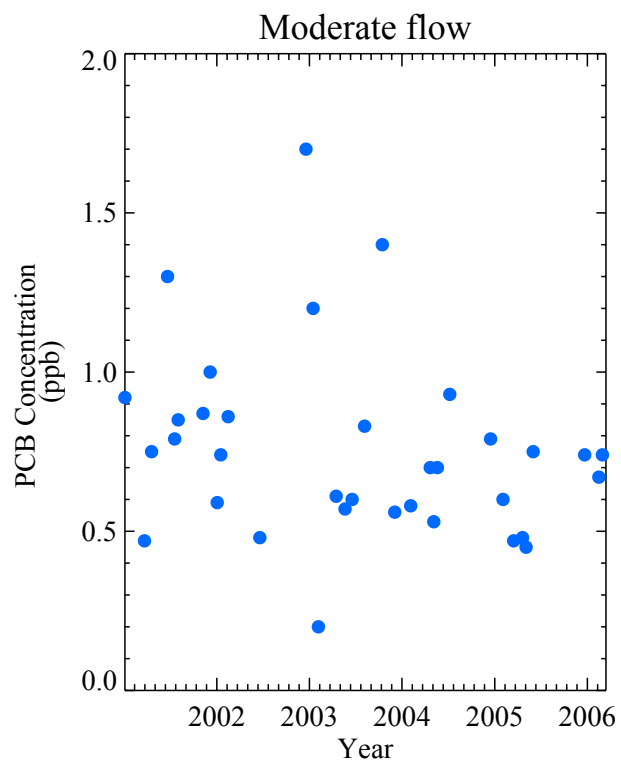
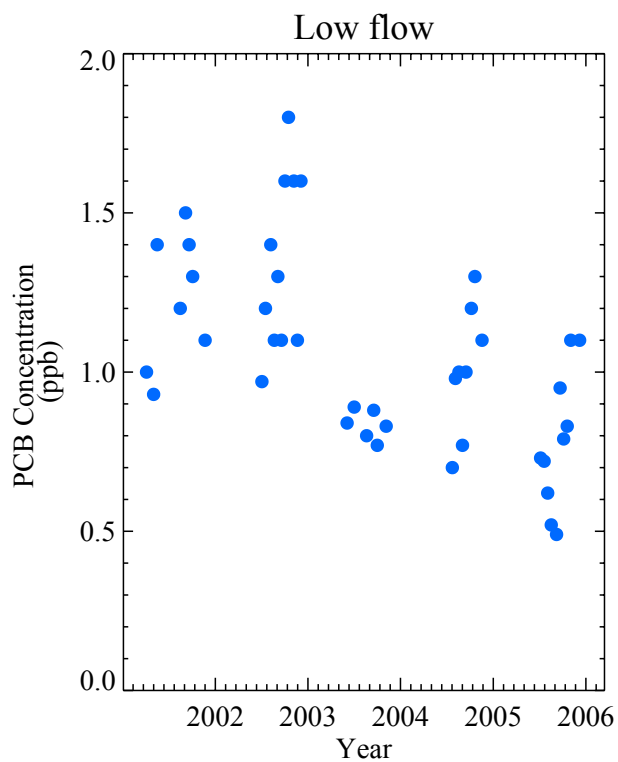


Figure 4c. Scatter plots of data for STF

Data measured between 1/1/2001 and 3/15/2006

Low flows lie below 110 GPM, high flows lie above 270 GPM and moderate flows lie within this range.

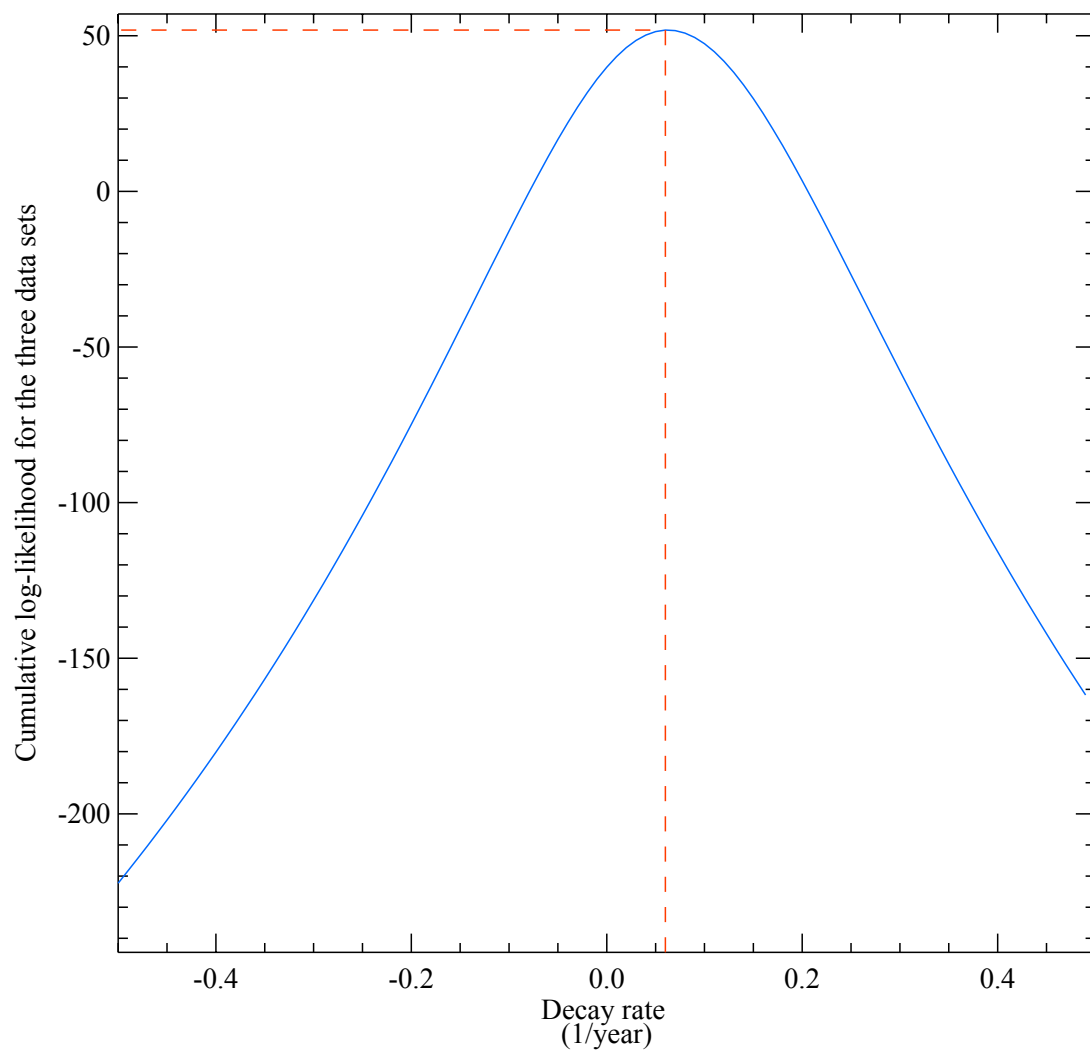


Figure 5. Cumulative log-likelihood of the three data sets as a function of the decay rate.

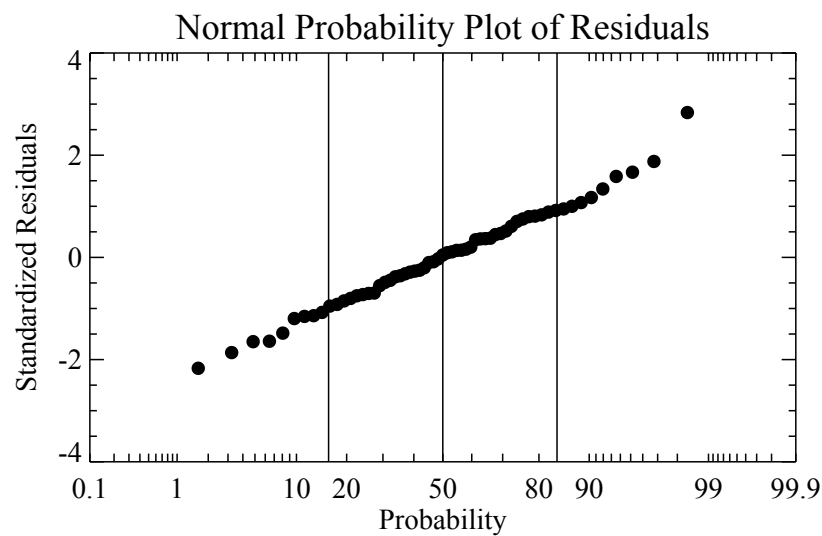
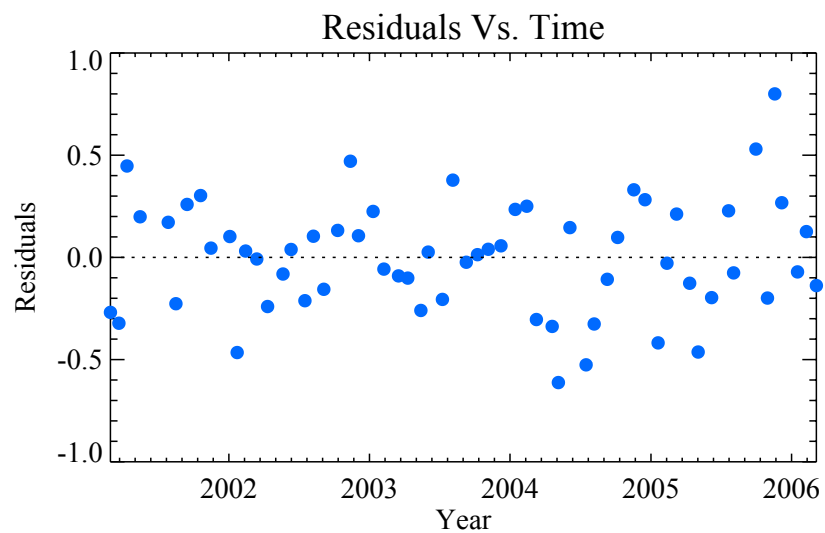
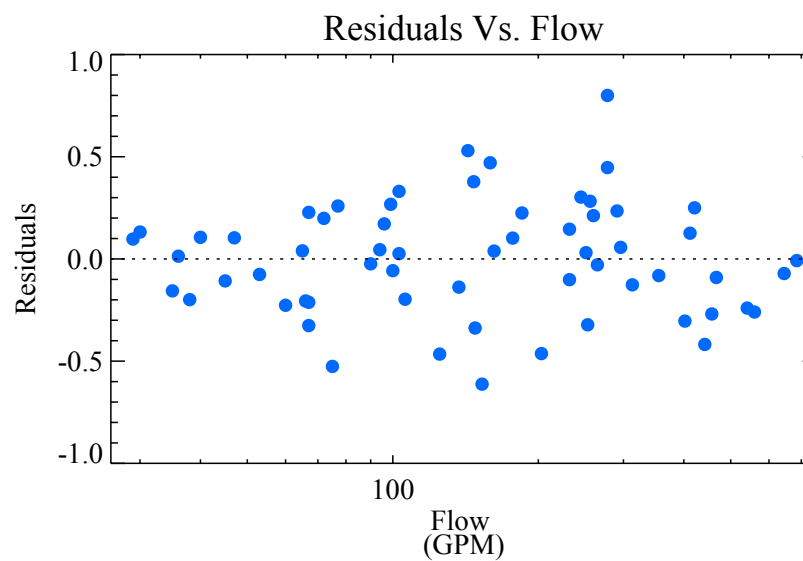
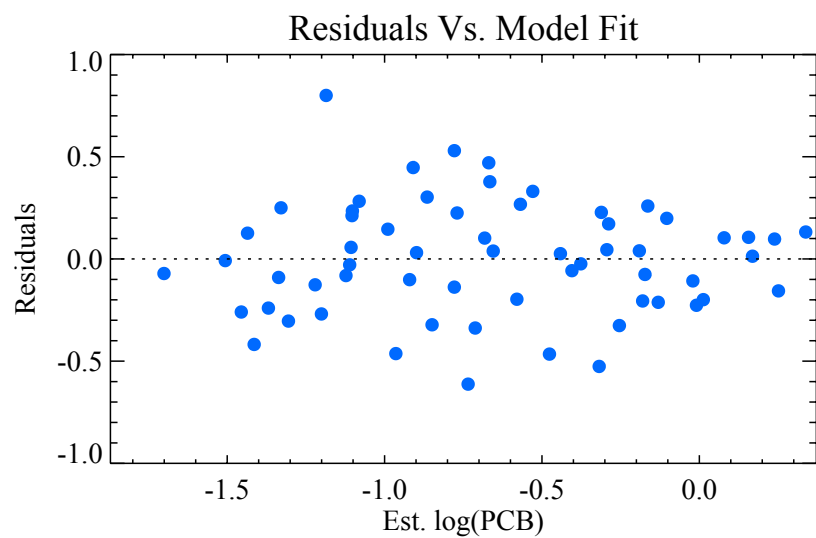


Figure 6a. Diagnostic plots for the fitted model for North spring

Data measured between 1/1/2001 and 3/15/2006. Parameters were estimated based on data measured through 3/15/2006.

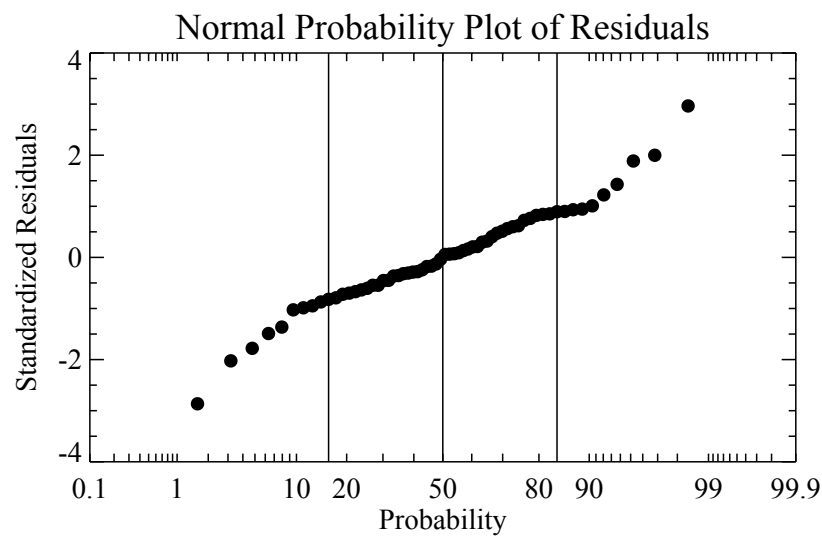
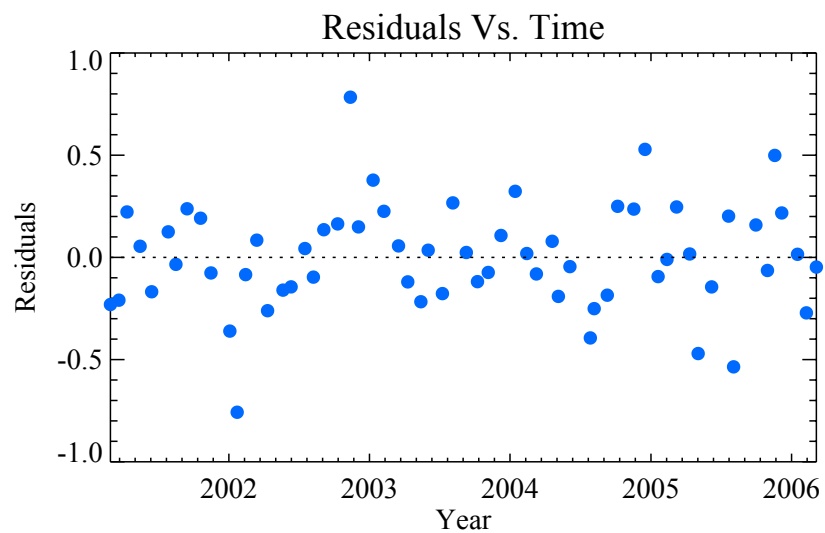
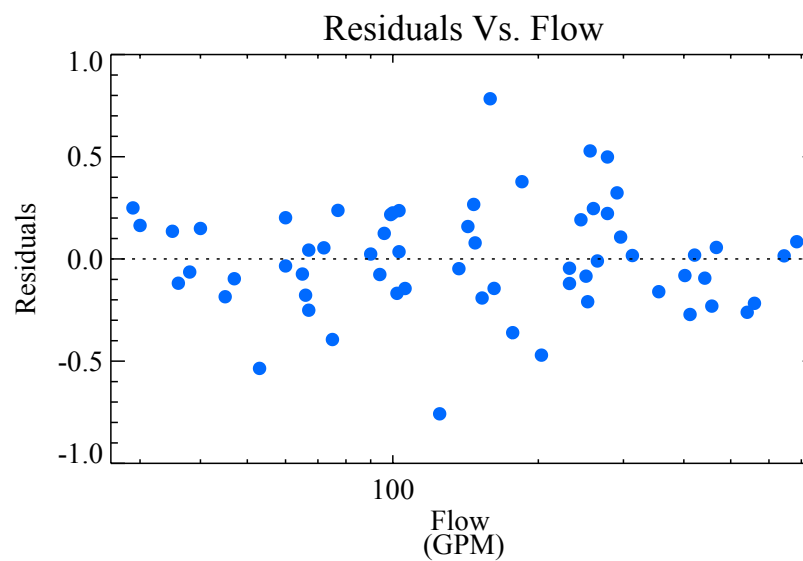
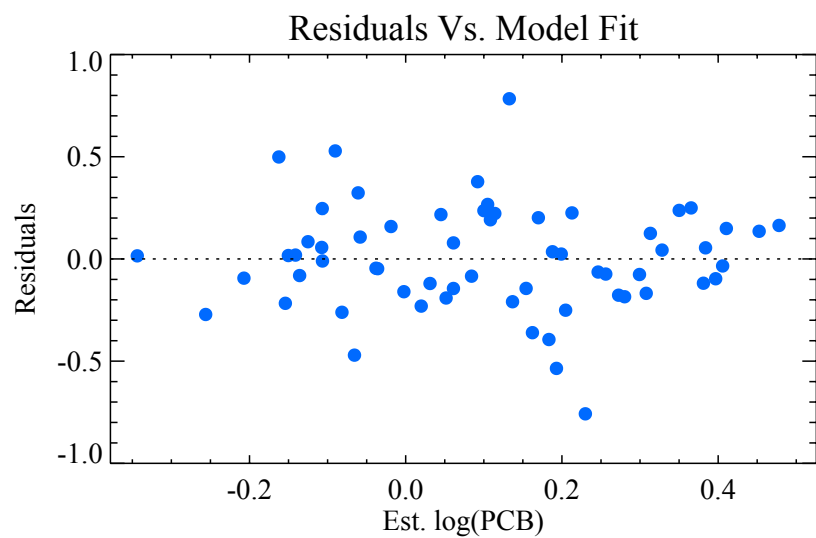


Figure 6b. Diagnostic plots for the fitted model for South spring

Data measured between 1/1/2001 and 3/15/2006. Parameters were estimated based on data measured through 3/15/2006.

