OEA

Model

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PCBs in the Upper Hudson River

Volume 1
Historical Perspective and Model Overview

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Introduction

Quantitative Environmental Analysis, LLC

SECTION 1

INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

In 1989, Region II of the U.S. Environmental Protection Agency (USEPA) announced it was reassessing its 1984 decision (USEPA 1984b), under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), that no action should be taken for PCBs within Upper Hudson River sediments. Since that time, USEPA has been involved in a multi-phased reassessment project that has included a review of site data, collection and analysis of new data, and evaluation of different remedial action strategies for Upper Hudson River sediments. The General Electric Company (GE) has been extensively involved in the reassessment process, providing comments on USEPA work products, performing independent data collection and analyses, and conducting field and laboratory research. USEPA and GE reassessment efforts are focused on answering three central questions (USEPA 1996):

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

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

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

To address these questions, GE has been developing quantitative models. These models mathematically describe the fundamental processes governing the behavior of PCBs within the Upper Hudson River and represent the principal means by which the above questions can be answered. This report, developed by Quantitative Environmental Analysis, LLC (QEA), on behalf of GE, documents a nine year effort to: 1) quantitatively understand PCB dynamics in the

Upper Hudson River, and 2) develop, calibrate, validate, and apply a state-of-the-science PCB fate, transport, and bioaccumulation model to the Upper Hudson River PCB problem. The model's most important feature is its ability to predict future PCB concentrations in water, sediment, and fish under continued No Action (natural recovery), as well as under various assumed remedial scenarios, making it a valuable tool in the decision-making process.

1.2 REPORT ORGANIZATION

This report on PCBs in the Upper Hudson River is presented in three volumes:

- Volume 1: Historical Perspective and Model Overview,
- Volume 2: A Model of PCB Fate, Transport, and Bioaccumulation, and
- Volume 3: Predictions of Natural Recovery and the Effectiveness of Active Remediation.

Volume 1 presents important physical and cultural features of the Upper Hudson River as well as PCB usage, distribution, and data trends, which collectively form the backbone upon which the PCB fate, transport, and bioaccumulation models presented in Volume 2 have been constructed. Specifically, the physical setting of the Upper Hudson River is presented, including a discussion of the geographical and cultural features that impact river hydrodynamics and sediment transport, and consequently PCB distribution. The history of PCB usage at the GE plant sites, major events affecting PCB distribution, and significant remediation events of the last 25 years are presented. A discussion of the historical PCB trends in water, sediment, and fish, as well as important processes that affect PCB fate, transport, and bioaccumulation are discussed. Volume 1 concludes with a presentation of the major sources and sinks of Upper Hudson River PCBs as derived from an integrated data analysis and modeling effort covering the past 20 years, and includes an accounting of the mass of PCBs that entered, exited, and remains within the system.

Volume 2 documents the development, calibration, and validation of a comprehensive mathematical model of PCBs in the Upper Hudson River, including submodels describing river hydrodynamics, sediment transport, PCB fate, and PCB bioaccumulation. A theoretical background including citations to relevant scientific literature and a presentation of the governing mathematical equations is presented for each model. This is followed by a detailed description of how the mathematical expressions constituting each model were applied to accurately represent the Upper Hudson River. The rigorous calibration and validation of the models to more than 20 years of Upper Hudson River water column, sediment, and biota PCB data is presented. Finally, the effects of uncertainty in the mathematical representation of the Upper Hudson River system are explored through sensitivity analyses of each model.

Volume 3 presents model-based predictions of future PCB levels in water column, sediment, and fish under continued No Action (natural recovery), simulations of various remedial action scenarios, and the potential occurrence of a 100-year flood event. The remedial scenarios include various combinations of sediment dredging, sediment capping, and plant site PCB source control. The report presents a description of how each of the remedial scenarios and the 100-year flood event are represented in the mathematical framework of the models. Volume 3 concludes with a discussion of the impact of different remedial scenarios on fish PCB recovery rates relative to Natural Recovery, and the implications these model simulations have on river management strategies.

The historical perspective of PCBs in the Upper Hudson River and an overview of the modeling effort (Volume 1) are presented herein. Volumes 2 and 3 are bound separately.

Section 2

Physical Characteristics

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SECTION 2
PHYSICAL CHARACTERISTICS

2.1 GEOGRAPHIC FEATURES

2.1.1 River Location

The Hudson River flows more than 300 miles in a southerly direction through eastern New York State. Its source is Lake Tear-of-the-Clouds on Mount Marcy in the Adirondack Mountains in Essex County, New York. In the northernmost portion of the Hudson, it is a fast-flowing mountain stream, fed by tributaries, lakes, and reservoirs. The Sacandaga River joins the Hudson near Hadley, NY, approximately 80 miles below the headwaters. At this point, it is the largest tributary to the Hudson, contributing an average of 30-40% of the flow, as measured in Fort Edward, NY (O'Brien and Gere 1993a). The Sacandaga River is the outlet from the Great Sacandaga Lake Reservoir. Management of the Sacandaga Reservoir outlet flow directly affects flow in the Hudson.

For the purpose of this report, the Upper Hudson River is defined as the 43-mile stretch of river between Hudson Falls, NY and the Federal Dam in Troy, NY (Figure 2-1). The Upper Hudson River is a run-of-the-river reservoir system with a series of locks and dams that serve as navigational controls for the Champlain Canal system. The Upper Hudson River is divided into eight reaches, or pools, that are bordered by a lock or dam at their downstream ends. Below the Federal Dam in Troy, the Lower Hudson River is a tidally influenced estuary that flows for approximately 150 miles to the Battery in New York City (Figure 2-1). The focus of this report is the Upper Hudson River between Hudson Falls and Troy, NY

2.1.2 River Dimensions and Characteristics

A river mile index for the Hudson River has been established by specifying the Battery in New York City as Mile Point (MP) 0. The Lower Hudson River spans from MP 0 to MP 154, and the Upper Hudson River (as defined for this report) extends from MP 154 to MP 197 in Hudson Falls. Upstream of Hudson Falls, the river spans an additional 110 miles. The eight dammed reaches of the Upper Hudson River that are the focus of this report extend from MP 195 in Fort Edward, NY to MP 154 in Troy (Figure 2-2). The Upper Hudson River is typically 500-1,500 feet wide, and generally widens with downstream distance. The Upper Hudson River reaches range from 2 to 16 miles in length, and have surface areas ranging from 200-1350 acres. Mean river depths for the Upper Hudson River reaches range from approximately 5 to 15 feet (O'Brien and Gere 1993a). Geographic features of these reaches are summarized in Table 2-1.

Table 2-1. Geographic Features of Upper Hudson River Reaches

River Reach	Downstream Boundary and Mile Point (MP)	Total Length (miles)	Average Width (feet)	Surface Area (acres)	Average Depth (feet)
8	Thompson Island Dam (MP 188.5)	6.0	680	500	9
7	Lock #6 / Fort Miller Dam (MP 186.2)	2.2	760	200	5
6	Lock #5 / Northumberland Dam (MP 183.5)	2.8	830	300	9
5	Lock #4 / Stillwater Dam (MP 167.8)	15.3	720	1,350	9
4	Lock #3 / Upper Mechanicville Dam (MP 166.0)	2.2	1,280	350	10
3	Lock #2 / Lower Mechanicville Dam (MP 163.5)	2.5	910	300	5
2	Lock #1 / Waterford Dam (MP 159.5)	4.0	970	450	6
1	Federal Dam in Troy (MP 154.0)	5.5	850	550	13

The Upper Hudson River undergoes a considerable reduction in elevation between its headwaters and the Federal Dam in Troy. Elevations near its source are approximately 1,000 feet above mean sea level (MSL), and the Sacandaga River meets the Hudson at an elevation of approximately 600 feet above MSL. As the river traverses a series of seven dams and three waterfalls, the elevation drops approximately 400 feet between the confluence with the Sacandaga and the Bakers Falls Dam in Hudson Falls, NY (USEPA 1984a).

The pool formed by the Thompson Island Dam (TID) has an approximate elevation of 120 feet above MSL. This pool is referred to as the Thompson Island Pool (TIP), and forms

Reach 8, with the TID serving as its downstream boundary. The river elevation drops only 35 feet over a distance of approximately 25 miles between reaches 8 and 5. The remaining four reaches of the Upper Hudson River have a steeper slope, with an elevation decrease from approximately 80 feet above MSL at Stillwater, NY, to approximately 15 feet above MSL at the crest of the Federal Dam in Troy, over a distance of about 12 miles. Downstream of the Federal Dam, the Lower Hudson River is at sea level (i.e., 0 feet above MSL). A profile of the Upper Hudson River elevation changes from the Great Sacandaga Lake Reservoir to Troy, NY is plotted in Figure 2-3.

Although the average river depths listed in Table 2-1 range from 5 to 15 feet, there is a great deal of lateral variability in water depth due to the Champlain Canal navigational channel. This variability is illustrated by bathymetric profiles developed along transects across the river. Several example transects, one from each Upper Hudson River reach, are presented in Figure 2-4. Cross sections for these transects are plotted in Figure 2-5. The dredged navigational channel is most notable near the western shore in the cross sections for Reaches 2 and 3 (Figure 2-5).

In the early 20th century, the Champlain Canal was dredged in parts of the river to provide a navigational channel with a minimum depth of 12 feet and a minimum width of 200 feet. The shallower, near shore areas on either side of the channel are typically less than 10 feet deep, with widths ranging from 10 to 500 feet. These shallower areas are the littoral zones that support a rich aquatic vegetation community (Exponent 1998a). A map of submerged aquatic vegetation density within the TIP is presented in Figure 2-6. The areas of high to medium vegetation density occur in near shore areas, with quiescent water and fine-grained sediment. Aquatic vegetation is typically absent within the navigational channel, which carries most of the river flow (Figure 2-6).

2.1.3 Drainage Basin Characteristics

The entire Hudson River basin drains over 13,000 square miles of northern and eastern New York State (Hetling *et al.* 1978). From its headwaters to Corinth, NY (just downstream of the Hudson's confluence with the Sacandaga River), the Hudson River watershed encompasses approximately 2,750 square miles, including a major portion of the southern and central Adirondack Mountains. The watershed between Corinth and Troy, NY covers an area of approximately 1,860 square miles (Figure 2-7). In addition to areas that directly drain to the Hudson (approximately 245 square miles), numerous tributaries flow into the Upper Hudson River between Fort Edward and Troy, encompassing a drainage area of approximately 1,615 square miles. The major tributaries within this section of the river are:

- Snook Kill (confluence at MP 191.8),
- Moses Kill (confluence at MP 189.3),
- Batten Kill (confluence at MP 182.0),
- Fish Creek (confluence at MP 181.2),
- the Hoosic River (confluence at MP 167.4), and
- Anthony Kill (confluence at MP 165.3).

In addition to these tributaries, the Mohawk River joins the Upper Hudson River just upstream of the Federal Dam in Troy, between MP 156 and MP 154. The Mohawk River basin covers an additional 3,500 square miles of central and eastern New York.

The Upper Hudson River watershed is located within the Hudson Champlain lowlands of the valley and ridge physiographic province (USEPA 1984a). Typical elevations within the lowlands of the river valley and surrounding area range from 100 to 400 feet above MSL. Higher elevations in rolling and hilly areas extend to the west and east of the valley. The northern portion of the Upper Hudson River watershed extends into the Adirondack mountain range, where elevations rise to more than 1,000 feet above MSL.

The geology of the Upper Hudson River basin consists mostly of consolidated shale bedrock overlain by unconsolidated glacial deposits. The unconsolidated deposits in the Upper Hudson River watershed range from less than one to 200 feet in thickness. The predominant composition of the unconsolidated deposits is lacustrine glacial sediments from the proglacial Lake Albany, which existed more than 10,000 years ago (USEPA 1984a). The lacustrine glacial sediments consist of clay and silt deposits that formed a rolling valley floor covering more than half of the Upper Hudson River watershed (USEPA 1984a). In parts of the Upper Hudson River watershed, unstratified deposits of clay to boulder-sized glacial till overlie the lacustrine sediments. Approximately one quarter of the Upper Hudson River basin contains stratified layers of gravel and sand that were deposited as glacial outwash. More recent geological deposits within the Hudson River basin include alluvial silts, clays, and sands within the floodplains of the river and its tributaries, as well as man-made land formations consisting of canal dredge spoils (USEPA 1984a).

The land in the Upper Hudson River is primarily mixed deciduous and coniferous forests. Areas of agricultural land (i.e., cropland and pastures) predominate within the river valley and adjacent areas (Figure 2-8). The major agricultural use in the Hudson Valley is dairy farming (USEPA 1991). There are areas of residential, commercial, and industrial use in the major population centers along the river (e.g., Glens Falls, Hudson Falls/Fort Edward, and Albany/Troy; Figure 2-8). The predominant land uses of the Upper Hudson River watershed are shown in Figure 2-8 and are summarized in Table 2-2.

Table 2-2. Land Use in the Upper Hudson River Watershed			
Subdrainage Basin	Area (square miles)	Predominant Land Use Type(s)	Secondary Land Use Type(s)
Hudson River Direct (Glens Falls to Fort Edward)	90	Forest	Agricultural with some residential and commercial
Hudson River Direct (Fort Edward to Stillwater)	100	Agricultural	Some forest
Hudson River Direct (Stillwater to Waterford)	40	Agricultural	Forest and residential
Hudson River Direct (Waterford to Troy)	15	Residential	Commercial
Snook Kill	75	Forest	Agricultural
Moses Kill	55	Agricultural	Some forest
Batten Kill	430	Forest	Agricultural
Fish Creek	245	Forest	Agricultural and residential
Flately Brook	10	Agricultural	Some forest
Hoosic River	720	Forest	Agricultural with some residential
Anthony Kill	65	Agricultural	Forest and residential
Deep Kill	15	Agricultural	Forest with some residential
TOTAL	**1860**		

2.2 CULTURAL FEATURES

The Hudson River is an important transportation route between the United States and Canada, connecting the Atlantic Ocean with Lake Champlain and the St. Lawrence River. The importance of the river is signified by the numerous battles fought for control of this region during the French and Indian War (1750's – 1760's) and the Revolutionary War (1770's – 1780's). The Upper Hudson River includes a series of natural waterfalls that have been harnessed for over 200 years to provide hydropower. With changes in elevation ranging up to 70 feet, these falls provided energy to power saw mills, grist mills, paper mills, and other industries in the late 18th century and throughout the 19th century. A significant portion of the Adirondack forest was harvested and floated down the Hudson to be turned into lumber and paper products at these mills. Most of the villages and cities along the Upper Hudson River, including Corinth, Glens Falls, Hudson Falls, Fort Edward, Stillwater, and Mechanicville (Figure 2-1) developed where the river provided hydropower from dams constructed of timber cribs or cut stone.

2.2.1 Hydroelectric Power Generation

Many of the dams and associated mills on the Upper Hudson River were rebuilt at the end of the 19th century and during the first decade of the 20th century as industry converted from mechanical hydropower to the use of hydropower to generate electricity. Many of these hydroelectric facilities are in use today. The locations of dams on the Upper Hudson River, including currently operating hydroelectric facilities, are illustrated in Figure 2-9 and are summarized below:

Table 2-3. Hydroelectric Facilities on the Upper Hudson River		
Facility Name[1]	Location	Function
E.J. West (Conklingville Dam)	Downstream extent of Great Sacandaga Lake	Flood control, power generation
Stewart's Bridge Dam	Approximately 3 miles downstream of E.J. West	Power generation
Palmer Falls Dam	MP 218[2]	Power generation
Curtis Dam	MP 216	Power generation
Spier Falls Dam	MP 213	Power generation
Sherman Island Dam	MP 209	Power generation
Feeder Dam	MP 202	Diversion of water to Champlain canal for navigation, power generation
South Glens Falls Dam	MP 200	Power generation
Glens Falls Dam	MP 200	Power generation
Bakers Falls Dam	MP 197	Power generation
Thompson Island Dam	MP 188.5	Navigation
Fort Miller Dam	MP 187	Navigation, power generation
Northumberland Dam	MP 185.5	Navigation[3]
Stillwater Dam	MP 168	Navigation, power generation
Upper Mechanicville Dam	MP 166	Navigation, power generation
Lower Mechanicville Dam	MP 164	Navigation, power generation
Green Island (Federal Dam)	MP 154	Navigation, power generation

(1) – Information in this table obtained from Malcolm Pirnie (1984) and AHDC (1991).
(2) – MP = Hudson River Mile Point. MP 0.0 is located at the Battery in New York City.
(3) – Formerly also used as source of hydropower.

2.2.2 Champlain Canal

In the 1820's, the State of New York completed a canal system that included the Erie, Oswego, Cayuga and Seneca, and Champlain Canals. Numerous other spur canals were built, including the Black River, Chemung, Genesse Valley, and Chenango Canals. The Champlain Canal connected the Erie Canal at Waterford with Lake Champlain at Whitehall. The original route of this canal paralleled the Upper Hudson River, and water was diverted from the river to maintain water levels in the canal. A feeder canal (still in use today) was constructed between Glens Falls and the Champlain Canal to provide water to the canal.

New York State rebuilt the Canal system, including the Champlain Canal, in the first part of the 20th century. The Champlain was relocated in the channel of the Hudson River from Waterford to Fort Edward wherever possible. The rebuilt Champlain Canal officially opened in 1918, and was used extensively for commercial transportation. As part of rebuilding the Champlain Canal, dams on the Upper Hudson River were reconfigured and additional dams were constructed. Figure 2-3 shows a profile of the Upper Hudson River with the locations of the dams. To augment the increases in water depth achieved with dams, the river was dredged to make a navigational channel approximately 200 feet wide and 12 feet deep. Dredge spoils were disposed of in the river and at upland sites. A Champlain Canal navigational chart shows the present-day canal between Fort Edward and Thompson Island Dam (Figure 2-10). Some of the dredge spoil disposal areas dating from when the river was dredged in the early 1900's are identified in this figure ("spoil areas"). At the end of the 20th century, the Champlain Canal is rarely used for commercial purposes, but it is widely used for recreation (Figure 2-11).

The Champlain Canal is maintained by the New York State Canal Corporation. Historically, this included periodic dredging of the channel to maintain a navigable depth of 12 feet. Dredge spoils from maintenance dredging were typically disposed of at dredge spoil sites established prior to 1918. Little dredging of the Champlain Canal has occurred since the late 1970's.

2.2.3 Hydropower Sites Affecting PCBs in the Hudson River

Of the numerous sites used for hydropower along the Upper Hudson River, three sites have had the most impact on the distribution of PCBs in the river. These sites are:

- Conklingville Dam,
- Fort Edward Dam, and
- Bakers Falls and the Allen Mill.

2.2.3.1 Conklingville Dam

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The Conklingville Dam was completed on the Sacandaga River in 1930, and formed the Great Sacandaga Lake (Figure 2-9). The Sacandaga River is tributary to the Hudson and typically contributes 30% - 40% of the flow in the Hudson at the confluence point. Prior to construction of the Conklingville Dam, the Upper Hudson River was prone to flooding, causing extensive damage to municipalities adjacent to the river, including the cities of Albany and Troy, NY (Stetson-Dale 1986). During high flow periods, flow from Great Sacandaga Lake is reduced to a minimum and the reservoir is allowed to fill. This practice reduces flow in the Hudson River by approximately 30% - 40%, providing a significant level of flood control. During low flow, the water in the reservoir is released at a controlled rate to provide downstream users with water for power generation. Management of flow at the Conklingville Dam is a significant factor in reducing the potential for resuspension and transport of PCB-containing sediment during high flow events.

2.2.3.2 Fort Edward Dam

The Fort Edward Dam was constructed in the early 1800's to provide hydropower for industries located along the east shore of the Hudson River in Fort Edward (Figures 2-12 and 2-13). The Fort Edward Dam was a timber crib structure that formed the first impoundment downstream of the discharges from GE's Hudson Falls and Fort Edward facilities' (Figure 2-14). The Fort Edward Dam raised the upstream level of the Hudson River by approximately 20 feet, providing a deep, slow moving reach of the river where large quantities of sediment and debris (primarily slab wood and sawdust from upstream sawmills) accumulated. Beginning with the onset of PCB discharges from the GE facilities in the late 1940's (see Section 3.1.2), PCBs started to accumulate in the sediment and debris in this reach of the river. In 1973, the Fort Edward Dam was removed by its owner (Niagara Mohawk Power Corporation) due to the deteriorated state of the structure. The removal of this dam, and subsequent mobilization of PCBs sequestered upstream of the dam, is the most significant PCB transport event to occur in the river (see Section 3.2). In addition, the lower water levels from the Fort Edward Dam removal resulted in exposed bank materials containing PCBs, which are referred to as the Remnant Deposits (Figure 2-14).

2.2.3.3 Bakers Falls and the Allen Mill

Bakers Falls has the largest change in elevation of any of the hydropower sites on the Upper Hudson River, and is the site of a recently expanded hydroelectric facility. Beginning in the late 18th century, Bakers Falls was also the site of numerous industrial facilities, clustered along the eastern shore of the falls, that went through phases of reconstruction and expansion. These facilities obtained water for hydropower through a raceway cut into bedrock that led from the head of the falls and ran parallel to the river for several hundred feet. Water was returned to the river through tailraces leading from the mills to the river. Most of the industrial facilities along Bakers Falls were eventually abandoned and torn down in the 20th century.

One of the largest industrial users of the hydropower provided by Bakers Falls was the Allen Mill (Figures 2-15 and 2-16). The Allen Mill was originally constructed in the mid-1800's and produced wallpaper through the first part of the 20th century. It was constructed out of cut stone, and was situated on exposed bedrock along the edge of the falls. The Allen Mill was partially dismantled in the mid 20th century, but the lower portion of the facility remained in place (Figure 2-17).

In addition to its main water supply from the raceway at the head of the falls (the eastern raceway), which it shared with other mills, the Allen Mill had additional waterways, including a drop shaft and tailrace tunnel extending through the mill and exiting at the base of the falls and a lower raceway that directed water to a lower part of the mill to power additional equipment (Figure 2-14 inset). These waterways were cut into bedrock within and beneath the mill. When the Allen Mill was shut down, the flow of water through the mill was minimized by blocking the mill's intake from the eastern raceway with a wooden gate and sealing the lower raceway intake with concrete. After being shut down, water continued to flow through the eastern raceway, but the drop shaft and tailrace tunnel were no longer in use. Use of the eastern raceway continued until the early 1970's, when a hydroelectric facility downstream of the Allen Mill ceased operating. The head gates at the upstream end of the eastern raceway were closed at that time, reducing flow through the raceway. The upper floor(s) of the mill were torn down sometime between 1947 and 1964 (based on aerial photographs). The mill owner allowed the building to deteriorate and by 1990 it was potentially dangerous to enter the building and access was extremely difficult.

The GE Hudson Falls plant site sits on top of the cliff adjacent to the abandoned Allen Mill. Reconstruction of events, after 1991, has shown that PCB dense nonaqueous phase liquid (DNAPL) was migrating through fractured bedrock from the GE Hudson Falls plant and accumulated within the waterways of the mill (O'Brien and Gere 1994a, see Section 3.2.3). In September, 1991, the wooden gate structure at the mill's intake to the eastern raceway collapsed and water from the eastern raceway flowed down the drop shaft into the tailrace tunnel, and PCBs and debris were washed directly to the river. This PCB loading event was the most important since the removal of the Fort Edward Dam in 1973.

2.3 RIVER HYDROLOGY/HYDRAULICS

2.3.1 Tributary Discharge and Average Annual Flow

The Upper Hudson River between Fort Edward and Waterford receives tributary discharge contributions at an average runoff rate of 1.6 cfs/mi^2, from a 1,793 mi^2 drainage basin. Tributary inflows cause the annual mean flow rate to increase from 5,200 cfs at Fort Edward to approximately 6,600 and 8,100 cfs at Stillwater and Waterford, respectively. The approximately 60% increase in discharge between Fort Edward and Waterford is primarily due to inflow from Batten Kill (Reach 5) and the Hoosic River (Reach 4), which together comprise 67% of the total tributary flow (Figure 2-18).

2.3.2 High Flow Events

Maximum flow rates in the historical record for Fort Edward (1977 to present) are approximately 34,000 cfs, which occurred during floods in 1983 and 1998. Although the Fort Edward gage was not in-place, the spring flood in 1976 was estimated to be more than 45,000 cfs (USEPA 1991). The 1983 and 1998 high flow events correspond to 10-year return-interval floods. The 100-year flood at Fort Edward has an estimated peak daily-average flow rate of 47,330 cfs (USEPA 1996). Thus, the 10-year floods that occurred in 1983 and 1998 had peak

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discharge that was only 28% lower than the 100-year flood (Figure 2-19). Dams control the elevation of the pool in each reach of the river, with the surface elevation (stage height) of the pool increasing as flow rate increases during a flood event (Figure 2-20).

2.3.3 River Current Velocities

Mean current velocities in the Upper Hudson River range from about 0.5 ft/s in Reaches 4 and 6 to about 1.0 ft/s in Reach 7 (Figure 2-21). However, considerable spatial and temporal variation in current velocities exists in the river. For example, the deeper, central channel of the river typically has higher velocities than the shallower, near shore areas. This generalized lateral distribution of velocity affects sediment transport processes in the Upper Hudson River. Shallow, near shore areas are relatively low energy environments that are more conducive to fine-grained sediment deposition than the higher energy zones in the deeper main channel. Thus, hydrodynamic processes in the Upper Hudson River are a primary reason that many fine-grained sediment deposits, where elevated PCB bed concentrations are usually found, are located in shallow, near shore zones.

2.4 SEDIMENT TRANSPORT

Rivers are conveyances for particulate matter that has eroded from the surrounding watershed or upstream areas within the river. Depending on the current velocities in the river and the nature of the particulate matter, a portion of the particulate matter may be deposited in the river channel, causing a decrease in water depth and an increase in the amount of soft sediment on the river bottom. The dams along the Upper Hudson River facilitate the deposition of particulate matter. Such deposition is one of the factors controlling the fate of Upper Hudson River PCBs.

2.4.1 Sediment Bed Characteristics

The Upper Hudson River sediment bed can be separated into three categories (or sediment types): (1) cohesive (muddy, composed of varying amounts of clay, silt and fine sand);

(2) non-cohesive (primarily sand and gravel); and (3) hard bottom (rocky). Sediment transport processes in the Upper Hudson River involve complex interactions between river hydrodynamics, sediment dynamics in cohesive and non-cohesive bed areas, and external sediment loading. River currents apply a shearing force to the sediment bed that significantly affects sediment deposition and resuspension rates. Sediment bed dynamics (i.e., deposition and erosion processes) are significantly different in cohesive and non-cohesive bed areas. Thus, understanding sediment transport processes in the Upper Hudson River requires knowledge about the areal distribution of these bed types in the river.

Upper Hudson River bed maps, which delineate areas of cohesive, non-cohesive, and rocky sediments, were created from sonar measurements and analyses of sediment samples collected by USEPA and GE. The bed map in Figure 2-22 shows that 22% of the total bed area in the TIP consists of cohesive sediments. In Reaches 1 to 7, cohesive bed areas range from about 1% (Reach 1) to 34% (Reach 4) of the total area.

2.4.2 Tributary Sediment Loading

Sediment loading from upstream and tributary sources to the Upper Hudson River is one of the primary factors controlling sedimentation rates in the river. Tributary sediment loads are a source of clean solids (i.e., particles with negligible PCB levels) that are deposited on the sediment surface and reduce the concentration of PCBs in the surface layer of the bed. Therefore, tributary sediment loading has a major impact on the rate of decline of surficial PCB bed concentrations in the Upper Hudson River.

Analysis of the data on sediment loading (see Volume 2, Section 3.2.2) shows that the average sediment load increases by more than a factor of five between Fort Edward and Waterford (Figure 2-23[1]), while the mean flow rate, as stated above, only increases by about 60% over that same stretch of river. This increase in sediment load, combined with the lower discharge increase, indicates that tributary sediment yield increases downstream of Fort Edward.

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Tributary solids and flow data were used to estimate tributary solids loading to the Upper Hudson River (Volume 2, Section 3.2.2). This analysis indicates that the tributary sediment yield between Thompson Island Dam and Stillwater (Reaches 7, 6 and 5) is approximately 84 MT/yr-mi^2, which is about 60% greater than the yield of the TIP tributaries (53 MT/yr-mi^2). Similarly, the Stillwater to Waterford (Reaches 4, 3 and 2) yield is 132 MT/yr-mi^2, which is about 2.5 times higher than the sediment yield of tributaries flowing into the TIP.

2.4.3 Long-Term Sedimentation in Cohesive Deposits

Net sedimentation, at various rates, occurs in nearly all of the cohesive sediment deposits of the Upper Hudson River. Several independent observations and analyses support this conclusion, including:

- presence of ^{7}Be within surface sediments,
- ^{137}Cs profiles within finely segmented sediment cores, and
- data analysis and mathematical modeling of solids loading and transport.

2.4.3.1 Presence of ^{7}Be in Surface Sediments

Beryllium-7 (^{7}Be) is a naturally-occurring isotope with a half-life of 53 days. It is produced by cosmic radiation entering the earth's atmosphere. ^{7}Be enters the water column through atmospheric deposition in the form of precipitation, with higher concentrations generally occurring in spring or early summer (Olsen *et al.* 1986). Due to its relatively short half-life, the presence of ^{7}Be in surface sediments indicates that suspended matter has been recently deposited.

The USEPA 1994 Low Resolution Coring effort (USEPA 1998b) found ^{7}Be present in 70% of the 169 surface sediment samples (0-2.5 cm) collected within the Upper Hudson River. Similarly, ^{7}Be was detected within the surficial 1-cm of sediments from 15 of the 28 (54%) cores collected from the river by GE in 1998 (O'Brien and Gere 1999a). Presence of ^{7}Be indicates that

[1] The sediment mass balance shown in Figure 2-23 has tributary sediment loads that have been adjusted (increased) to account for net deposition in the Upper Hudson River. The depositional masses needed to complete the mass

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these areas were depositional, at least at the time of sample collection. However, due to the fast ^{7}Be decay rate (i.e., 53-day half life), the time between probable ^{7}Be deposition and measurement of the element, and variability in the ^{7}Be detection limit, the lack of ^{7}Be at the remaining coring sites is not evidence for a lack of deposition. Rather, lack of ^{7}Be at those locations simply indicates that the deposition rate was insufficient to yield detectable ^{7}Be concentrations within the surficial sediment core sections.

2.4.3.2 ^{137}Cs-Based Estimates of Sediment Burial Rates

USEPA collected finely-segmented sediment cores from the Upper Hudson River in 1992 (USEPA 1997). Data collected from these cores were used to establish the deposition history of PCBs within fine-grained sediment deposits at select locations within the river. The cores were dated by interpreting Cesium-137 (^{137}Cs) concentration profiles and from knowledge of the depositional history of ^{137}Cs.

^{137}Cs was produced during the atmospheric detonation of nuclear weapons. This testing activity began in 1954 and peaked in the mid 1960's. Hence, sediments deposited prior to 1954 contain little or no ^{137}Cs and sediments deposited at or around 1963 contain the maximum ^{137}Cs levels within the sediment cores. Using these two characteristics of the sediment core profiles as event markers, an estimate of the average sedimentation rate over the intervening years can be calculated. For high resolution sediment cores collected from the Upper Hudson River, the calculated deposition rate ranged from 0.8 to 1.8 cm/yr. These cores were collected from continuously depositional regions of the river. Therefore, caution should be applied to extrapolating these observations to all of the fine-grained sediment deposits. However, these data are further indication that the cohesive sediment deposits are undergoing net deposition.

2.4.3.3 Sediment Mass Balance Analyses

The Upper Hudson River is a net depositional environment on an annual time scale, as would be expected of a run-of-the-river reservoir system. Based on the Upper Hudson River

balance were estimated in this data analysis and are not shown in the figure.

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model presented in Volume 2, a sediment mass balance for the Upper Hudson River over a 22-year period (from 1977 through 1998) projected that net deposition occurred in all eight reaches (Figure 2-24). A significant portion of the incoming sediment, from upstream and tributary sources, was deposited in the river, with the trapping efficiency (i.e., percent of mass retained) of individual reaches varying between < 0.1 and 11%. The Upper Hudson River model predicted widespread deposition in the cohesive bed areas of the river, with long-term average deposition rates projected to range between about 0.02 cm/yr (Reach 1) and 3.8 cm/yr (Reach 4).

Mass balance results for the TIP, based on model results, for this 22-year period yielded a trapping efficiency of 8.8%. Most of the deposition (87%) was projected to occur in the cohesive bed areas in this reach. Approximately 7% of the cohesive bed area was projected to have net erosion between 1977 and 1998 (with an average erosional depth of 1 cm). The simulation showed significant net deposition (average rate of 0.8 cm/yr) in most (93%) of the TIP cohesive bed (Figure 2-25). This sedimentation rate equates to an average deposition of about 18 cm (7 inches) over this 22-year period. These modeling results are consistent with the observed decrease in surficial bed PCB concentrations since 1977 and the occurrence of maximum PCB bed concentrations at depth. These analyses indicate that less-contaminated sediments enter the Upper Hudson River and bury historical PCB deposits in cohesive bed areas. This conclusion is further supported by measurements of ^{7}Be in surface sediments and ^{137}Cs in cores as described above.

Mass balance analyses, based on model predictions, for the TIP during the 1994 (27,700 cfs peak flow) and 1997 (~18,000 cfs peak flow) spring floods indicate that net deposition occurred in the cohesive bed areas, even though net erosion occurred within the entire TIP (Figure 2-26). These results are consistent with the concept of episodic deposition, where significant deposition occurs during floods and relatively minor deposition occurs during non-flooding periods, e.g., 90% of the annual deposition may happen during 10% of the year (Ager 1981, Walling *et al.* 1992). Net deposition in the TIP cohesive bed area during these floods is consistent with observed depositional patterns in fine-grained areas of the Upper Mississippi River during major flooding in 1993 (Barber and Writer 1998).

2.4.4 The Importance of the Non-Cohesive Bed

Non-cohesive bed areas are important contributors to sediment transport within the Upper Hudson River. Clay, silt and fine sand (fine-grained sediments) are deposited in the non-cohesive bed during low to moderate flows. These fine-grained sediments may be resuspended during high flow events and transported downstream. Additionally, a portion of the fine sand resuspended from the non-cohesive bed during high flow events is re-deposited in downstream cohesive bed areas, which are generally located in relatively low-energy depositional environments. Thus, the non-cohesive bed effectively serves as a temporary storage reservoir for coarser suspended sediment; fine sand accumulates during low to moderate flows and is released back to the water column during high flow events, contributing to deposition in downstream cohesive bed areas.

Cohesive sediment particles (clay and silt) deposited in non-cohesive bed areas erode and are transported downstream during floods. However, in contrast to fine sand re-deposition, significantly less re-deposition of the eroded cohesive particles occurs because of the depositional characteristics of this sediment type. A large fraction of the cohesive sediment particles within the surficial layer of the non-cohesive bed is resuspended during high flow events. Therefore, non-cohesive bed areas serve as a temporary storage area for cohesive sediment particles between floods. Thus, long-term accumulation of PCBs associated with cohesive sediment particles does not generally occur in the non-cohesive bed of the Upper Hudson River.

2.4.5 Resuspension During Low Flow Periods

Modeling results for 22 years (1977 through 1998) showed that hydrodynamically-induced resuspension from both cohesive and non-cohesive bed areas is negligible during low flow conditions (e.g., flow rates less than about 3,000 cfs at Fort Edward). This is because, under these flow conditions, shear forces exerted by the flow of water over the sediments are insufficient to induce resuspension of contaminated sediments.

2.4.6 Impacts of a Rare Flood Event

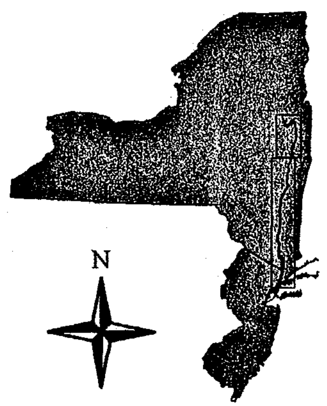
The rare flood event, typically referred to as the 100-year flood, is defined statistically as a discharge that has a 1% chance of occurring in any given year. Based on this annual probability of occurrence, there is a 63% chance that at least one 100-year flood will occur in any 100-year period. The impacts of a 100-year flood on sediment transport processes were investigated using the Upper Hudson River sediment transport model (Volume 2, Section 3.5).

This rare flood event would generate high current velocities in the Upper Hudson River, resulting in erosion at various locations, but it would also cause large quantities of sediment to be transported into the river from tributaries. High sediment loads in the river will make it possible for net deposition to occur at some locations during a 100-year flood. Therefore, a rare flood event does not necessarily cause net sediment loss to occur throughout the river.

The 100-year flood (47,330 cfs, USEPA 1996) simulation showed that relatively minor erosion, in both cohesive and non-cohesive bed areas, would occur in the TIP, with mean erosion depths of less than 1 cm and maximum scour depths of about 9 cm. Erosion would occur in approximately 94% of the cohesive bed area, with net deposition in the remainder of the area (Figure 2-27). In the eroded portions of the TIP cohesive bed, erosional depths of 2 cm or less were predicted for 78% of the total cohesive area and about 4% of the area had erosional depths greater than 5 cm. Scour depths of 1 cm or less were predicted in approximately 97% of the non-cohesive bed area.

These results are consistent with another sediment transport model that was used to evaluate the impact of a rare flood event on the TIP sediment bed (Zimmie 1985). Zimmie predicted that for a flood with a peak flow rate of 46,600 cfs (2% lower than the 100-year flood discussed above), the maximum and mean erosion depths would be 5 cm and 0.5 cm, respectively. While the Zimmie results indicate a slightly greater average erosional depth, the two models yield the same basic conclusion: the 100-year flood causes relatively minor erosion in the TIP.

LOCATION MAP OF THE HUDSON RIVER



Upper Hudson Scale

3 0 3 6 Miles

Lower Hudson Scale

7 0 7 14 21 28 Miles

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Figure 2-1.

Hudson River location map.

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

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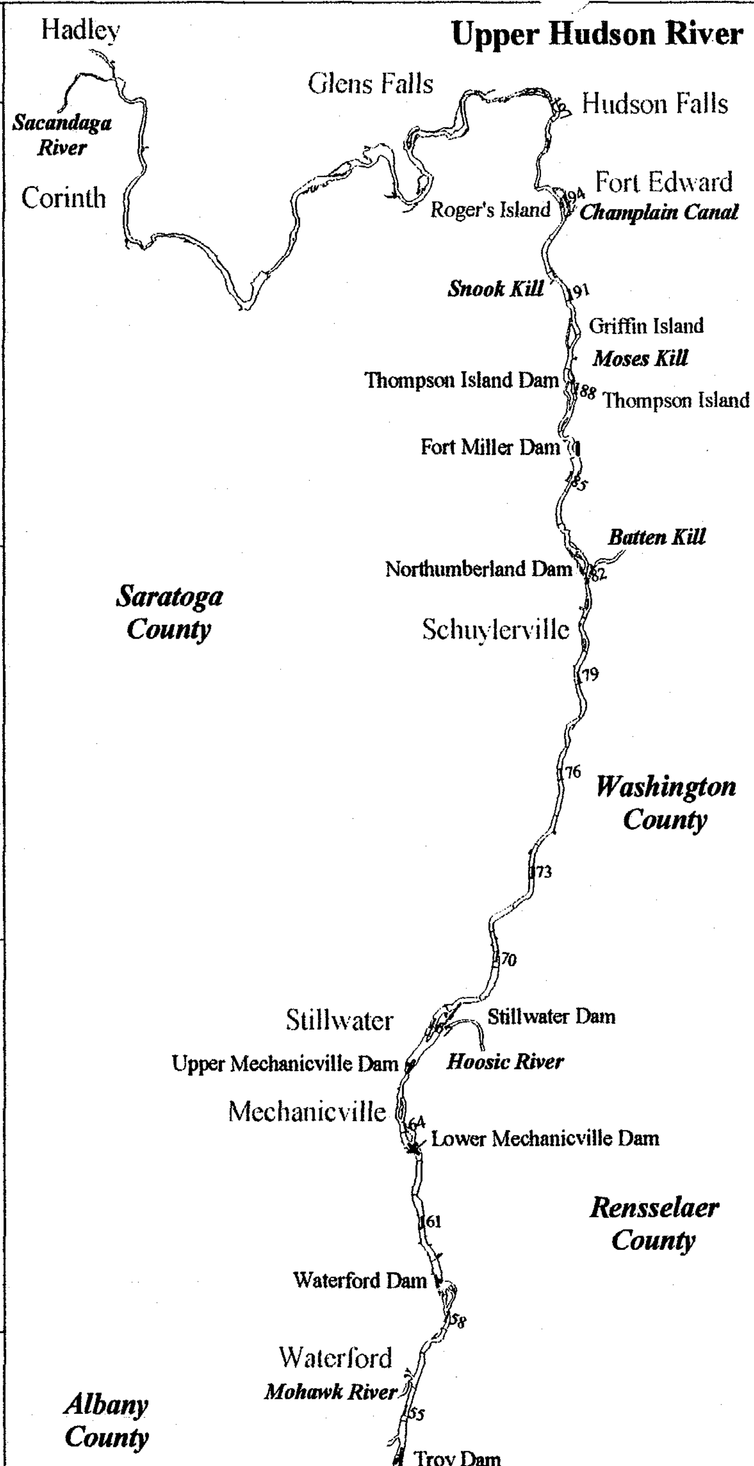

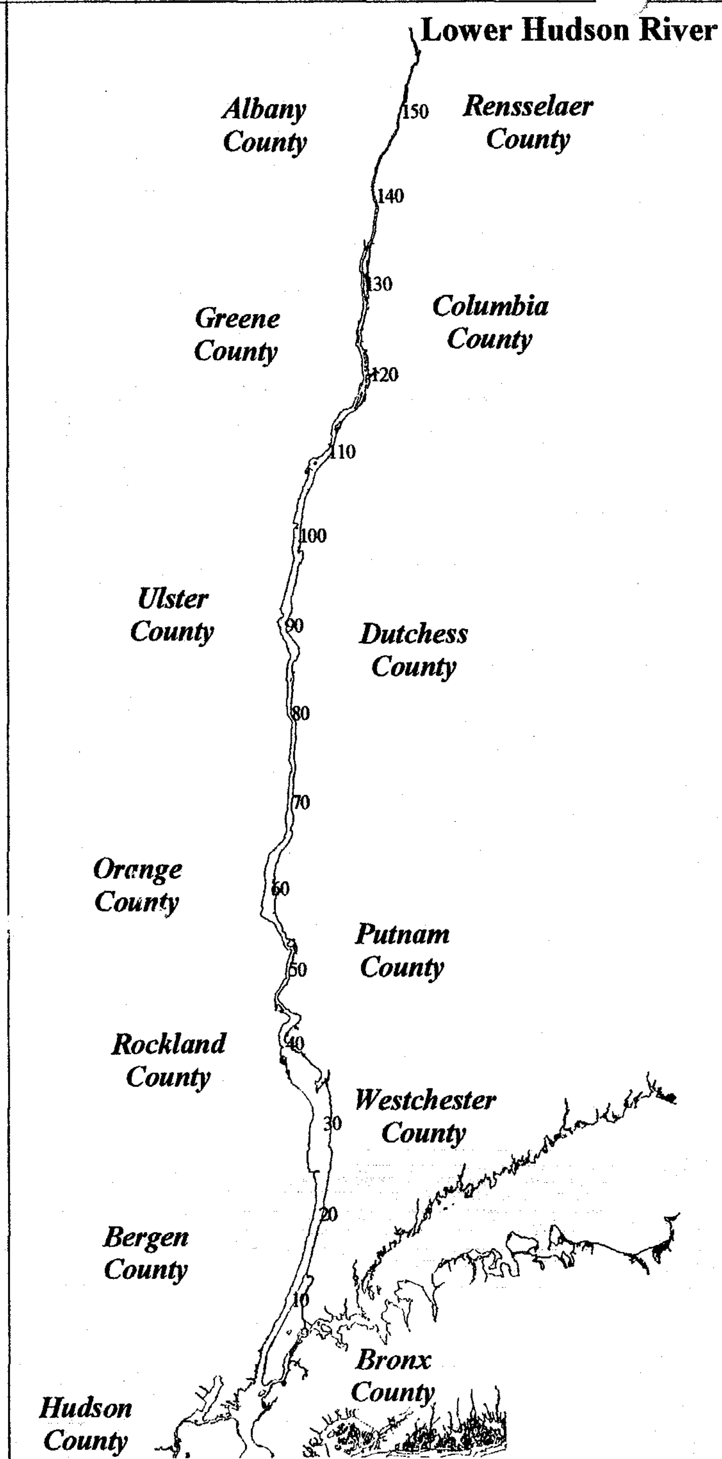

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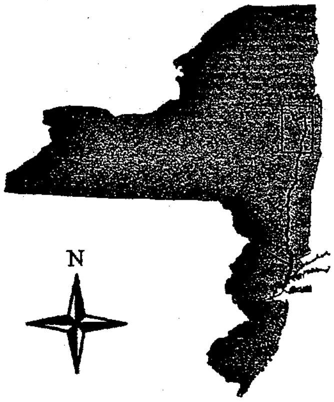
LOCATION MAP OF THE
UPPER HUDSON RIVER



Graphic Scale

2 0 2 4 Miles

Legend

Mile Points

Shoreline

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Figure 2-2.
Upper Hudson River reaches.

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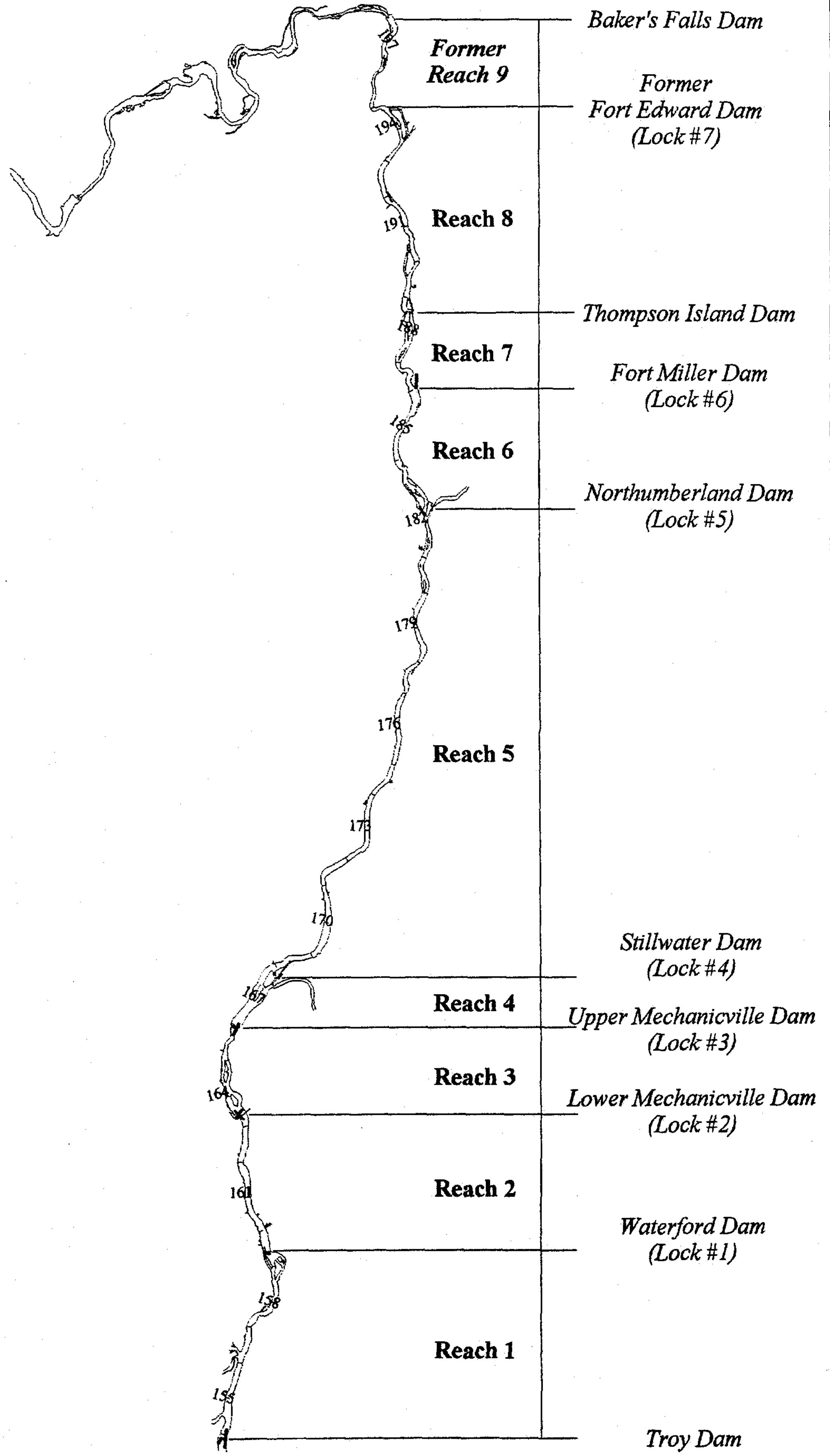

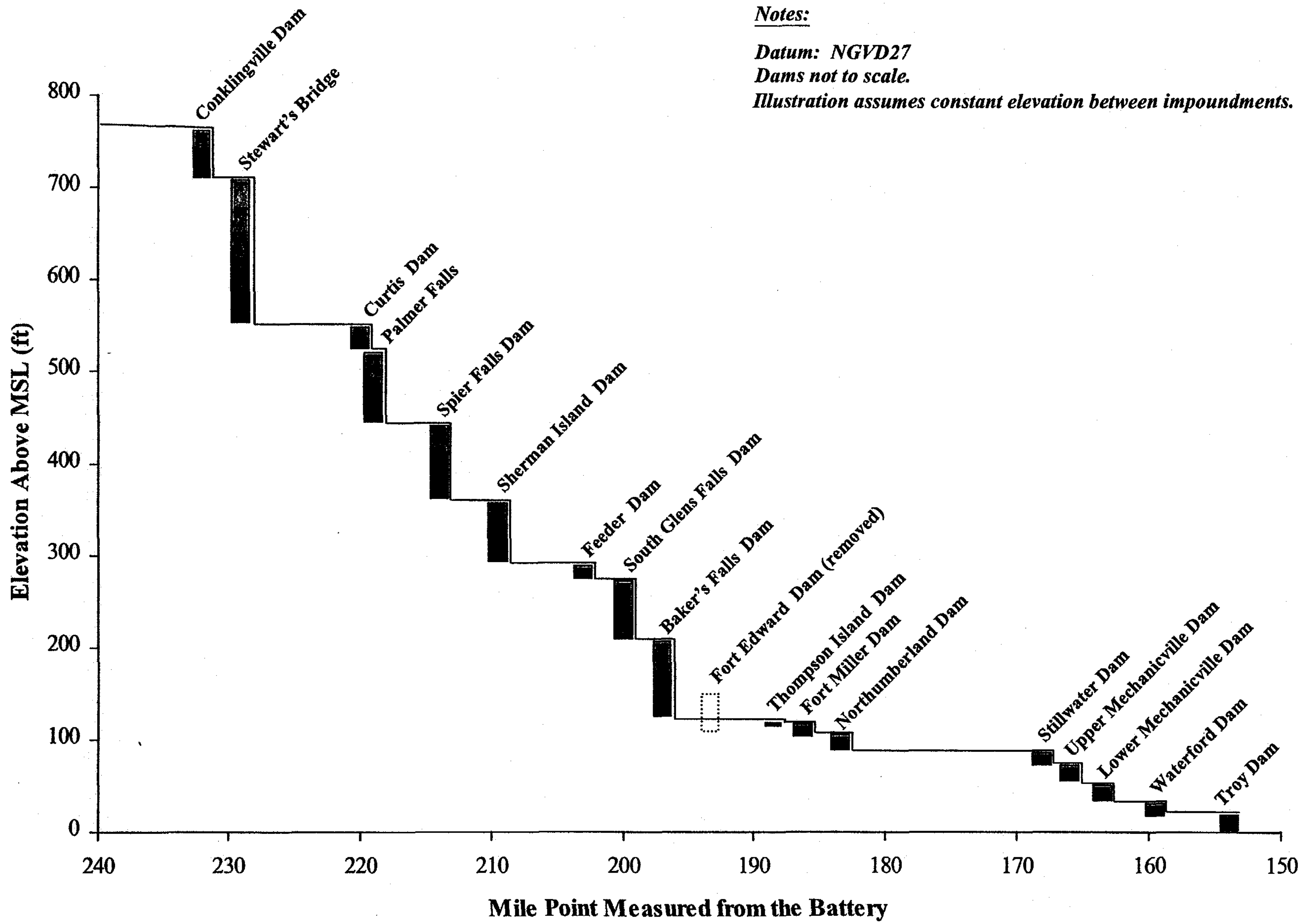

Figure 2-3. Upper Hudson River dam elevation profile.

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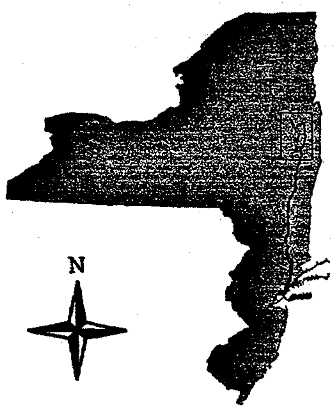
LOCATION MAP OF THE
UPPER HUDSON RIVER



Graphic Scale

1 0 1 2 3 4 5 Miles

Note:

Cross sections of the bathymetric transects illustrated are plotted in Figure 2-5.

Legend

Mile Points

Shoreline

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Figure 2-4.
Bathymetric transect locations.

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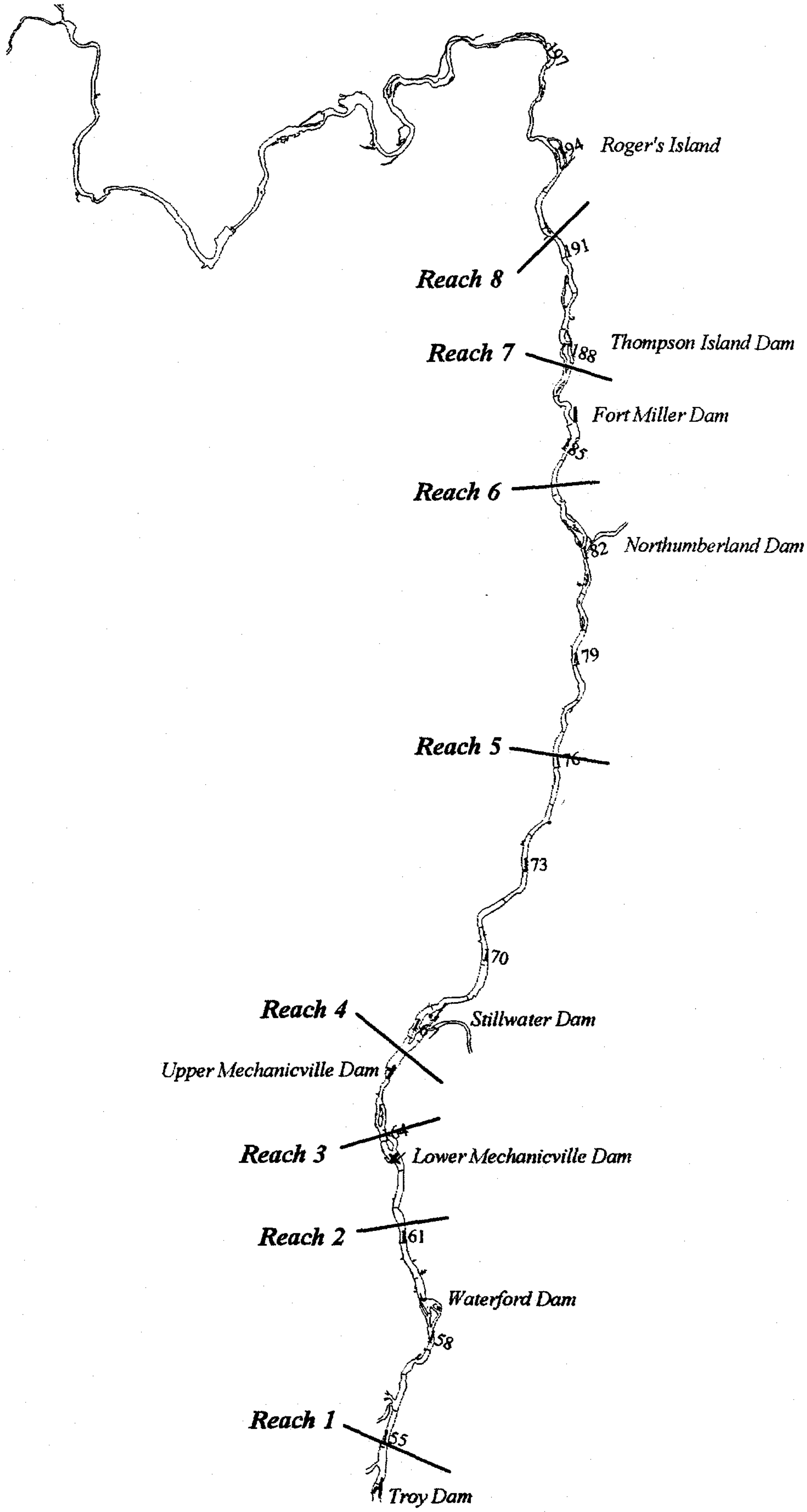

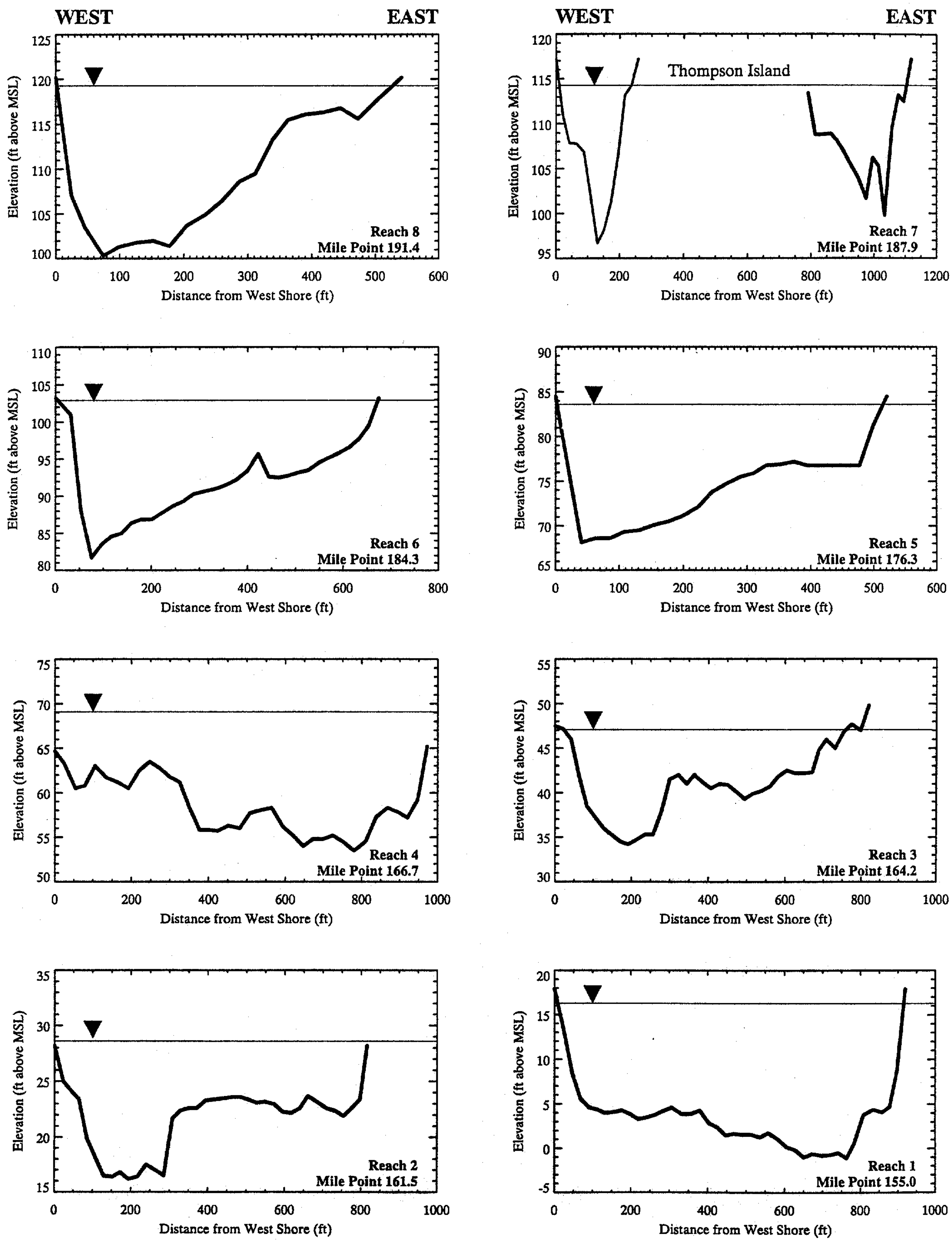

Data Source: 1991 GE Bathymetric Survey.

Notes: Transect locations illustrated on Figure 2-4. Horizontal line is crest elevation of dam at downstream reach boundary. Elevations reference New York State barge canal datum.

Figure 2-5. Cross sections of Upper Hudson River bed elevations.

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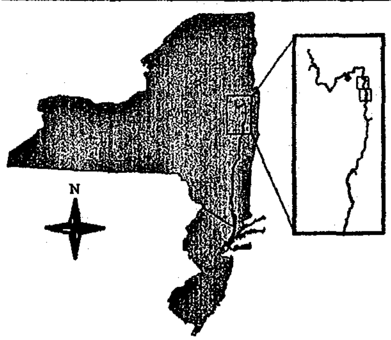
LOCATION MAP OF THE
THOMPSON ISLAND POOL



LEGEND

Density of Submerged Aquatic Vegetation

- High
- Medium
- Low
- Absent
- Mile Points

Data Source: Exponent (1998a)

Graphic Scale

0.1 0 0.1 0.2 0.3 0.4 0.5 Miles

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PCBs in the Upper Hudson River
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Figure 2-6.

Density of submerged aquatic vegetation in Thompson Island Pool.

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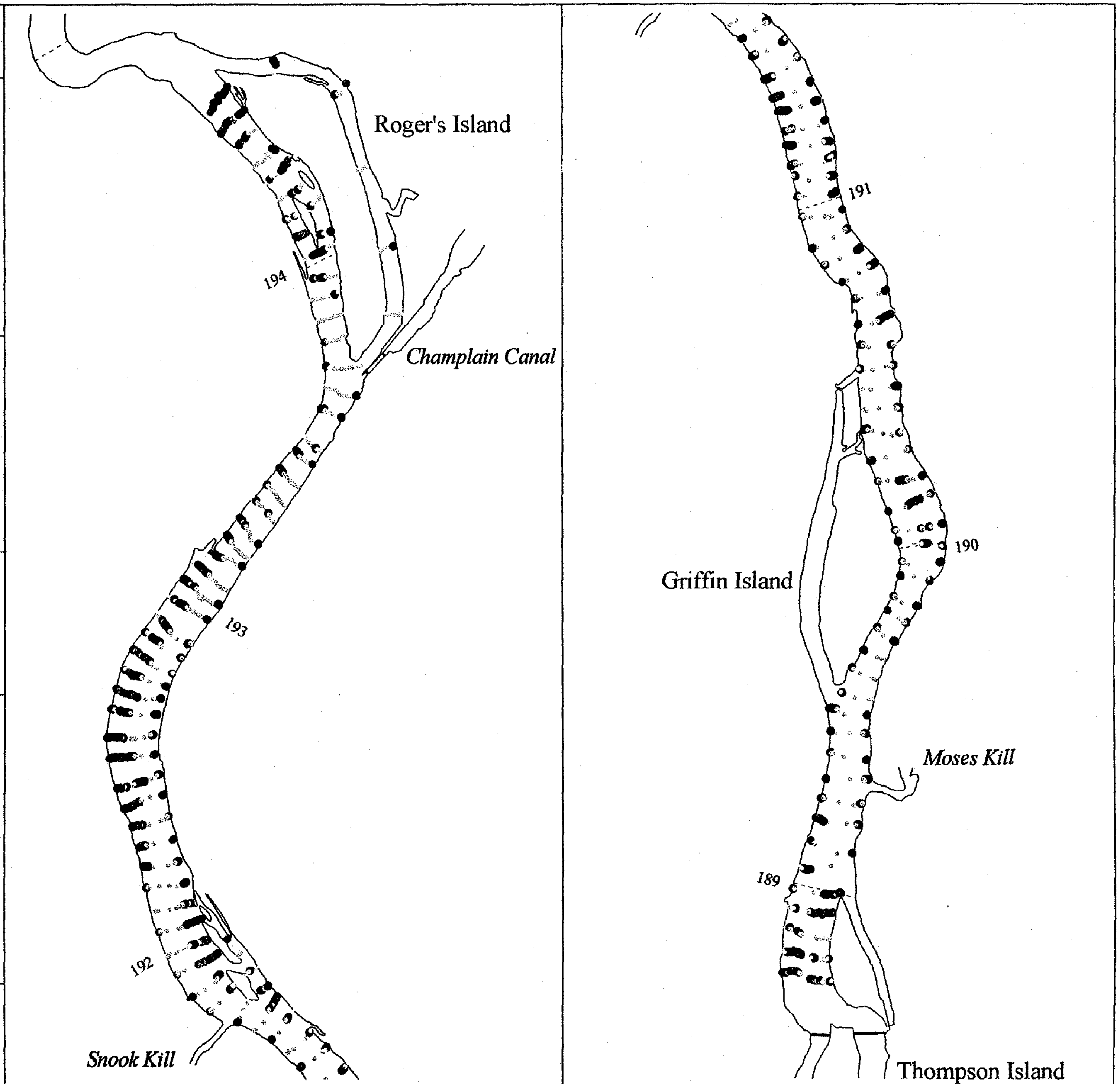
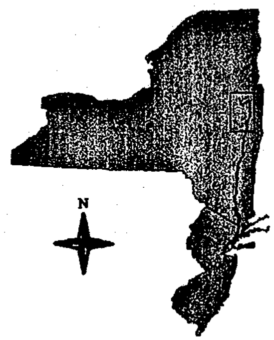


LOCATION MAP OF THE
UPPER HUDSON RIVER



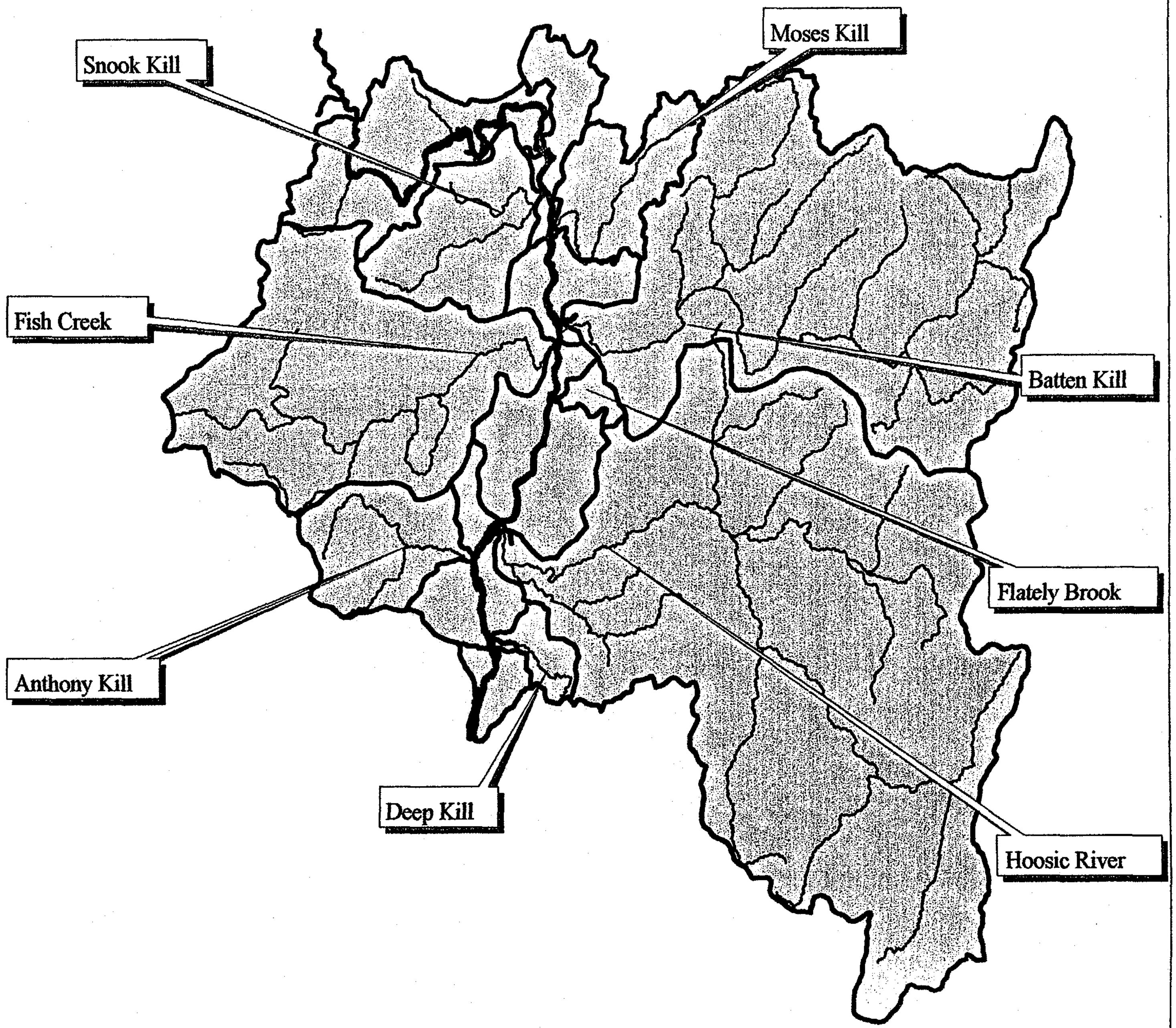
LEGEND

Direct Drainage

Tributary Watersheds

Graphic Scale

3 0 3 6 9 12 Miles



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PCBs in the Upper Hudson River
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Figure 2-7.
Watersheds and tributaries of the Upper Hudson River between Corinth and Troy, NY.