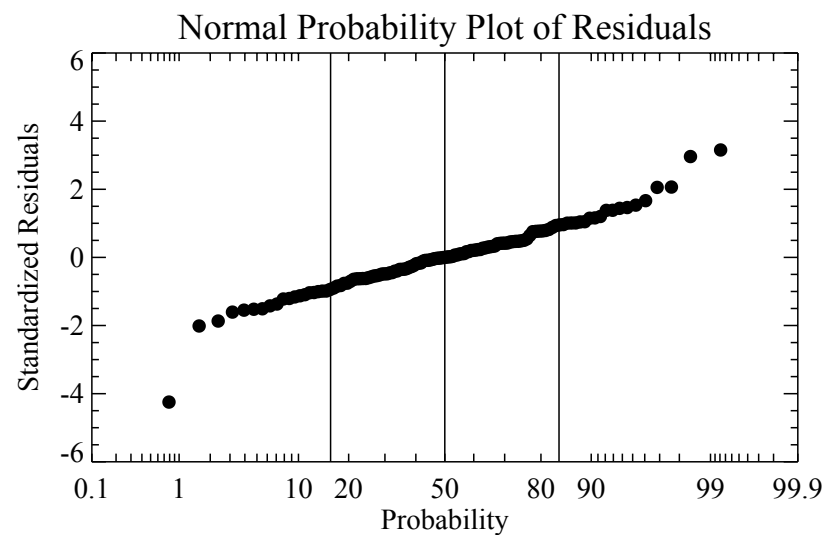
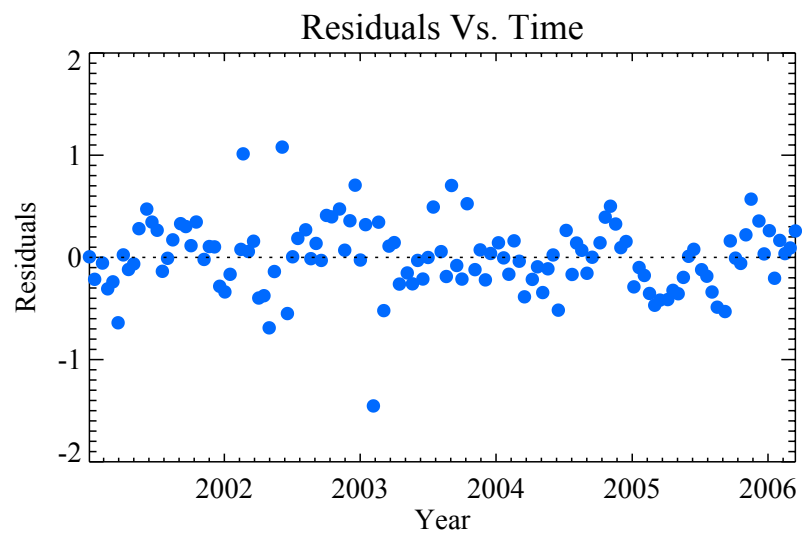
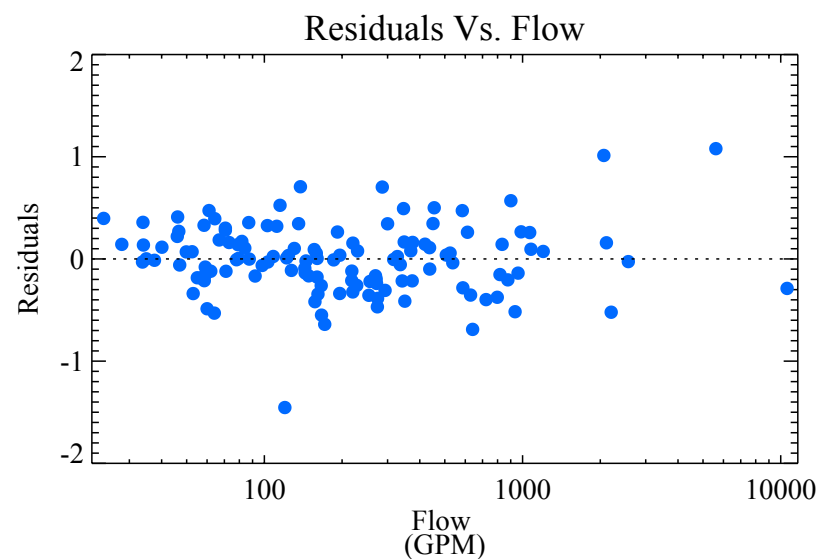
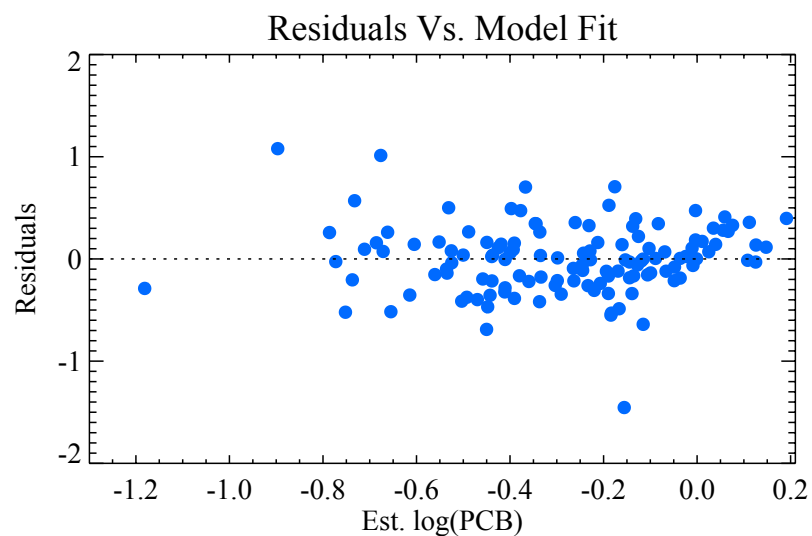


Figure 6c. Diagnostic plots for the fitted model for STF

Data measured between 1/1/2001 and 3/15/2006. Parameters were estimated based on data measured through 3/15/2006.

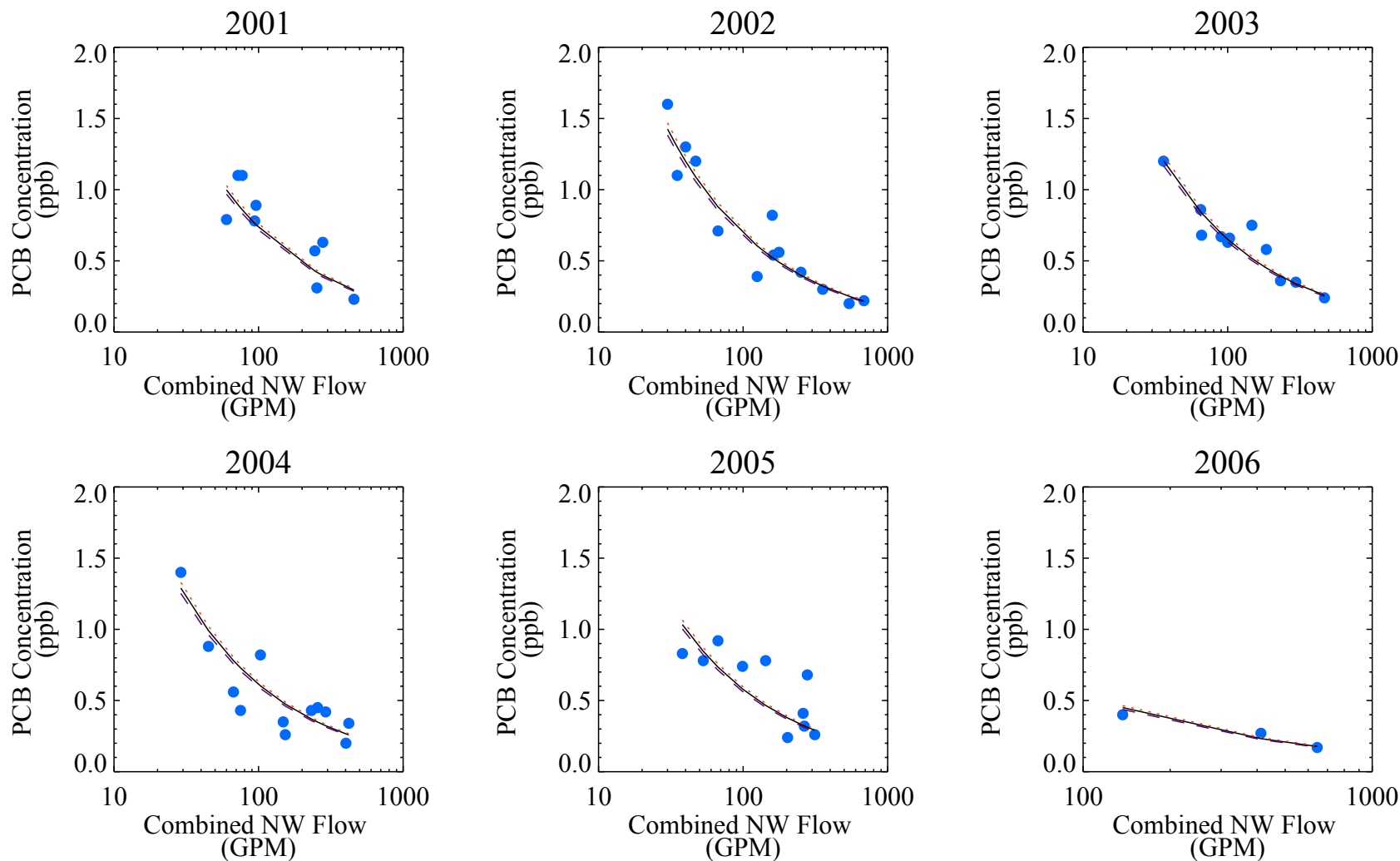


Figure 7a. Annual plots of PCB levels vs. combined NW flow for North spring

Data measured between 1/1/2001 and 3/15/2006. All measured data (through 3/15/2006) were used in estimating the parameters

Blue dots represent measured data. Fits shown here were obtained using the value of elapsed time at Jan-1 (dotted-red line), mid-year (solid-black line), and Dec-31 (dashed-purple line) every year. Open circles represent non-detects.

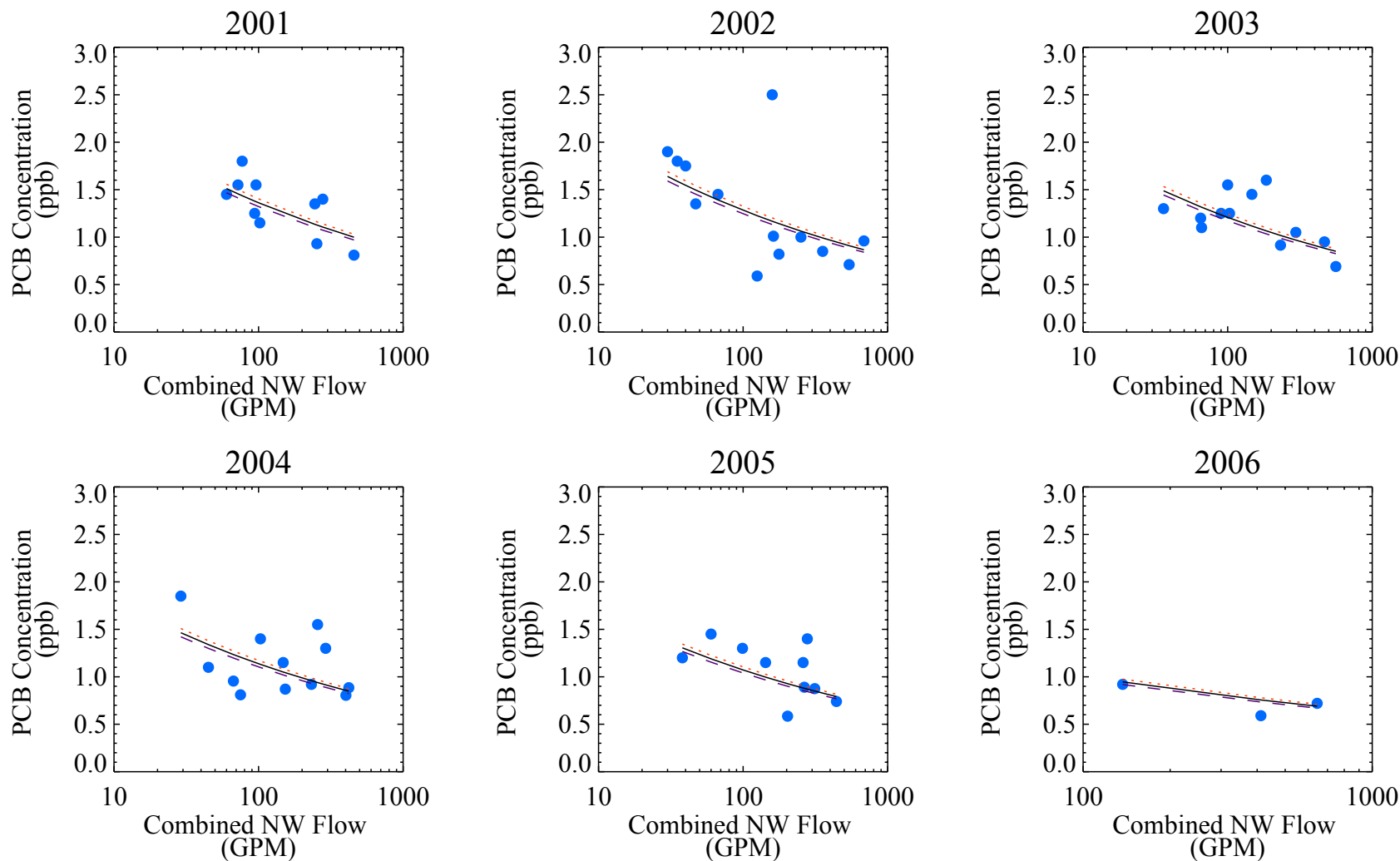


Figure 7b. Annual plots of PCB levels vs. combined NW flow for South spring

Data measured between 1/1/2001 and 3/15/2006. All measured data (through 3/15/2006) were used in estimating the parameters

Blue dots represent measured data. Fits shown here were obtained using the value of elapsed time at Jan-1 (dotted-red line), mid-year (solid-black line), and Dec-31 (dashed-purple line) every year. Open circles represent non-detects.