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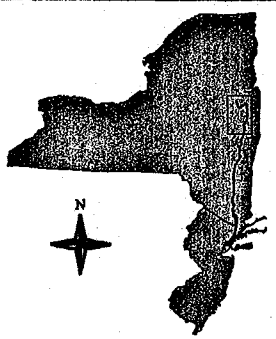
LOCATION MAP OF THE
UPPER HUDSON RIVER

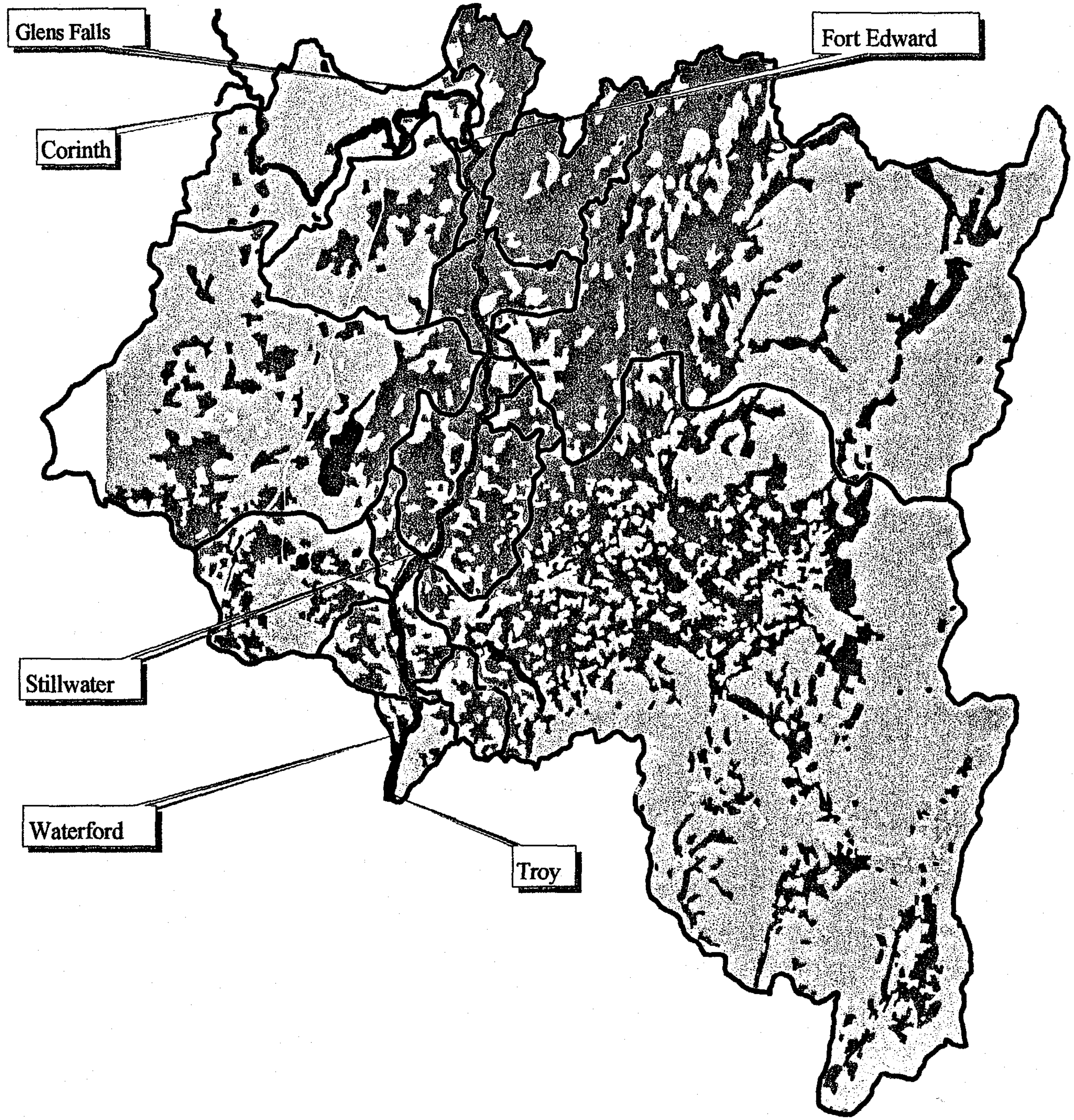


LEGEND
Land Use Types

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

Data Source: USEPA Basins

Graphic Scale
3 0 3 6 9 Miles



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PCBs in the Upper Hudson River
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Figure 2-8.
Land use patterns in the Upper Hudson River drainage basin between Corinth and Troy, NY.

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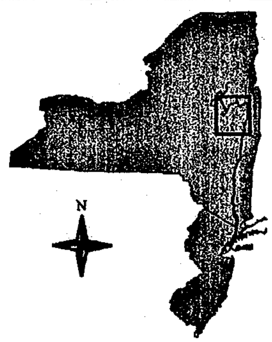
LOCATION MAP OF THE
UPPER HUDSON AND
SACANDAGA RIVERS



Graphic Scale

3 0 3 6 Miles

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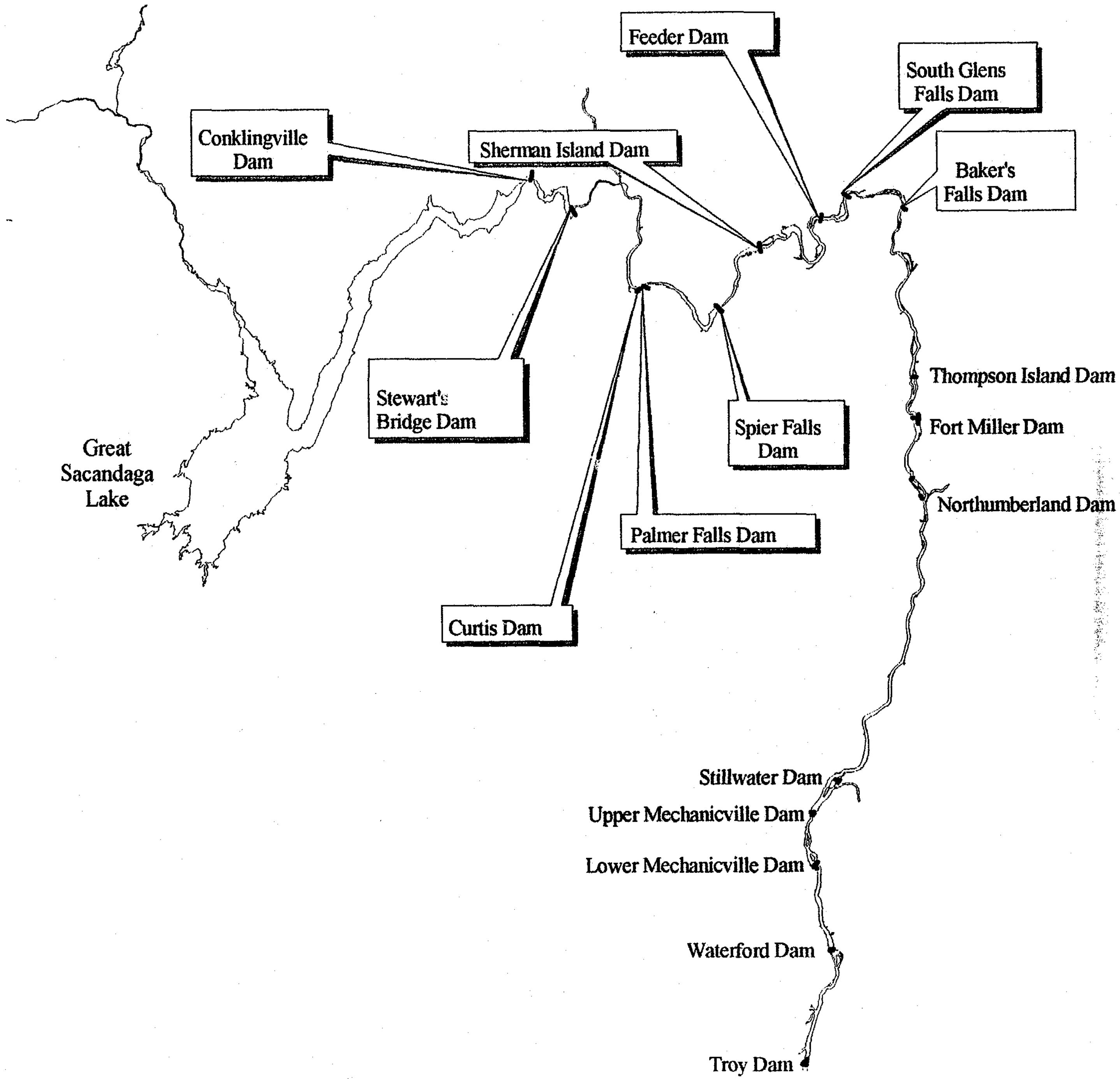
PCBs in the Upper Hudson River
Volume 1. Historical Perspective and
Model Overview

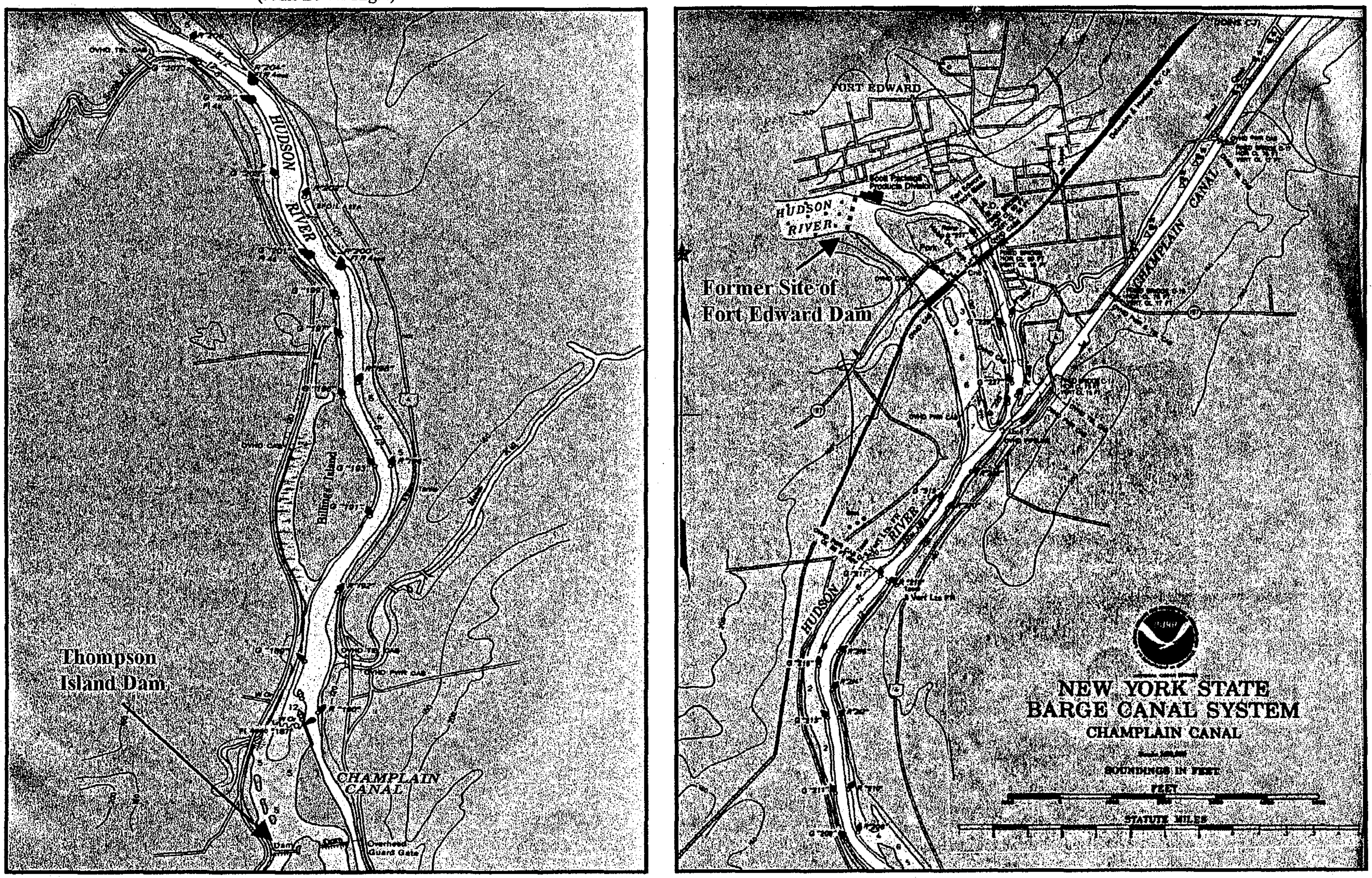
Figure 2-9.
Locations of hydroelectric dams on the Upper Hudson and Sacandaga Rivers.

Quantitative Environmental Analysis, LLC



313500

(Joins Lower Right)



(Joins Upper Left)

GENERAL ELECTRIC COMPANY
Hudson River Project
Champlain Canal navigational chart (NOAA, 1991)

FIGURE 2-10.

SCALE: NONE

QEA Quantitative Environmental Analysis, LLC

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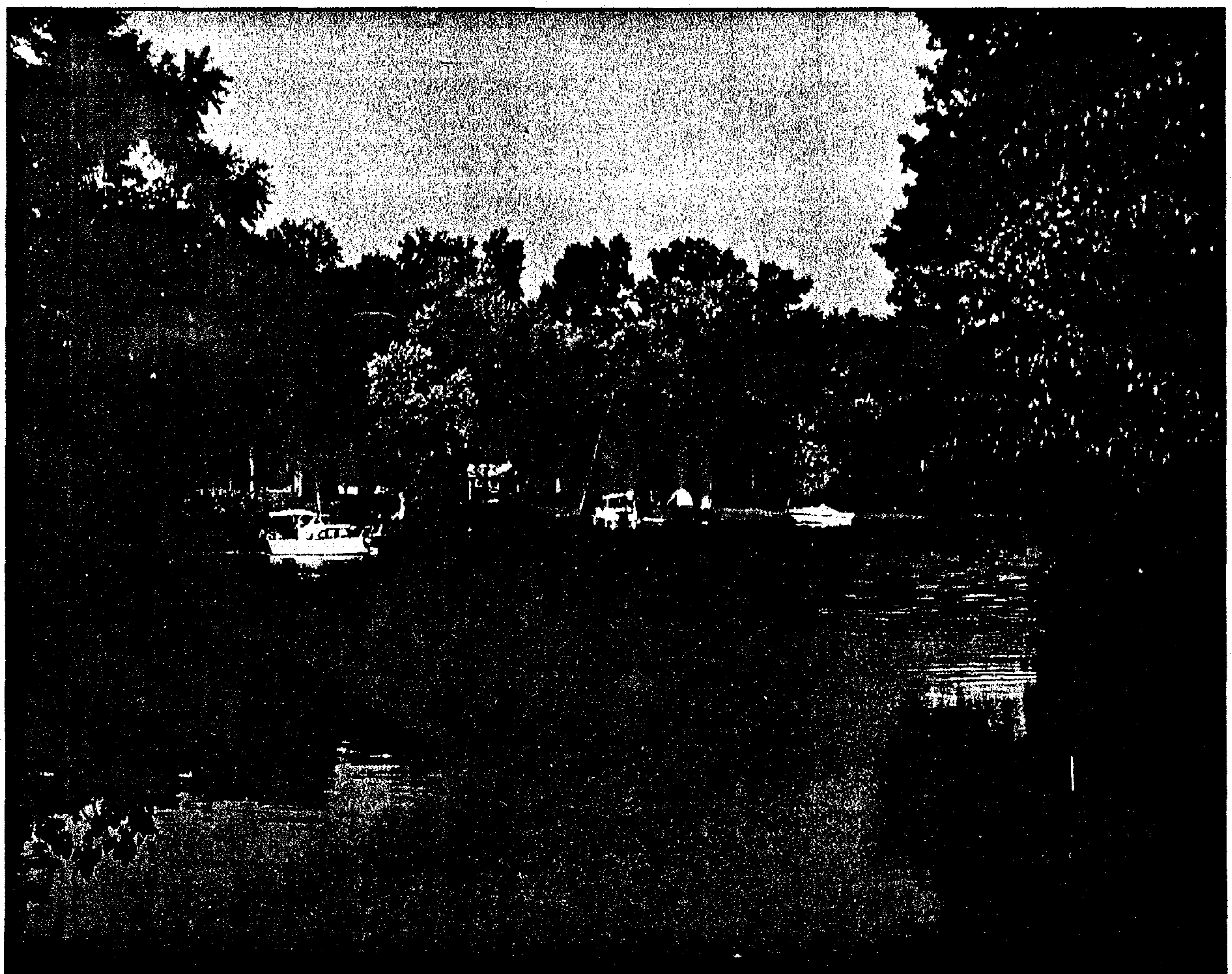
GENhud 131

May, 1999



Pleasure boats traveling on the Thompson Island Pool reach of the Hudson River (Champlain Canal)

GENERAL ELECTRIC COMPANY **Hudson River Project** **Recreational use of the Champlain Canal** MDL: D:\GENhud\v1fig2-11_RecrUse.ppt	FIGURE 2-11. SCALE: NONE	QEA Quantitative Environmental Analysis, LLC GENhud 131	May, 1999

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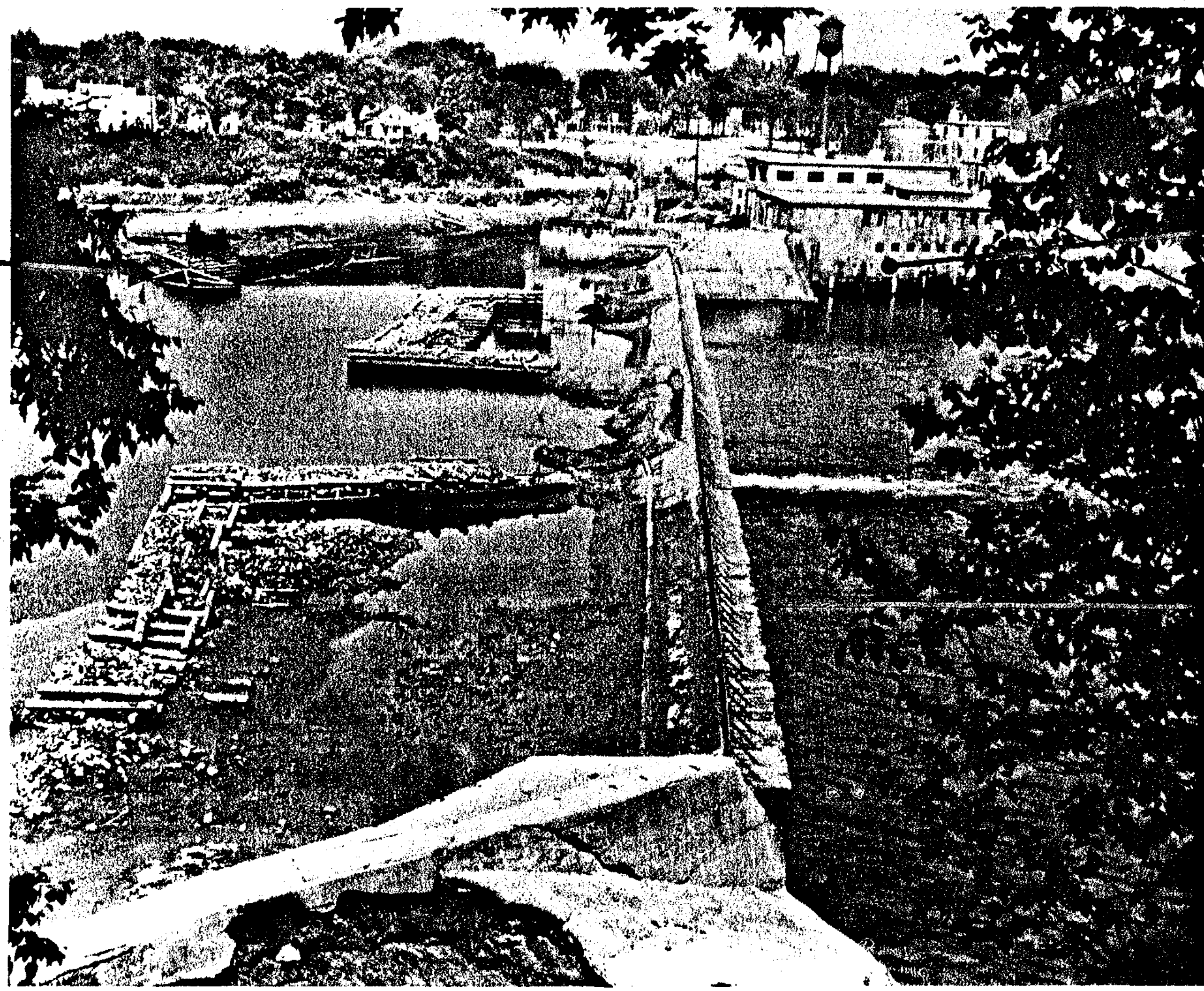
313503



GENERAL ELECTRIC COMPANY
Hudson River Project
Fort Edward Dam (looking east, 1949)

MDL: D:\GENhud\w1fig2-12_FEdam1.ppt

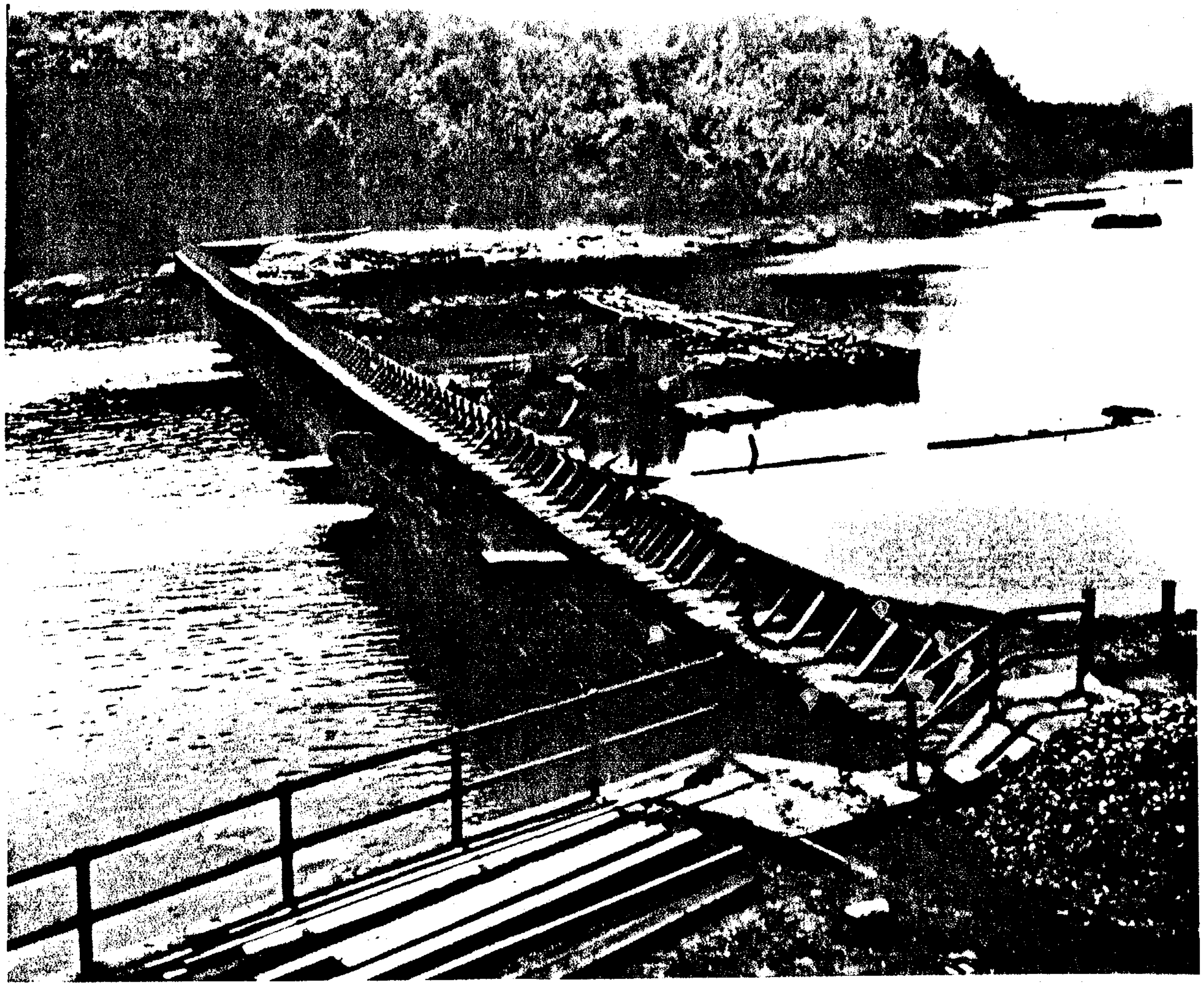
FIGURE 2-12.

SCALE: NONE

QEA Quantitative Environmental Analysis, LLC

GENhud 131

May, 1999



GENERAL ELECTRIC COMPANY
Hudson River Project
Fort Edward Dam (looking west, 1949)

MDL: D:\GENhud\w1fig2-13_FEdam2.ppt

FIGURE 2-13.

SCALE: NONE

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Quantitative Environmental Analysis, LLC

GENhud 131

May, 1999

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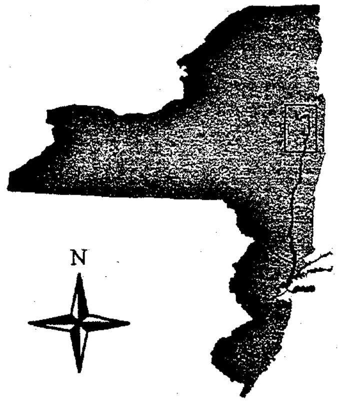
LOCATION MAP OF THE
UPPER HUDSON RIVER



Graphic Scale

500 0 500 1000 1500 Feet

Legend

Remnant Deposits
Routine Water Monitoring Stations
Mile Points
Shoreline

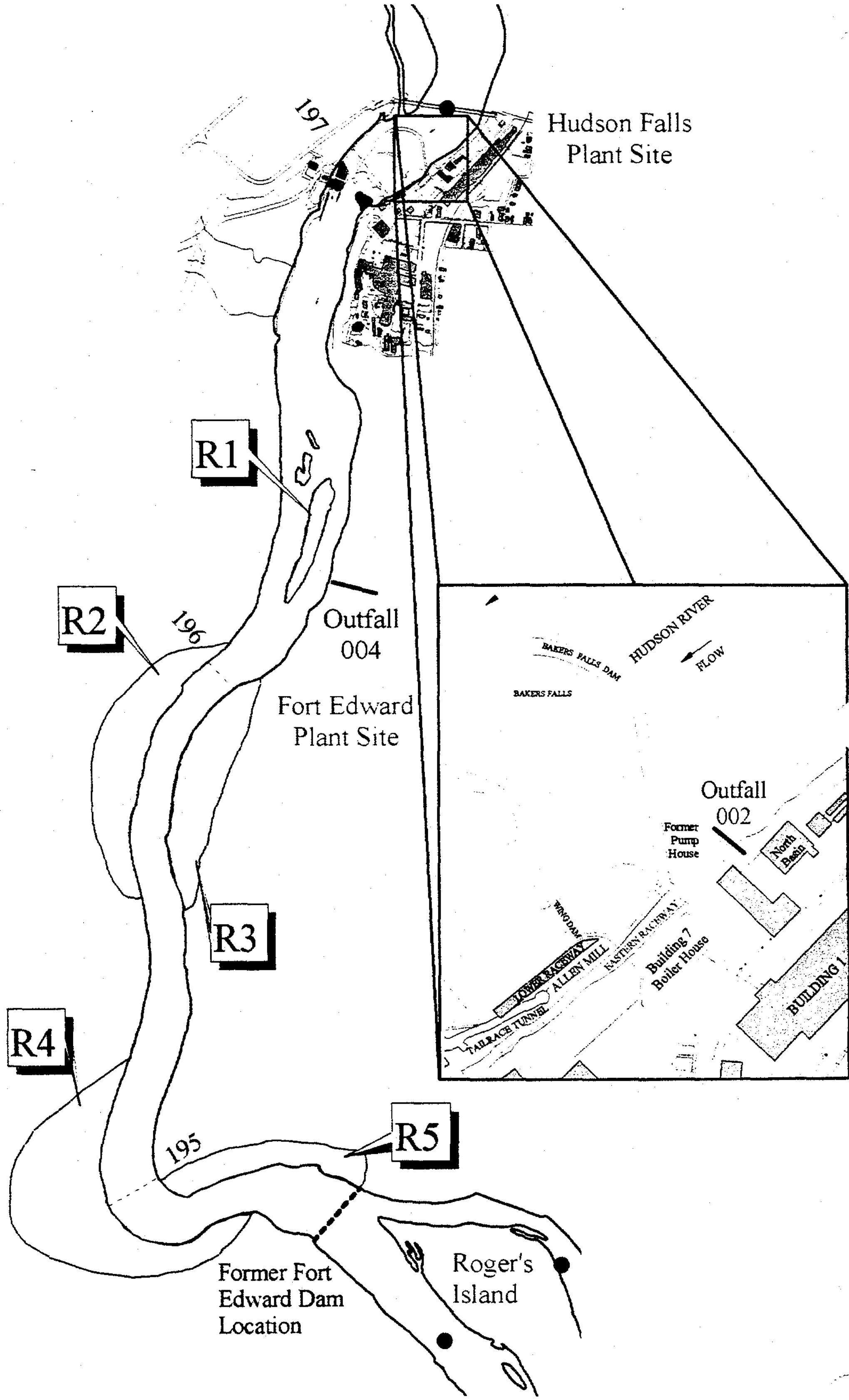
GENERAL ELECTRIC COMPANY
Hudson River Project

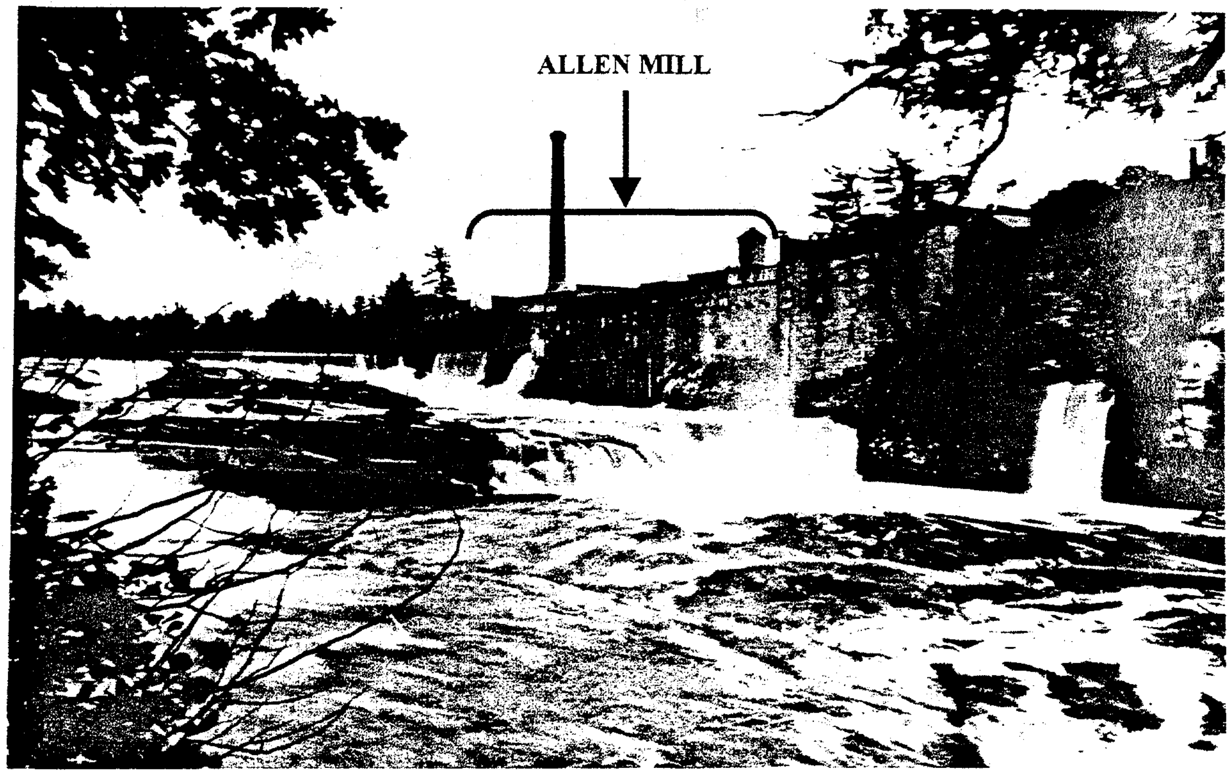
PCBs in the Upper Hudson River
Volume 1. Historical Perspective and Model Overview

Figure 2-14.
Remnant Deposits in former Reach 9 of the Upper Hudson River.

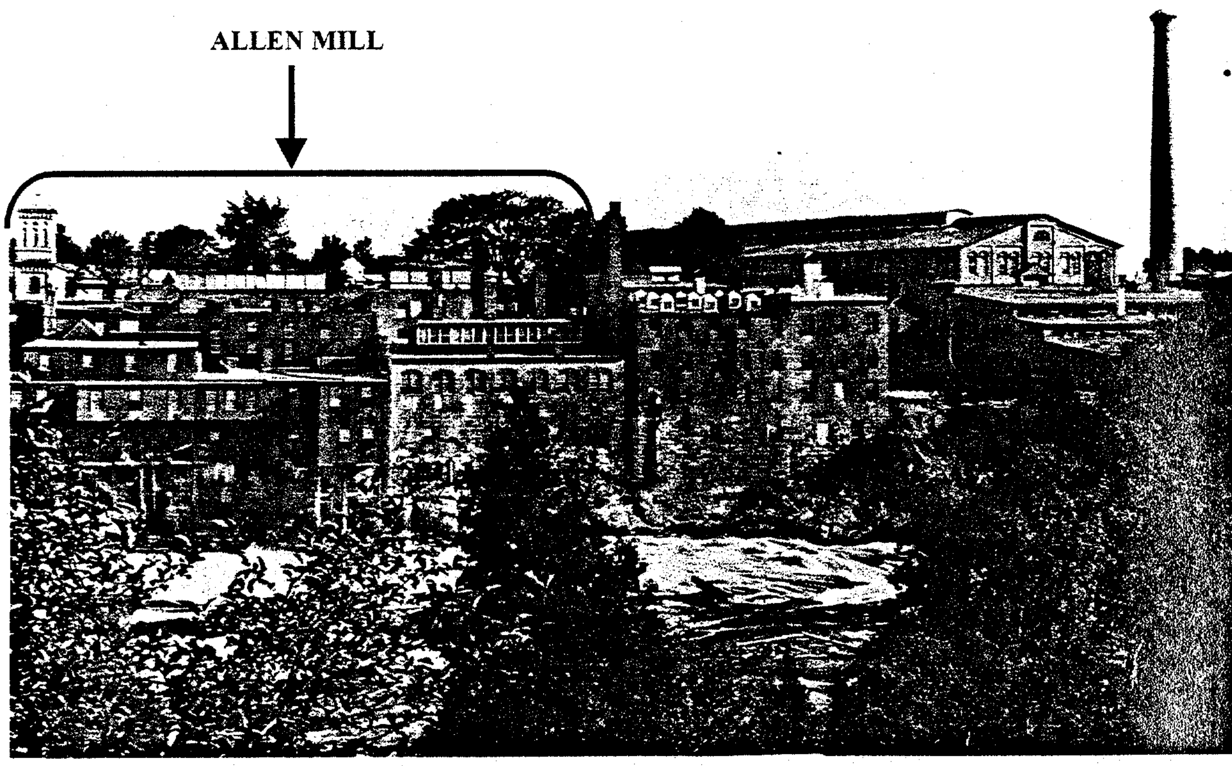
Quantitative Environmental Analysis, LLC

Project: GEHud 151 May, 1999





Bakers Falls Looking Northeast (Date Unknown. Photo Taken Between 1888 and 1907)



Allen Mill and Adjacent Industries (Looking East. 1893)

GENERAL ELECTRIC COMPANY **Hudson River Project** **Bakers Falls area (prior to 1907)** D:\v1fig2-15_AllenMillhist1.ppt	**FIGURE 2-15.** **SCALE: NONE**	QEA Quantitative Environmental Analysis, LLC GENhud 131 May, 1999

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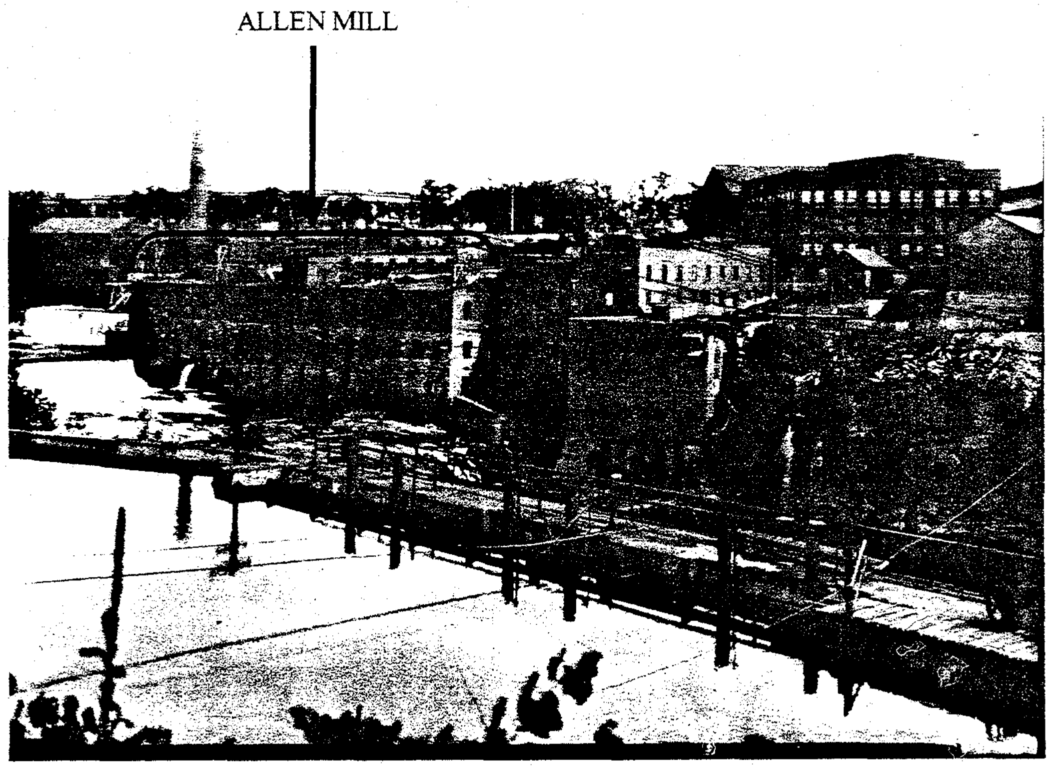
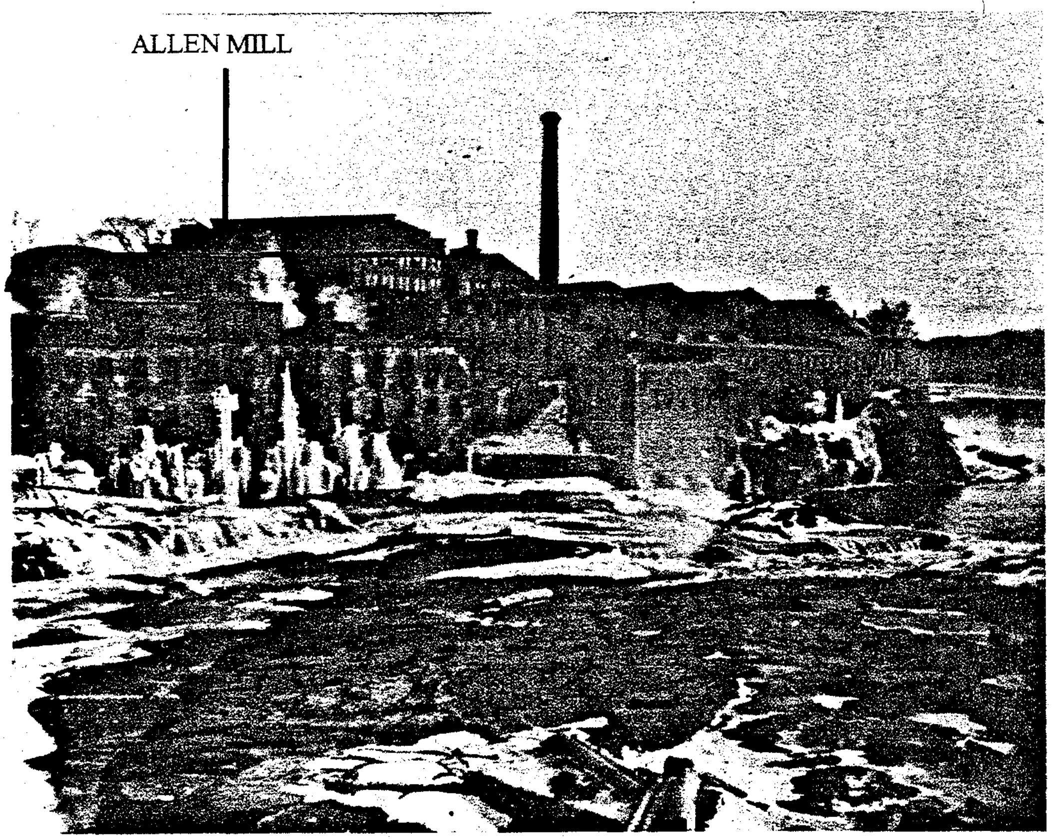


Bakers Falls. Looking Northeast. (Photo Taken Between 1920 and 1947)



Bakers Falls. Looking Southeast. (Photo Taken Between 1907 and 1947)

GENERAL ELECTRIC COMPANY **Hudson River Project** **Bakers Falls area (1907 - 1947)** D:\w1fig2-16_AllenMillhist.ppt	**FIGURE 2-16.** **SCALE: NONE**	QEA Quantitative Environmental Analysis, LLC GENhud 131 May, 1999

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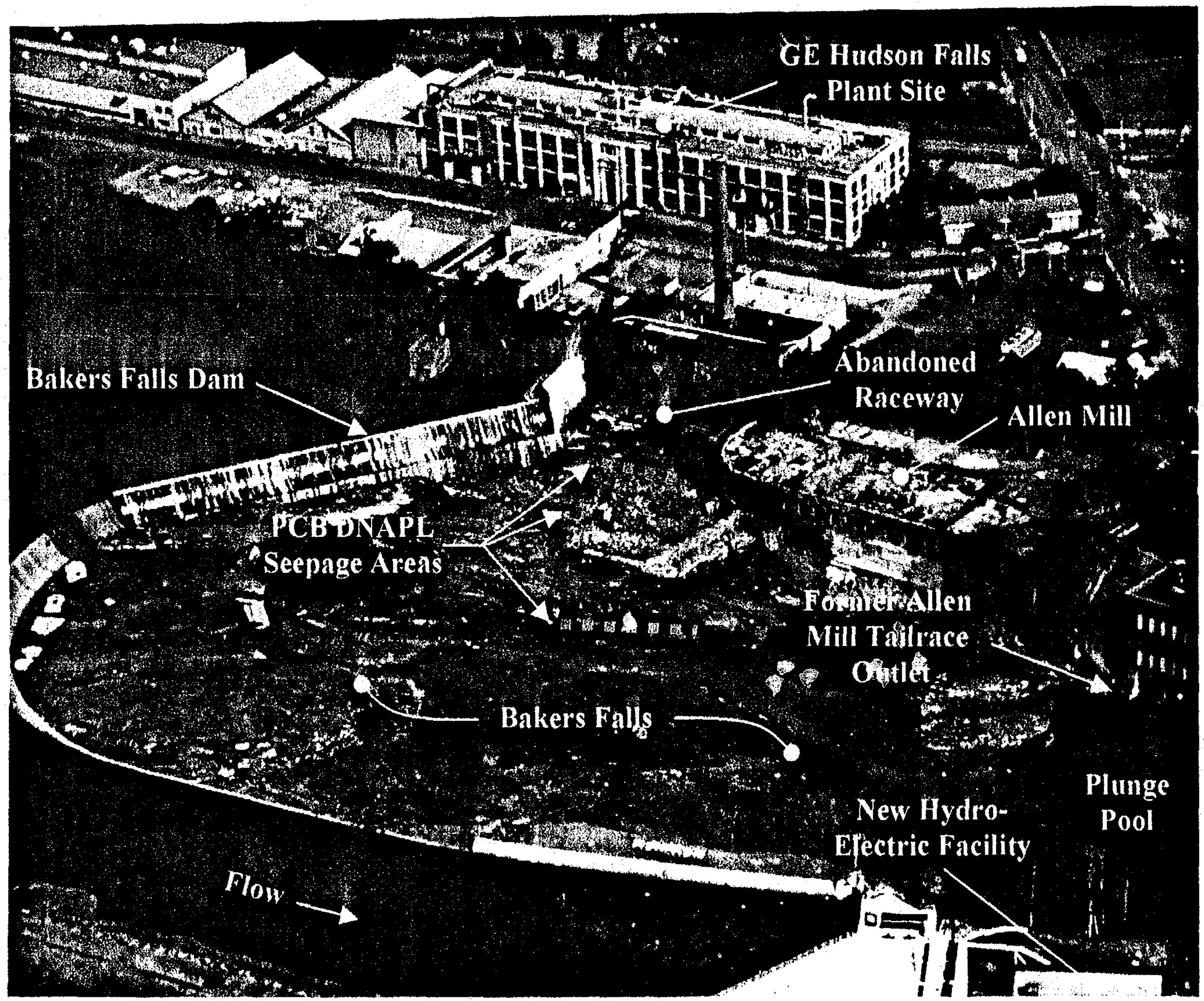

GENERAL ELECTRIC COMPANY
Hudson River Project
Allen Mill and GE Hudson Falls facility (ca. 1996)

MDL: D:\GENhud\w1fig2-17_BFallsAerial.ppt

FIGURE 2-17.

SCALE: NONE

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GENhud 131 May, 1999

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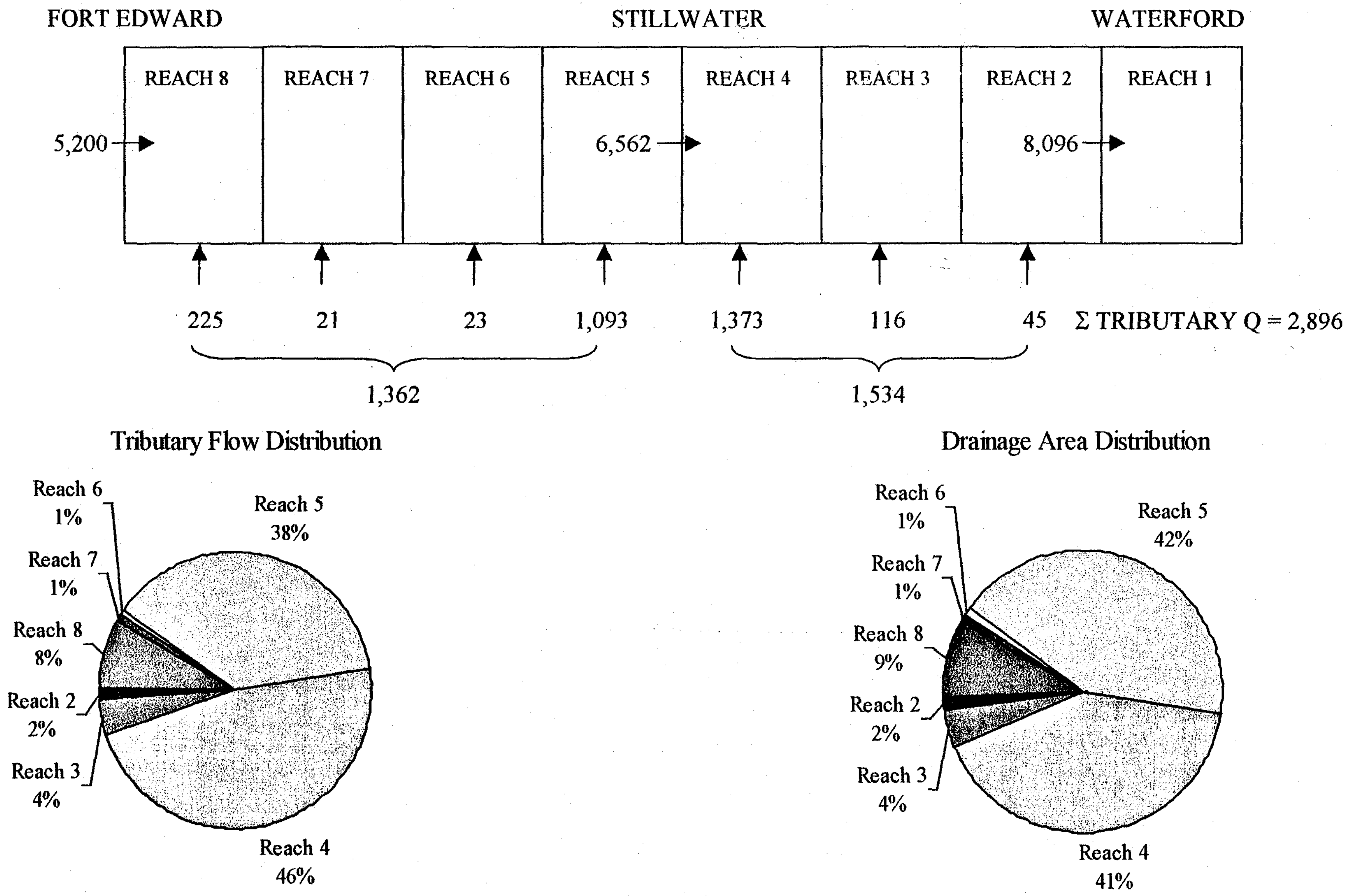

Figure 2-18. Mean flow balance for the Upper Hudson River between Fort Edward and Waterford (flow rates are in cfs).

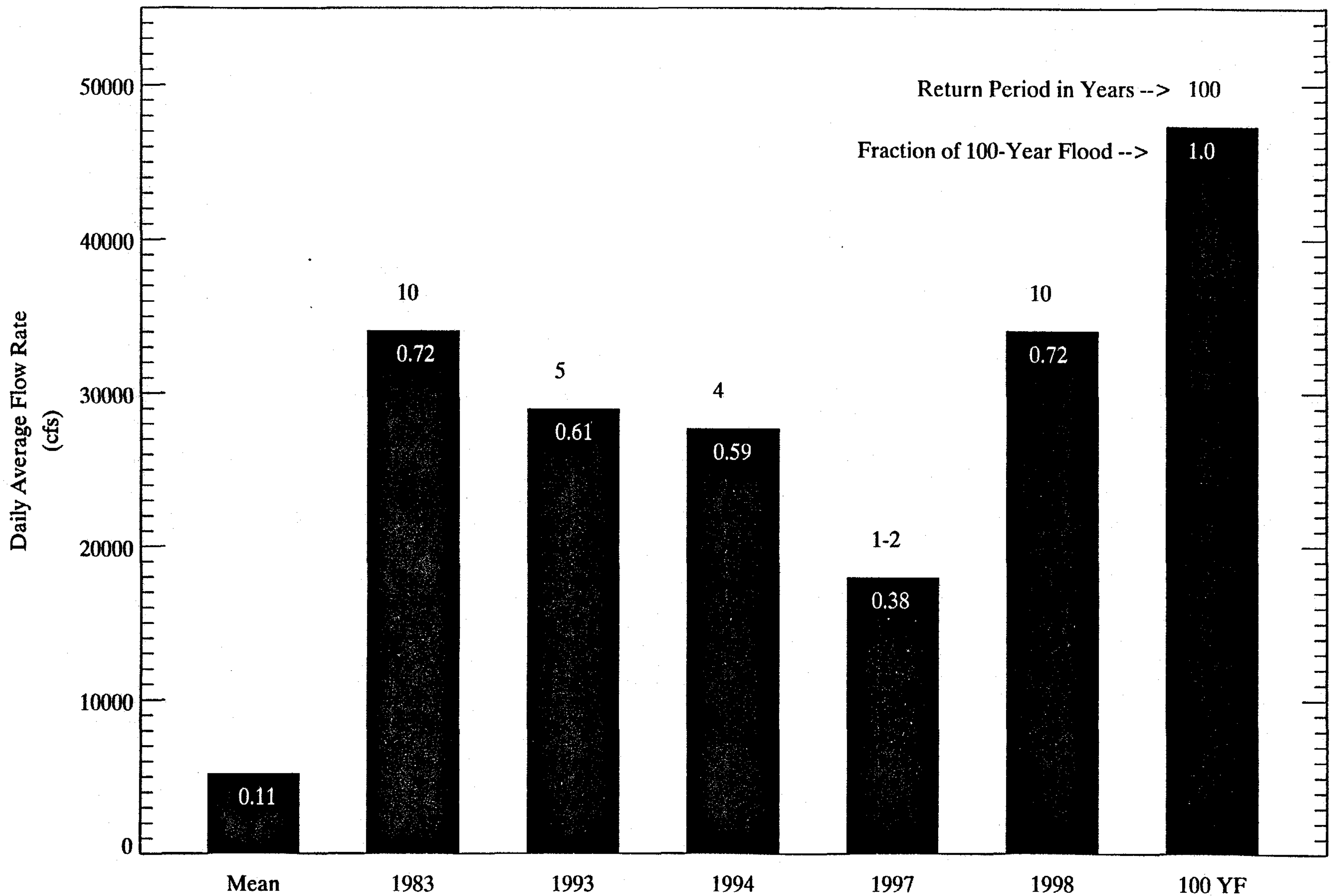

Figure 2-19. Comparison of peak daily average flow rates at Fort Edward during various historical floods to 100-year flood peak discharge. Mean flow rate represents long-term average at that gauging station.

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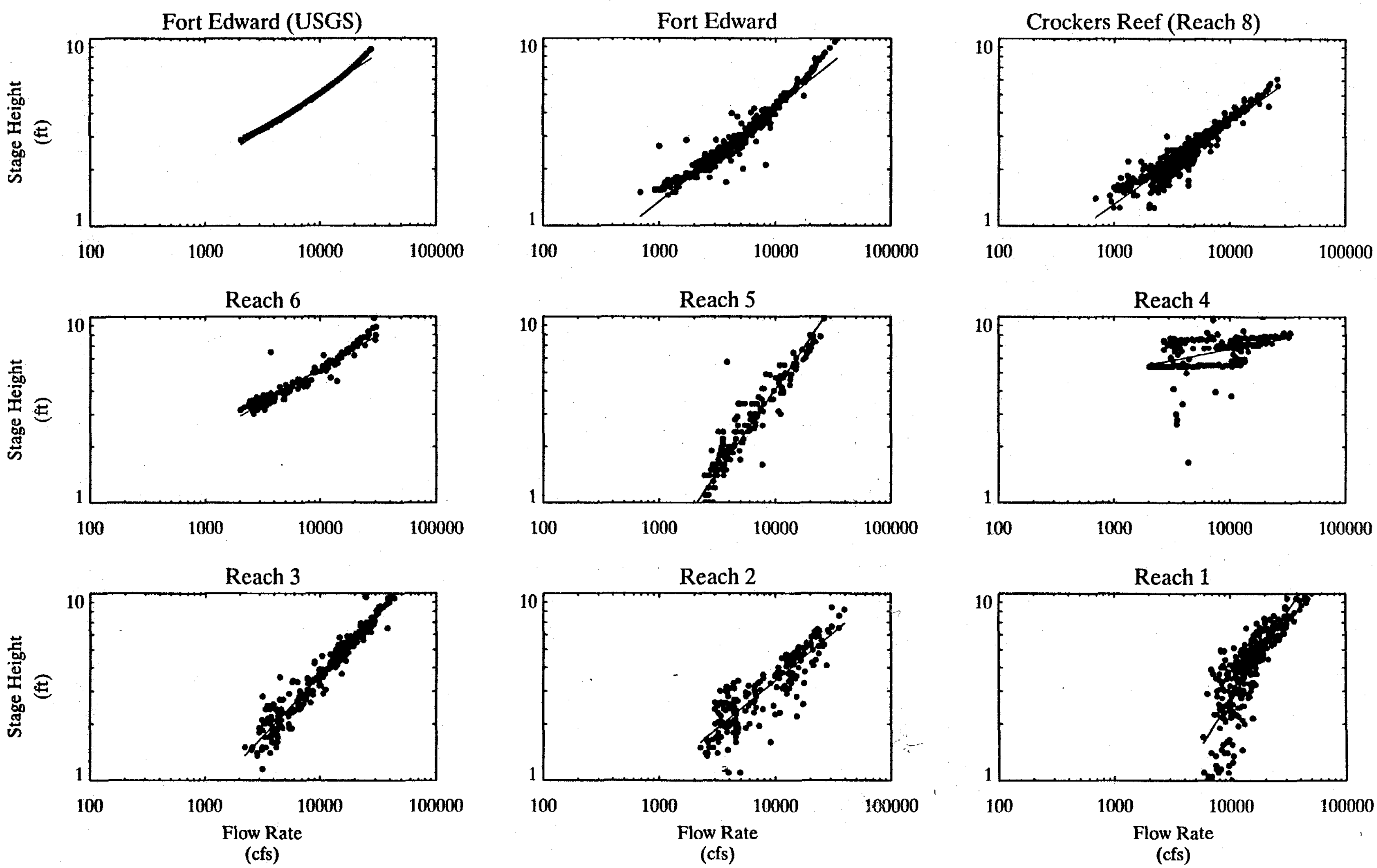
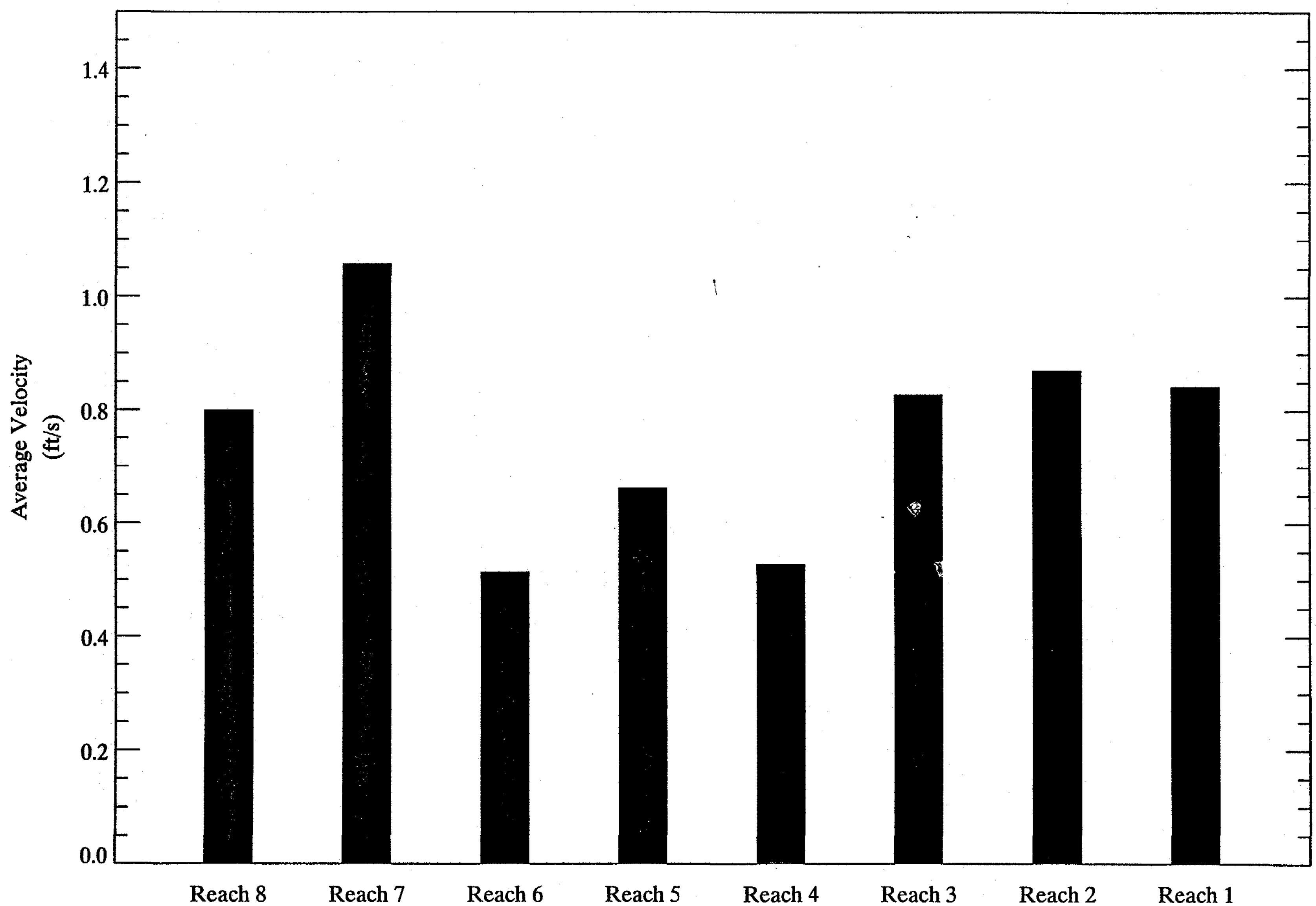


Figure 2-20. Stage height rating curves and data for Reaches 1 to 8. Champlain Canal data displayed at all locations except as noted at Fort Edward.



Note: Values were determined from hydrodynamic model results averaged over 22-year simulation (1977-1998)

Figure 2-21. Average current velocity in Reaches 1 to 8.

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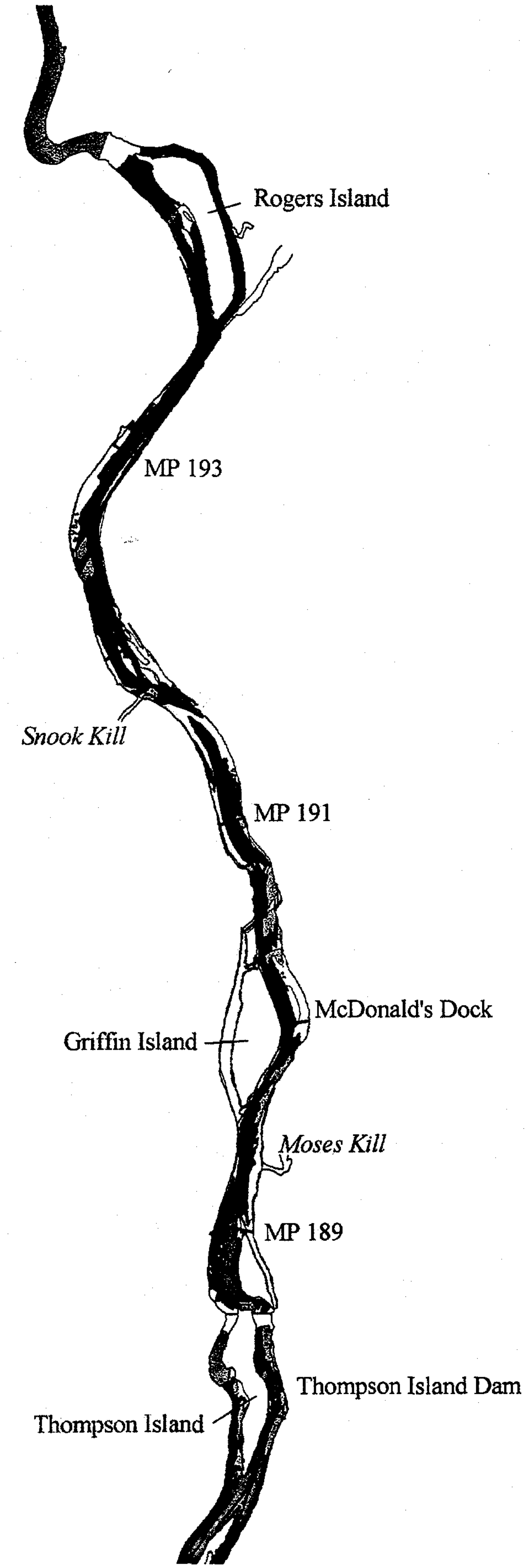
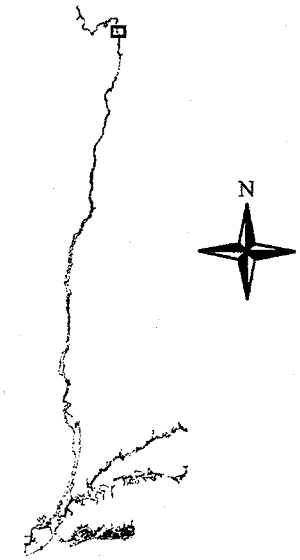


LOCATION MAP OF THE HUDSON RIVER



GRAPHIC SCALE

0.4 0 0.4 0.8 Miles

LEGEND

Shoreline
Mile Points
Dams & Locks
Side Scan Sonar
NON COHESIVE
COHESIVE
ROCKY

GENERAL ELECTRIC COMPANY
Hudson River Project

PCBs in the Upper Hudson River
Volume 1. Historical Perspective and Model Overview.

Figure 2-22.

Thompson Island Pool bed map based on side scan sonar information.

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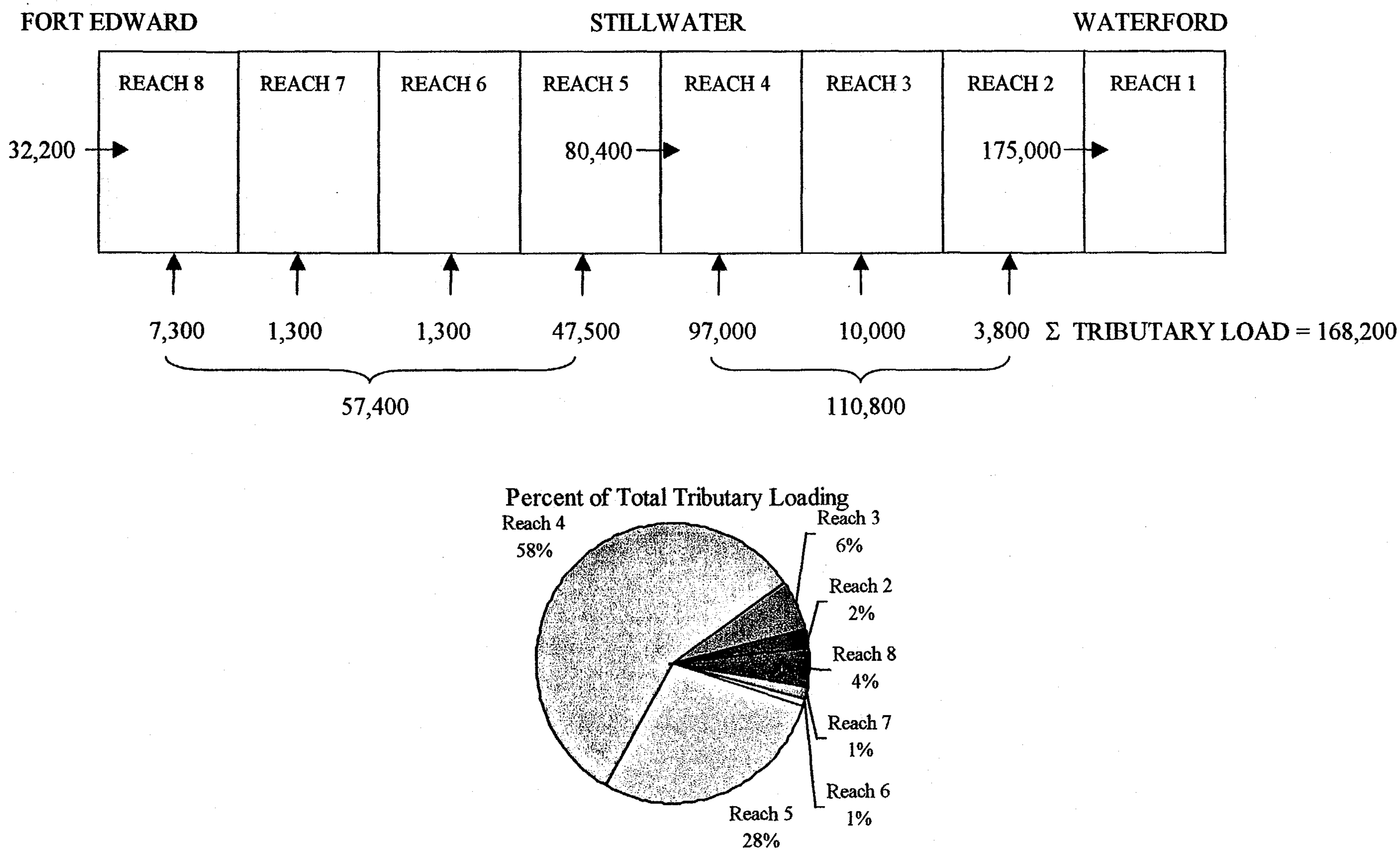

Figure 2-23. Data-based sediment mass balance and estimated tributary loading for the Upper Hudson River. Sediment loadings are in MT/yr.