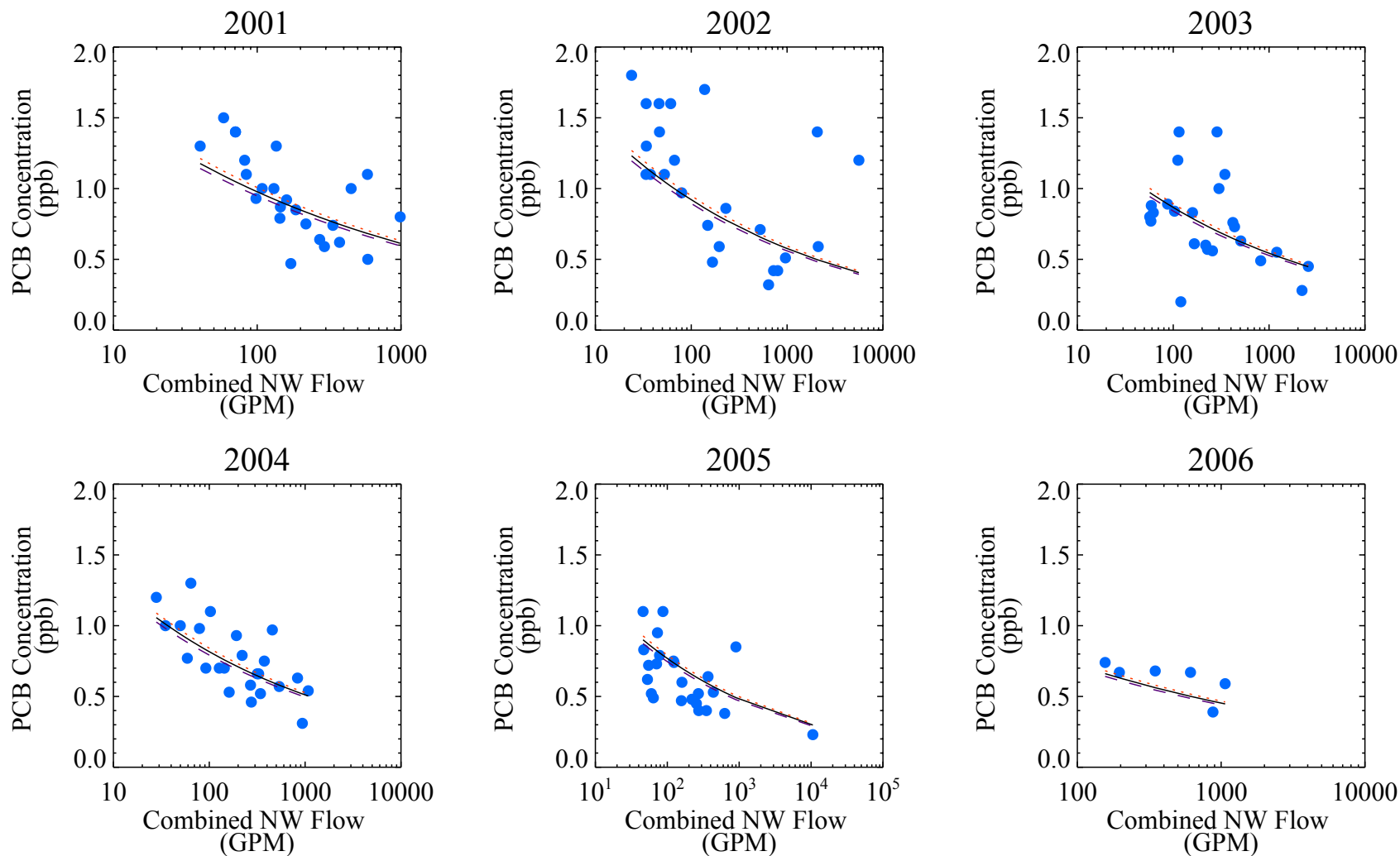


Figure 7c. Annual plots of PCB levels vs. combined NW flow for STF

Data measured between 1/1/2001 and 3/15/2006. All measured data (through 3/15/2006) were used in estimating the parameters

Blue dots represent measured data. Fits shown here were obtained using the value of elapsed time at Jan-1 (dotted-red line), mid-year (solid-black line), and Dec-31 (dashed-purple line) every year. Open circles represent non-detects.

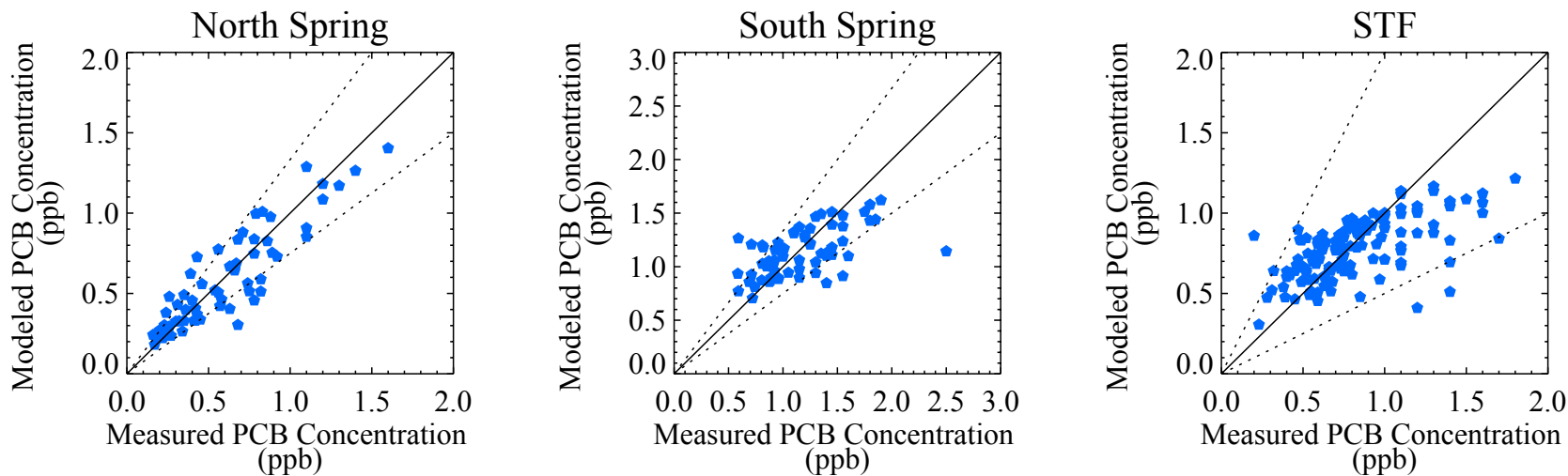


Figure 8. Validation plot: comparison of measured and median estimate of modeled PCB concentrations at the Neal's landfill site.

Data measured between 1/1/2001 and 3/15/2006. Estimation of parameters was carried out with data through 3/15/2006.

The median estimate of PCB concentrations are based on the estimated model parameters in 1000 bootstrap simulations, for the same flow and time at which the PCB measurements were made.

Solid line represents the 45-degree line. Dotted lines represent 25% deviation off the 45-degree line for North and South springs and 50% deviation off the 45-degree line for STF.

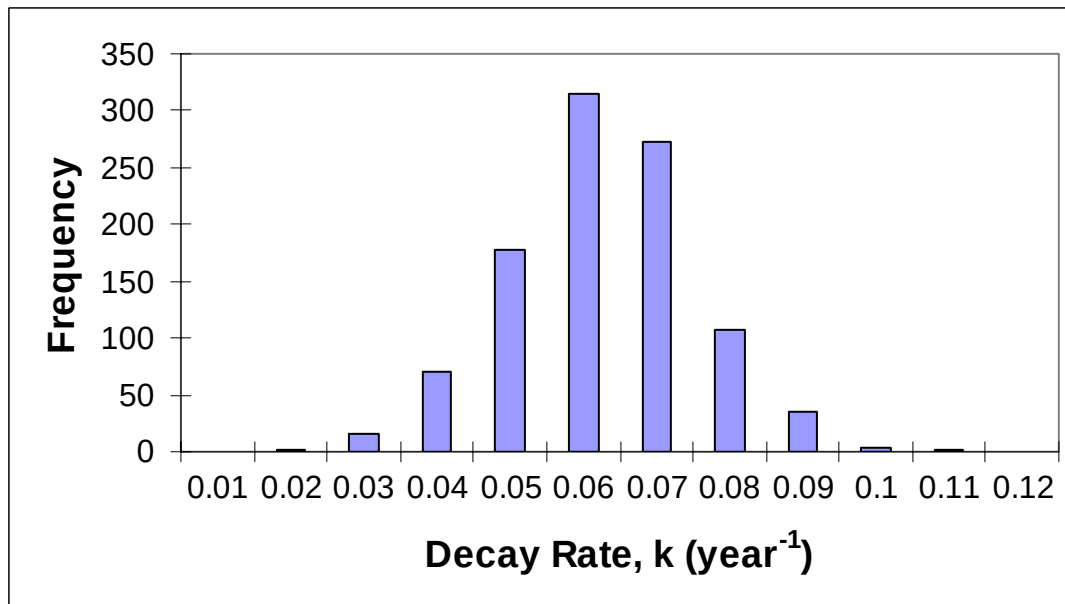


Figure 9. Histogram of estimated k based on 1000 bootstrap samples using all measured data (through 3/15/2006).

95% CI for k

Lower limit (2.5 percentile) = 0.04

Median (50th percentile) = 0.06

Upper limit (97.5 percentile) = 0.09

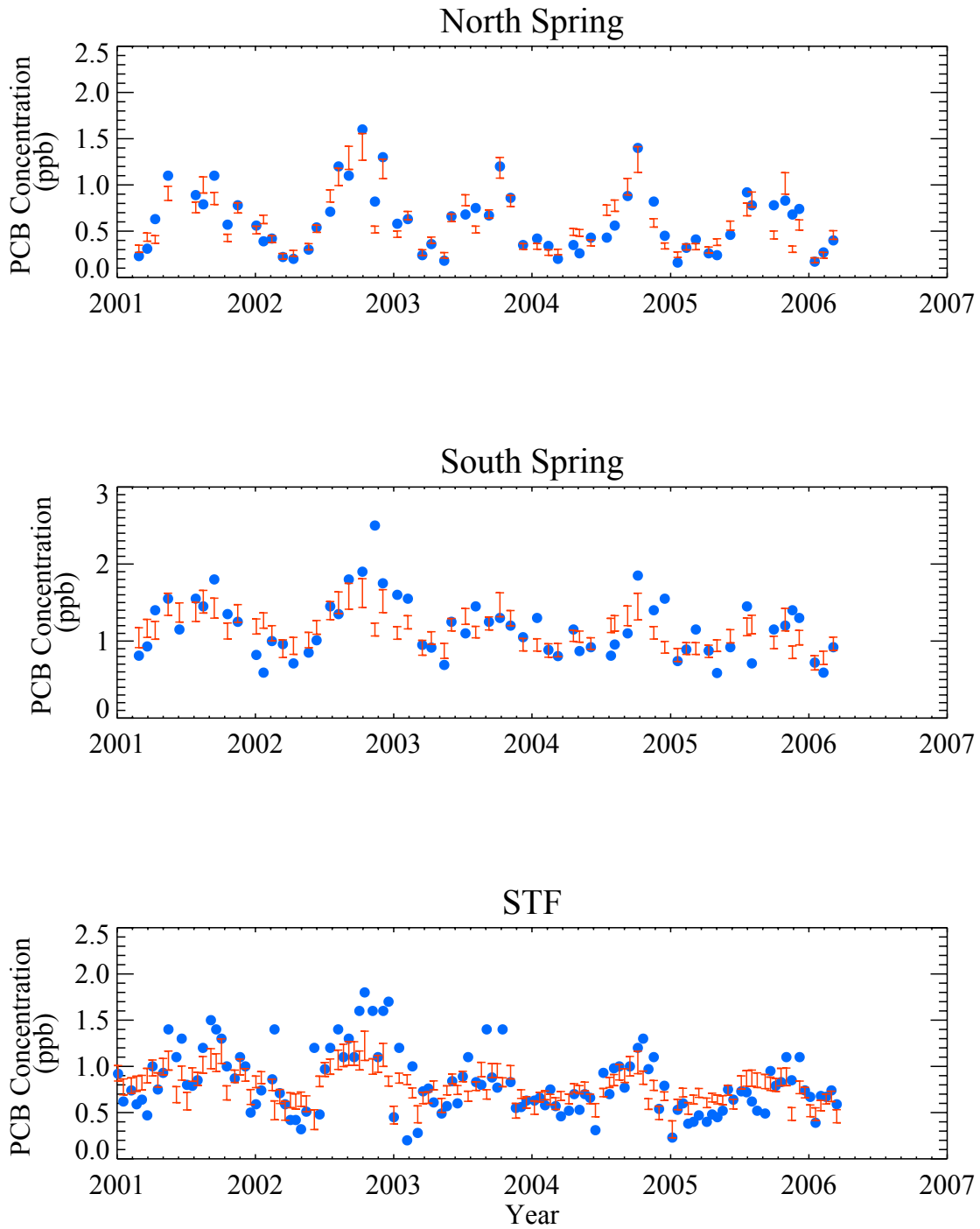


Figure 10. PCB concentrations in the springs of the Neal's landfill site: data and range of model results.

Data measured between 1/1/2001 and 3/15/2006. Data measured through 3/15/2006 were used in estimating parameters.
The solid blue circles represent measured data. The red bars represent the 95% confidence interval based on the estimated model parameters in 1000 bootstrap simulations, for the same flow and time at which the PCB measurements were made.

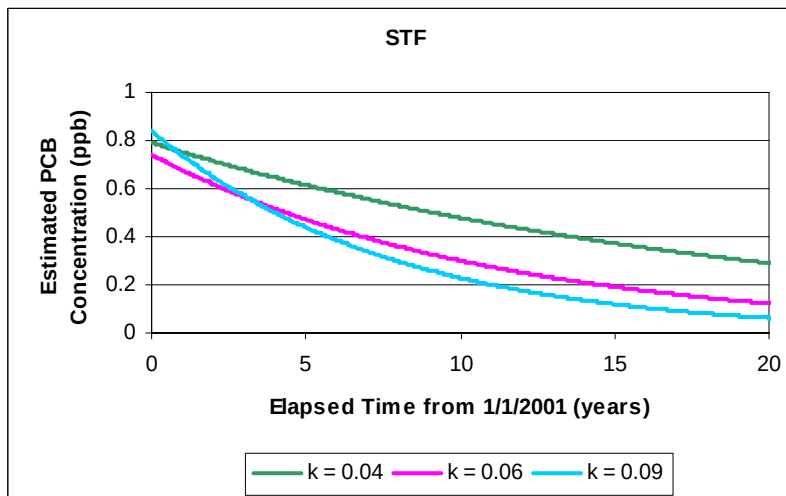
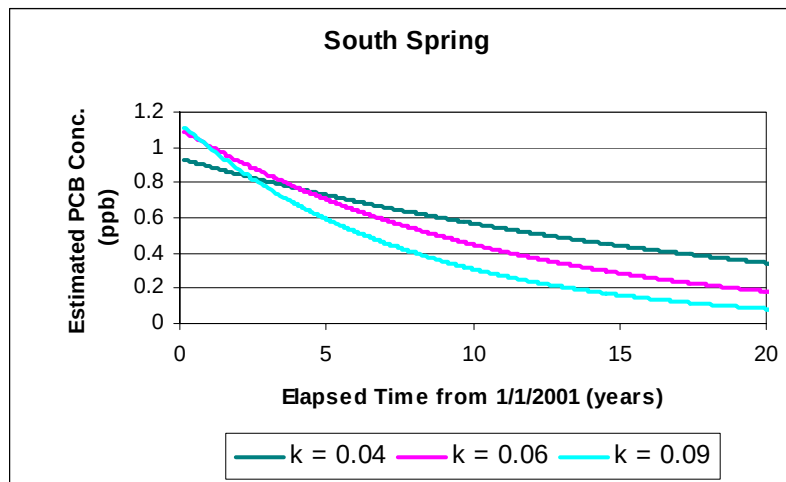
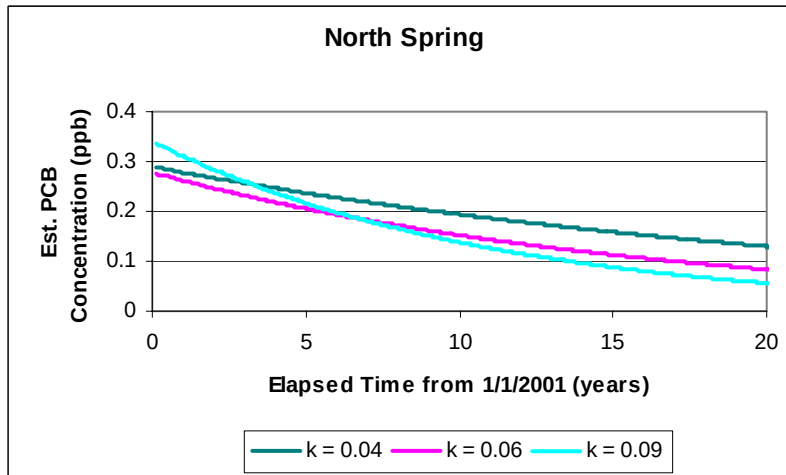


Figure 11. Illustration of future PCB concentrations at the North and South Springs and the STF. An average flow of 455 GPM was used in the projections.

Appendix B

Technical Memorandum

To: Russ Cepko, CBS

From: David Glaser, QEA

April 20, 2006

**RE: Analysis of PCB Trends at the Neal's Landfill Site:
Fate and Bioaccumulation Models**

TECHNICAL MEMORANDUM

TO: Russ Cepko - CBS
FROM: David Glaser
CC: Kevin Russell - QEA
Jim Rhea - QEA
Paul Switzer – Stanford University

DATE: April 20, 2006
RE: Analysis of PCB Trends at the Neal's Landfill Site: Fate and Bioaccumulation Models
JOB#: VIAtre:110

Introduction

Understanding the rate of natural recovery of PCBs in Conard's Branch and Richland Creek is an important element in the development of a management plan for the Neal's Landfill Site. As discussed with United States Environmental Protection Agency (USEPA)¹, a statistical data analysis has been undertaken focusing on the direct estimation of the projected rate of change in PCB concentrations, along with its associated confidence interval. To make the best use of all of the data and to account for the important confounding co-factors, a unified modeling approach has been used, one that incorporates both statistical analysis as well as scientific understanding of the underlying physical, chemical, and biological processes through which PCBs are transferred from spring water entering Conard's Branch to fish tissue. Such understanding is provided by the mechanistic simulation model that includes hydrodynamic, sediment transport, chemical fate and bioaccumulation components.