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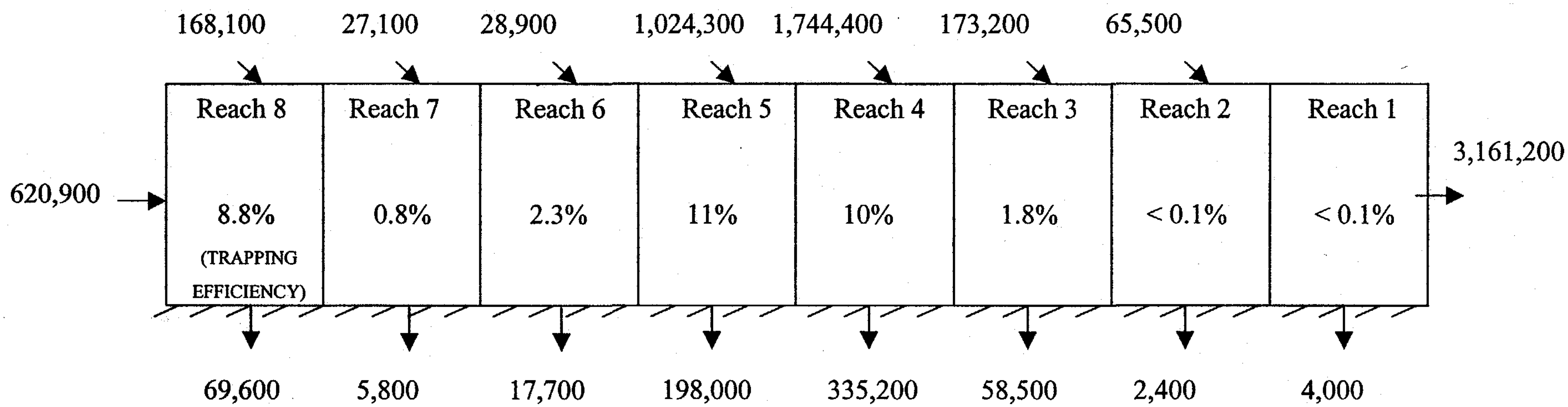

Figure 2-24. Sediment mass balance for the 22-year (May 1977 - December 1998) simulation, Reaches 1-8. Sediment masses are in MT.

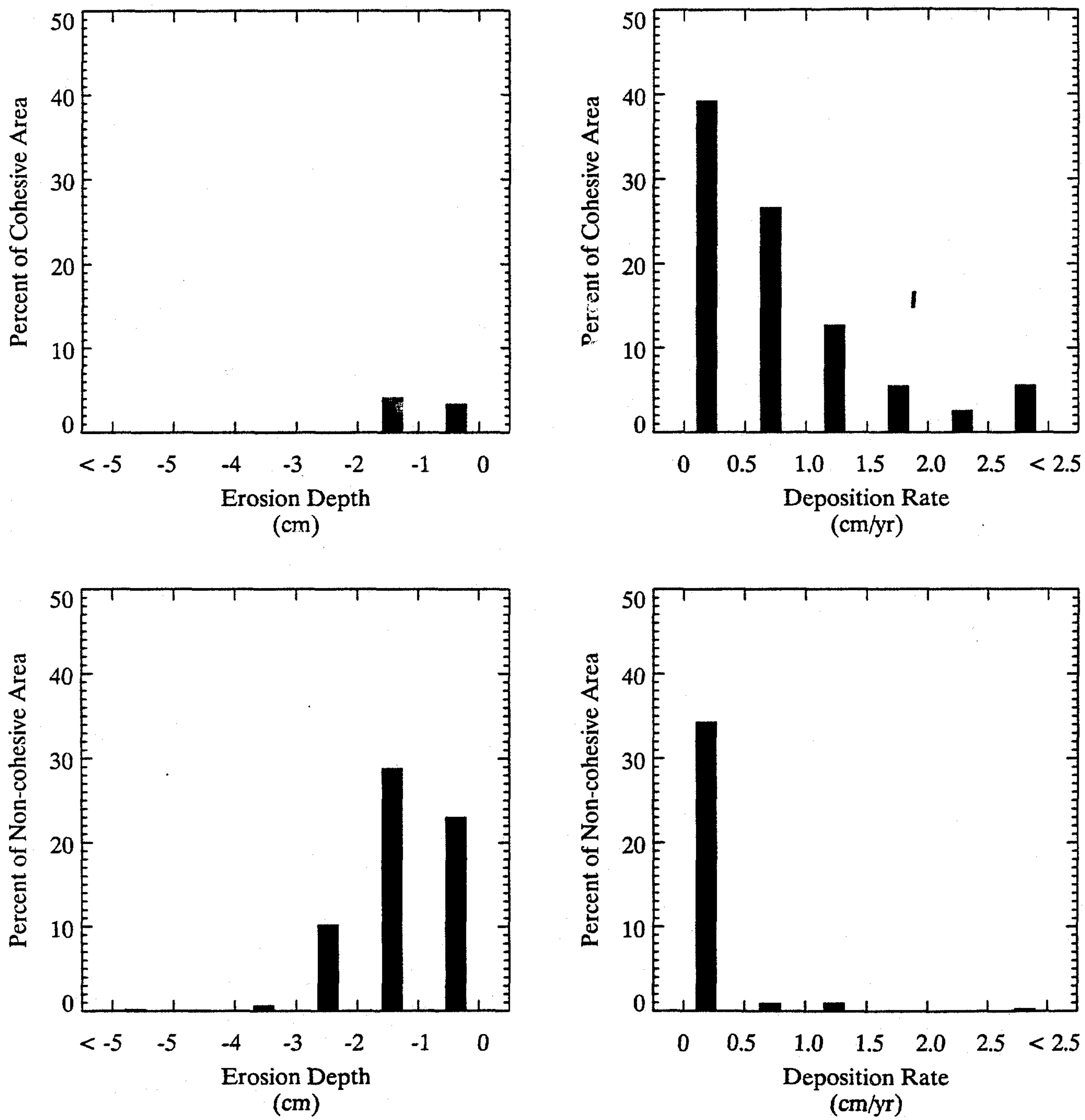

Figure 2-25. Distributions of cohesive and non-cohesive bed elevation changes in the TIP at the end of the 22-year (1977-1998) simulation.

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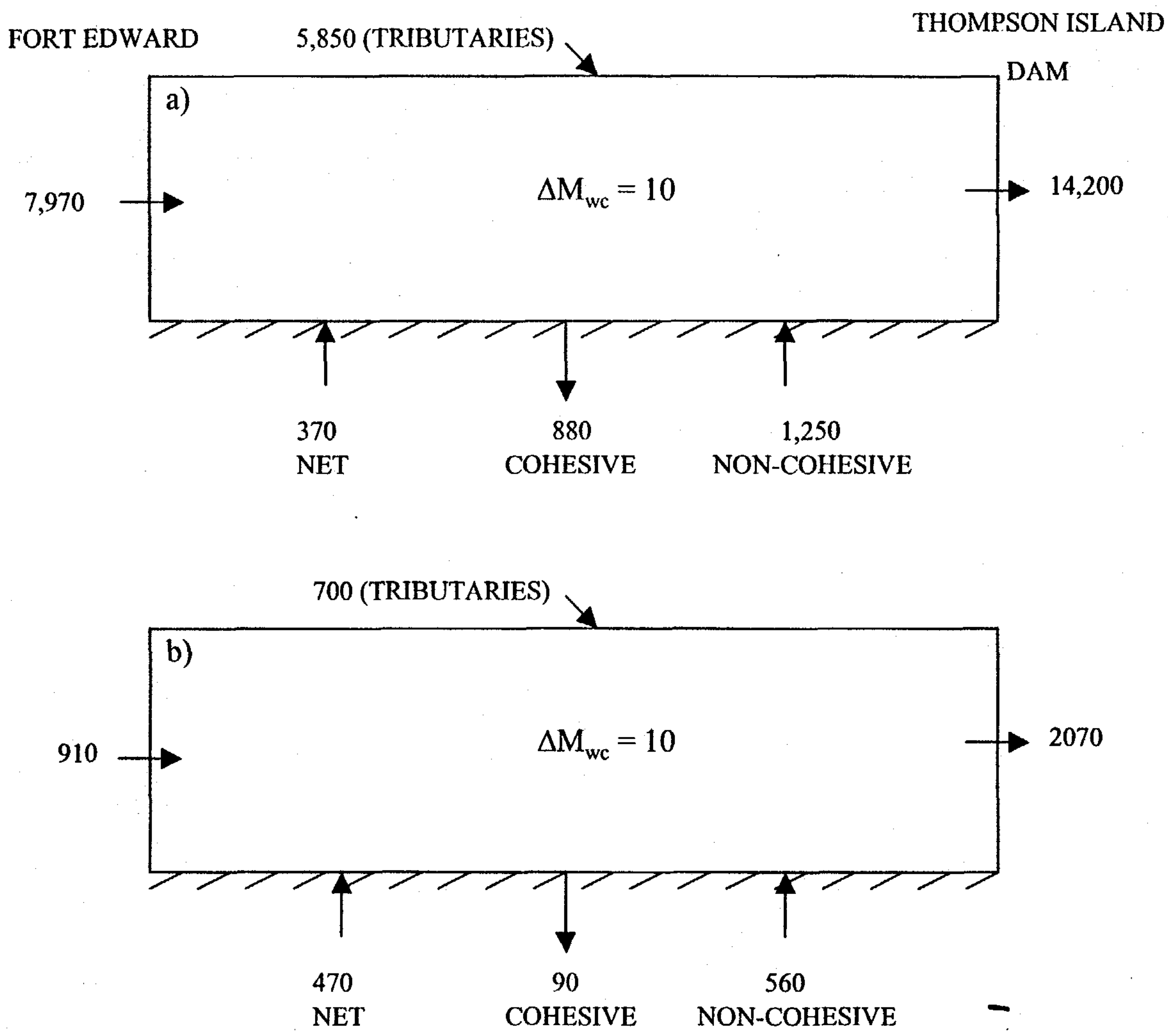

Figure 2-26. Predicted sediment mass balance for (a) 1994 and (b) 1997 spring floods in the TIP. Sediment masses are in MT. ΔM_{wc} represents change in mass of suspended sediment in the water column.

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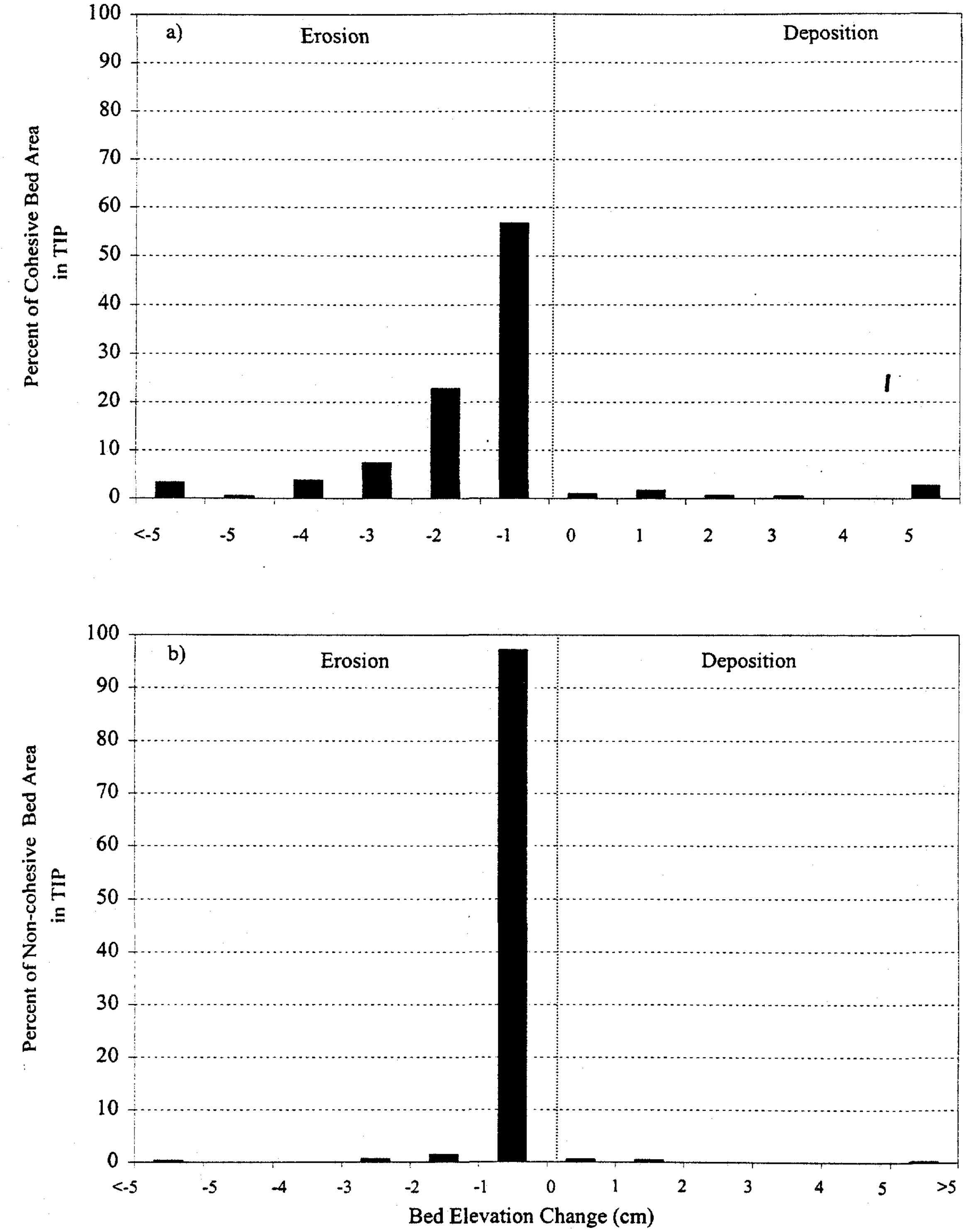

Figure 2-27. Predicted distributions of (a) cohesive and (b) non-cohesive bed elevation changes in the TIP at the end of the 100-year flood.

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History of PCBs in the Upper Hudson River

Section 3

Quantitative Environmental Analysis, LLC

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SECTION 3
HISTORY OF PCBs IN THE UPPER HUDSON RIVER

3.1 HISTORICAL PCB USES

3.1.1 PCBs

PCBs are 209 related chemical compounds that were manufactured and sold as mixtures under various trade names, including Aroclor, Phenoclor, Clophen, and Kenechlor. They were used from approximately the 1940's through the 1970's (Hutzinger *et al.* 1974). Because they possess excellent dielectric and flame resistant properties PCBs were extensively used as heat transfer fluids, hydraulic fluids, flame retardants, and dielectric fluids. These same properties also result in their persistence in the environment. Moreover, PCBs' lipophilicity (affinity for lipids) has led to their accumulation in fatty tissues of biota and subsequent bioaccumulation in the food chain. Concerns over potential human health effects led to the cessation of PCB production and use in the United States in the 1970's.

Each of the 209 possible PCB compounds (generically called congeners) consist of a biphenyl (two six carbon rings bonded by a carbon bridge) containing ten binding sites, five on each ring, which are occupied by either chlorine or hydrogen atoms. These binding sites are numbered sequentially from the carbon bridge (2 to 6 on one ring and 2' to 6' on the opposite ring, Figure 3-1). Individual PCB congeners differ in the number and position of the chlorine atoms. Groups of PCB congeners with the same number of chlorines are chemical homologs. For example, the group of PCB congeners containing two chlorines, regardless of position, are dichlorobiphenyls and 2,2' dichlorobiphenyl and 2,4 dichlorobiphenyl are isomers of the dichlorobiphenyl homolog group. The chlorine substitution pattern of PCB congeners is also distinguished based upon the chlorines' position relative to the carbon bridge. Chlorines located adjacent to the carbon bridge are referred to as ortho chlorines (2,2',6, or 6' positions); chlorines located opposite the carbon bridge are referred to as para chlorines (4 and 4' positions); chlorines located in the remaining sites are referred to as meta chlorines (3,5,3' or 5' positions, Figure 3-1).

PCBs were manufactured and sold in the United States under the Aroclor tradename. Several Aroclor products were manufactured; the five principal compounds were Aroclor 1221, 1242, 1016, 1254, and 1260. These products differed in their degree of chlorination, as depicted in the homolog patterns presented in Table 3-1.

Table 3-1. Weight Percent of Each Homolog Group Within Manufactured Aroclors[1]

Homolog Group	Aroclor Compound						
	1221	1232	1016	1242	1248	1254	1260
Mono	65%	31%					
Di	30%	24%	21%	15%			
Tri	5%	23%	52%	46%	21%	2%	
Tetra		16%	27%	30%	60%	17%	
Penta		6%		9%	18%	49%	9%
Hexa					1%	28%	47%
Hepta						4%	37%
Octa							6%
Nona							1%
Deca							

[1]Weight percents obtained from Frame *et al.* (1996).

3.1.2 GE Plant Sites

Two General Electric Company plants located in Hudson Falls (MP 197) and Fort Edward (MP 196, Figure 2-14) manufactured capacitors that contained PCBs for approximately 30 years until 1977. PCBs were discharged to the river from the two GE plants *via* wastewater outfalls (Figure 2-14). The PCB discharges originated from: 1) accidental spillage and other handling losses, and 2) exterior washing of flood-filled capacitors, which produced a waste stream consisting of a mixture of wash water and PCB oils (Brown *et al.* 1984). The latter practice occurred between the early 1950's and early 1970's and likely accounted for the majority of the discharges to the river (Brown *et al.* 1984). Based upon these practices, it is likely the majority of PCBs discharged from the plants entered the river in either a dissolved or DNAPL form.

3.1.3 PCB Usage

The Fort Edward and Hudson Falls plant sites used a number of PCB Aroclors in their manufacture of capacitors. Based upon use history, which was constructed from fragmented production, product specification and purchase records, the principal Aroclor used was Aroclor 1242 (Brown *et al.* 1984, Table 3-2). However, other Aroclors, including Aroclor 1016 and 1254 were also used at the plants and likely made up a portion of the discharges to the river. Nonetheless, considering the timing of the capacitor washing practices (i.e., 1950's to early 1970's), Aroclor 1242 likely accounted for the large majority of the PCBs discharged from the plants to the Upper Hudson River.

Table 3-2. Aroclor PCB Usage at the Hudson Falls and Fort Edward Plant Sites[1]

Fort Edward Plant				Hudson Falls Plant			
	1242	1254	1016		1242	1254	1016
1946-1950		100%					
1950-1955	20%	80%		1952-1953		100%	
				1953-1955	25%	75%	
1955-19??[2]	95%	5%		1955-19??[2]	95%	5%	
1964-1971	99%	1%		1964-1971	99%	1%	
1971-1977			100%	1971-1977			100%

[1]Historical usage as documented in Brown *et al.* 1984
[2]Dates for this period are unclear from historical records.

3.2 TRANSPORT/LOADING EVENTS

There were a number of significant transport events in the early 1970's that contributed to the current distribution of PCBs within the Upper Hudson River. Additionally, a significant external PCB source was discovered in the vicinity of the Hudson Falls plant in the early 1990's.

3.2.1 Accumulation of PCBs Behind Fort Edward Dam

The majority of PCBs discharged from the Hudson Falls and Fort Edward plant sites during the 1940's to 1970's are believed to have accumulated upstream of the former Fort Edward Dam (USEPA 1984a). The pool created by this dam extended more than 1 mile

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upstream. It was an efficient trap not only for sediments but also for wood waste from a number of saw mills upstream. The wood waste included saw dust, wood chips and slab lumber, and was most likely a significant portion of the organic loadings to the system upstream of Fort Edward from the 1850's to the 1950's. These wood wastes provided an effective adsorbent material for the PCBs discharged from the plants, thus retaining much of the PCB loadings to the system within the Fort Edward Dam impoundment (former Reach 9).

3.2.2 Fort Edward Dam Removal and Subsequent Flood Events

In 1973, the owner of the dam, Niagara Mohawk Power Corporation, removed the structure, lowering the water level of Reach 9 by approximately 20 feet. The dam removal exposed contaminated sediment and wood wastes that had accumulated. Subsequent high flow events in 1973 and 1974 moved an estimated 850,000 cubic yards of sediment downstream (Malcolm Pirnie 1980). Figure 3-2 is a photograph of sediment and wood waste that accumulated near Rogers Island (MP 194.2) following the flood events of 1973 and 1974. An additional 260,000 cubic yards were scoured during the approximately 100 year flood event of 1976 (Malcolm Pirnie 1980). Scouring of sediments from this portion of the river also occurred during the approximately 10 year flood event of 1983. In total, USEPA estimated 1.1 million cubic yards of sediment that contained an estimated 887,000 to 1.1 million pounds of PCBs were transported downstream from Reach 9 following the Fort Edward Dam removal (USEPA 1984a).

The exposed sediments remaining upstream of the Fort Edward Dam site following the dam removal and subsequent scour events are referred to as the Remnant Deposits. Five discrete Remnant Deposits exist within the 1.5-mile reach of the river upstream of Fort Edward (Figure 2-14). The estimated 56 acres of these deposits contained approximately 380,000 cubic yards of PCB-contaminated sediments and wood debris (Tofflemire 1980, Table 3-3). Four of the five remnant areas have undergone extensive remediation since the 1970's (see Section 3.3.1).

Table 3-3. Physical Characteristics of the Fort Edward Dam Remnant Deposits (USEPA 1984a)				
Remnant Area	Area (acres)	Average PCB Concentration (mg/kg dry wt)	Average Depth of Contamination (ft)	Contaminated Volume (yd^3)
1	4.0	20	2.0	12,910
2	8.0	5	5.0	64,530
3*	19.3	118	5.5	171,660
4*	20.5	33	2.4	79,380
5	4.0	250	8.0	51,630
TOTAL	55.8			380,110
* PCB concentration in this area is a volume weighted average of two sub-areas.				

A significant proportion of the sediments and associated PCBs scoured from the former Reach 9 during the 1970's settled within depositional zones of the downstream reaches. These areas were extensively sampled and analyzed for PCBs by the New York State Department of Environmental Conservation (NYSDEC) between 1976 and 1978. From these data, 40 sediment "hot spots" containing PCBs in excess of 50 mg/kg (parts per million) were identified along the 40 miles of the river between Fort Edward and Troy, NY (Tofflemire *et al.* 1979, Figure 3-3). Twenty of these sites are located within the Thompson Island Pool (Figure 3-3).

3.2.3 Allen Mill Loadings

During routine water column monitoring at Fort Edward, a significant increase in water column PCB loading was detected after mid-September 1991 (Figure 3-4). Within a week's time, PCB levels within the river increased from less than 100 ng/L to approximately 4,000 ng/L (O'Brien & Gere 1994a). This loading originated upstream of the Fort Edward and downstream of the Hudson Falls stations (Figure 2-14). After an extensive investigation, the source of the increased water column PCB loading was attributed to PCB DNAPL releases associated with the collapse of a wooden gate structure within the Allen Mill adjacent to GE's Hudson Falls plant (Figure 3-5, Section 2.2.3.3). The gate had kept water from flowing through a tunnel cut into bedrock below the mill, presumably since the mill's closure in the early 1900's. PCB DNAPL, originating from a plume beneath the Hudson Falls plant site (Figure 2-17), migrated through bedrock fractures and accumulated within the tunnel (O'Brien & Gere 1994a). Apparently, collapse of the gate caused water to wash PCB DNAPL from the tunnel into the river. Water column PCB concentrations remained elevated from 1991 until 1993, after which remediation efforts controlled the releases from the tunnel (see Section 3.3.3).

3.2.4 Bedrock PCB Sources

In addition to the sources within the Allen Mill structure, dissolved and DNAPL PCBs were discovered in the fractured bedrock beneath the GE Hudson Falls plant site (O'Brien and Gere 1994a, O'Brien and Gere 1996d). Upon investigation, PCB DNAPL seeps were discovered within the bedrock adjacent to the Allen Mill, and within the river bed at the base of Bakers Falls (Figure 2-17). Although these seeps likely contributed to the historic PCB loadings to the river, the nature and magnitude of this source, and how it may have changed over time, is not well understood. Presumably, the subsurface DNAPL plume originated during the GE plant operations and subsequently migrated through bedrock fractures to the vicinity of the falls, where it accumulated or was transported downstream. Recent remediation efforts have been directed at controlling this PCB source to the river (Section 3.3.3).

3.3 REMEDIATION HISTORY

3.3.1 Remnant Deposits

As described in Section 3.2.2, the Remnant Deposits consist of approximately 56 acres of sediment and debris that became exposed when the Fort Edward Dam was removed in 1973. Several limited remedial activities were performed on the Remnant Deposits by New York State between 1974 and 1978 (USEPA 1984a). In 1975, bank stabilization activities were conducted at Remnant Deposits 2, 3, and 5 (Figure 2-14). Approximately 1,100 feet of shoreline along Remnant Deposit 5 were covered with rip-rap. A limited amount of rip-rap was also placed along the bank of Remnant Deposit 3. In addition, the steep bank of Remnant Deposit 2 was cut back to reduce the slope. In 1977 and 1978, approximately 17,000 cubic yards of exposed sediment were excavated from Remnant Deposit 3 and placed in a lined containment cell located in the Town of Moreau, New York (USEPA 1984a).

In-place containment of the Remnant Deposits was completed by GE in 1991 in accordance with a Record of Decision (ROD) issued by USEPA and a 1990 Consent Decree between the Federal Government and GE. The containment design consisted of grading the surface of the sediment and placement of a layer of low permeability material (Claymax®). The Claymax® was covered with a 12-inch sand drainage layer, then 6 inches of topsoil. The containment was completed by vegetation of the topsoil and stabilization of the banks by the river with rip-rap (J.L. Engineering 1992). A photograph of Remnant Deposit 4 after completion of the containment remedy is presented in Figure 3-6. Maintenance and post-construction monitoring associated with the Remnant Deposit containment are conducted on an ongoing basis by GE.

3.3.2 Thompson Island Pool

Following removal of the Fort Edward Dam in 1973 and subsequent downstream movement of sediment and debris, several sediment removal actions were undertaken by New York State in the Hudson River, primarily in the upper reaches of the Thompson Island Pool near Rogers Island. These removal activities were associated with maintenance of the Champlain Canal navigational channel, and included dredging approximately 775,000 cubic yards (cy) of sediment and debris. These materials were placed in several disposal sites located along the river in the Fort Edward area (Figure 3-7). These disposal sites were covered with low permeability soil caps and are vegetated and maintained by New York State. A summary of these removal actions is presented in Table 3-4.

Table 3-4. Summary of Sediment Removal Actions Performed in TIP			
Date(s)	Location	Approximate Mile Point(s)	Volume of Sediment Removed (cy)
April 1974 – Dec. 1974	Main Channel Near Lock 7	193.7	175,000
April 1974 – Dec. 1974	East Channel of Rogers Island	193.7 – 194.4	85,000
July 1974 – June 1975	East Channel of Rogers Island	194.4 – 194.7	180,000
May 1975 – Nov. 1975	West Channel of Rogers Island	193.7 – 194.7	130,000
1976	Near Buoy 212	192.5	35,000
Fall 1977 – Spring 1978	Canal Channel near Rogers Island	194	170,000
Source: Malcolm Pirnie 1980 and USEPA 1984a			

In addition to the sediment removal operations listed above, containment of the dredge spoils at the New Moreau Site was completed between Fall 1977 and Spring 1978.

3.3.3 Allen Mill and GE Hudson Falls Plant Remediation

In January 1993, with the cooperation of the Bakers Falls Hydroelectric Dam owner and NYSDEC, water flow through the Allen Mill and the associated PCB discharges were largely controlled. By Spring 1993, two of the three waterways within the mill were isolated from the river and planning began to remove PCB-containing material from within the Allen Mill. An estimated 45 tons of PCBs were contained in the 3,430 tons of sediment removed from the Allen Mill in 1994 and 1995 (O'Brien & Gere 1996d).

A number of actions have been taken to contain and control the PCB DNAPL seeps observed in the river bed adjacent to the Allen Mill (Section 3.2.4, Figure 3-8). These activities include grouting of bedrock fractures, manual collection of DNAPL, when accessible, and installation and operation of pumping wells to hydraulically control the seeps. The release of PCB DNAPL through these bedrock seeps has declined in response to mitigation efforts, but has not ceased. During elevated river flow events that inundate the Bakers Falls, additional PCB DNAPL seeps into the river.

In September 1996, divers discovered an additional area of PCB DNAPL seepage at the base of Bakers Falls adjacent to the eastern shore of the plunge pool (Figure 2-17). This seep was producing approximately 0.5 pounds per day of PCBs. A sub-aquatic collection system was installed to arrest the flow of the PCBs into the river. In January 1997, a groundwater collection well was installed on shore and upgradient in an effort to hydraulically control PCB discharges from the seep. Significant quantities of PCB DNAPL are recovered from this well, which appears to have controlled discharges from the seep. It is not known how long this seep was active.

In addition to the activities to control riverbed PCB seeps and PCB movement from the Allen Mill, GE conducted an intensive subsurface investigation and remedial program at the Hudson Falls plant site. To date, more than 3,000 gallons of DNAPL have been removed from the subsurface and shipped off-site for appropriate disposal. A network of more than 230 groundwater recovery and monitoring wells has been installed to create a hydraulic barrier between the site and the river, and to collect PCB-containing groundwater and DNAPL (Dames and Moore 1997, HSI GeoTrans 1999). The effectiveness of this system in reducing PCB flux from the site to the river is being monitored by measuring PCB levels in the river and through an assessment of the hydraulic capture zone created by the groundwater pumping system. Based on the results of this monitoring, the system is expanded or reconfigured, as appropriate. Collected groundwater is treated on-site with an advanced wastewater treatment facility operated by GE prior to discharge back to the Hudson River.

Between October 1997 and September 1998, GE performed an Interim Remedial Measure (IRM) in the Hudson River between the former GE pumphouse and the eastern raceway intake structure (Figure 2-14). The primary outfall for the GE Hudson Falls facility discharged into this area (Outfall 002, Figure 2-14). The objective of this IRM was to remove debris and sediment containing PCBs from the area to allow inspection of the underlying bedrock for the presence of DNAPL. This information was used to further evaluate the sources of bedrock DNAPL seeps observed downstream in Bakers Falls, as discussed in Section 3.2.4.

Approximately 1,075 cy of material was removed from the river and transported off-site for appropriate disposal (QEA 1999).

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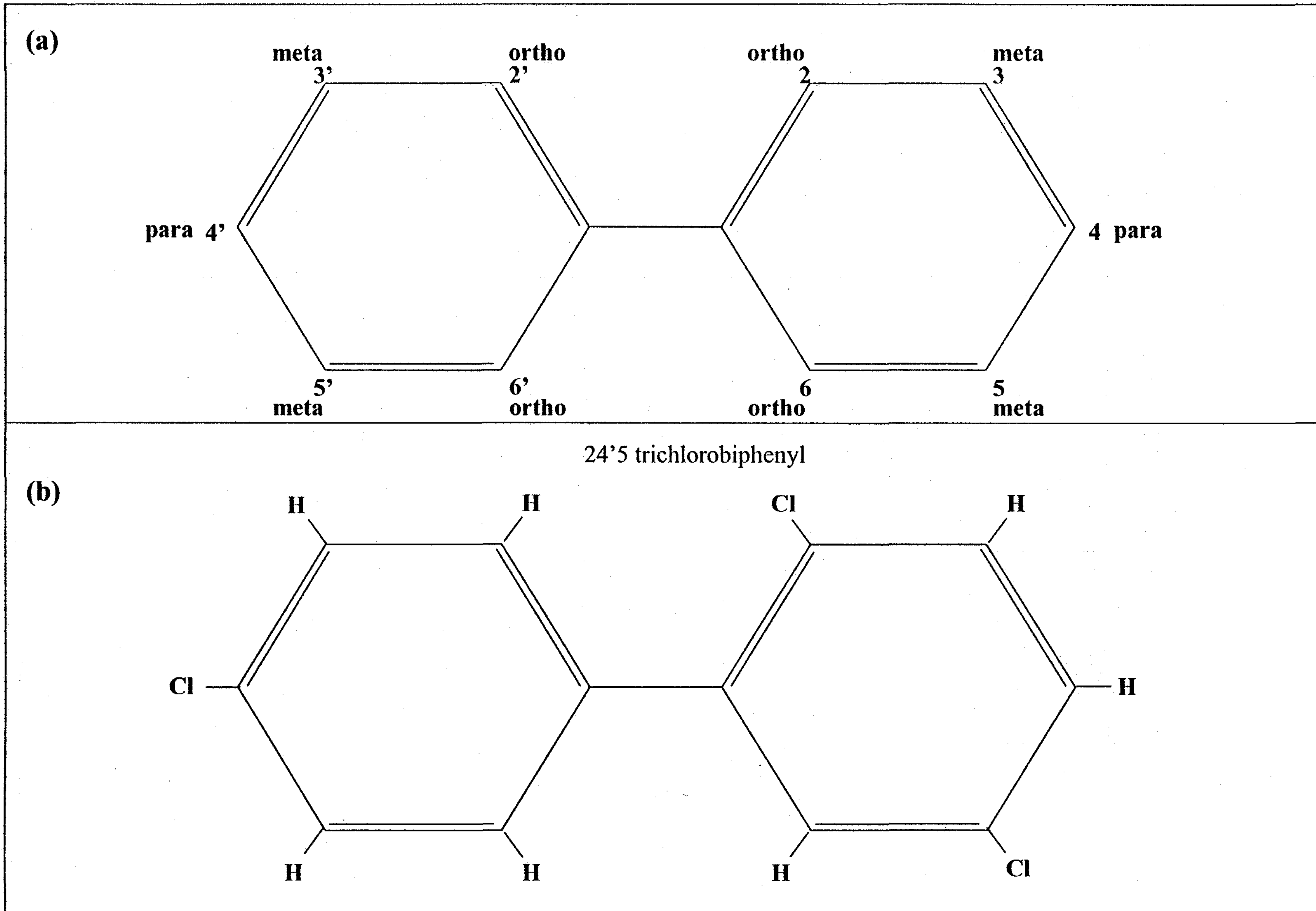

Figure 3-1. Molecular structure and substitution nomenclature of (a) Polychlorinated Biphenyls and (b) a representative PCB congener.

QEA Quantitative Environmental Analysis, LLC

GENhud 131 May, 1999

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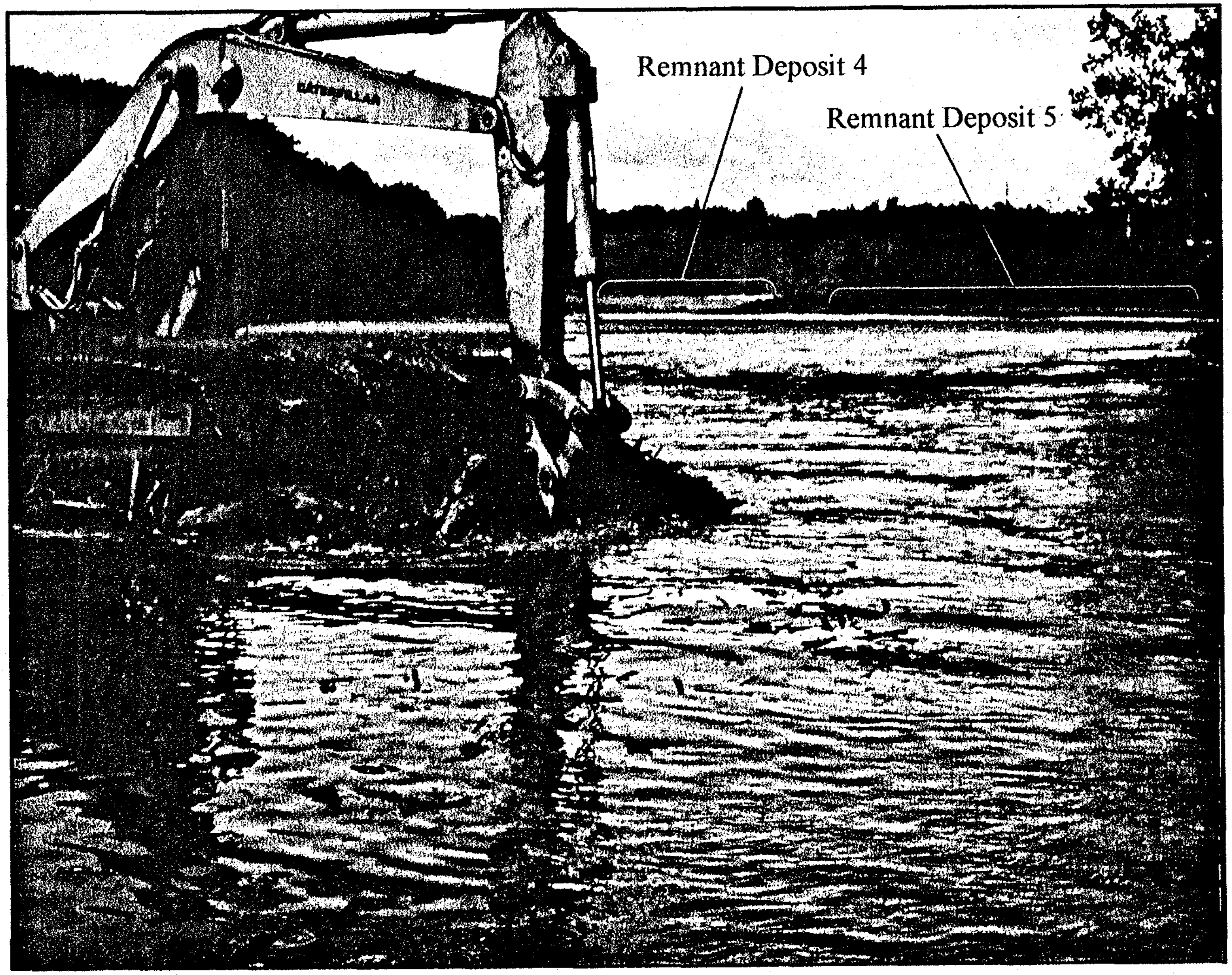


Removal of sediment and debris from western channel of Hudson River near Rogers Island, looking upstream. Remnant Deposits are visible in background.

GENERAL ELECTRIC COMPANY
Hudson River Project
Sediment and debris in Hudson River near Rogers Island (1975)

MDL: D:\GENhud\w1fig3-02_SedRemoval.ppt

FIGURE 3-2.

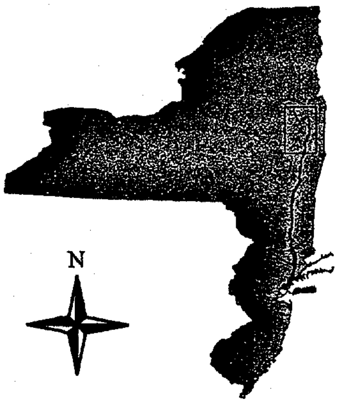
SCALE: NONE

QEA Quantitative Environmental Analysis, LLC

GENhud 131

May, 1999

LOCATION MAP OF THE UPPER HUDSON RIVER



Graphic Scale

2 0 2 4 Miles

Legend

Shoreline

1976 NYSDEC hot spots

Data Source: Tofflemire et al., 1979

GENERAL ELECTRIC COMPANY
Hudson River Project

PCBs in the Upper Hudson River
Volume 1. Historical Perspective and Model Overview

Figure 3-3.

NYSDEC designated PCB hot spot locations.

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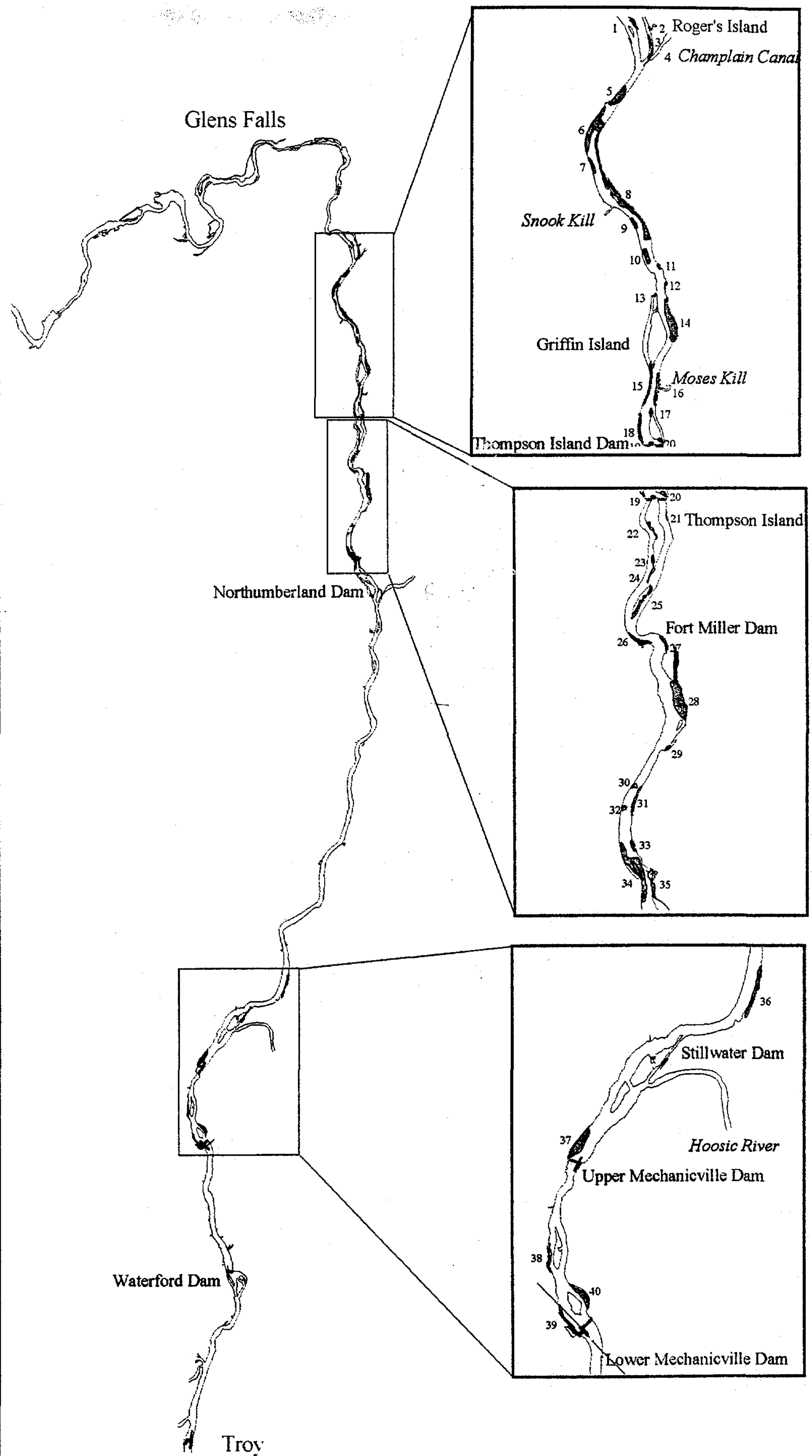

313533

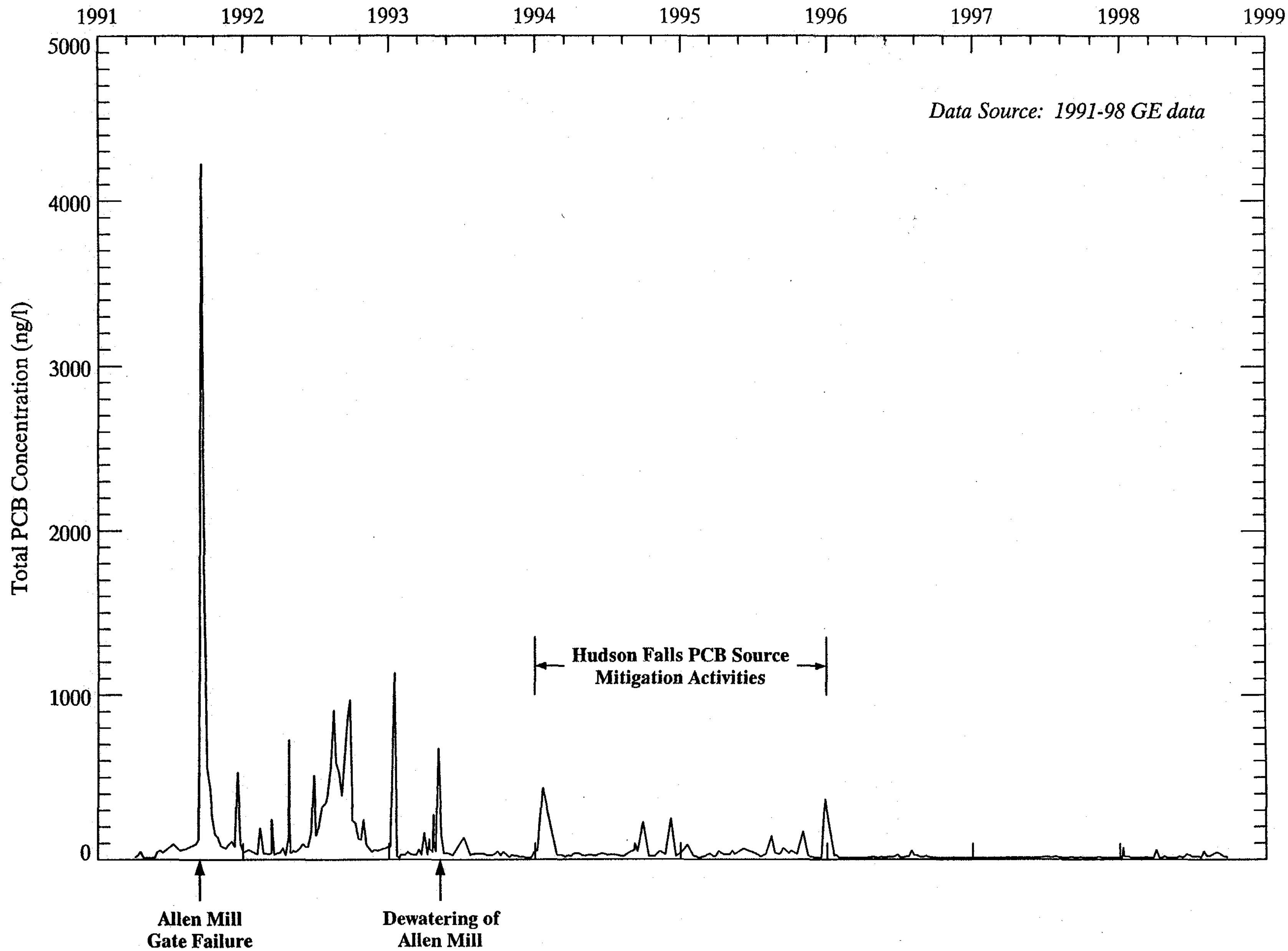

Figure 3-4. Temporal profile of total PCB concentration at the Fort Edward monitoring station (1991-1998).

Water flowing through collapsed gate into interior of Allen Mill (1992).

GENERAL ELECTRIC COMPANY **Hudson River Project** **Allen Mill gate failure** MDL: D:\GENhud\w1fig3-05_MillGate.ppt	FIGURE 3-5.	QEA Quantitative Environmental Analysis, LLC
	SCALE: NONE	GENhud 131 May, 1999

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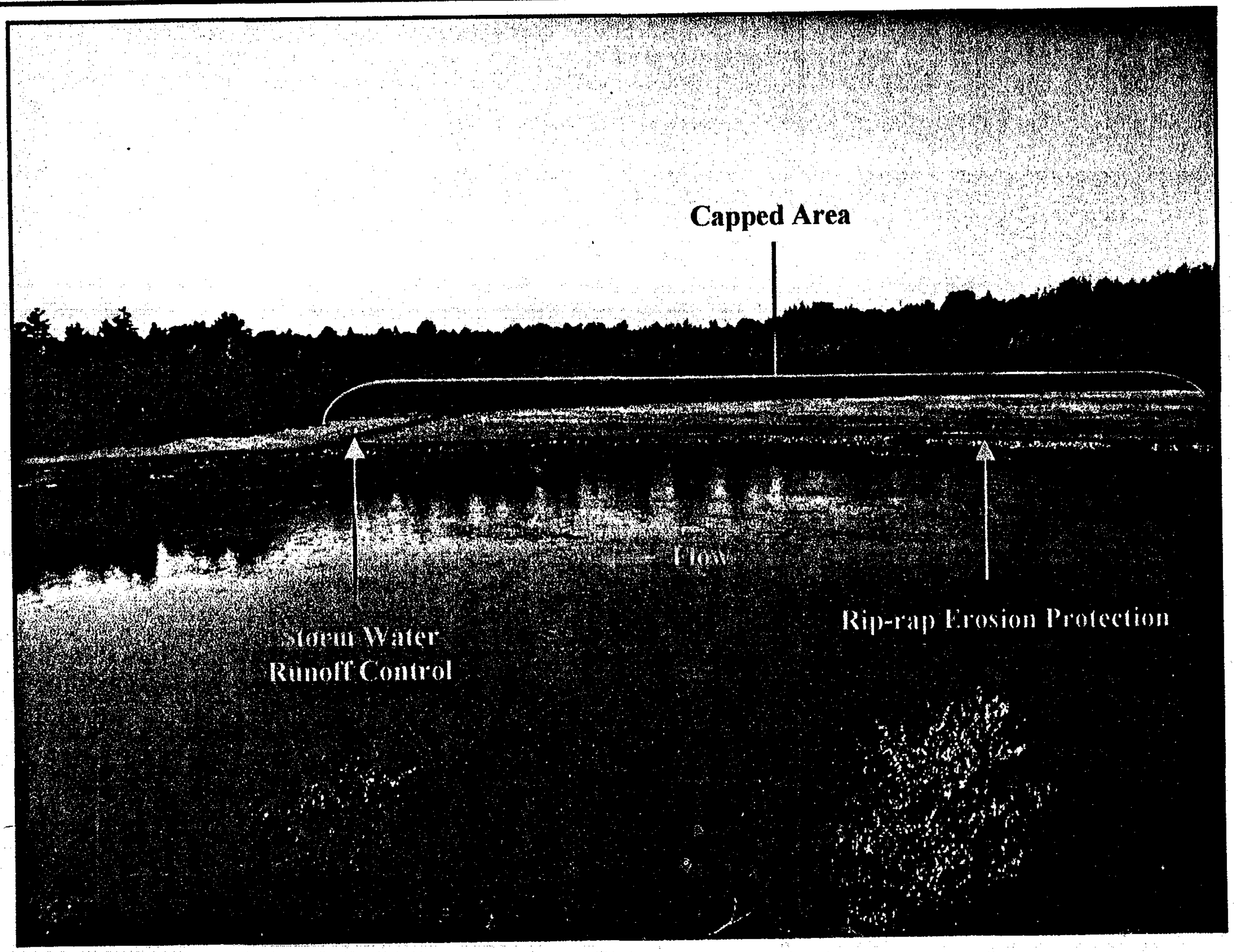

Remnant Deposit 4 looking west (1998).

GENERAL ELECTRIC COMPANY
Hudson River Project
Remnant Deposit after containment

MDL: D:\GENhud\v1fig3-06_RemContain.ppt

FIGURE 3-6.

SCALE: NONE

QEA
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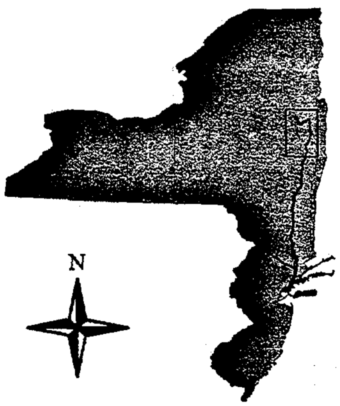
May, 1999

LOCATION MAP OF THE
UPPER HUDSON RIVER



Graphic Scale

0.5 0 0.5 Miles

Legend

PCB Sediment Disposal Sites
Remnant Deposits
Mile Points
Shoreline

Data source: Malcolm Pirnie, 1980

GENERAL ELECTRIC COMPANY
Hudson River Project

PCBs in the Upper Hudson River
Volume 1. Historical Perspective and Model Overview

Figure 3-7.
PCB sediment disposal sites.

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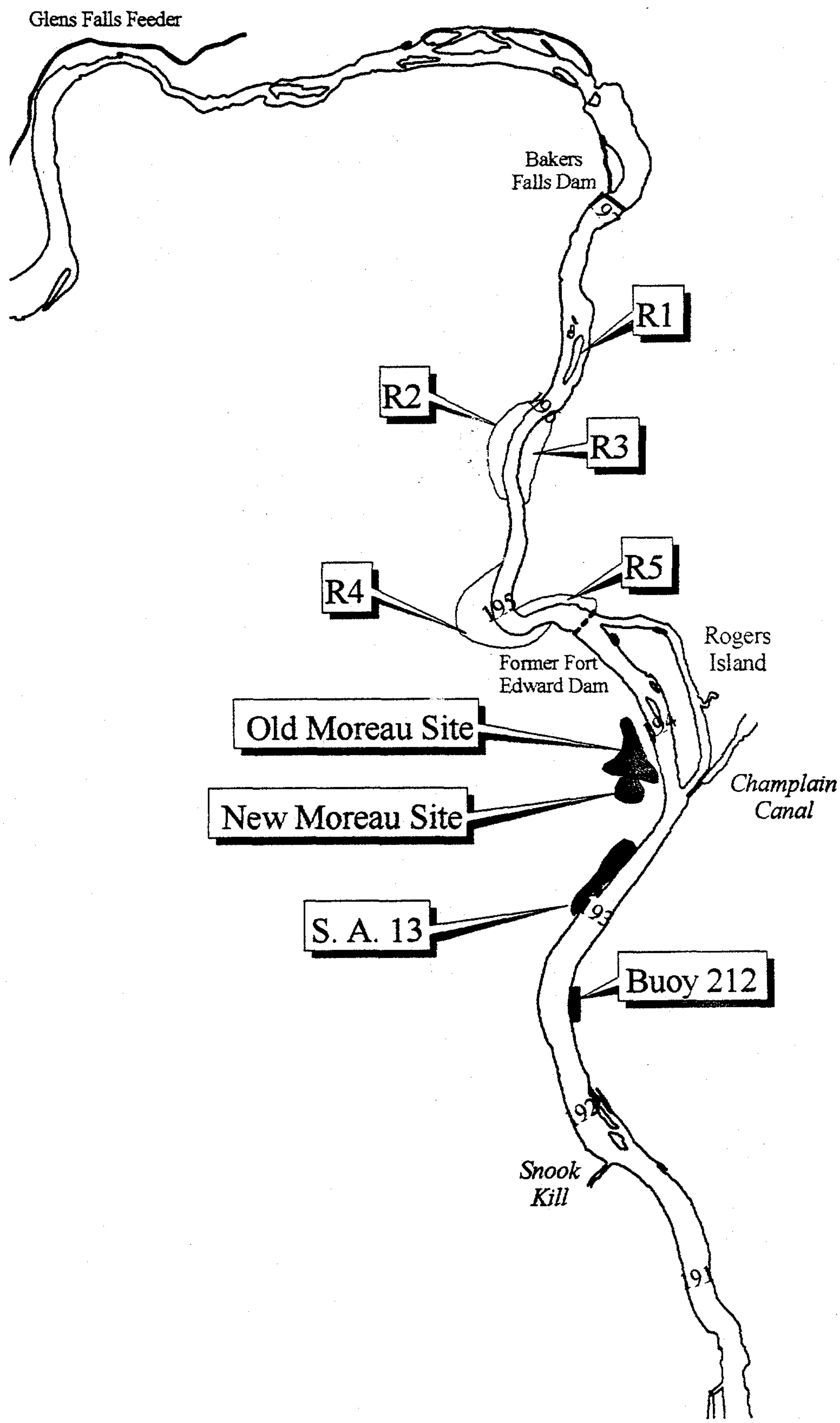
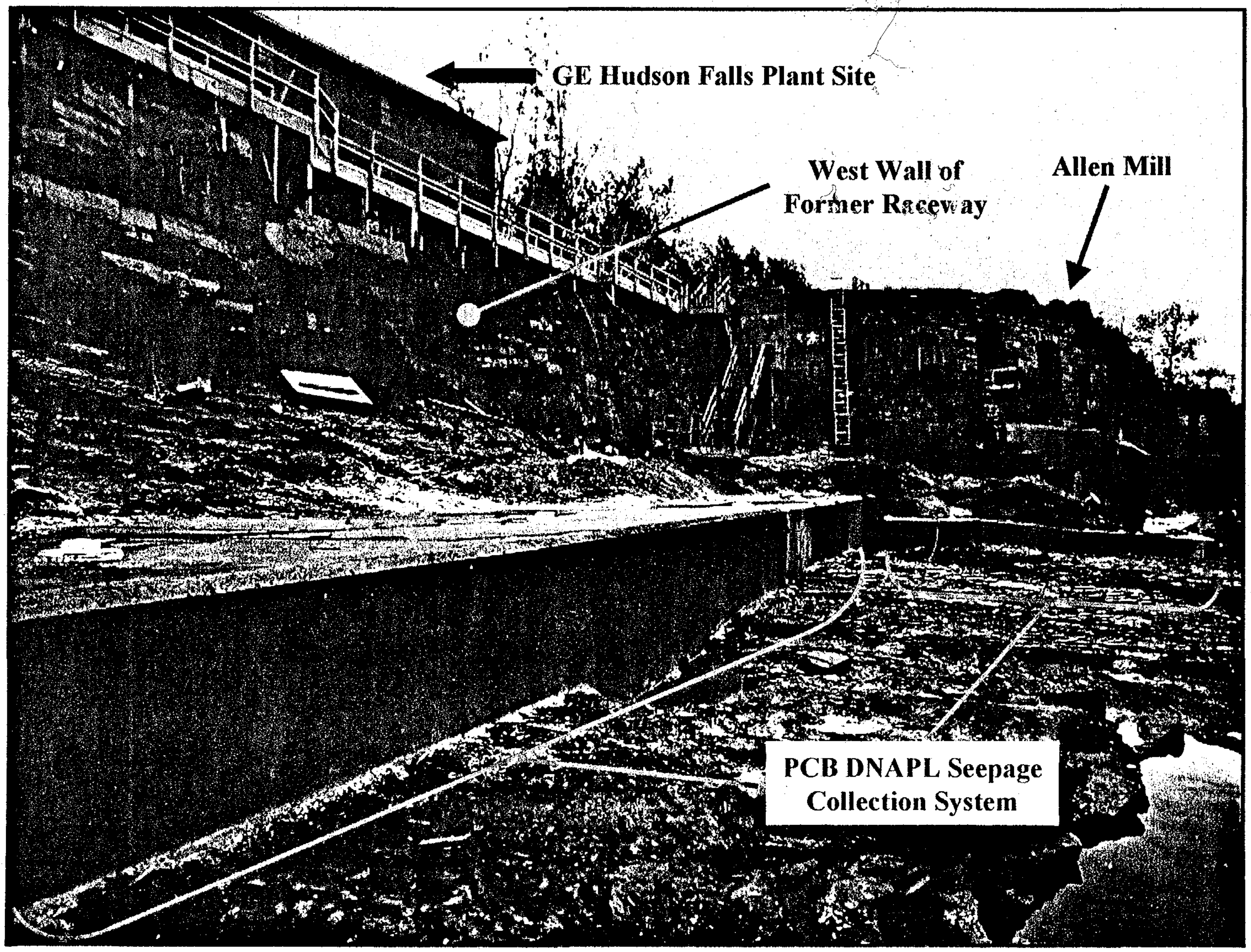


313536



GENERAL ELECTRIC COMPANY
Hudson River Project
Riverbed PCB DNAPL seep control measures

MDL: D:\GENhud\v1fig3-08_SeepControl.ppt

FIGURE 3-8.

SCALE: NONE

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May, 1999

Major Sampling Programs on the Upper Hudson River

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SECTION 4
MAJOR SAMPLING PROGRAMS ON THE UPPER HUDSON RIVER

As a result of its long regulatory history, numerous sampling and analysis programs have been conducted to evaluate the distribution, fate, and effects of PCBs in the Upper Hudson River. Indeed, the Hudson River PCB site is one of the most data-rich sites in the country, with more than 20 years of monitoring data for the water column, sediment, and biota.

4.1 WATER COLUMN PCB SAMPLING

The U.S. Geological Survey (USGS) initiated PCB sampling in the Upper Hudson River in 1975. Through 1995, the USGS continued PCB sampling at an average frequency of approximately one round every two to three weeks. The USGS water column PCB sampling frequency has fluctuated over the years and typically focused on periods of high flow. Sampling locations employed by USGS have also varied over the years; however the most frequent sampling occurred at Fort Edward, Schuylerville, Stillwater, and Waterford.

In 1991, GE began weekly water column PCB sampling, a part of which was conducted pursuant to the USEPA consent order for the remediation and monitoring of the PCB Remnant Deposits (Section 3.3.1). This sampling continues through the present day. GE's routine water column monitoring stations have been located primarily between Hudson Falls and TID. In addition to this weekly monitoring, GE has sponsored several water column sampling programs to examine PCB fate and transport issues within the Upper Hudson River. Such programs include:

- transect studies to evaluate lateral variability in water column PCBs,
- time-of-travel surveys to assess the spatial distribution of water column PCB loading,
- studies to assess the representativeness of routine sampling stations,
- high frequency monitoring to evaluate PCB dynamics during flood periods, and
- sampling to assess PCB sources within the region of the former GE plant sites.

As part of the Hudson River Reassessment Remedial Investigation and Feasibility Study (RRI/FS), USEPA conducted water column sampling in both the Upper Hudson River and Lower Hudson River during 1993. Two water column sampling programs were performed as part of the RRI/FS:

- transect studies, in which the river was sampled upstream to downstream in a time-of-travel fashion, and
- flow averaging studies, in which large volume composite samples were collected over week-long periods.

The major water column PCB sampling programs for the Upper Hudson River are summarized in Table 4-1.

Table 4-1. Major Water Column PCB Sampling Programs of the Upper Hudson River

Sponsor	Program	Timeframe	Stations Sampled[1]	# PCB Samples[2]	Reference [3]
USGS	Water Quality Sampling	1977-1995	FE, SCH, STI, WAT	2150[4]	1
GE	Temporal Water Column Monitoring	1991-92	HF, FE, TID, SCH, STI, WAT	750	2
GE	Time-of-Travel Surveys	1991, 92, 93, 96, 97	TIP	330	3,4,5,6,7
GE	High Flow Sampling	1992, 97, 98	BF, FE, TID, (SCH, STI, WAT)[5]	170	8,9,10
GE	Sampling Location & Lateral Transect Surveys	1992, 1996-7	HF, FE, TIP, TID	240	4,5,11
GE	Plant Site Area Sampling	1992-93, 1996-present	HF, FE	630	12,13,14
GE	Remnant Deposit Monitoring	1992-present	HF, FE, TID,SCH[6]	1690	6,7,15,16, 17,18
USEPA	RRI/FS Transect Studies	1993	GF, HF, FE, TID, STI, WAT	80	19
USEPA	RRI/FS Flow Averaging Studies	1993	HF, FE, TID, WAT	30	19

[1] Station Abbreviations: GF = Glens Falls; HF = Hudson Falls; FE = Fort Edward; TIP = multiple stations in Thompson Island Pool; TID = Thompson Island Dam; SCH = Schuylerville; STI = Stillwater; WAT = Waterford.
[2] Sample numbers are current as of March 1999.
[3] Reference numbers are as follows: 1 = USEPA 1998a; 2 = O'Brien and Gere 1993b; 3 = O'Brien and Gere 1993c; 4 = O'Brien and Gere 1996c; 5 = O'Brien and Gere 1998a; 6 = O'Brien and Gere 1993f; 7 = O'Brien and Gere 1994b; 8 = O'Brien and Gere 1999b; 9 = O'Brien and Gere 1993d; 10 = O'Brien and Gere 1997b; 11 = O'Brien and Gere 1996a; 12 = O'Brien and Gere 1994a; 13 = GE 1992-98; 14 = O'Brien and Gere 1997a; 15 = O'Brien and Gere 1998b; 16 = O'Brien and Gere 1998c; 17 = O'Brien and Gere 1996b; 18 = O'Brien and Gere 1995; 19 = USEPA 1995.
[4] Number of USGS water column samples as of 1995.
[5] Years for high flow sampling: Schuylerville = 1992 and 1998; Stillwater and Waterford = 1992.
[6] Routine sampling at Schuylerville was not performed between 1993 and 1997.

4.2 SEDIMENT PCB SAMPLING

As discussed in Sections 3.1 and 3.2, the historical PCB discharges from the GE plant sites and the large sediment loading event associated with the removal of the Fort Edward Dam and subsequent floods have resulted in PCB-containing sediment throughout the Upper Hudson River. Since 1977, numerous sampling programs have been implemented to assess various aspects of sediment PCB contamination within the Upper Hudson River reaches, including:

- evaluation of PCB distribution and depth of contamination,
- delineation of sediment PCB hot spots,
- estimation of total sediment PCB inventory,
- evaluation of sediment PCB depositional history, and
- assessment of changes in sediment PCBs over time.

The first large-scale sediment sampling program on the Upper Hudson River was conducted between 1976 and 1978 by NYSDEC. The program included collection of approximately 1,800 sediment samples from the Upper Hudson River. Of these, approximately 75% were surface grab samples, and 25% were deep cores. Results from this survey were used to delineate sediment hot spot areas (PCB concentrations higher than 50 part per million, or ppm). In 1984-85, NYSDEC conducted another large-scale survey, consisting of surface grab samples and deep cores within the TIP. The purpose of the 1984 survey was to further characterize the PCB distribution in the TIP, and to provide mass estimates for preliminary delineation of areas to be dredged.

Beginning in 1990, GE sponsored a number of sediment PCB sampling programs. Two hot spot coring surveys were conducted in 1990 to further delineate the PCB distribution in selected hot spots within the Upper Hudson River (USEPA 1998a). In 1991, GE sponsored a large-scale sediment survey, in which composite samples were collected from the entire Upper Hudson River, with an emphasis on TIP. The 1991 samples consisted of 25-cm deep cores, and surface grabs in regions where cores could not be collected (i.e., coarse sediments). GE also conducted a sediment sampling program in 1998, which focused on evaluating changes in sediment PCBs from previous surveys and provided additional data to delineate temporal trends in the TIP surface sediment concentration and composition.

As part of the RRI/FS, USEPA conducted two major sediment PCB sampling and analysis programs. In 1992, USEPA sponsored a high resolution coring program, in which a limited number of finely segmented sediment cores were collected from known depositional regions within the Upper Hudson River. The high resolution cores were used to evaluate the PCB depositional history in the Upper Hudson River. Also, USEPA collected deep low resolution sediment cores in 1994, which targeted select areas from TIP and selected hot spots from the downstream reaches of the Upper Hudson River. The low resolution coring program was focused on evaluating changes in sediment PCB inventory between 1984 and 1994.

The major data collection efforts for sediment PCBs within the Upper Hudson River are summarized below in Table 4-2.

Table 4-2. Major Sediment PCB Sampling Programs of the Upper Hudson River

Sponsor	Program / Timeframe	Reaches	# Stations	# PCB Samples	Reference
NYSDEC	1976-78 Survey*	Reaches 1-8, former Reach 9	960	1770	Tofflemire *et al.* 1979
NYSDEC	1984-85 Survey	Reach 8	550	930	Brown *et al.* 1988
GE	1991 Survey*	Reaches 1-8	1050[1]	380	O'Brien & Gere 1993e
USEPA	RRI/FS 1992 High Resolution Coring	Selected regions in Reaches 8, 6, 5, 4, & 1	12	200	USEPA 1995
USEPA	RRI/FS 1994 Low Resolution Coring*	Reach 8 and selected hot spots in Reaches 7-2	170	370	USEPA 1995
GE	1998 TIP Sediment Survey*	Reach 8 and selected hot spots in Reaches 6 & 4	210[2]	430	O'Brien and Gere 1999a

* *indicates programs with a higher sampling density in TIP.*

[1] 1991 GE sediment survey samples were composited from individual stations at an average ratio of 10:1.
[2] Approximately 70% of the 1998 GE sediment survey samples were composited from individual stations at an average ratio of 7:1.

4.3 BIOTA PCB SAMPLING

Exposure to sediment and water column PCBs has resulted in PCB bioaccumulation within the food web of the Upper Hudson River ecosystem. Several programs have been conducted to examine PCB concentrations over space and time in various levels of the food web, including:

- benthic invertebrates,
- phytophilous macroinvertebrates,
- forage feeding fish, and
- predatory fish.

NYSDEC began sampling biota for PCBs in the late 1970's as a part of its trend monitoring program. Beginning in 1976, the New York State Department of Health (NYSDOH) conducted both long-term (1976 – 1985) and short-term biomonitoring studies to assess temporal PCB trends in the macroinvertebrate population. Sampling locations ranged from Hudson Falls to Nyack, New York. The National Oceanic and Atmospheric Administration (NOAA), USEPA, and GE have conducted additional biota sampling. The number and type of PCB samples collected during the major biota sampling programs in the Upper Hudson River are summarized in Table 4-3. Smaller programs with less extensive temporal and spatial data coverage were not included in this table.