Initial efforts at estimating the rate of natural recovery at the Neal's Landfill Site focused on the statistical analysis of trends in fish tissue PCB levels. These efforts were inconclusive for several reasons:

¹ Viacom presented USEPA with a technical memorandum describing the method on August 25, 2005. This was followed by a conference call with USEPA and their consulting statistician on September 26, 2005. On October 12, 2005, Viacom provided USEPA with a series of slides describing the method in greater detail. A technical memorandum was transmitted to USEPA on December 5, 2005 summarizing the statistical modeling work performed for the springs, using data collected through September 2004. USEPA provided Viacom with comments on this memo developed by Neptune and Co. on January 9, 2006, and Indiana Department of Environmental Management provided comments on February 9, 2006. This memo has been revised and presented to USEPA.

- There is a strong seasonal pattern in the data, with wet weight-based PCB levels generally higher in spring and lower in fall. This confounding factor requires either that the data be segregated or that additional predicting variable(s) be incorporated, in either case reducing the power of the analysis.
- Year-to-year variation in hydrology has caused PCB concentrations in spring water to vary.
- Changes to the collection system have resulted in an increase in the amount of spring water collected and treated at the Spring Treatment Facility (STF).
- Changes to the treatment system have reduced STF effluent PCB concentrations; in August 2003, the carbon in the system was exchanged.
- The fish data are variable, and the period since the last major remediation (2001 - 2005) is relatively short, leading to uncertainty in estimated rates of decline.

Because these analyses were inconclusive, the unified modeling approach was undertaken, with the goal of integrating the available information: the spring data (which provide probably the clearest evidence regarding recovery in the system); the sediment and water data for the stream; the fish data; as well as our understanding of the underlying physical, chemical and biological processes, as codified in the calibrated fate and transport and bioaccumulation simulation models.

The first step in the analysis involved a statistical evaluation of trends in PCB concentrations in the spring water entering the system, which was reported to USEPA in a memo sent December 6, 2005 (QEA 2005a) and is currently under revision. The best estimate of the rate of natural recovery of PCB concentrations in the spring system of Neal's Landfill from this analysis was found to be 0.06 yr^{-1} . The uncertainty analysis demonstrated that a value of $k = 0$ lies outside of the 95% confidence interval (0.04 to 0.09 yr^{-1}), and thus it is unlikely that there is no recovery in the system.

The second stage of the analysis involved an evaluation of the rate of recovery in the fish using mechanistic fate and transport and bioaccumulation models of the system. The goal of this memo is to provide a brief description of the results of the application of the PCB fate and transport and bioaccumulation models developed for the Neal's Landfill site (QEA 2005b) in evaluating time trends in PCB levels in the fish.

Approach

Starting with a range of reasonable rates of recovery in the springs, a series of simulations with the fate and transport and bioaccumulation models was performed. Because of computational limitations, three simulations were performed, using the best estimate of 0.06 yr^{-1} , and the upper and lower 95% confidence limits of 0.04 and 0.09 yr^{-1} . For each simulation, the sum of the log likelihoods was then calculated for the fish data. These were evaluated to see if the difference in

the sum of log likelihoods among the simulations was sufficient to choose one decline rate over the others.

As described below, these results have led to the conclusion that the results achieved so far provide sufficient information to meet the goals of the overall trend analysis: more sophisticated analyses, including development of an empirical fate model and performance of a large number simulations for optimization, are not necessary; such efforts will not materially improve the analysis.

Model Updates

The development and calibration of the PCB fate and transport and bioaccumulation models are described by QEA (2005b). A limited number of changes to boundary conditions and model parameter values have been made since that report was released; these are described below.

PCB fate model

The representation of PCB concentrations in the spring waters entering Conard's Branch, as well as PCB loads from bank soils in the vicinity of North Spring were altered to reflect the temporal trends in Spring PCB levels. The original boundary conditions for the Neal's Landfill PCB fate sub-model were developed based on regression relationships with flow. These relationships pooled available data without accounting for any time trends in spring water PCB concentrations. Here, to reflect the temporal trends in PCB levels in the spring waters, the spring model was used to compute PCB concentrations of water entering Conard's Branch. Two model boundaries were updated: 1) Conard's Branch at the weir; and 2) North Spring and its bypass. The updates are described in Appendix A.

Bioaccumulation model

The parameterization of the bioaccumulation model was changed from that reported in QEA (2005b) as follows:

- Respiration parameters were updated to better reflect the fish species in the system. Previously, respiration rates were determined using measurements conducted on smelt and alewife. The revised rates use measurements for pumpkinseed (for longear sunfish; see QEA 1999) and dace (for creek chub; Hanson et al. 1997). This change had only a minimal impact on the extent of bioaccumulation.
- The trophic transfer coefficients for the benthic and water column invertebrates were adjusted to better reflect published data. The data were described in QEA (2005b, Section 3.3.1.3.1).

- Growth rates and lipid compositions were modified to better reflect the data. The revised values are shown in the calibration figures discussed below.
- The composition of the diets of the creek chub and longear sunfish were modified during calibration. The revised values are presented in the calibration discussion.
- The efficiency of transfer of PCBs across the gill surface was modified during calibration; the final value lies within the range of values used in previous applications of this model to other sites.

The results of the bioaccumulation model were compared with the congener-based and Aroclor-based fish data. These are indicated separately on Figure 2, because of the uncertainty associated with the differences between the congener and Aroclor data². Only congener data are presented on Figures 3 and 4.

Model Calibration

PCB fate model

The PCB fate model was recalibrated using the decline rate of 0.06 yr^{-1} in the spring system, by adjusting two parameters associated with the boundary conditions, α and W_{bank} (see Appendix A). Calibration was achieved visually.

Following calibration to the decline rate of 0.06 yr^{-1} , the boundary conditions were re-estimated for decline rates of 0.04 and 0.09 yr^{-1} . These represent the 95% confidence limits as determined by the spring model (QEA 2005a). Simulations with the PCB fate model were then performed using these alternative boundary conditions. Aside from boundary conditions, no parameters were changed when applying the model using the 0.04 and 0.09 yr^{-1} decline rates.

The data and recalibrated model results for PCB concentrations in water and sediment are presented in Figure 1 for one location in Conard's Branch and one location in Richland Creek. The three decline rates are represented. For the water, the spread among the model simulations using the three decline rates is minimal in comparison with the short-term variability in the model as well as the spread in the data. It should be noted that because no additional calibration was performed for each decline rate, the results provide a conservative characterization of the model differences between decline rates; differences would only be further reduced if the models were recalibrated for each decline rate estimate. Similarly, the model results for surface sediment concentrations, which exhibit very little change over the five-year calibration period, exhibit no discernable difference among the three decline rates evaluated.

² In addition, due to laboratory issues associated with the 2005 data, some of the samples were adjusted. On average, the adjusted values are 13% greater than the original values. As can be seen in the figures discussed below, the overall quality of model/data fit is not affected materially by uncertainty of this magnitude.

The three decline rates result in similar water column PCB concentrations throughout the simulation in large part because PCB levels in the water are determined not only by the levels in the springs, but by the sediments, the STF effluent, and the load from North Spring Bypass and the banks, all of which are sources of PCBs to Conard's Branch (see Appendix A and QEA 2005b). PCB levels in the sediments changed very little over the course of the calibration period, and sediment PCB concentrations differed by less than 1% among the model runs. PCB levels in the effluent from the STF were the same in all of the simulations.

These results imply that the downstream water data are ineffective for distinguishing among the alternative decline rates in the spring system. Furthermore, it is clear from Figure 1 that modifying the calibration through additional statistical evaluation would not reduce the already minimal differences among the decline rates to any important degree, and would be unlikely to materially improve the predictive ability of the model.

Bioaccumulation model

The bioaccumulation model was recalibrated using the results of the 0.06 yr^{-1} fate and transport simulation, by adjusting the efficiency of transfer of PCBs across the gill surface and the diets of the fish. The dietary compositions are listed in Table 1. These satisfy the constraints described in QEA (2005b). Recalibration was performed visually by comparing model results using a range of diets.

Table 1. Diet of the fish in the calibrated model.

Location	Species	Winter			Summer		
		WCI	BMI	Terrestrial	WCI	BMI	Terrestrial
Conard's Branch, Location B	Creek Chub	0.25	0.15	0.60	0.20	0.10	0.70
Richland Creek, Location D	Creek Chub	0.60	0.30	0.10	0.60	0.30	0.10
	Longear Sunfish	0.40	0.60	0.00	0.40	0.60	0.00

Results of the 0.06 simulation are shown in Figure 2, with computed PCB levels in each age class indicated individually. Lipid contents and body weights are also presented. In Figure 3, results for the 0.04 and 0.09 simulations are presented as well, with results for each simulation presented as averages over the primary age classes represented in the data. Model/data comparisons are discussed below with reference to Figure 3.

For creek chub at Location B (Figure 3a), on a wet weight basis, in two cases, the model overestimates the mean, in two cases it underestimates the mean, and in one case it is quite close to mean. On a lipid basis, in three cases the model passes very close to the mean and in two

cases overestimates the mean. Calibration compared with data collected in November 2005 matches well. The original and adjusted data exhibit similar means.

For creek chub at Location D (Figure 3b), on both wet weight and lipid bases, the model is very close to the mean in two cases. Note that the best fits do not occur on the same sampling events for the wet weight and lipid data. The inability of the model to capture every data point is reflective of the model's structure and inherent process resolution. By necessity, the model does not represent each average lipid content precisely (Figure 2b), and does not incorporate all of the underlying physical, chemical and biological processes that act on short time scales (days to months) and control water column and sediment PCB concentrations as well as fish physiology and ecology. The model overestimates PCB concentrations in 2005. This may be due to uncertainty associated with the flows in Richland Creek during 2005; flows during this period were not measured, but were estimated based upon correlations with data collected at a nearby well. Since creek chub feed strongly in the water, their exposure levels may have been estimated inaccurately during this period. For management purposes, the model as calibrated provides a conservative representation of the 2005 data.

For longear sunfish at Location D (Figure 3c), the model matches the data quite accurately. In every case, the model runs within the error bars of the data.

In performing the model simulations using the 0.04 and 0.09 yr^{-1} decline rates, no parameters were changed. The three simulations differ to only a minimal extent: the computed PCB concentrations are visually nearly identical (Figure 3), and the sums of log likelihood for the three decline rates are nearly identical (Table 2). Note that because no additional calibration was performed for each decline rate for the fate and bioaccumulation models, the results provide a conservative characterization of the model differences between decline rates; differences would only be further reduced if the models were recalibrated at each decline rate.

Table 2. Sum of the log likelihoods for the bioaccumulation model.

Location	Species	Sum of Log Likelihoods		
		0.06 yr ⁻¹	0.04 yr ⁻¹	0.09 yr ⁻¹
Wet Weight-Based Results				
Conard’s Branch, Location B	Creek Chub	-50.6	-50.8	-50.5
Richland Creek, Location D	Creek Chub	7.1	6.9	7.9
	Longear Sunfish	-14.7	-14.7	-14.6
Lipid-Based Results				
Conard’s Branch, Location B	Creek Chub	-201.8	-201.1	-201.2
Richland Creek, Location D	Creek Chub	-127.9	-128.4	-126.7
	Longear Sunfish	-105.0	-105.0	-105.2

The similarity among the three simulations reflects the lack of a direct relationship between fish PCB levels and those of the springs. This is because the fate model results do not directly track the springs for reasons discussed above. In addition, fish are exposed to PCB sources other than the springs, including the sediments, which differ imperceptibly between simulations (Figure 1). Sediments contribute to fish PCB levels both directly through the benthic component of the fish diets, and indirectly through their contribution to the water column.

Evaluation of the Rate of Recovery at the Neal's Landfill Site

A least-squares regression of the fish data results supports the conclusion that natural recovery is proceeding: all three values (creek chub at Location B, creek chub and longear sunfish at Location D) are less than 0.0 (Table 3). The 95% confidence intervals overlap 0.0, however, indicating that a statistical test of significance would not permit these rates to be distinguished from 0.0. As discussed above, during the period over which these data were collected, there were several events and processes that introduced uncertainty to the interpretation of these rates (hydrology, engineering controls). The model results for this period are subject to the same sources of uncertainty.

The uncertainty associated with the evaluation of the trends over the past several years is also evident in the model comparisons of the different spring decline rates (Figure 3). It is clear from Figures 1 and 3 and from the sums of the log likelihoods in Table 2 that the model results for the three decline rates are nearly identical: variability in the water and fish data prevent one from effectively distinguishing among them.

Table 3. Rates of natural recovery in fish determined by regression.

Location	Species	Rate of Decline (yr ⁻¹)	95% Confidence Interval
Conard's Branch, Location B	Creek Chub	-0.072	-1.0 – 0.89
Richland Creek, Location D	Creek Chub	-0.39	-1.2 – 0.46
	Longear Sunfish	-0.11	-0.95 – 0.73
<i>Notes:</i> <i>Least squares regression using the natural logarithm of the lipid-normalized congener data, collected in fall. Multiple Y values for each X. Adjusted values used for November 2005.</i>			

The long-term rate of decline is best estimated by projecting the model into the future under constant hydrologic conditions, with no additional engineering controls. Thus, a 10-year future projection with the fate and transport and bioaccumulation models was conducted. For this simulation, the hydrologic conditions from 2001-2005 (i.e., spring and tributary flows input to the model) were repeated twice. The spring concentrations and bank loadings input to the model continued to decline at 0.06 yr⁻¹ in this simulation, and the STF effluent concentrations were specified to be 0.02 µg/L until year 10, where breakthrough of the GAC was simulated by an increase to 0.10 µg/L. Figure 4 presents the results from this ten-year no-action projection, for creek chub in Conard's Branch and for creek chub and longear sunfish in Richland Creek. Over this period, the model projects rates of decline for fish ranging from 0.03 to 0.04 yr⁻¹ (Table 4). Over the long term, the fish decline at a slower rate than the springs, because the STF does not change (on average), and sediment sources decline at a slower rate than the springs.

Table 4. Projected rates of natural recovery in fish.

Location	Species	Rate of Decline (yr ⁻¹)
Conard's Branch, Location B	Creek Chub	-0.04
Richland Creek, Location D	Creek Chub	-0.04
	Longear Sunfish	-0.03

Conclusions

There is clear evidence of natural recovery at the Neal's Landfill site: the PCB levels in the springs entering Conard's Branch exhibit a rate of decline of 0.06 yr⁻¹ (95% confidence limit 0.04 to 0.09). In addition, the fish data suggest declines: all three best estimates of the rate of change are negative. However, these estimates are only suggestive, insofar as the 95% confidence limits overlap 0.0.

The mechanistic models developed and calibrated for the Neal's Landfill site provide the best tool for projecting system response to alternative remediation activities, since they incorporate all of the available information: spring data, water and sediment data, fish data, knowledge of PCB sources to the stream, and understanding of the underlying mechanisms. These projections have provided an estimate of 0.03 to 0.04 yr⁻¹ for long-term declines in the fish.

References

Hanson, P.C., T.B. Johnson, D.E. Schindler, and J.F. Kitchell, 1997. *Fish Bioenergetics 3.0*. University of Wisconsin – Madison Center for Limnology and University of Wisconsin Sea Grant Institute. <http://www.seagrant.wisc.edu/fish.html>.

Quantitative Environmental Analysis, LLC, 2005a. Memo on spring trend statistical model (sent from Viacom to the Agencies and now under revision).

Quantitative Environmental Analysis, LLC, 2005b. *Development and Calibration of a Mathematical Model of Surface Water PCB Fate, Transport, and Bioaccumulation at the Neal's Landfill Site, Bloomington, IN*. Prepared for Viacom, Inc., December 2005.

Quantitative Environmental Analysis, LLC, 1999. *PCBs in the Upper Hudson River*. Prepared for General Electric Company, Albany, NY.

Appendix A Update of the PCB Fate Sub-Model PCB Boundary Conditions

Conard's Branch at the Weir (CBW)

The CBW boundary condition consists of different relationships between PCBs and flow for storm and non-storm conditions, where storm conditions are defined by hourly CBW flow exceeding 300 gpm for a duration of six hours or more (QEA 2005b). For non-storm conditions, the updated boundary condition was defined by the South Spring statistical trend model (QEA 2005a), since South Spring accounts for the majority of the untreated spring flow entering Conard's Branch at this location. The updated CBW low flow boundary condition is thus given by:

$$C_{CBW} = a Q_{sys}^b e^{-kt} \quad (1)$$

where:

C_{CBW} = low flow CBW PCB concentration;
 Q_{sys} = total hourly system flow rate;
 a, b = constants, determined from South Spring statistical modeling (3.59, -0.20, respectively; QEA 2005a);
 k = decline rate from South Spring statistical modeling (0.06 yr⁻¹; QEA 2005a, under revision); and
 t = time in years since 1/1/2001.

Upon applying this equation to the hourly flow data for the entire 2001-2005 calibration period, it was found that for a small fraction of the time (i.e., < 1%), the total system flow was extremely low (< 1 gpm), which caused the spring model to compute very high PCB concentrations (i.e., > 4 µg/L). Since the maximum PCB concentration measured at South Spring during the 2001-2005 routine monitoring was 2.6 µg/L, it was decided to adjust these unrealistically high values (i.e., > 4 µg/L at total system flow of < 1 gpm) by capping the low flow CBW boundary concentration at 3 µg/L.