Table 4-3. Major Biota PCB Sampling Programs of the Upper Hudson River

Sponsor	Program / Timeframe	Reaches	# Stations	Sample Types	# PCB Samples	Ref.
NYSDEC	Trend Monitoring (1975-97)	Glens Falls Area, former Reach 9, Reaches 8, 7, 6, 5, & 1	16	Fish Individuals and Composites	4350	NYSDEC 1999
NYSDOH	1976-85	Former Reach 9, Reaches 8, 7, 5, & 1	7	Macro-invertebrates	570	USEPA 1995
GE	1990	Reaches 8, 7, 6, 5, 4, 3, & 2	9	Fish	90	USEPA 1995
NOAA	1993 Ecological Survey	Glens Falls Area, Reaches 8 & 5	5	Fish Composites	60	USEPA 1995
USEPA	1993 RRI/FS Ecological Program	Glens Falls Area, Reaches 8 & 5	11	Fish & Invertebrate Composites	100	USEPA 1995
GE	1997 Fish Sampling	Reaches 8 & 5	5	Fish	130	PTI 1998

PCB Fate and Bioaccumulation Processes in the Upper Hudson River

Section 5

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SECTION 5
PCB FATE AND BIOACCUMULATION PROCESSES IN THE UPPER HUDSON RIVER

5.1 HISTORICAL TRENDS IN WATER, SEDIMENT AND FISH

During the period of direct discharges, water column PCB levels most likely mirrored Aroclor use patterns at the GE plants. The cessation of direct discharges in 1977 resulted in the onset of a declining trend in water column PCB levels in the Upper Hudson River. However, as discussed in Section 3.2, the historical discharges resulted in high PCB concentrations in the sediments in former Reach 9. Removal of the Fort Edward Dam in 1973 and the subsequent high flow events resulted in redistribution of this PCB-contaminated sediment and likely changed the pattern of Upper Hudson River PCB transport and bioaccumulation. Water column and sediment data collected since 1977 provide a means for developing an understanding of the fate and transport of PCBs in the Upper Hudson River. Historical trends are useful for examining the impacts of major PCB transport events, and for the evaluation of the system's response to various transient events, such as spring high flows and elevated loadings from the plant sites.

Prior to the evaluation of historical trends, a method was required to account for the changes in PCB analytical techniques that have occurred over the years. In the 1970's and 1980's packed column gas chromatographic (GC) techniques were used to quantify PCBs in environmental media. Higher resolution methods utilizing capillary column GC techniques became available in the 1990's and allowed for PCB measurement at the congener level. The packed column methods used during the 1970's and 1980's did not completely resolve the mono- and dichlorinated PCB congeners (USEPA 1998b). To allow a uniform comparison of Upper Hudson River data over time and to account for different analytical methods, the PCB data discussed in this report are the trichlorinated and higher homolog sum of PCBs (PCB_{3+}). Although the mono- and dichlorinated PCB congeners account for a significant portion of total PCBs in the Upper Hudson River water and sediment, they do not significantly bioaccumulate in fish, which are the principal PCB exposure source for humans.

5.1.1 Trends in Water Column PCBs

Rogers Island (MP 194) in Fort Edward is the first water column monitoring station downstream of the GE plant sites that has been sampled routinely since 1977. PCB data from this station are the best indicator of upstream loadings to Reach 8. Temporal profiles of river flow, PCB_{3+} concentration and mass loading at Fort Edward from 1977 to present are presented in Figure 5-1. In response to reductions in PCB discharges to the river, the average PCB_{3+} concentrations at this location declined from the range of 100-200 ng/L in 1978-79 to less than 100 ng/L in the mid 1980's and near 50 ng/L in the late 1980's (Figure 5-1b). The large variability in PCB concentrations in the 1970's and 1980's was largely due to variable dilution, high flow related resuspension of PCB-containing sediment, and probable intermittent DNAPL releases from the plant site area. For example, the Spring 1983 flood (Figure 5-1a) resulted in PCB_{3+} concentrations that exceeded 1,000 ng/L at Fort Edward (Figure 5-1b).

In late 1991, PCB_{3+} concentrations at Fort Edward increased to 4,000 ng/L due to the Allen Mill loading event (Section 3.2.3). Remediation of the Allen Mill source, which began in 1993, reduced average PCB_{3+} concentrations to levels similar to those in the late 1980's (Figure 5-1b). Concentrations continued to decline and by 1997 were typically at or near the total PCB method detection limit of 11 ng/L (Figure 5-1b). This later decline was the result of remedial efforts to control bedrock DNAPL seeps in the Bakers Falls area (Section 3.3.3), which reduced average PCB loadings at Fort Edward to less than 0.5 lb/day (Figure 5-1c). An increase in PCB_{3+} concentrations between 1997 and 1998 is also observable in Figure 5-1. This may be related to the remedial actions at Hudson Falls during 1998 (Section 3.3.3, QEA 1999).

Similar to the trend at Fort Edward, PCB_{3+} concentrations at the Schuylerville station (MP 181.4) declined from the late 1970's to the late 1980's (Figure 5-2b). However, in the late 1970's, PCB_{3+} concentrations at Schuylerville were much higher than at Fort Edward because of sediment-derived PCB loadings from Reaches 8 and 7. By the late 1980's, the concentrations at Schuylerville had decreased to between 50 and 100 ng/L and were similar to the levels at Fort Edward (Figure 5-2b). This similarity suggests that sediment-derived PCB loading had decreased in importance between the late 1970's and late 1980's. The effect of the Allen Mill loading event in 1991 and subsequent source control measures (1992-1996) are also evident in the Schuylerville/TID data. However, the average TID PCB_{3+} loading of 1-2 lb/day in the late 1990's is higher than that observed at Fort Edward. This suggests that sediments within TIP became a relatively more important source of PCB_{3+} in the mid to late 1990's due to the reductions in plant area loadings (Figure 5-2c).

Comparison of PCB_{3+} concentration profiles at Fort Edward (Figure 5-1b) and Schuylerville/TID (Figure 5-2b) highlights the importance of sediment/water interactions. The coincidence of high flow events and increased PCB_{3+} concentration at Schuylerville/TID relative to that at Fort Edward suggests PCB loadings from sediment resuspension occur at elevated flows. For example, in Spring 1982, PCB_{3+} at Fort Edward peaked at approximately 300 ng/L, while concentrations exceeding 700 ng/L were observed at Schuylerville. In addition to increased concentrations at elevated flows, a distinct seasonal pattern in the low flow Schuylerville/TID PCB_{3+} concentration can be seen in the temporal profile. The pattern is more evident in the weekly sampling data from the 1990's (Figure 5-2b). This seasonal trend is characterized by increases in concentration in summer and decreases in late fall/winter periods.

The importance of sediment-water exchange at low flows is also evident in the weekly data collected at TID and Fort Edward from 1997 to 1998 (Figure 5-3)[2]. The PCB_{3+} concentrations at TID were high in summer and low in winter, while the Fort Edward levels remained relatively stable. This seasonal trend may be attributed to temperature changes, as PCB loadings from sediment pore water diffusion increase with increasing temperature. In addition, enhanced pore water exchange by biological mixing within the surface sediments during the summer months may be partially responsible for the seasonality of low flow PCB_{3+} loadings from TIP sediments. The seasonality of sediment-water exchange in the TIP is discussed more fully in Section 5.2.2.4.

[2]Although a sampling bias was discovered at the TID station used in Figure 4-3 (QEA, 1998b), data collected from an unbiased station at TID since October 1997 exhibit a consistent seasonal pattern.

The relative magnitude of upstream water column PCB loadings and low flow loadings from Reach 8 sediments appears to have changed over the 20-year sampling history. This change is evident in Figure 5-4, which displays the spatial profile of low flow PCB_{3+} concentration in the late 1970's, late 1980's, and 1998. The large increase in average concentration from Fort Edward to Schuylerville in 1978-80 indicates that loadings from the sediment in TIP and Reach 7 were substantial. Concentrations decreased slightly between Schuylerville and Waterford, suggesting dilution from tributary inflow. By the 1986-89 period, mean PCB_{3+} concentrations throughout the Upper Hudson River were significantly lower than they had been in the late 1970's. In addition, the concentration increase between Fort Edward and Schuylerville observed in 1978-80 is not evident in the 1986-89 averages, suggesting that a reduction in surface sediment PCB_{3+} concentrations had occurred between those periods. Due to lower sediment-derived PCB loading from Reach 8 in 1986-89, upstream loadings became more important to the system. This lack of a spatial gradient also indicates that inputs and outputs of PCB mass to the water column were approximately balanced across the TIP. The Allen Mill loading event (Section 3.2.3) and the remedial efforts in the plant site area during the mid-1990's (Section 3.3.3) appear to have resulted in another change in the PCB loading patterns betwee Fort Edward and Schuylerville. The average 1998 PCB_{3+} concentration at Fort Edward is much lower than the 1986-89 value as a result of efforts to control plant site PCB DNAPL sources. However, increases in PCB_{3+} across Reach 8 and Reach 7 indicate that sediment PCB loadings had again become relatively more significant than PCB loadings from upstream at Hudson Falls. The large reduction in loadings from the Hudson Falls vicinity have thus resulted in the TIP sediments being the largest PCB input to the Reach 8 water column.

5.1.2 Trends in Sediment PCBs

Since PCBs are hydrophobic, they preferentially partition to organic carbon on water column suspended particulate matter and, upon settling, are deposited in riverbed sediments. Changes in water column PCB loading are therefore reflected in the sediment PCB concentrations. The PCB loadings to the system from the two GE plant sites in the early 1970's, the Fort Edward Dam removal, and the high flow events in the mid-1970's resulted in high PCB concentrations in sediment downstream of Fort Edward (Section 3.2). Decreases in loading since

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the mid-1970's have resulted in sediment with lower PCB concentrations being deposited over the sediment with higher PCB concentrations previously deposited.

Sediment PCB sampling in the Upper Hudson River (Section 4.2) has typically consisted of surface grab and core sampling at various depth intervals. Deep samples have the highest PCB concentrations because they were deposited during high loading periods (i.e., through the 1970's), while surface samples are typically lower in concentration and reflect more recently-deposited material. For understanding PCB dynamics in the Upper Hudson River, much of the focus is on surface sediments (i.e., the top few cm) because exchange with the water column occurs in this layer, as evidenced by the spatial water column PCB patterns presented in Section 5.1.1. In addition, PCBs in surface sediment are available for uptake by benthic organisms and therefore directly affect PCB bioaccumulation.

Data from the sampling programs that covered the entire Upper Hudson River (e.g., 1977 NYSDEC, 1991 GE, and 1994 USEPA, Section 4.2) indicate that sediment PCBs generally decrease with downstream distance from the GE facilities. This trend is depicted by the 8-reach spatial profile of surface sediment PCB_{3+} concentrations from the 1991 GE composite samples (Figure 5-5). On a straight reach-averaged basis, 1991 PCB_{3+} concentrations in the top 5 cm of TIP were approximately 15 ppm, and decreased throughout the Upper Hudson River to an average of about 1-2 ppm in Reach 1 (Figure 5-5b). The high degree of variability in 1991 TIP PCB_{3+} concentrations (Figure 5-5a) is largely due to spatial heterogeneity in sediment deposition. In general, near-shore areas with fine-grained sediment (i.e., hot spots, Figure 3-3) exhibit much higher PCB concentrations than the coarse-grained materials farther from shore and within the navigational channel.

For most of the sediments sampled, PCB concentrations from the deeper depths (more than 5 cm) exceeded those in the surface layers, suggesting a decline in concentration over time. An example of a deep sediment core collected from Thompson Island Pool in 1998 is presented in Figure 5-6. Due to its known depositional history, radioactive ^{137}Cs levels in the sediment were used to develop approximate dates for the different layers (see Section 2.4.3.2). The chronology of PCB_{3+} concentrations in Figure 5-6 reflects PCB transport history. Measurable

PCB_{3+} levels are first evident in the sediment deposited in the 1950's, which is consistent with the Aroclor use patterns discussed in Section 3.1.3. PCB_{3+} concentrations peaked in the early 1970's in response to high plant site loadings and the Fort Edward Dam removal (Section 3.2). Lower PCB_{3+} concentrations in sediment deposited in the 1990's are indicative of the decrease in loadings and source control measures upstream of Fort Edward. This core, taken near the TID, shows PCB_{3+} concentrations in the top 1-cm of approximately 15 ppm.

The mean surface PCB_{3+} concentration in cohesive sediment regions (e.g., hot spots) of the TIP decreased from more than 100 ppm in 1977 to less than 20 ppm in 1998 (Figure 5-7a). A similar decreasing trend is shown in the non-cohesive surface sediment averages within TIP, where the 1977 average of 40 ppm decreased to a 1998 average of less than 10 ppm (Figure 5-7b). However, the PCB_{3+} concentrations in non-cohesive surface sediments were 2-3 times less on average than those in the cohesive areas. When an area-weighted mean is used to develop a single TIP average for surface sediment PCB_{3+} concentrations over time, the 1977 average of over 50 ppm decreases to a mean of approximately 10 ppm in 1998 (Figure 5-7c).

5.1.3 Trends in Fish PCBs

PCB concentrations in fish from the Upper Hudson River have declined since the late 1970's, consistent with the trends in water and sediment (Figures 5-8 through 5-11). For example, total PCB levels in largemouth bass fillets collected in Stillwater averaged 78 μg/g in the late 1970's (1975 through 1979) and 3.8 μg/g in 1997, a decrease of 95% (NYSDEC data, Figure 5-9). The highest PCB levels are found in fish collected from TIP. For example, the average concentration in largemouth bass sampled from TIP in 1997 was 10 μg/g, approximately 2.5 times the concentration at Stillwater (Figure 5-11). In 1997, all of the fish sampled from Thompson Island Pool and 65% of those from Stillwater had concentrations greater than the 2 μg/g Food and Drug Administration (FDA) tolerance.

Lipid-based total PCB concentrations[3] in largemouth bass from Stillwater declined in phases from the late 1970's to 1997 (Figure 5-8). A relatively rapid decline occurred between 1977 and 1982 with a half-life of 1.9 years, followed by a slower decline between 1982 and 1994 (half-life of 15 years) and a more rapid decline since 1995 (half-life of 3.6 years). Total PCB levels in pumpkinseed also exhibit three phases: levels declined relatively rapidly from 1979 to 1982 and again from 1995 to 1997. Concentrations declined at a considerably slower rate between 1982 and 1995. Annual average concentrations in brown bullhead show three phases, as well (Figure 5-8). The increase from 1991 to 1992 is contemporaneous with the Allen Mill event and is similar to trends observed in Thompson Island Pool brown bullhead (Figure 5-10).

At Thompson Island Pool, the pumpkinseed exhibit no clear trend in lipid-based PCB concentration between 1988 and 1994 (Figure 5-10). Levels declined from 1994 to 1997 as they did at Stillwater. Levels in brown bullhead declined consistently from 1986 to 1991. The average concentration then increased approximately 3-fold from 1991 to 1992, possibly in response to the Allen Mill event, the 1992 sampling was the first after the event. Levels again declined from 1992 to 1997.

Lipid-based PCB concentrations in the largemouth bass from TIP declined from 1984 through 1988, increased in 1990, and remained high through 1993. The 1990 to 1993 data are not consistent with PCB measurements in other fish species, sediments and water. For example, lipid-based levels in Thompson Island Pool largemouth bass increased 85% from 1988 to 1990 while the average water and forage fish exposure levels did not appear to change significantly over this period; no increases were observed in brown bullhead, pumpkinseed or water column PCB levels. In addition, the increase observed in 1990 was considerably before the Allen Mill PCB loading event.

The decline in largemouth bass lipid-normalized PCB concentrations from 1993 to 1994 is also inconsistent with our understanding of trophic transfer. Levels in brown bullhead and

[3] PCBs are hydrophobic and bioaccumulate in the fatty tissues of fish and other organisms. For this reason, wet weight fish PCB concentrations vary with the lipid content of the fish; the concentrations are lower in fish with low

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pumpkinseed declined 20 to 30%, while levels in the largemouth bass declined to a greater degree, 40%. Such a rapid change in the largemouth bass might be possible if their exposure to PCBs declined to near zero in 1994; however this was clearly not the case. Levels in a top predator should change at a slower rate than levels in forage fish, because of the relatively long half-life of PCBs in large fish (Sijm *et al.* 1992). These aspects of the largemouth bass data confuse the interpretation of trends from 1990 to 1993. A more complete discussion of this issue is contained in Volume 2.

Effects of the Allen Mill PCB loading event (Section 3.2.3) are evident in the brown bullhead data. Lipid-based PCB levels at both Stillwater and Thompson Island Pool decreased from the 1970's and 1980's to 1991, increased in 1992, and decreased thereafter. In contrast, the effects of the Allen Mill PCB loading event are not seen in the largemouth bass data. Possible effects may have been masked by the extreme changes in lipid content of both species that occurred in 1991; the lipid content at both locations was lower than any other year since 1982 (see Volume 2). Such extreme changes can affect trends based upon lipid-normalized as well as wet weight-based data (see Volume 2).

The declines in fish PCB levels were consistently slow from 1982 through 1993/95 relative to the more rapid declines observed before and after this period (Figure 5-12). This suggests that the mechanisms controlling PCB fate and bioaccumulation may have changed over time, and that plant site loadings may have altered fish PCB exposure between 1982 and 1993/95.

The spatial profile of total PCB levels in fish exhibits a decline from Thompson Island Pool to Waterford (Figure 5-13). The spatial gradient in fish paralleled the gradient in PCB_{3+} concentrations in sediments. In contrast, PCB_{3+} concentrations in the water column exhibited little, if any, spatial gradient.

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lipid levels and higher in fish with high lipid levels. To compensate for this, spatial and temporal trends in fish PCB levels are typically examined on a lipid normalized basis, that is, mass of PCB per mass of fish lipid.

5.2 PCB FATE PROCESSES

A number of processes affect the fate of PCBs within the Upper Hudson River (Figure 5-14). PCB exchange between the sediments and overlying water occurs by a number of mechanisms, including molecular diffusion, ground water advection, sediment bed resuspension, and settling of water column particulates. PCBs are lost from the system by exchange between the water column and atmosphere through the process of volatilization. PCBs can also be removed from the biologically active part of the system *via* burial into the deep sediment bed layers. Finally, PCBs can be lost from the system by biodegradation including aerobic degradation and microbially-mediated reductive dechlorination.

5.2.1 PCB Biodegradation

PCBs are chemically and physically stable under many conditions. This accounts for their persistence in the environment. However, recent advances in our understanding of microbially-mediated processes indicate that PCBs can be destroyed and transformed within the environment. PCB biodegradation is accomplished by two major processes: aerobic biodegradation and anaerobic dechlorination.

5.2.1.1 Aerobic Biodegradation

Numerous microorganisms have been isolated that aerobically degrade a variety of PCBs, although the more lightly chlorinated congeners are preferentially degraded (Abramowicz 1990, Bedard 1990, Bedard and Quensen 1995). These organisms convert PCBs to their corresponding chlorobenzoic acids, which can be readily degraded further into carbon dioxide, water, and chloride ions. Harkness *et al.* (1993) isolated numerous organisms from the Upper Hudson River with the capability of aerobically degrading PCBs and the chlorobenzoic acids that are the intermediate degradation product. Additionally, in a field reactor test conducted within the Upper Hudson River, significant aerobic biodegradation of PCBs was accomplished without the addition of nutrients, oxygen, or other supplements (Harkness *et al.* 1993). In these tests, simple mixing provided sufficient oxygen to promote the degradation of lower chlorinated PCBs.

The discovery of chlorobenzoic acids within Upper Hudson River sediments indicates the aerobic biodegradation process is active within the aerobic zones of these sediments (Flanagan and May 1993). However, as measured in laboratory experiments, the aerobic zone of Upper Hudson River sediments is only a few millimeters at the sediment-water interface (Fish and Principe 1994). Therefore, the aerobic degradation process is not likely to have a measurable impact on sediment PCB inventories.

5.2.1.2 Anaerobic Dechlorination

Anaerobic bacteria attack more highly chlorinated PCB congeners through reductive dechlorination. This process preferentially removes meta- and para- chlorines, resulting in a conversion of highly chlorinated PCB congeners into lower chlorinated congeners. The altered congener distribution within Upper Hudson River sediments was the earliest evidence of the anaerobic dechlorination of PCBs (Brown *et al.* 1984). The same activity has been observed in numerous other systems (Abramowicz 1990, Brown and Wagner 1990, Risatti 1992).

The microbial consortia of Upper Hudson River sediments are capable of extensive PCB dechlorination (Quensen *et al.* 1990). In fact, several different dechlorination patterns have been identified within Upper Hudson River sediments (Brown *et al.* 1987). Although subtle differences exist among the different patterns, each produces a PCB mixture lower in tri-, tetra-, and pentachlorinated PCBs and higher in mono- and dichlorinated PCBs relative to the starting Aroclor mixture. Figure 5-15 illustrates the changes observed in Aroclor 1242 PCB composition as a result of microbially-mediated reductive dechlorination within Upper Hudson River sediments.

The 1991 GE sediment survey confirmed, on a river-scale, the widespread occurrence of PCB dechlorination within Upper Hudson River sediments (Mondello *et al.* 1998). This survey included the sampling and congener specific PCB analysis of sediments from over 1000 locations within the 40 mile-long Upper Hudson River, with more than half of these samples collected from the six mile-long TIP (Section 4.2). The data from this survey indicated that over

50% of the PCBs found within the upper 25 cm of the sediments were mono- and dichlorinated PCBs. In contrast, Aroclor 1242 contains approximately 18% mono- and dichlorinated PCBs (Figure 5-15).

Laboratory experiments indicate that PCB dechlorination is accomplished over a period of several months to a year. A lag is sometimes observed, follow by a rapid phase and then a slow phase to completion (Abramowicz *et al.* 1993, Fish 1996, Sokol *et al.* 1998). The dechlorination status of PCBs within Upper Hudson River sediments indicates that sediments with lower concentrations generally exhibit less dechlorination (USEPA 1997, Schweiger *et al.* 1997). However, these same sediments have a PCB congener makeup indicative of on-going dechlorination (Schweiger *et al.* 1997) suggesting dechlorination is occurring at a slower rate. In support of this, *in-situ* dechlorination rate estimates, derived from sediment cores collected from the Upper Hudson River, suggest dechlorination occurs continuously over decadal time scales (McNulty 1997).

Because bioaccumulation potential and PCB toxicity are related to PCB chlorination level, reductive dechlorination has had an ameliorating effect on sediments containing PCBs. However, this process will not likely exert a significant long-term effect on PCB inventory in the Upper Hudson River because the bulk of the PCBs within the system have already undergone dechlorination (USEPA 1997).

5.2.2 PCB Exchange between Sediment and Water

PCB exchange across the sediment-water interface occurs as a result of numerous physical, chemical, and biological processes. Hydrodynamically induced resuspension dominates sediment-water exchange during periods of elevated flow (see Section 2.4). During low flow periods, a number of mechanisms can contribute to sediment-water exchange, including:

- molecular diffusion of PCBs contained within sediment pore waters,
- groundwater advection of contaminated pore water, and

- bioturbation induced pore water and particulate transport.

5.2.2.1 Molecular Diffusion

Water column PCB loading *via* molecular diffusion occurs as a result of the random molecular motion that transports dissolved PCB molecules from within surface sediment pore waters to the overlying water column. Molecular diffusion, the most ubiquitous mechanism of PCB transport across the sediment-water interface, occurs wherever a concentration gradient exists between sediment pore water (a region of high concentration) and the overlying water column (a region of lower concentration). Measured PCB concentrations within the Upper Hudson River surface sediment (0-5 cm) pore water range from 1 to 30 ug/L (O'Brien & Gere 1993e). In contrast, water column dissolved phase PCB concentrations are generally below 0.1 ug/L (O'Brien & Gere 1998b). This difference in dissolved phase PCB concentrations between pore waters and the overlying water column provides a continuous and substantial driving force for the diffusion of PCBs from the sediments into the water column.

5.2.2.2 Groundwater Advection

The advection (upward flow) of groundwater across the sediment-water interface is due to hydraulic gradients between the adjacent groundwater aquifer and the river. The upward flow of groundwater through surface sediments and into the overlying water column results in water column PCB loading. Groundwater traveling through sediments accumulates PCBs as a result of partitioning between groundwater and the contaminated sediment particles. This process is regulated by the hydraulic conductivity of the sediment, which varies by sediment type.

Direct measurements of groundwater seepage were taken within the Upper Hudson River during a one-month period between late May and late June 1997 (HSI GeoTrans 1997). Groundwater seepage followed pronounced temporal and spatial patterns. These patterns were consistent with those expected in response to seasonal changes in surface water and groundwater elevation and the artificially elevated surface water at the downstream limit of the TIP as a consequence of the dam (HSI GeoTrans 1997). Average seepage rates declined over the monitoring period from a high of 0.18 L m^2 hr^{-1} in late May to a low of -0.03 L m^2 hr^{-1} in mid June. Using estimated sediment pore water PCB concentrations, groundwater advection accounted for 4% of the average PCB loading observed within the TIP between 1993 and 1996 (QEA 1998), indicating that groundwater advection is not likely a significant source of water column PCBs.

5.2.2.3 Bioturbation

Bioturbation is a term that describes the transport of pore waters and sediment particles as a result of the activities of benthic organisms such as macroinvertebrates. Benthic macroinvertebrates process sediment during burrowing, sediment ingestion, sediment defecation, and tube building. The net result of bioturbation is the vertical movement of sediment particles and pore water that enhances the exchange of contaminants to and across the interface between the sediments and overlying water column. The importance of bioturbation to sediment/water PCB flux depends on the structure and abundance of the benthic invertebrate community.

A recent benthic macroinvertebrate survey of the Upper Hudson River found between 10,000 and 35,000 individuals per square meter in the surface sediments (Exponent 1998b). Although the community structure depended on substrate and vegetation type, Chironomid midges were generally the most abundant taxa. Chironomids construct burrows in the surface sediments from which they feed. The type of burrow and depth of burrowing activity is species and substrate specific. Based upon knowledge of the structure and abundance of the benthic macroinvertebrate community, it is likely that bioturbation has contributed to the sediment/water exchange of PCBs with the Upper Hudson River.

5.2.2.4 Seasonality and Source of Observed PCB Loadings in the TIP

Low flow[4] PCB_{3+} loading observed between the Fort Edward station at the headwaters of the TIP and the TID appears to follow a distinct seasonal pattern (Figures 5-16 and 5-17). The lowest loads generally occur during the winter low-flow periods and maximum daily loads

[4]For this discussion, low flow is defined as less than 10,000 cfs at Fort Edward.

generally occur following spring high flow periods. Although a sampling bias was discovered for the sampling station (TID-west) used to calculate these loadings (QEA 1998), simultaneous monitoring from this station and an unbiased station in 1998 indicates there is a seasonal loading pattern (Figure 5-17). These data indicate that seasonally-varying low-flow sediment-water exchange, attributable to a number of possible mechanisms, is a characteristic of the Upper Hudson River.

PCB congener patterns were used to evaluate potential sources of TIP water column PCB loading. Congener patterns are typically examined on a weight percent basis, in which each PCB congener's mass is represented as a percent of the total PCB in the sample. By plotting weight percent against the ordinal congener number (which increases with chlorination level), a "signature" or "chemical fingerprint" of the PCB composition is created for a given sample. Congener patterns have been useful for evaluation of Upper Hudson River sediment PCB sources because deeper sediments typically contain a higher weight percent of the less chlorinated congeners than surface sediments (due to more extensive dechlorination). The use of PCB congener patterns from water column loading data in conjunction with sediment congener patterns can thus be used to examine potential sediment PCB sources. In this manner, the composition of the 1998 summer (June-August) low-flow PCB loadings from the TIP was used to infer the nature of the sediment PCB source. The water column PCB composition was calculated as the difference between water column PCB congener loading at Fort Edward and the unbiased station at the TID (QEA 1998). The source of this loading was assessed by:

1) using the TIP water column PCB load composition to calculate the "required" PCB composition of a particulate-phase sediment source under the assumption of a pore water loading mechanism and equilibrium partitioning between sediments and pore water[5], and
2) comparing the "required" sediment source congener pattern with recent sediment data obtained from different depths within the TIP.

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The sediment source required to produce the PCB congener loadings observed from the TIP in 1998 best matches the surface sediment PCB composition as represented by the 0-2 cm sections of the cores collected from the TIP in 1998 (Figure 5-18a). In contrast, the source of the TIP load does not appear to match the composition of PCBs found at depths greater than 23 cm (Figure 5-18b) because the deeper sediments contain a much higher fraction of the mono- and dichlorinated PCB congeners than the observed TIP water column loading. This is evident in Figure 5-18b, in which the primary mono- and di- congeners (i.e., DB-1 peaks[6] #2 and #5) account for approximately 65% of the TIP deep sediment PCBs, but only 35% of the TIP water column PCB loading. This analysis indicates that the source of the TIP PCB load is surface sediments as expressed through either a direct pore water exchange process (e.g., diffusion, bioturbation, or groundwater advection) or surface sediment resuspension and subsequent PCB desorption. Regardless of the mechanism, the PCB loadings observed from the TIP appear to be consistent with partitioning from surface sediment (0-2 cm) to the water column.

5.2.3 PCB Exchange between Water and Air

PCB exchange across the air/water interface occurs *via* the process of volatilization. The rate of mass transfer by volatilization is a function of the surface area of the air/water interface, the concentration difference between the water and air, and a mass transfer coefficient that depends on chemical-specific and system-specific properties.

The equilibrium distribution of a chemical between air and water is described by the chemical's Henry's Law constant. Chemicals with high Henry's constants are considered volatile, and will preferentially migrate to the air, whereas volatilization is typically not an important process for chemicals with low Henry's constants. Volatilization is a function of temperature, as Henry's constant increases with increasing temperature. PCB Henry's constants vary among the different PCB congeners, with a trend of decreasing Henry's constant with increasing level of chlorination (Burkhardt *et al.* 1985). Measured values for PCB congener

[5] Equilibrium partition coefficients were derived from USEPA water column particulate and aqueous phase PCB data and were adjusted for temperature effects (USEPA, 1997).
[6] DB-1 Peaks are groupings of 1-3 PCB congeners, with chlorine level generally increasing with increasing DB-1 Peak #.

Henry's constants fall in the range of low volatility (Murphy *et al.* 1987). Therefore, volatilization is not expected to be a significant mass loss mechanism for PCBs in the Upper Hudson River. However, in regions of the river with a shallow depth and large surface area, volatilization may become important when the residence time is great (i.e., periods of low flow). Using average values for the PCB Henry's constant and typical flow conditions (average water velocity and depth) within the Thompson Island Pool, the average dissolved phase mass loss within TIP by volatilization is estimated to be on the order of 5%.

Waterfalls and dams in rivers enhance the process of volatilization by causing an enhanced mixing environment at the base of the falling water. Entrained air bubbles and water droplets have a high surface area to volume ratio, and result in a more rapid mass transfer than the surface exchange process described earlier. The rate of volatilization at waterfalls and dams increases with increasing energy dissipation. This enhanced mixing depends on the height of the dam or waterfall (McLachlan *et al.* 1990), as a larger elevation drop will result in a higher mixing intensity. The volatilization loss of PCBs across dams in the Upper Hudson River was estimated to be less than 1% (Section 4.3.7, Volume 2), primarily due to the low dam heights (Figure 2-3).

5.2.4 PCB Bioaccumulation

Bioaccumulation involves the uptake of water- and sediment-borne PCBs by invertebrates and the transfer of those PCBs through the food web *via* predation. The sources of exposure are PCBs dissolved in water and PCBs associated with particulate organic material. At the base of the food web, benthic macroinvertebrates (BMI) accumulate PCBs from surface sediment particles. Phytophilous macroinvertebrates (PMI) accumulate PCBs from particulate matter in contact with the water column, which includes periphyton, phytoplankton and nonliving organic material.

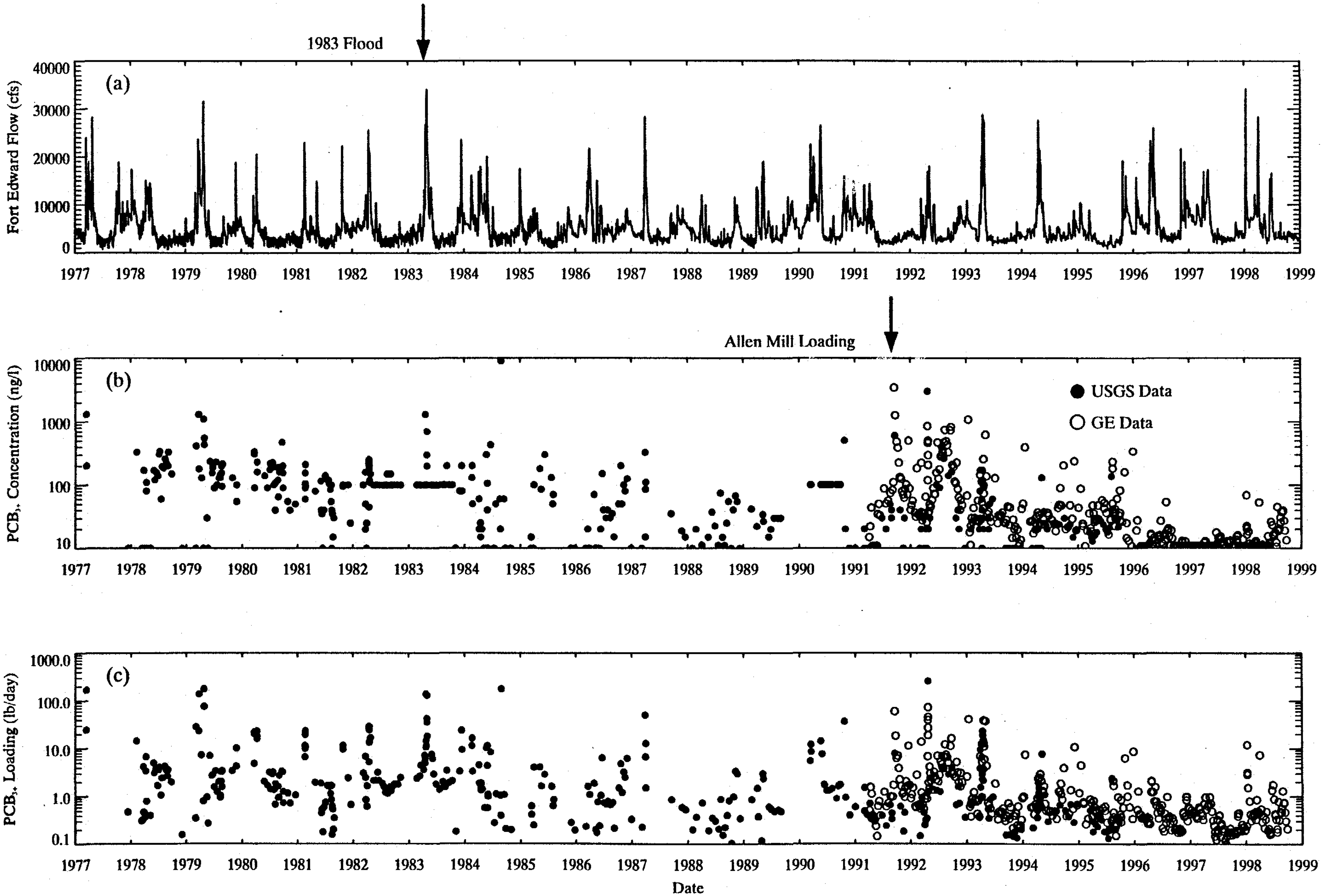
The Upper Hudson River food web contains hundreds of species of invertebrates and more than 30 species of fish interrelated by complex feeding relationships. In spite of the complexity of individual feeding behaviors, the biota and their energy sources fall into four trophic levels (Figure 5-19). Trophic Level 1 (TL1) includes water column and surface sediment particulate matter. The invertebrate fauna of the Upper Hudson River (TL2), dominated by chironomids and oligochaetes, is classified into two functional groups according to their source of organic material: BMI and PMI. Forage fish (TL3) in the Upper Hudson River are generally opportunistic feeders and consume a mixture of BMI and PMI. Predatory fish (TL4) are also generally opportunistic in their feeding behavior, consuming a mixture of the available forage fish species. Because the fish generally fall into two trophic levels and are generally opportunistic foragers, trends that are representative of the fish in general can be monitored in just a few species. Therefore, the extensive monitoring database of PCB levels in brown bullhead (TL3), pumpkinseed (TL3), and largemouth bass (TL4), collected since the late 1970's can be used for developing an understanding of PCB dynamics in the Upper Hudson River.