For storm conditions at CBW, event-based relationships for total PCB mass and peak PCB concentrations were developed in the original boundary condition (QEA 2005b). The approach for updating this boundary condition consisted of modifying these relationships to include the temporal decline term. In addition, based on further review of the storm PCB and flow data, it was found that a concentration-based relationship that includes a exponential flow term provides an improved fit to both the mean storm concentration and the total storm PCB mass data than does the original logarithmic mass-based relationship (e.g., Figures 3-15 and 3-16 in QEA 2005b). The updated relationship is given by:

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 (201) 930-9805 fax

290 Elwood Davis Road
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 Liverpool, NY 13088
 (315) 453-9009
 (315) 453-9010 fax

80 Glen Street
 Suite 2
 Glens Falls, NY 12801
 (518) 792-3709
 (518) 792-3719 fax

800 Brazos Street
 Suite 1040
 Austin, TX 78701
 (512) 707-0090
 (512) 275-0915 fax

$$C_{avg} = a Q_{avg} e^{-m Q_{avg}} e^{-kt} \quad (2)$$

where:

C_{avg} = event-mean PCB concentration (i.e., flow-weighted average) at CBW during a given storm event;
 a, m = best fit constants; and
 Q_{avg} = average CBW flow over a given storm event.

The flow relationship in this equation represents our current understanding of the nature of the spring system during storm conditions: at relatively lower flows, event-mean PCB concentration increases with increasing flow, representing increased mobilization of the PCB contaminated material by the increasing flows. As flow rises further, the relationship produces a leveling off of the PCB mass that is mobilized, eventually resulting in a PCB load that is relatively independent of flow. These patterns are illustrated in the figures discussed below.

The parameters of this relationship (i.e., a and m) were estimated by least squares fitting. Best fit values for the coefficients a and m were computed for a range of decline rates ranging from 0.00 to 0.13 yr⁻¹. Comparison of the alternative decline rates indicated that values in the range of 0.05 to 0.13 yr⁻¹ all provided a similarly good fit to the data. For consistency with the spring statistical model (i.e., QEA 2005a), the spring PCB decline rate determined from the trend analyses of 0.06 yr⁻¹ (95% confidence interval of 0.04 to 0.09) was used for the updated CBW storm flow PCB boundary condition.

The resulting function used to define the updated CBW event mean PCB concentration during storms provides a good representation of the data, as shown in Figure A1. The functions representing the event-mean storm PCB concentration, the total storm PCB mass, and the storm peak concentration scaling factor used for the updated CBW boundary condition are compared with the data in Figure A2. The colors of the symbols and the different lines represent different years over the analysis period. The rise in event mean PCB concentration with flow is seen in Figure A2, top-left panel, and the leveling off of total storm PCB load with flow is seen in Figure A2, top-right panel. It should be noted that the relationship that defines peak storm PCB concentration as a function of peak flow (bottom left panel in Figure A2) did not explicitly include the decline term. The reason for this is that this relationship is used to define a scaling factor that is applied to mean storm PCB concentration, which follows a temporal decline according to Equation 2.

North Spring and Its Bypass (NSB)

In the PCB fate sub-model, the North Spring boundary condition was developed to represent a combination of three sources: 1) ‘true’ flow from North Spring entering Conard’s Branch; 2) additional PCB-containing spring/groundwater seepage found to be entering Conard’s Branch in the vicinity of North Spring; and 3) PCB loads associated with the cycling of the STF effluent, in which PCBs are desorbed from bank soils that are inundated during periods of STF discharge and are subsequently released to Conard’s Branch when the stage height in the branch decreases and the water drains from the banks. Note that Sources 1 and 2 are associated with additional water flowing into Conard’s Branch, while Source 3 is not.

As described in QEA (2005b), the total flow includes two components:

$$Q_{NSB} = Q_{NS} + Q_{bypass} \quad (3)$$

where:

Q_{NSB} = total flow entering Conard’s Branch in the vicinity of North Spring;
 Q_{NS} = ‘true’ flow from North Spring (estimated as a function of MW5A groundwater elevation); and
 Q_{bypass} = North Spring bypass flow calculated as a function of total system flow (Figure 3-5 in QEA 2005b).

In the original PCB fate sub-model boundary condition, the North Spring sources were represented by a lumped term consisting of a single flow and a single representative concentration (QEA 2005b). The concentration for the original boundary condition was estimated through calibration to low flow monitoring data collected in 2004. For the updated NSB boundary condition, a function is proposed that: 1) explicitly accounts for each of the three sources comprising the PCB load entering Conard’s Branch in this area; and 2) reflects the temporal trend in North Spring PCB concentrations. This relationship is written in terms of the total PCB load and total flow:

$$C_{NSB} = \frac{W_{NSB}}{Q_{NSB}} \quad (4)$$

where:

C_{NSB} = average PCB concentration associated with the total flow; and
 W_{NSB} = total PCB load associated with the North Spring and its bypass.

As in the original boundary specification, the total flow is the sum of the ‘true’ North Spring flow and the estimated bypass flow (Equation 3). The total load is equal to the sum of the loads from the three sources described above:

$$W_{NSB} = W_{NS} + W_{bank} + W_{seepage} \quad (5)$$

where:

W_{NS} = the PCB load associated with the ‘true’ North Spring flow entering Conard’s Branch;
 W_{bank} = the PCB load associated with bank recharge/discharge caused by the STF effluent cycling; and
 $W_{seepage}$ = the PCB load associated with groundwater seepage.

W_{NS} is given by the product of the North Spring flow and the statistical trend model for its PCB concentration:

$$\begin{aligned} W_{NS} &= Q_{NS} C_{NS} \\ C_{NS} &= a Q_{sys}^b e^{-kt} \end{aligned} \quad (6)$$

where:

C_{NS} = North Spring PCB concentration;
 a, b = constants, determined from North Spring statistical modeling (12.03, -0.60, respectively; QEA 2005a, under revision);
 k = decline rate from North Spring statistical modeling (0.06 yr⁻¹; QEA 2005a, under revision); and
 t = time in years since January 1, 2001.

W_{bank} is independent of flow in the updated boundary condition. Because the ultimate source of PCB concentrations in the bank soils is the landfill via the springs, the 0.06 yr⁻¹ decline was applied to the bank loading as well.

$W_{seepage}$ can be expressed by the product of the bypass flow and an effective groundwater PCB concentration:

$$W_{seepage} = Q_{bypass} C_{GW} \quad (7)$$

where:

C_{GW} = the PCB concentration associated with the groundwater seepage.

C_{GW} is hypothesized to be a mixture of PCB-impacted spring water from the landfill and uncontaminated groundwater. Thus, the seepage PCB concentration can be represented by the North Spring concentration multiplied by a dilution factor (α):

$$C_{GW} = \alpha C_{NS} \quad (8)$$

The dilution factor can be estimated based on sampling conducted by Viacom in April and May 2005, which indicated that C_{GW} was on the order of 0.15 $\mu\text{g/L}$. PCB concentrations measured from North Spring during this time ranged from approximately 0.2 to 0.3 $\mu\text{g/L}$. Thus, a value in the range of 0.5 to 0.8 was deemed an appropriate estimate of α .

Combining Equations 3 through 8 yields:

$$C_{NSB} = \frac{(W_{bank} + (Q_{NS} + \alpha Q_{NSB}) a Q_{sys}^b) e^{-kt}}{Q_{NS} + Q_{NSB}} \quad (9)$$

The only term in Equation 9 that is not known from either measurement or estimation is W_{bank} . Thus, the value for W_{bank} , along with the final value for α , was determined by calibration to the low flow monitoring data in Conard's Branch. W_{bank} was set to zero from June 24, 2005 through December 31, 2005 to represent the relocation of the STF discharge 1000 feet downstream of the North Spring area that occurred during this time.

Upon applying this equation to the hourly flow data for the entire 2001-2005 calibration period, it was found that for small fraction of the time (i.e., $< 1\%$), the total system flow was extremely low ($< 1\text{gpm}$), which caused the spring model to compute very high PCB concentrations (i.e., $> 10 \mu\text{g/L}$) for C_{NS} . Since the maximum PCB concentration measured at North Spring during the 2001-2005 routine monitoring was 1.6 $\mu\text{g/L}$, it was decided to adjust these unrealistically high values (i.e., $> 10 \mu\text{g/L}$ at total system flow of $< 1 \text{gpm}$) by capping the NSB boundary concentration at 3 $\mu\text{g/L}$.

One additional adjustment was made to the NBS boundary condition to avoid unrealistically high values for C_{NSB} at times when the total system flow and the STF flow were very low. When the STF flow was less than 20 gpm, W_{bank} was set to zero, to avoid unrealistically high values of C_{NSB} in the range of 5 to 10 $\mu\text{g/L}$. This adjustment is appropriate because the PCB loading associated with bank exchange would not be expected to occur at times of very low STF flow.

The final calibrated values used for calculation of C_{NSB} were $\alpha = 0.8$ and $W_{bank} = 27 \text{mg/day}$ (starting on January 1, 2001, subject to a 0.06yr^{-1} decline).

FIGURES

CB at Vernal Pike

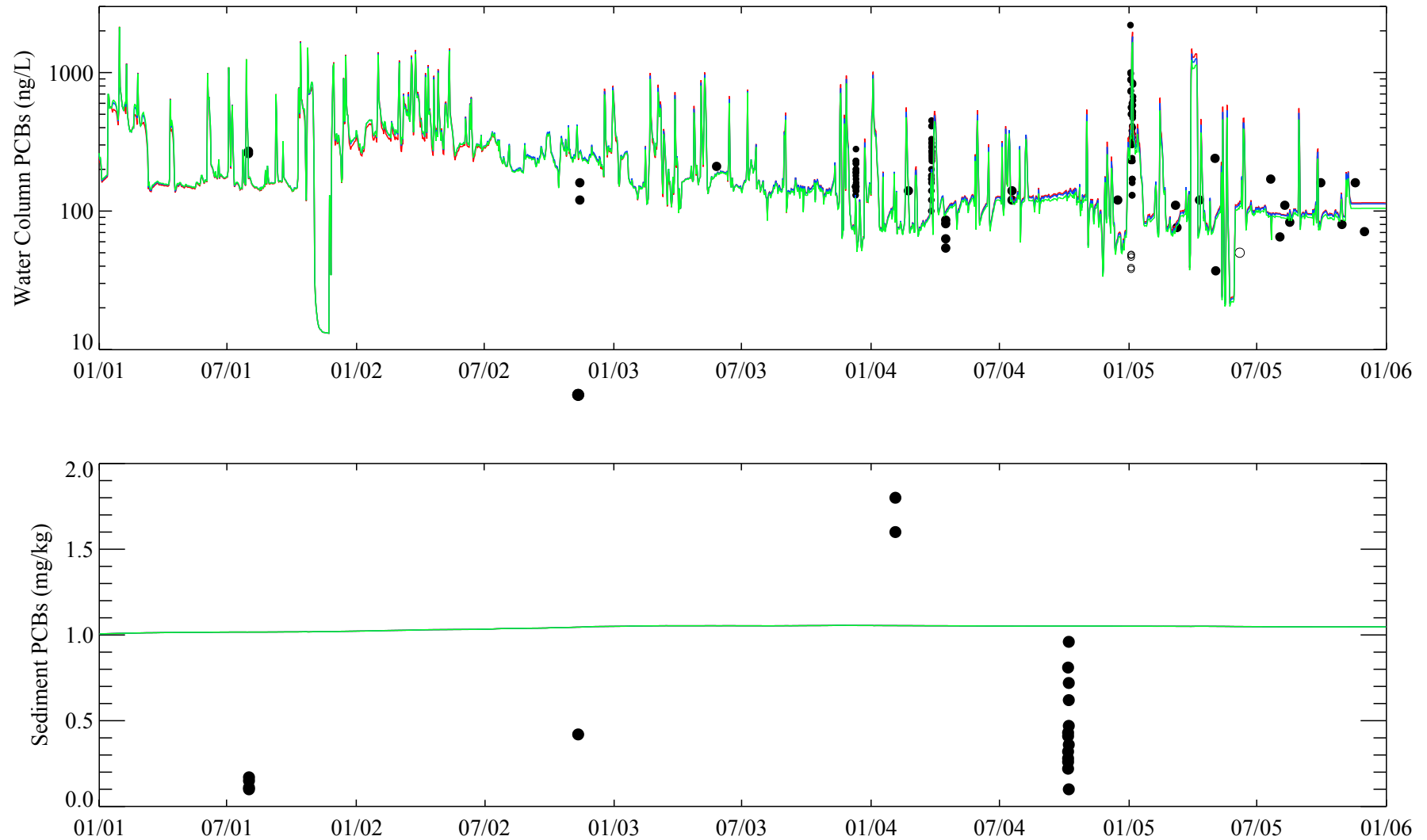
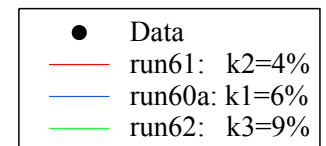


Figure 1a. Comparison of predicted and observed water column and sediment PCB concentrations in Conard's Branch and Richland Creek.

Runs: run60a, run61, run62

Note: Non-detect PCBs plotted as open symbol at 1/2MDL.L:\VIAnea\model\outputs\calibrate\runs\run62\run62\



RC at Vernal Pike

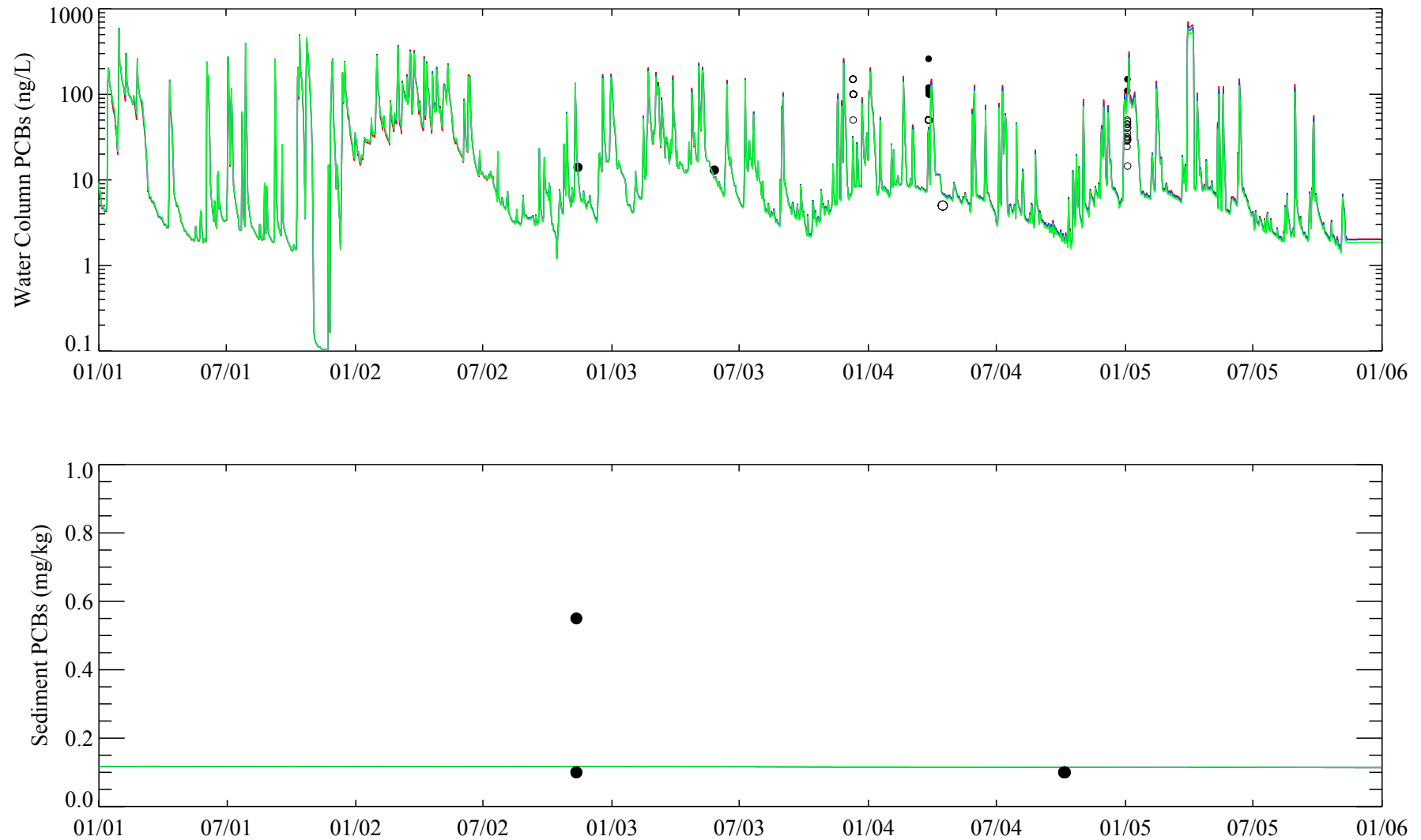
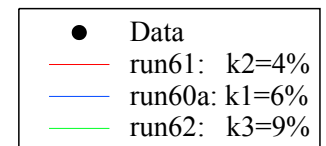


Figure 1b. Comparison of predicted and observed water column and sediment PCB concentrations in Conard's Branch and Richland Creek.

Runs: run60a, run61, run62

Note: Non-detect PCBs plotted as open symbol at 1/2MDL.L:\VIAnea\model\outputs\calibrate\runs\run62\run62\



Location B Creek Chubs

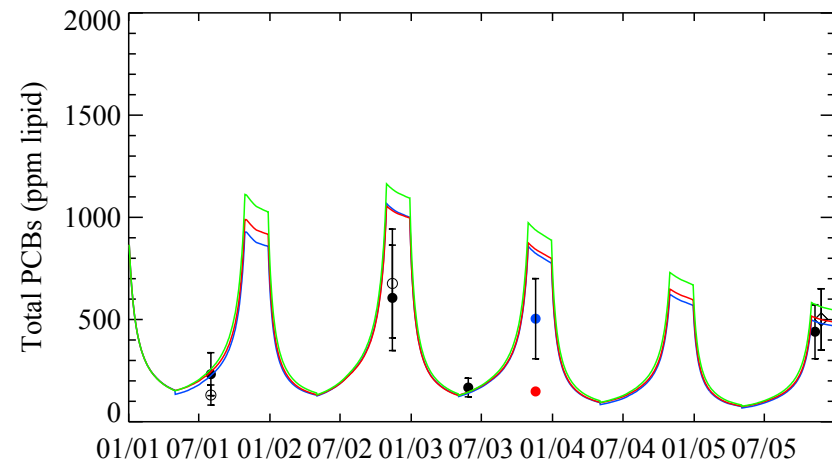
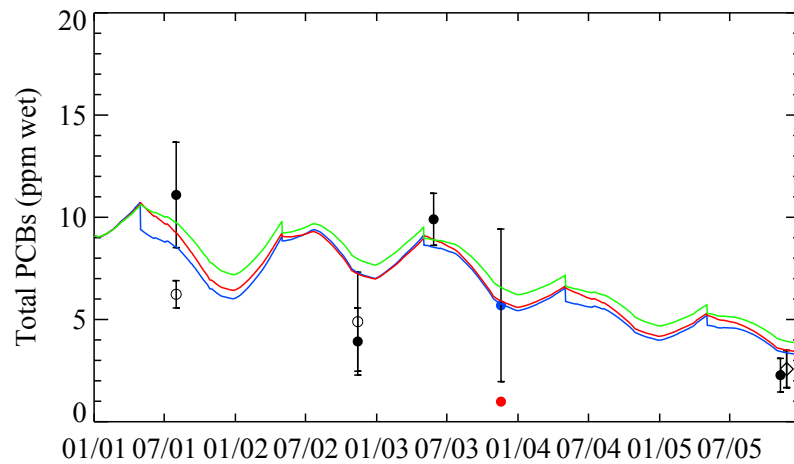
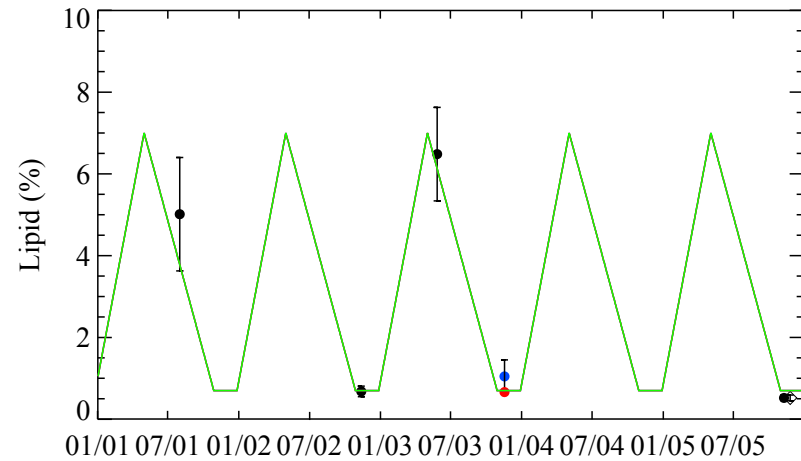
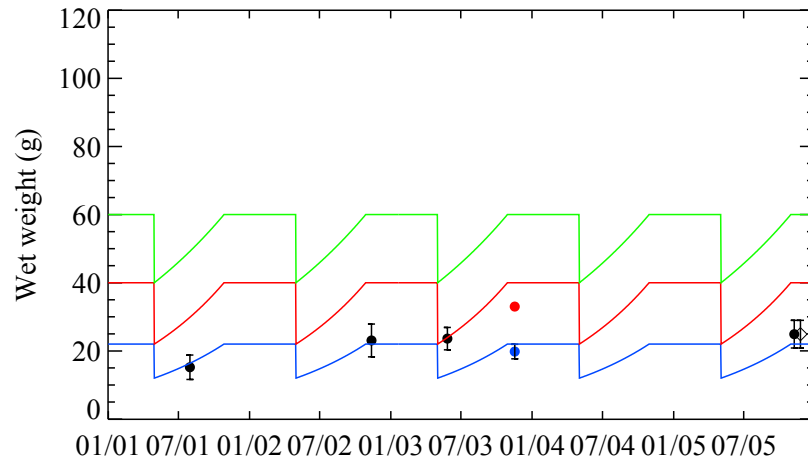
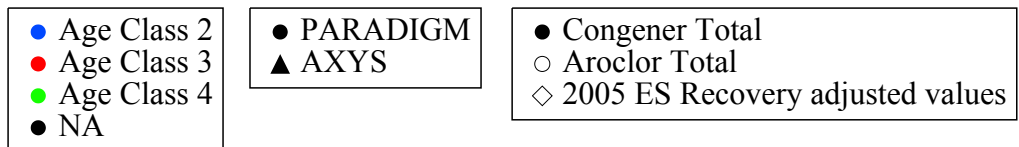


Figure 2a. Observed and computed PCB concentrations in fish from the Neal's Landfill Site.

Note: Whole body data only.

Model Source: \\Legolas\d_drive\VIAnea\model\FDCHN\output\runD90

Open diamonds represent 2005 ES Recovery adjusted congener values (offset to view)



Location D Creek Chubs

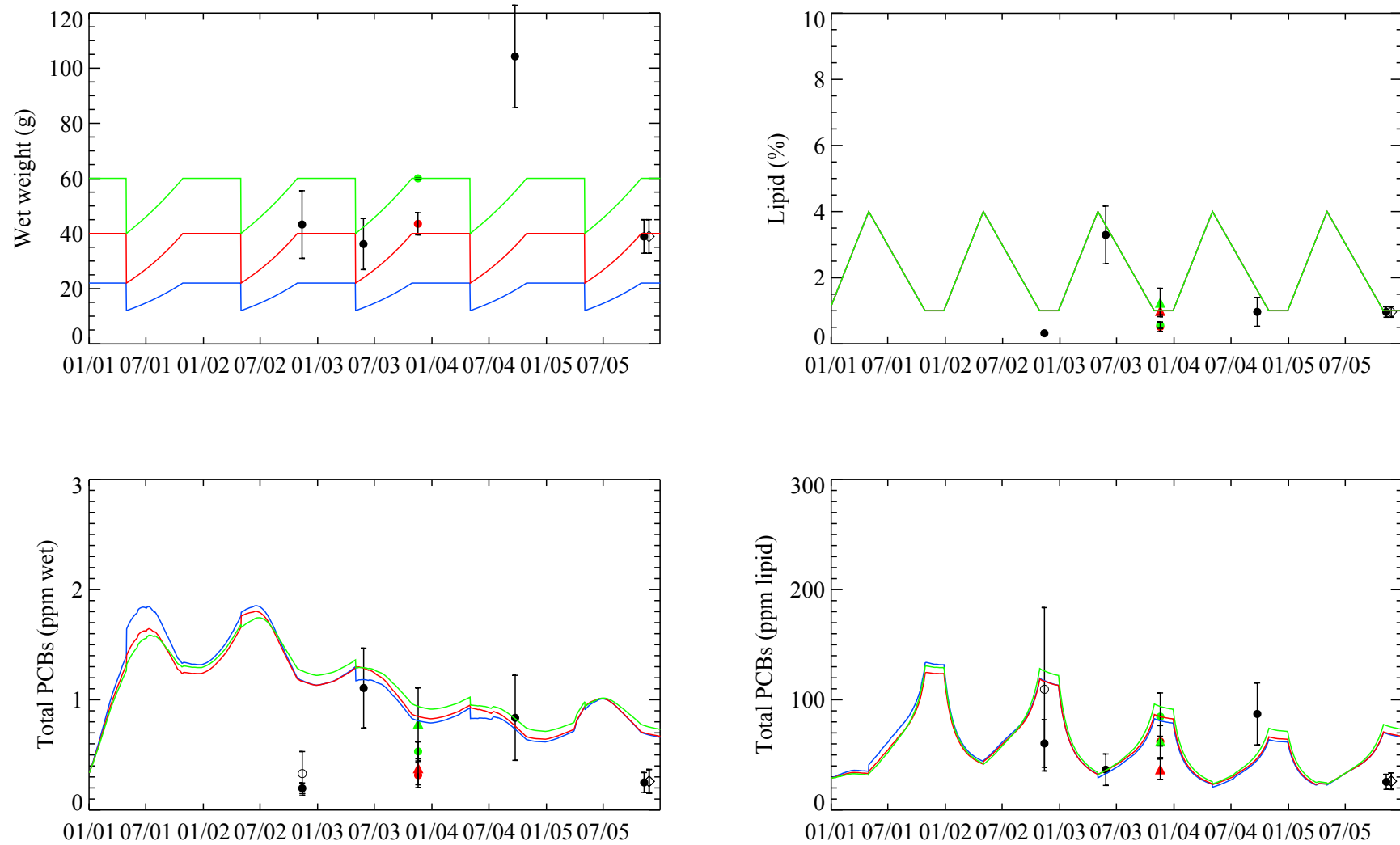
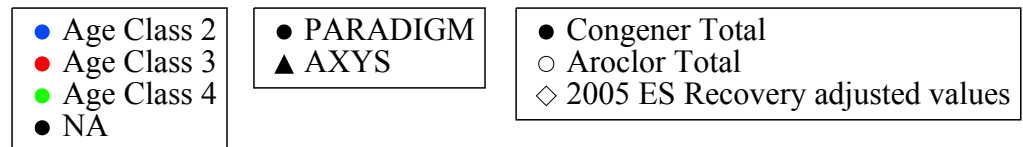


Figure 2b. Observed and computed PCB concentrations in fish from the Neal's Landfill Site.

Note: Whole body data only.

Model Source: \\Legolas\d_drive\VIAnea\model\FDCHN\output\runD90

Open diamonds represent 2005 ES Recovery adjusted congener values (offset to view)



Location D **Longear Sunfish**

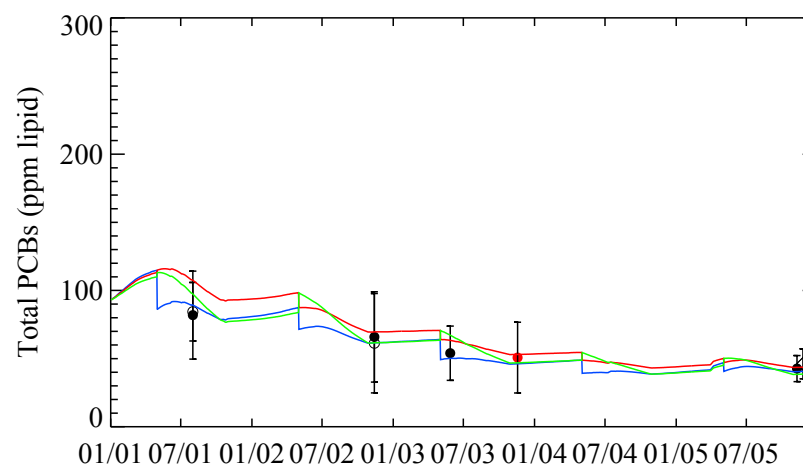
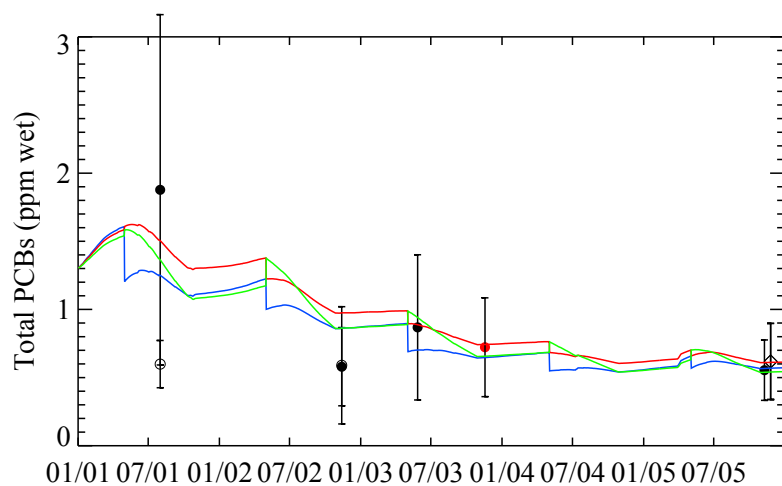
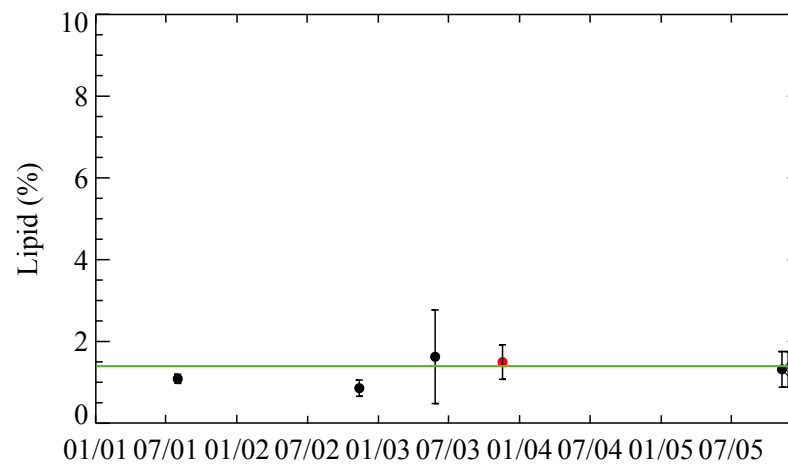
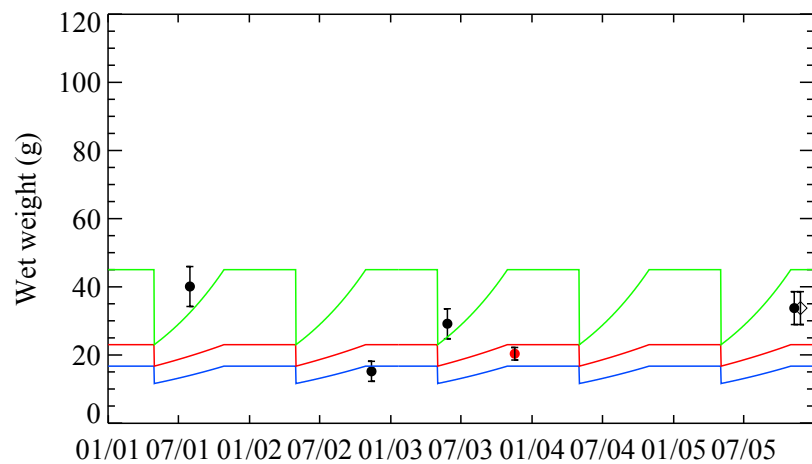
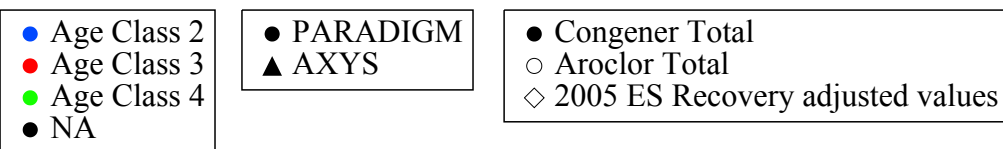


Figure 2c. Observed and computed PCB concentrations in fish from the Neal's Landfill Site.

Note: Whole body data only.

Model Source: \\Legolas\d_drive\VIAnea\model\FDCHN\output\runD90

Open diamonds represent 2005 ES Recovery adjusted congener values (offset to view)



Location B
Creek Chubs

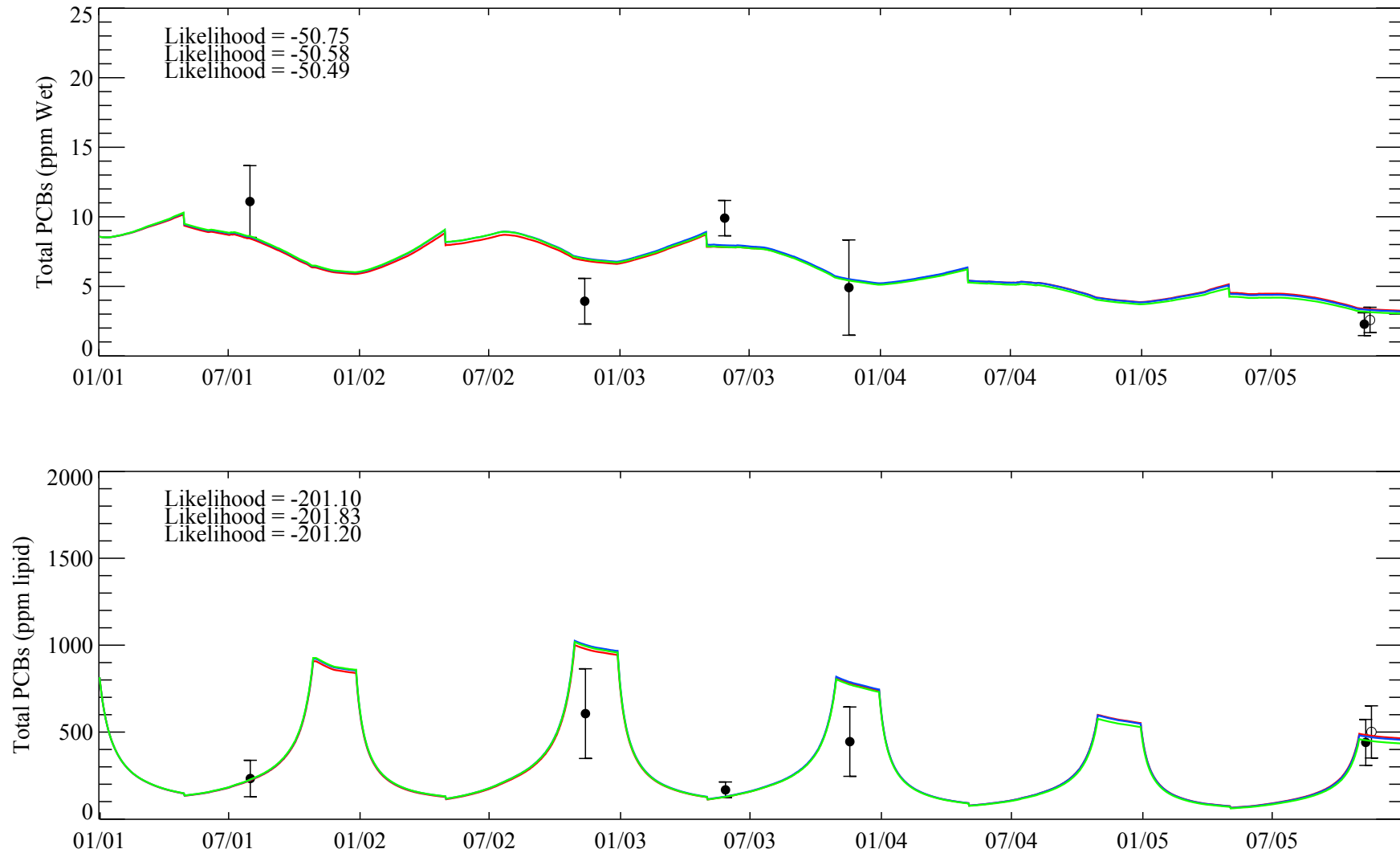


Figure 3a. Observed and computed PCB concentrations in creek chubs at Location B for three spring model decay rates.

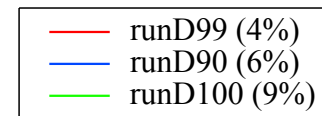
Temporal profiles of model PCB concentrations in creek chubs at Location B.

Note: 2005 data plotted on 11/9/2005.

Congener PCB data shown; open symbols represent ES Recovery adjusted values (offset to view).

Data plotted as mean $\pm$ 2SE.

Model output is average of ageclass 2,3, and 4.



Location D

Creek Chubs

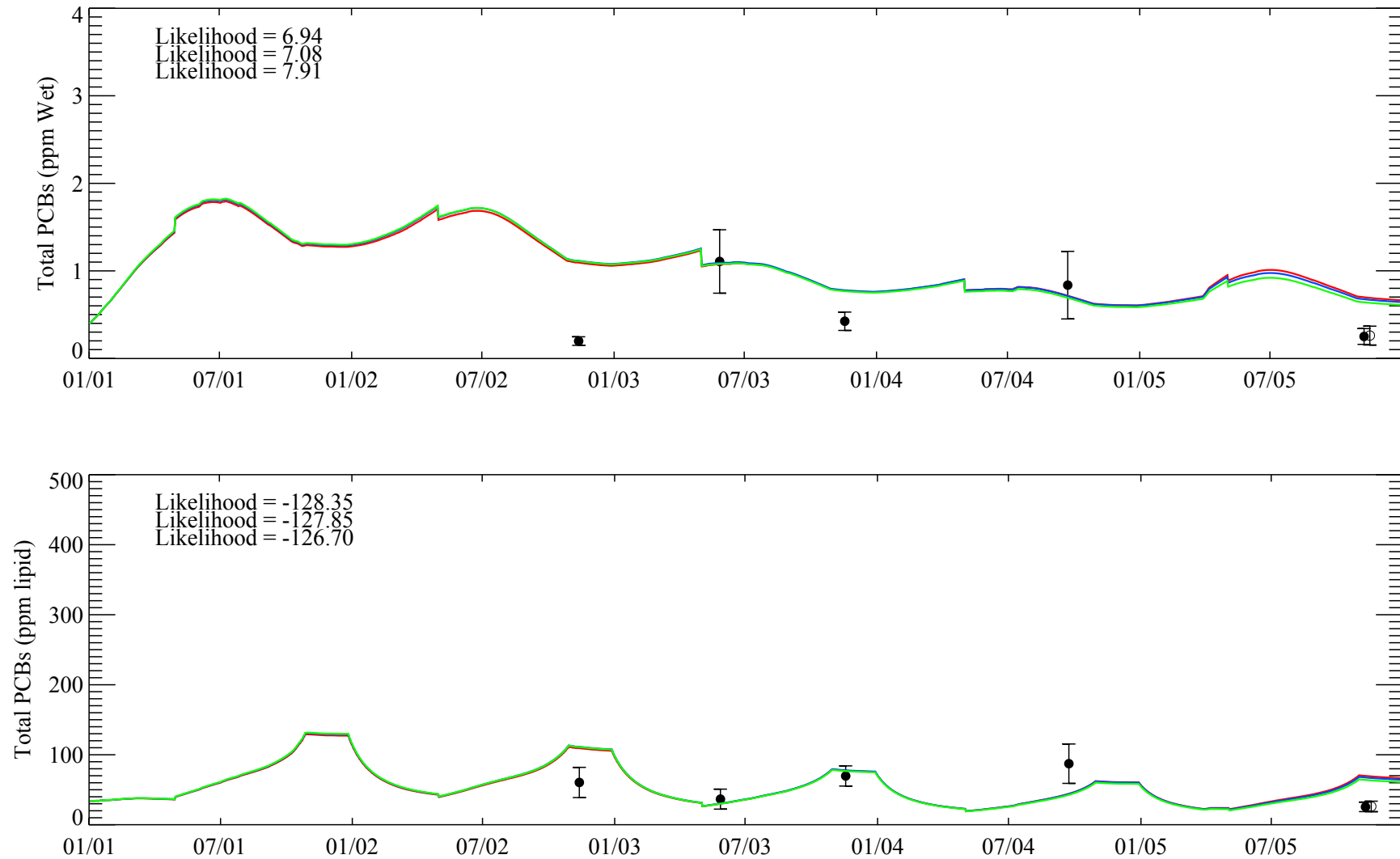


Figure 3b. Observed and computed PCB concentrations in creek chubs at Location D for three spring model decay rates.

Temporal profiles of model PCB concentrations in creek chubs at Location D.

Note: 2005 data plotted on 11/9/2005.

Congener PCB data shown; open symbols represent ES Recovery adjusted values (offset to view).

Data plotted as mean $\pm$ 2SE.

Model output is average of ageclass 2,3, and 4.

Location D

Longear Sunfish

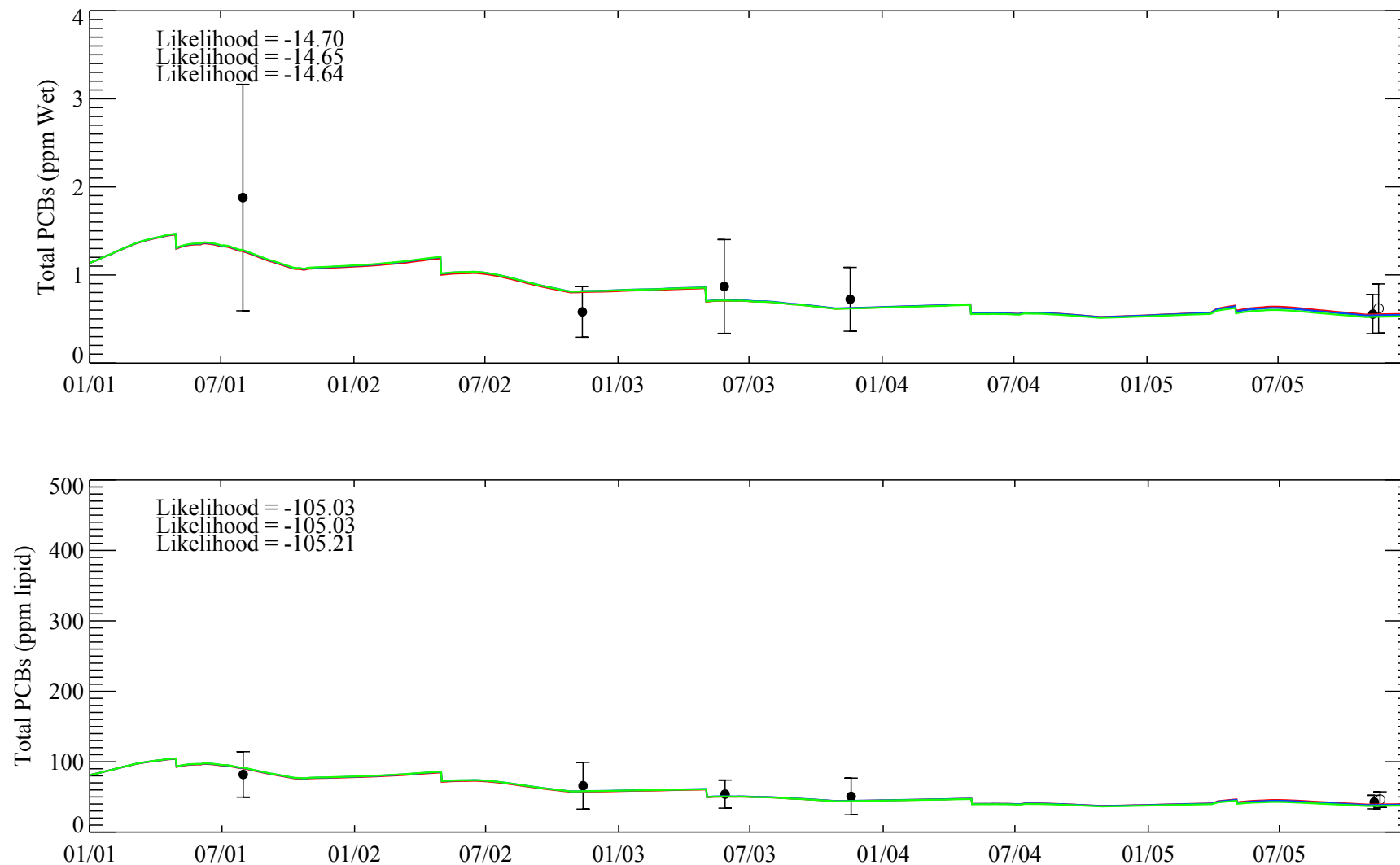


Figure 3c. Observed and computed PCB concentrations in longear sunfish at Location D for three spring model decay rates.

Temporal profiles of model PCB concentrations in longear sunfish at Location D.

Note: 2005 data plotted on 11/9/2005.

Congener PCB data shown; open symbols represent ES Recovery adjusted values (offset to view).

Data plotted as mean $\pm$ 2SE.

Model output is average of ageclass 2,3, and 4.

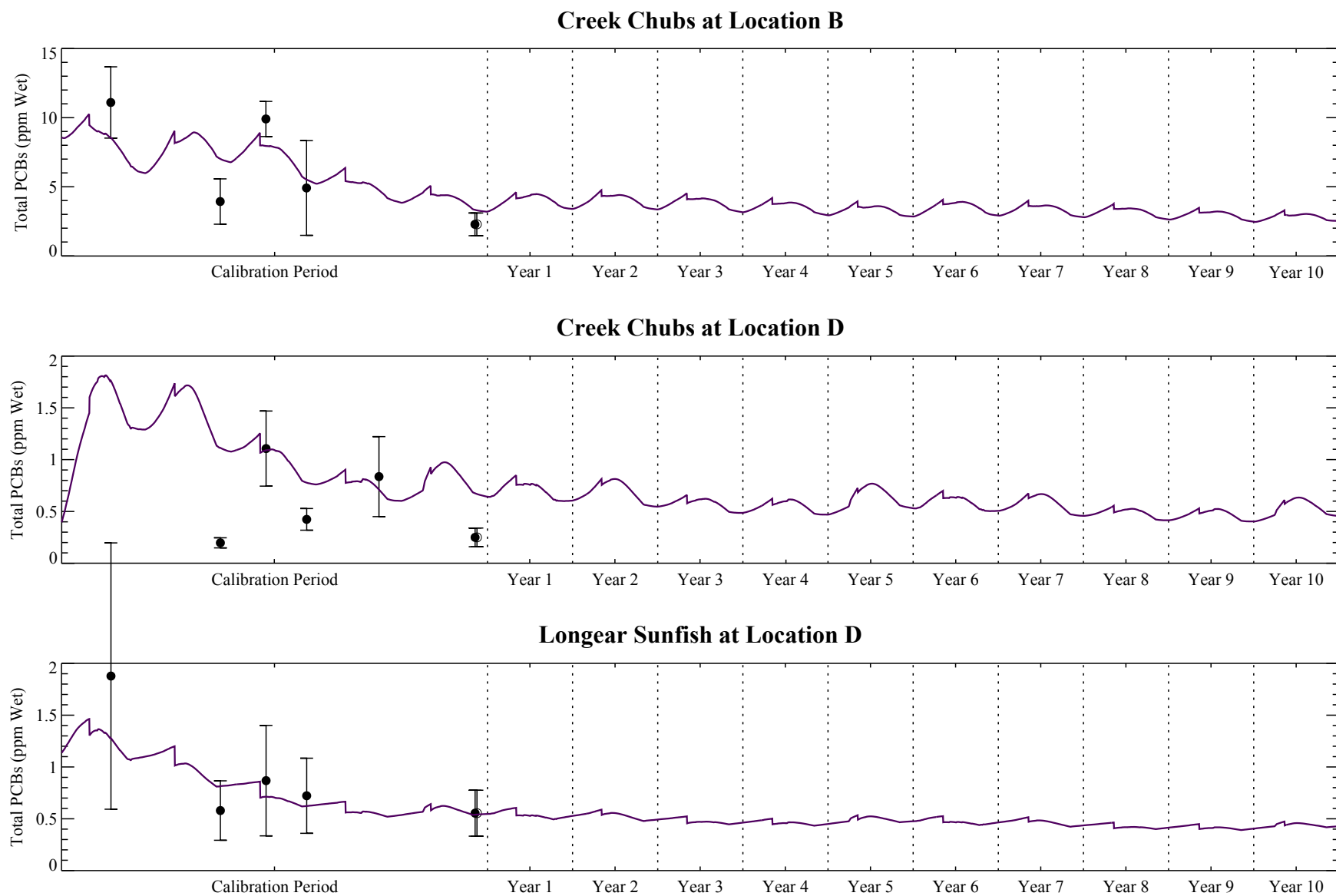


Figure 4. Observed and computed PCB concentrations in fish from Conard's Branch and Richland Creek.

Temporal profiles of model PCB concentrations in fish during 2001-2005 calibration and 10-year projection period.

Note: Congener PCB data shown. 2005 data plotted on 11/9/2005. Open symbols represent ES Recovery adjusted values (offset to view).

Data plotted as mean $\pm$ 2SE.

Model output is average of ageclass 2,3, and 4.

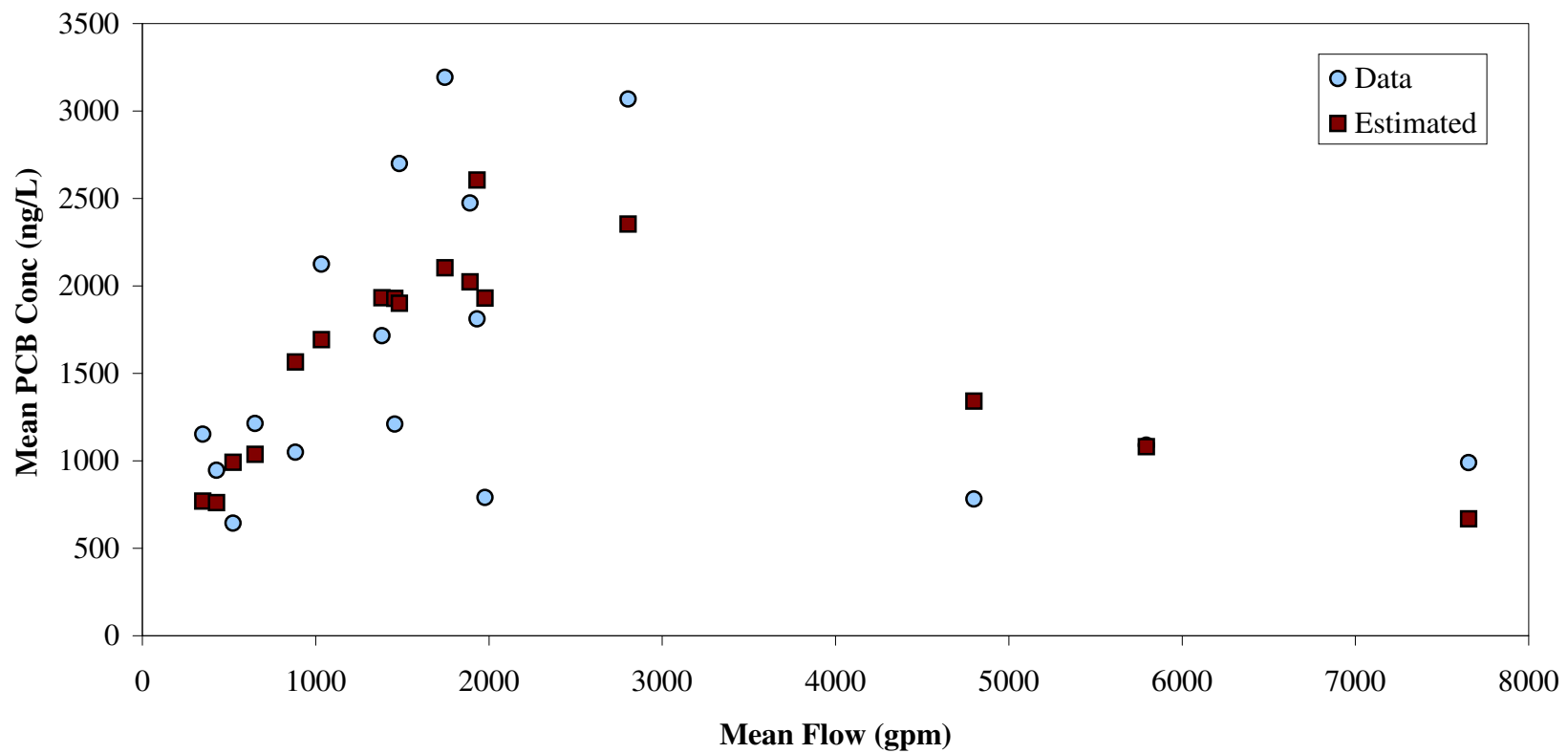


Figure A1. Comparison of measured and calculated event-mean PCB concentration vs. flow for Conard's Branch storm events.

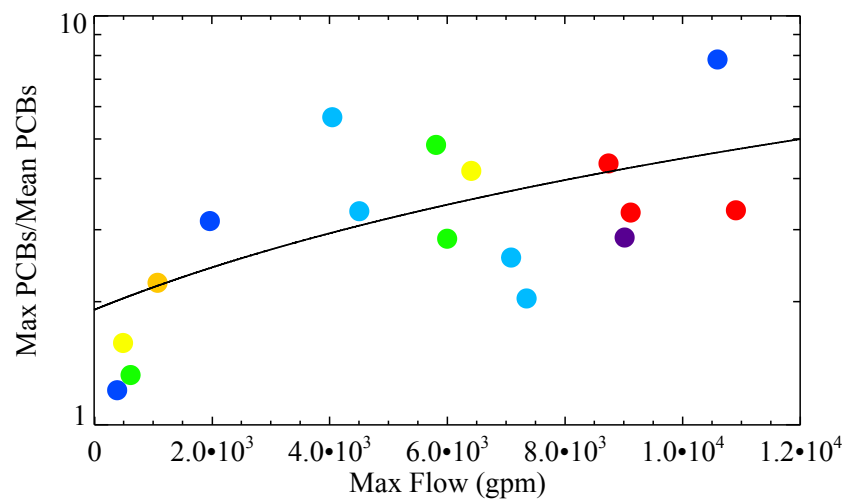
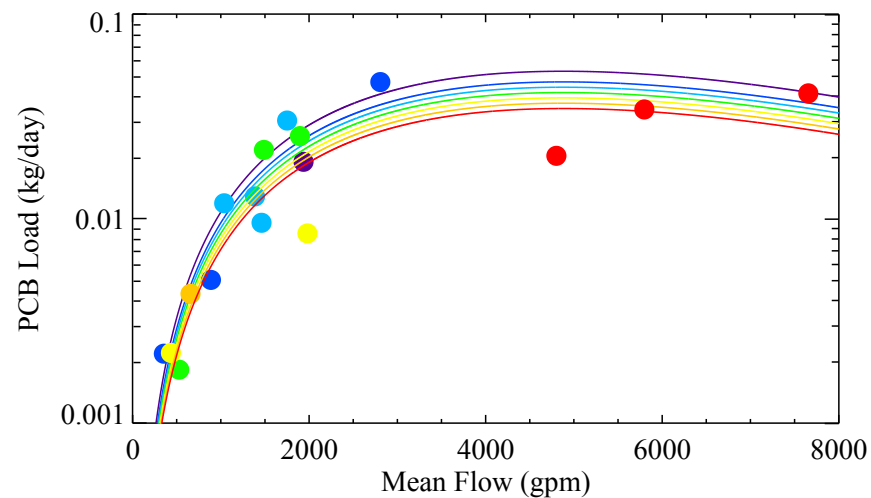
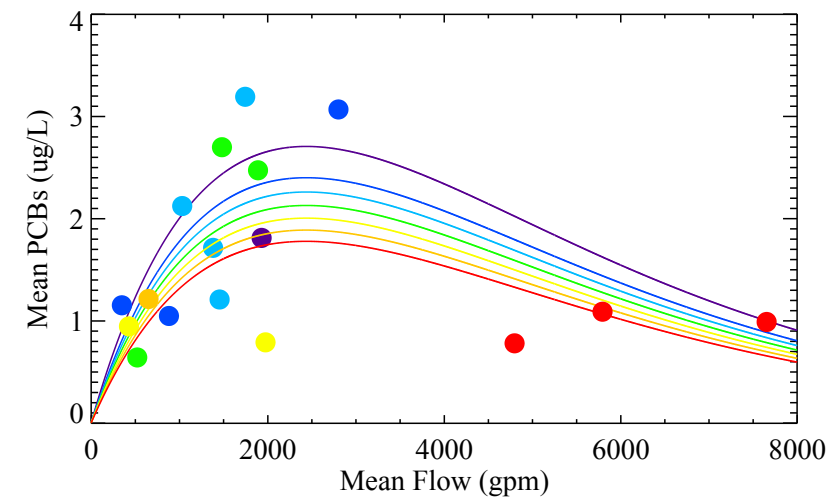
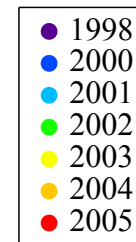


Figure A2. Model representation of PCB concentration at CBW during storms.

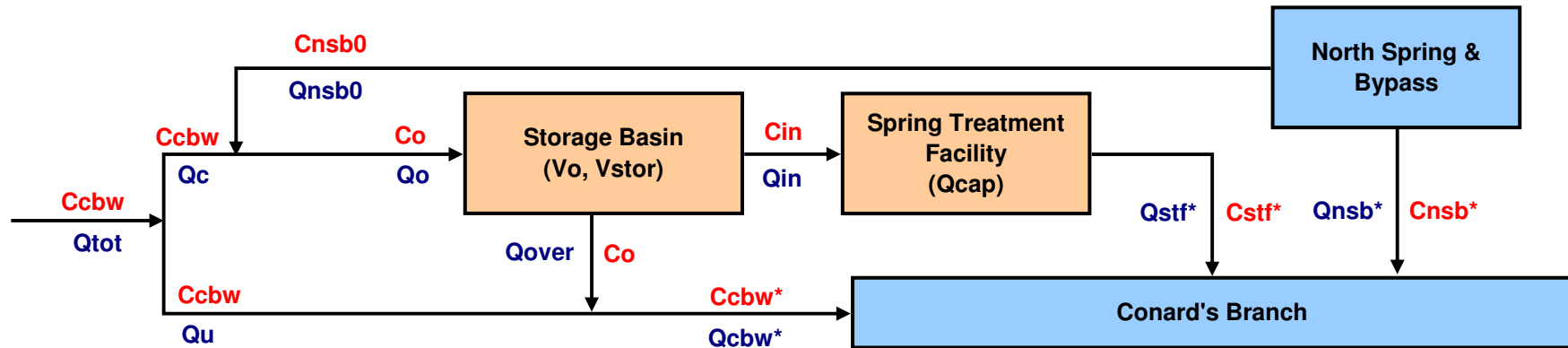
Note: Trend NOT applied to max PCBs/mean PCBs vs max flow plot.



Appendix C

Schematic Diagrams for Representation of Storage and Settling Basins in Model Simulation of Remedial Alternatives

Appendix C-1. Diagram of modeling storage basin.



Flows & Volumes

Qcbw, Qstf, Qnsb = flows at CBW, STF, and NSB for base condition

Qtot = total flow = Qcbw + Qstf

Qc = Qtot captured by STF

Qu = Qtot uncaptured by STF = (Qtot - Qc)

Qnsb0 = additional flow collected from NSB

Qo = Qc + Qnsb0

Qcap = STF capacity

Vstor = Storage Basin Volume = 2,000,000 gallon

Vo = Volume of water in Storage Basin (gallon)
= min(Vstor, Vo(t-1)+Qo/dt)

Qover = flow routed back to CBW, while Vo(t) > Vstor
= max(0, Qo - Qcap - (Vo(t) - Vo(t-1))/dt)

Qin = amount of flow entering STF
= min(Qcap, Qo + Vo(t)/dt)

Qstf* = flow BC at STF for projection runs (=Qin)

Qcbw* = flow BC at CBW for projection runs = Qu + Qover

Qnsb* = flow BC at NSB for projection runs = Qnsb - Qnsb0

Concentrations

Ccbw, Cstf, Cnsb = TSS/PCB at CBW, STF, and NSB for base condition

Cnsb0 = TSS/PCB at NS&Bypass (NS + seepage)
for PCB: Cnsb0 = (Wnsb - Wbank) / Qnsb
for TSS: Cnsb0 = Cnsb

Wnsb = NSB TSS/PCB load for base condition

Co = (Csb x Qc + Cnsb0 x Qnsb0) / Qo

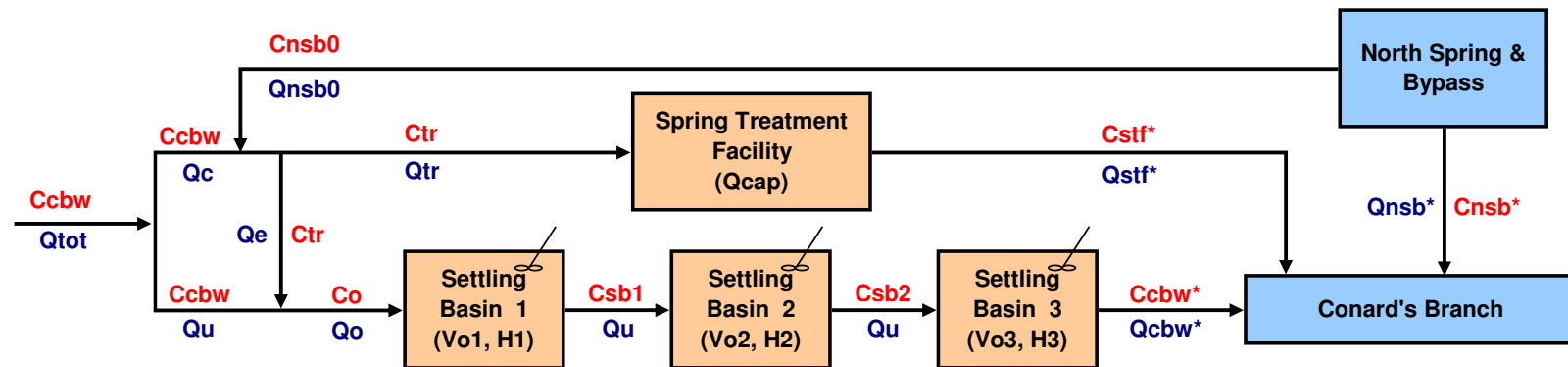
Cin = Co (no need to calculate)

Cstf* = concentration BC at STF for projection runs

Ccbw* = concentration BC at CBW for projection runs
= (Ccbw x Qu + Co x Qover) / Qcbw*

Cnsb* = concentration BC at NSB for projection runs
= (Wnsb - Cnsb0 x Qnsb0) / Qnsb*

Appendix C-2. Diagram of modeling series of 3 settling basins.



Flows & Volumes

Q_{cbw} , Q_{stf} , Q_{nsb} = flows at CBW, STF, and NSB for base condition

$$Q_{tot} = Q_{cbw} + Q_{stf}$$

$$Q_c = Q_{tot} \text{ captured by STF}$$

$$Q_u = Q_{tot} \text{ uncaptured by STF} = (Q_{tot} - Q_c)$$

$$Q_{nsb0} = \text{additional flow collected from NSB}$$

$$Q_{cap} = \text{STF capacity}$$

$$Q_{tr} = \text{final flow entering STF} = \min(Q_c + Q_{nsb0}, Q_{cap})$$

$$Q_e = \text{excess flow} = Q_c + Q_{nsb0} - Q_{tr}$$

$$Q_o = \text{flow entering SB1} = Q_u + Q_e$$

$$V_{oi} = \text{volume of Settling Basin } i$$

$$V_{o1} = 2.4 \text{ M Gallon}$$

$$V_{o2} = 3.0 \text{ M Gallon}$$

$$V_{o3} = 6.1 \text{ M Gallon}$$

$$H_i = \text{depth of Settling Basin } i$$

$$H_1 = 8 \text{ ft}$$

$$H_2 = 10 \text{ ft}$$

$$H_3 = 12 \text{ ft}$$

$$Q_{cbw}^* = \text{flow BC at CBW for projection runs} = Q_u$$

$$Q_{stf}^* = \text{flow BC at STF for projection runs} = Q_c$$

$$Q_{nsb}^* = \text{flow BC at NSB for projection runs} = Q_{nsb} - Q_{nsb0}$$

Concentrations

C_{cbw} , C_{stf} , C_{nsb} = TSS/PCB at CBW, STF, and NSB for base condition

$$C_{cbw} = \text{TSS/PCB at CBW upstream}$$

$$C_{nsb0} = \text{TSS/PCB at NS\&Bypass (NS + seepage)}$$

$$\text{for PCB: } C_{nsb0} = (W_{nsb} - W_{bank}) / Q_{nsb}$$

$$\text{for TSS: } C_{nsb0} = C_{nsb}$$

$$W_{nsb} = \text{NSB TSS/PCB load for base condition}$$

$$C_{tr} = (C_{cbw} \times Q_c + C_{nsb0} \times Q_{nsb0}) / (Q_c + Q_{nsb0})$$

$$C_o = (C_{cbw} \times Q_u + C_{tr} \times Q_e) / (Q_u + Q_e)$$

For settleable solids and associated particulate phase PCBs only

$$C_{sb1} = \text{TSS/PCB leaving Settling Basin 1}$$

$$dC_{sb1}/dt = (C_o Q_u / V_{o1}) - (Q_u / V_{o1} + V_s / H_1) \times C_{sb1}$$

$$\text{Solve } C_{sb1}(t) \text{ numerically}$$

$$C_{sb2} = \text{TSS/PCB leaving Settling Basin 2}$$

$$dC_{sb2}/dt = (C_{sb1} Q_u / V_{o2}) - (Q_u / V_{o2} + V_s / H_2) \times C_{sb2}$$

$$\text{Solve } C_{sb2}(t) \text{ numerically}$$

$$C_{cbw}^* = \text{concentration BC at CBW for projection runs} = \text{TSS/PCB leaving Settling Basin 1}$$

$$dC_{cbw}^*/dt = (C_{sb2} Q_u / V_{o3}) - (Q_{cbw}^* / V_{o3} + V_s / H_3) \times C_{cbw}^*$$

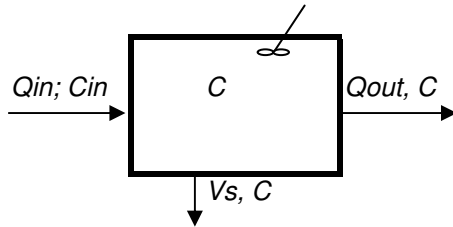
$$\text{Solve } C_{cbw}^*(t) \text{ numerically}$$

$$C_{stf}^* = \text{concentration BC at STF for projection runs} = C_{stf}$$

$$C_{nsb}^* = \text{concentration BC at NSB for projection runs}$$

$$= (W_{nsb} - C_{nsb0} \times Q_{nsb0}) / Q_{nsb}^*$$

Appendix C-2 (continue). Algorithms for calculating TSS and PCBs leaving a settling basin.



(a) Since the Settling Basin is always full of water

$$Q_{in} = Q_{out} = Q$$

(b) Volume and dimensions of the Settling Basin

$$V = A_s * H$$

(c) For TSS; consider settleable fraction = F_s

$$d(C * V)/dt = Q_{in} * C_{in} - (Q_{out}) * C - A_s * V_s * (C * F_s)$$

$$V * dC/dt = Q * C_{in} - Q * C - A_s * V_s * C * F_s$$

$$dC/dt = Q / V * C_{in} - (Q / V + F_s * V_s / H) * C$$

$$(C[i] - C[i-1]) / dt = Q[i-1] / V * C_{in}[i-1] - (Q[i-1] / V + F_s * V_s / H) * C[i-1]$$

$$C[i] = dt * Q[i-1] / V * C_{in}[i-1] + C[i-1] * (1 - Q[i-1] / V * dt + F_s * V_s / H * dt)$$

(d) For PCBs

$$C \text{ (total PCB)} = C_{part} \text{ (particulate PCB)} + C_{diss} \text{ (dissolved PCB)}$$

$$C_{part} = f_p * C; f_p = TSS * f_{oc} * K_{oc} / (1 + TSS * f_{oc} * K_{oc})$$

$$C_{diss} = f_d * C; f_d = 1 - f_p$$

$$C[i] = dt * Q[i-1] / V * C_{in}[i-1] + C[i-1] * (1 - Q[i-1] / V * dt + V_s * f_p * F_s / H * dt)$$