Fish accumulate most of their PCBs by consuming their prey (Figure 5-20); dissolved PCBs in the water column, taken up by fish during respiration, represent a relatively minor source. Growth dilution and elimination across the gill surface are the primary mechanisms reducing PCB levels in fish.

Fish lipid content controls the PCB elimination rate because PCBs are stored principally in lipids. Lipid contents in largemouth bass from the Upper Hudson River have varied more than ten-fold since 1977. The reasons for these changes in lipid content are not known. Lipids are the primary energy storage compartment in many species of fish, and lipid content can vary depending on food availability (Weatherly and Gill 1987). The observed changes in lipid content in Upper Hudson River fish could be due to changes in the composition of the fish community, possibly resulting from the institution of the fishing ban in the late 1970's. Whatever the reason, the variation in lipid content and the resultant variation in PCB excretion rate complicates the interpretation of the spatial and temporal trends in fish PCB data. Using lipid-normalized data can compensate for this variation. However, lipid-normalizing data does not completely eliminate the effects of extreme variation in lipid content such as that observed in the Upper Hudson River largemouth bass in 1991 (Section 5.1.3).

PCB concentrations in invertebrates respond relatively quickly to changes in their exposure levels. In contrast, fish integrate exposure levels over a relatively long period. For example, the half-life of PCBs in the Upper Hudson River predatory fish is on the order of a few years (Figure 5-12). This means that predators' PCB body burden is slow to respond to the changes in PCB levels in their prey. Thus, fish are not expected to be at steady state with respect to their exposure sources if the exposure levels fluctuate widely. This is an important consideration in interpreting temporal trends in Upper Hudson River fish, because in the past 20 years PCB levels in the water and sediment have changed dramatically over both long and short time scales.

The primary determinant of how fish PCB levels change with exposure levels is the relative dose of sediment and water column PCBs. This is controlled by the relative contributions of BMI and PMI in the diets of the forage fish community, the relative PCB concentrations on water column and sediment particulate material, and the relative bioavailability of those PCBs. The sources of PCBs to the food web are discussed in Section 6.



Notes: Total PCB detection limit was used for plotting and load calculations for non-detects. Concentration outlier in 1983 and loading outlier in 1984 removed. Tick marks on date axis correspond to January 1st.

Figure 5-1. Temporal trends in (a) flow, (b) PCB_{3+} concentration, and (c) PCB_{3+} loading at Fort Edward.

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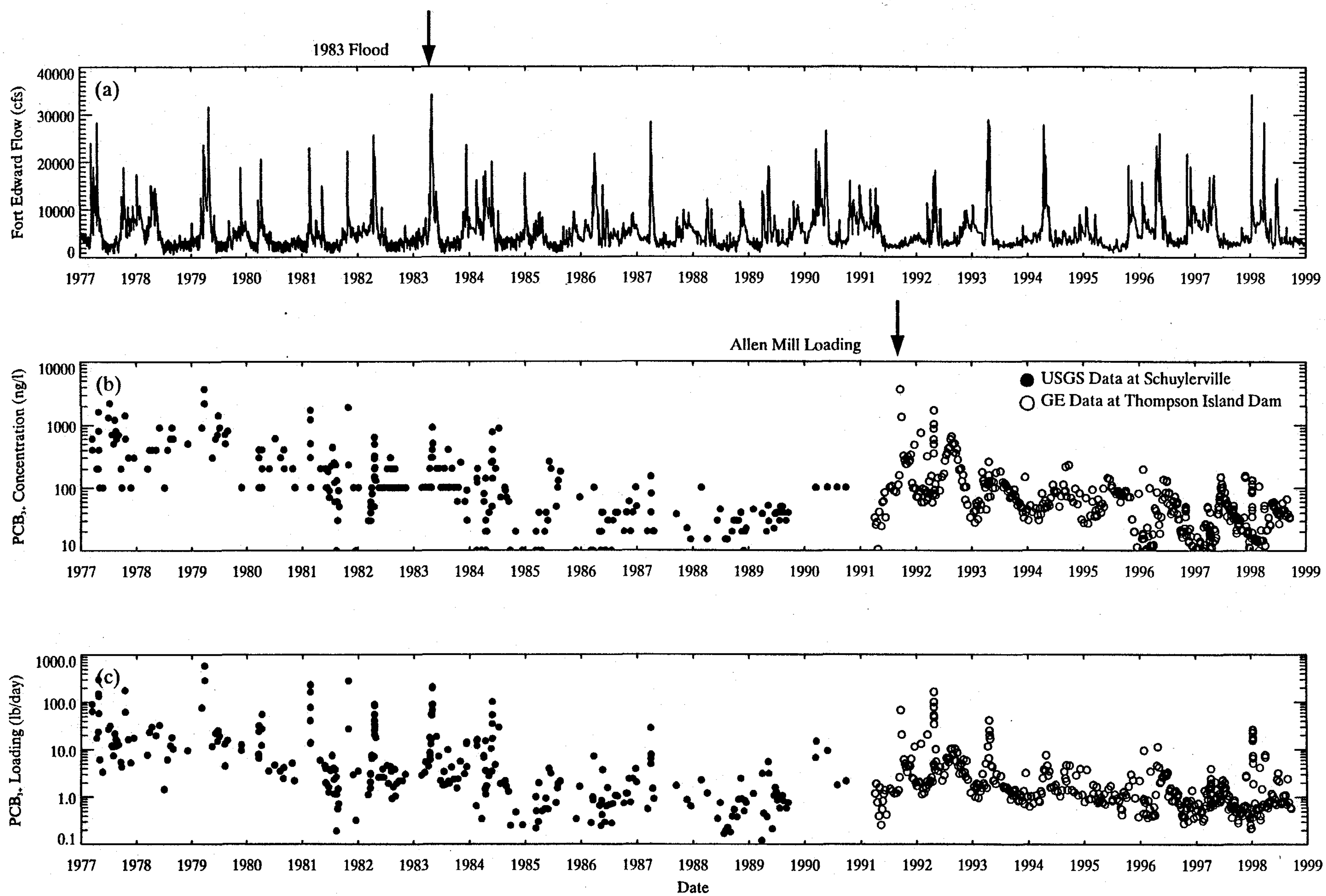
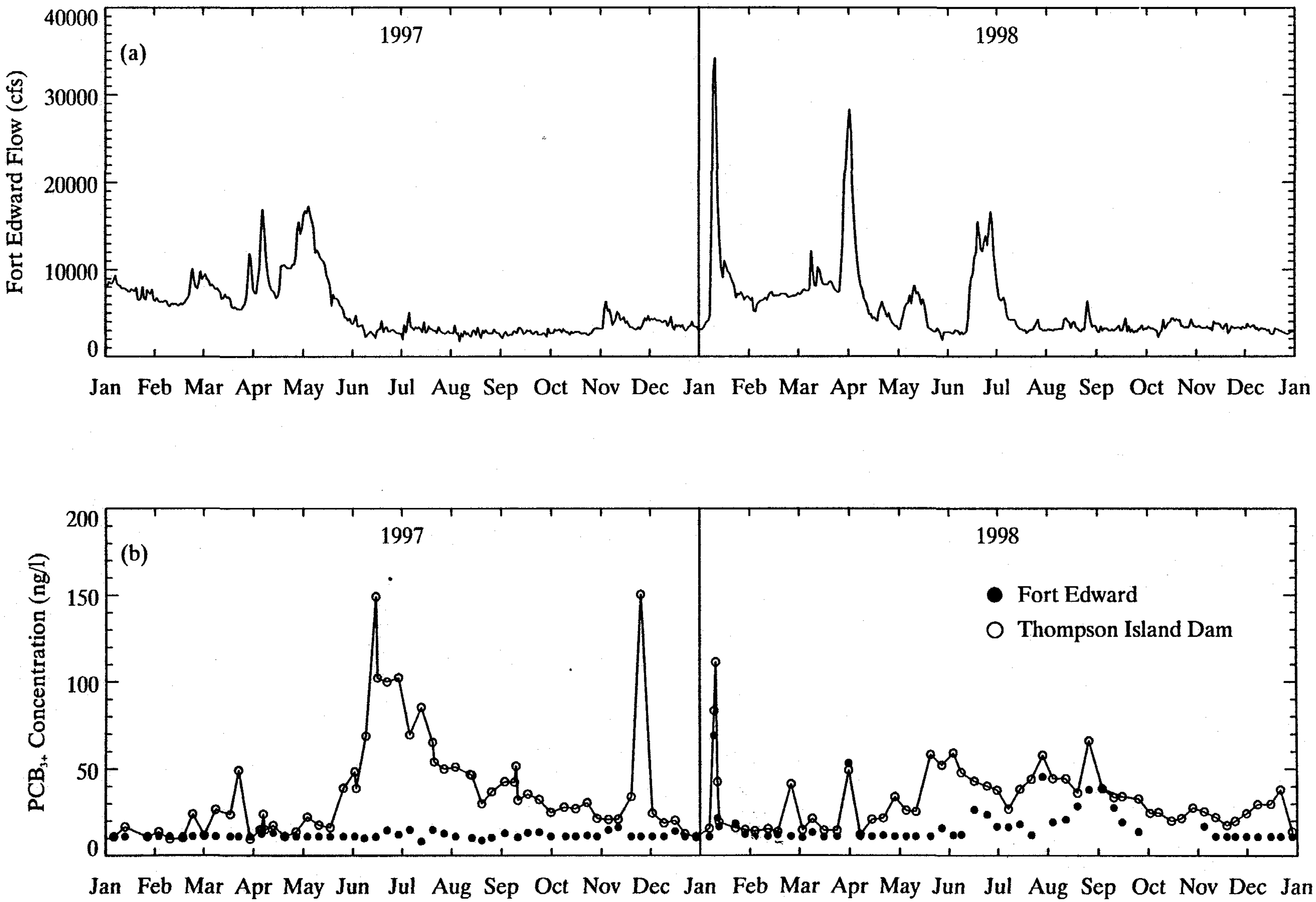


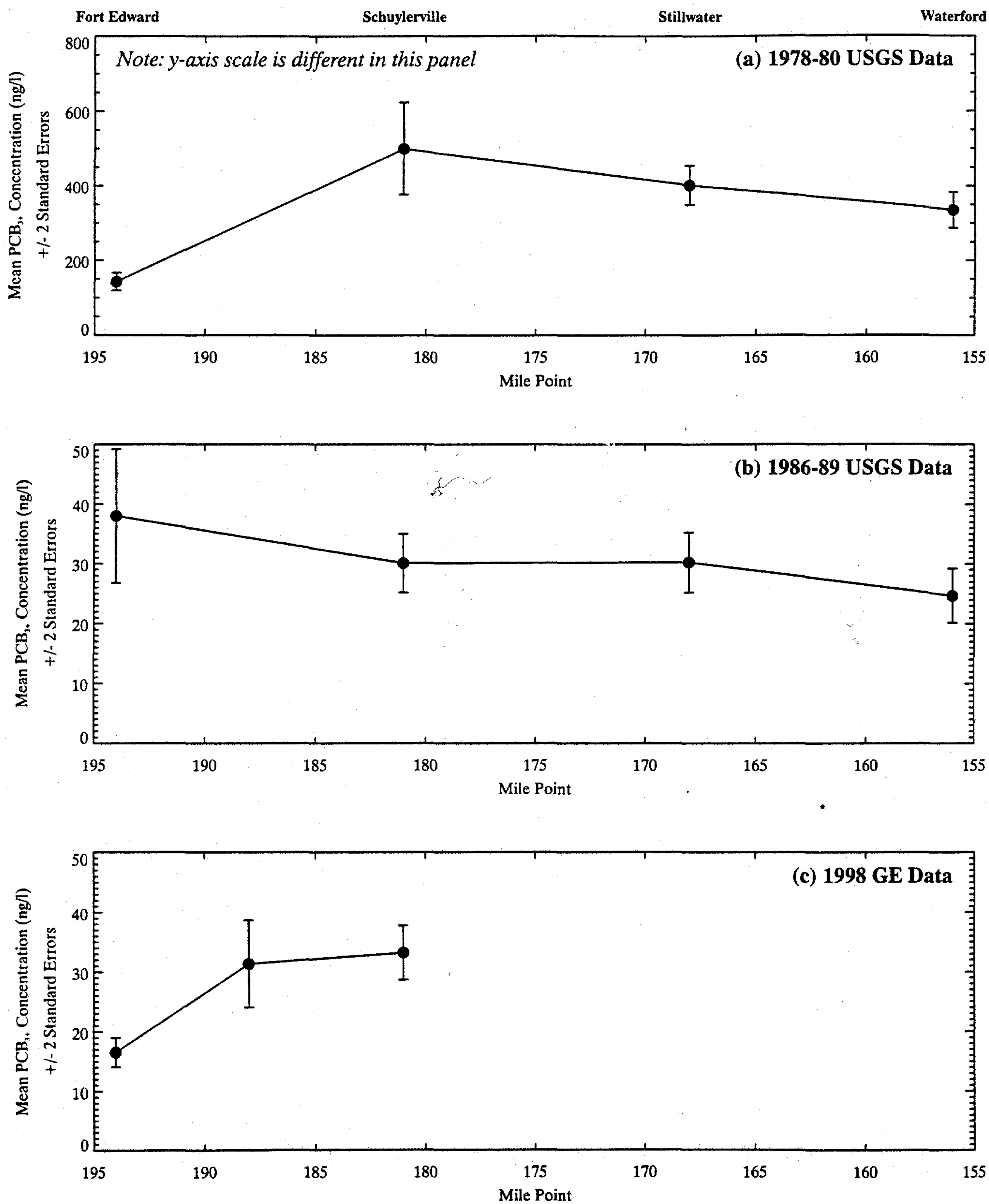
Notes: Total PCB detection limit was used for plotting and load calculations for non-detects. Tick marks on date axis correspond to January 1st.

Figure 5-2. Temporal trends in (a) flow, (b) PCB_{3+} concentration, and (c) PCB_{3+} loading at Thompson Island Dam and Schuylerville.



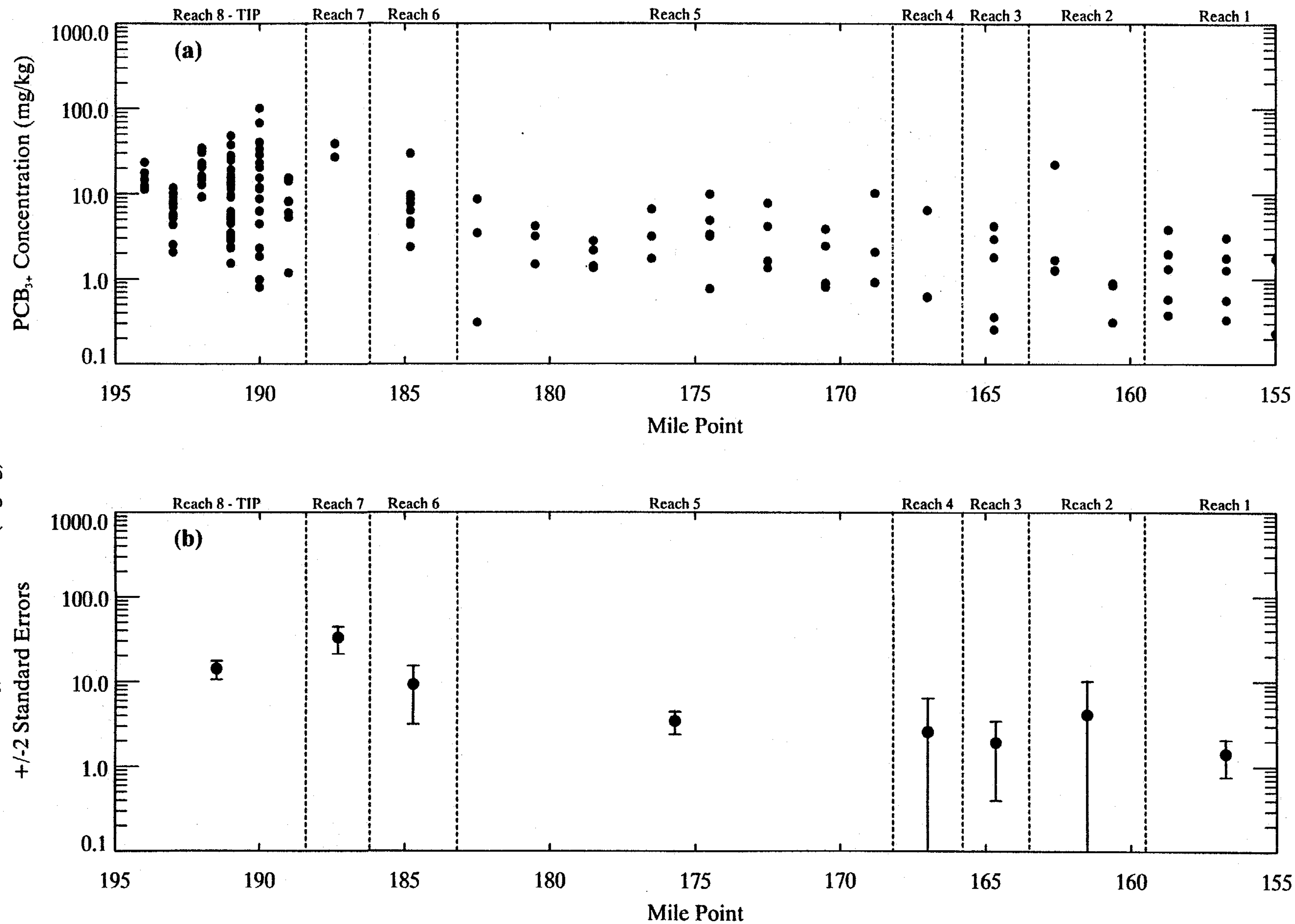
Notes: Non-detects plotted at detection limit. Data are from GE Remnant Monitoring Program; TID data are from biased TID-WEST station.

Figure 5-3. 1997-98 temporal trend in (a) flow, and (b) PCB$_{3+}$ concentration at Fort Edward and Thompson Island Dam.



Notes: Non-detects plotted at detection limit; low flow defined as less than 10,000 cfs at Fort Edward.

Figure 5-4. Spatial profile of Upper Hudson River low flow average PCB_{3+} concentrations in (a) 1978-80, (b) 1986-89, and (c) 1998.



Notes: Mile points are approximate for 1991 data since samples represent composites over a range of river miles. Data are from 1991 GE sediment sampling program.

Figure 5-5. Spatial profiles of (a) 1991 surface sediment (0-5 cm), and (b) 1991 reach averaged surface sediment (0-5 cm) concentrations.

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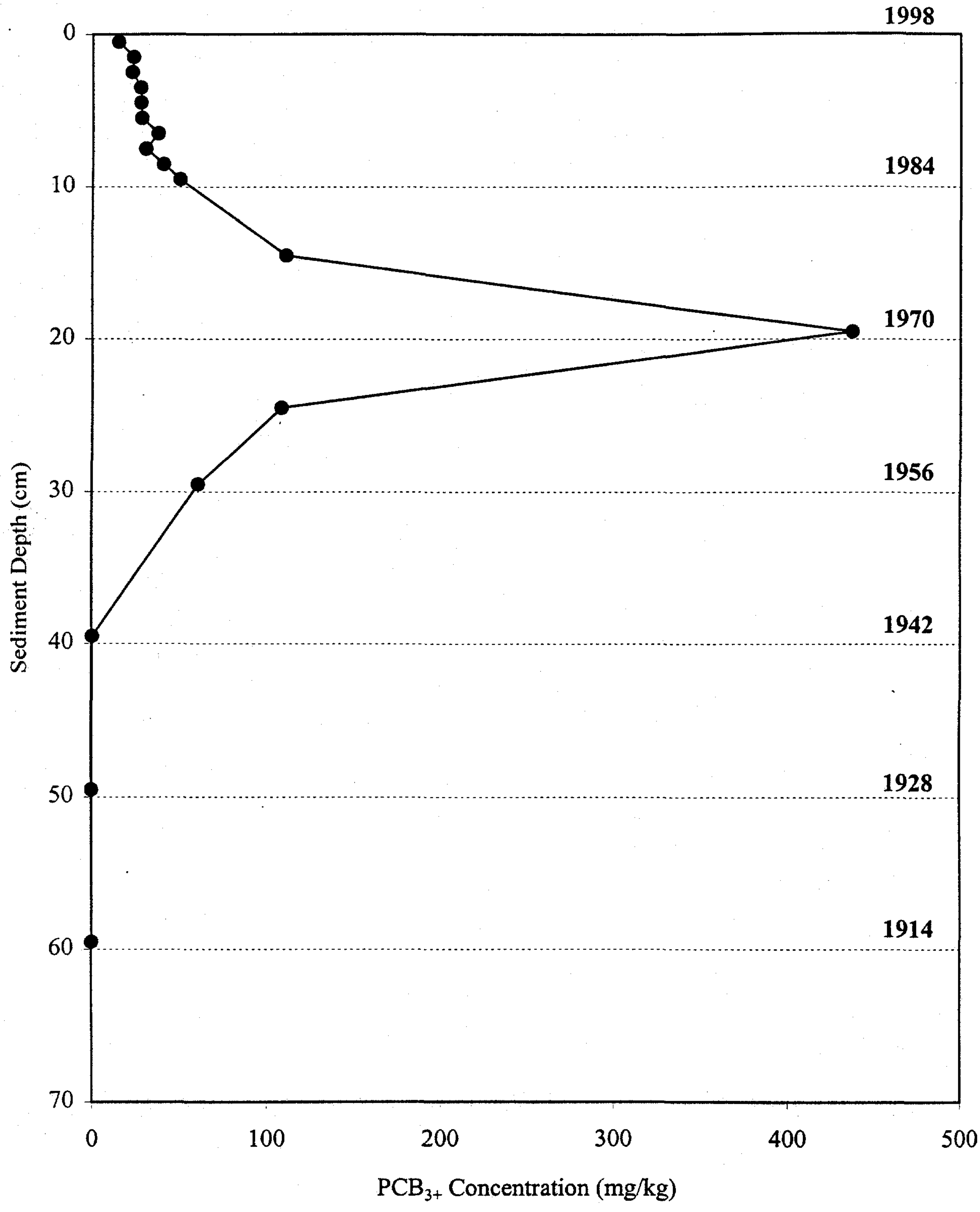
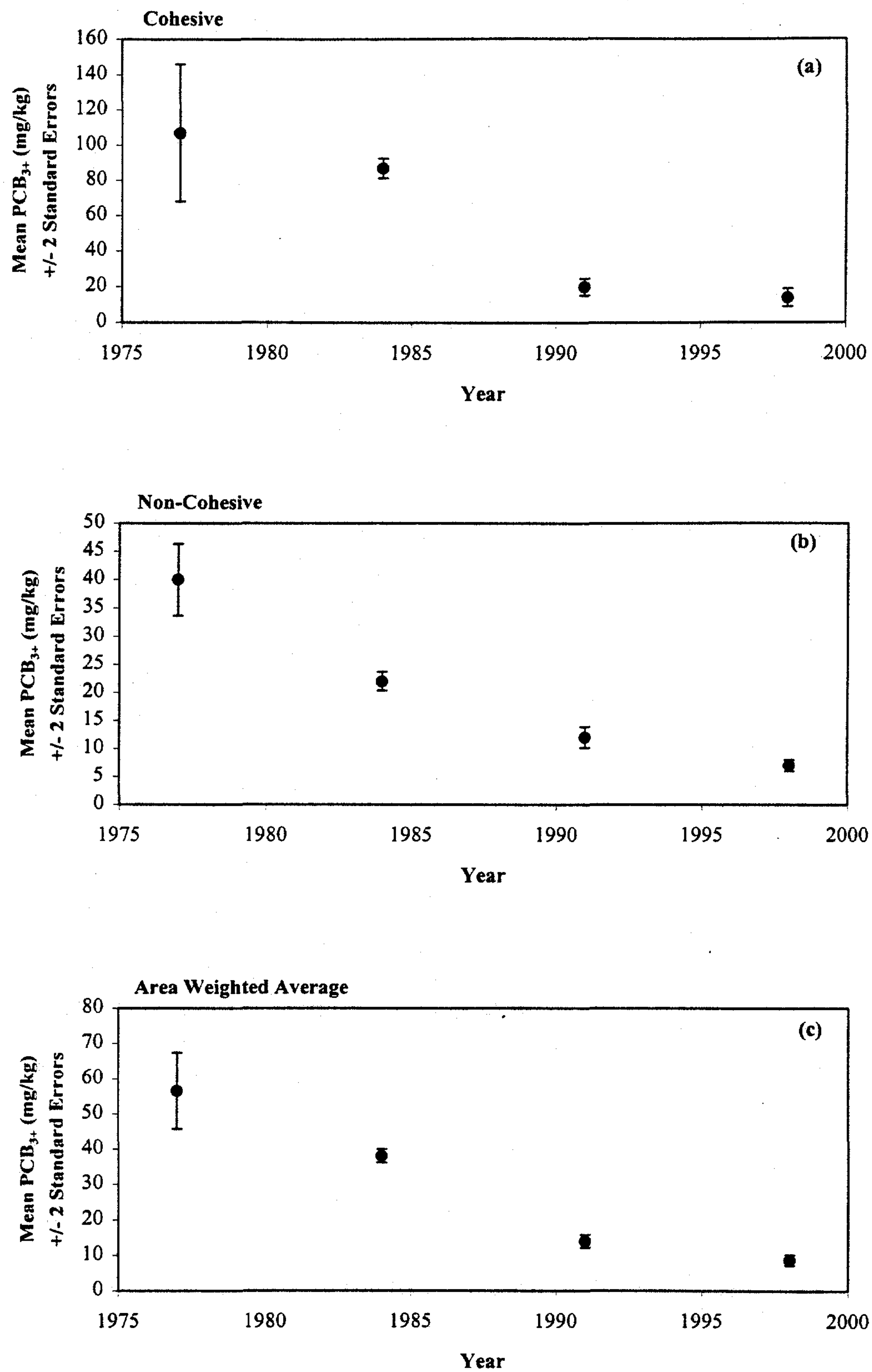


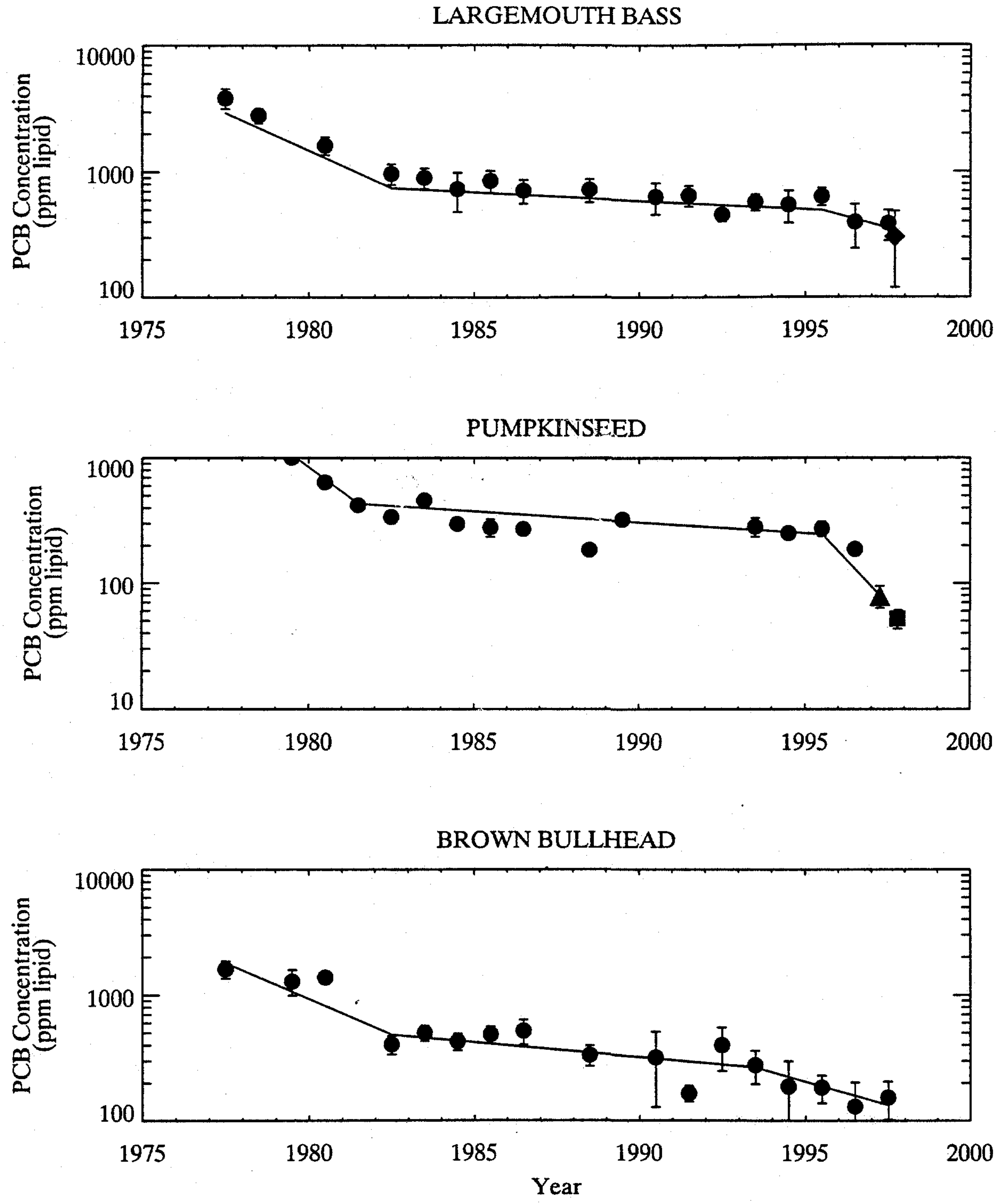
Note: Dates based on assumed 1963 ^{137}Cs peak.

Figure 5-6. PCB_{3+} depth profile for 1998 GE core CS-04.



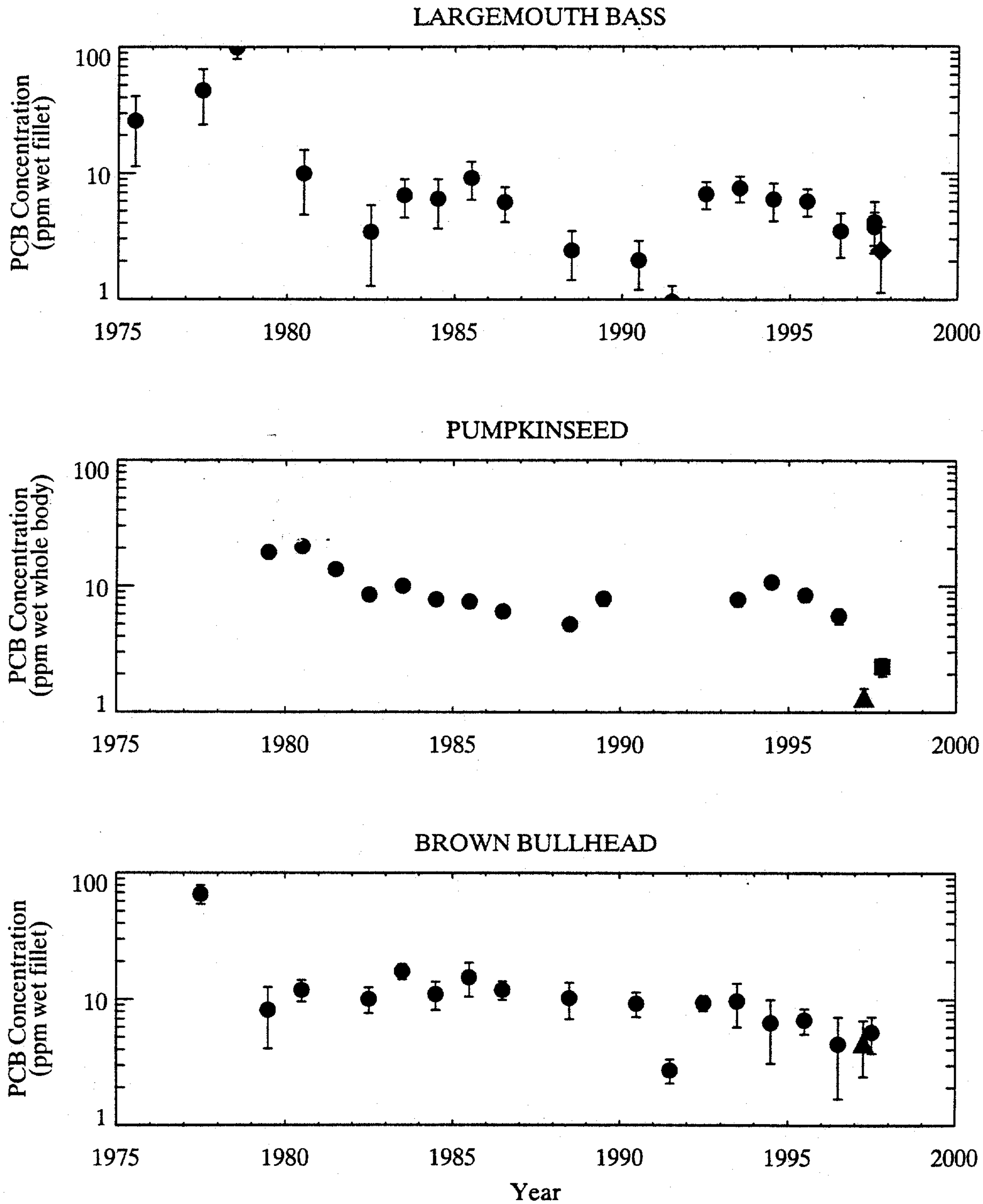
Note: Data averages were developed to represent 0-5 cm layer. However, 1984 average includes surface samples with depths up to 20 cm.

Figure 5-7. Temporal profile of PCB_{3+} concentration in (a) cohesive, (b) non-cohesive, and (c) area weighted average surface sediments within Thompson Island Pool.



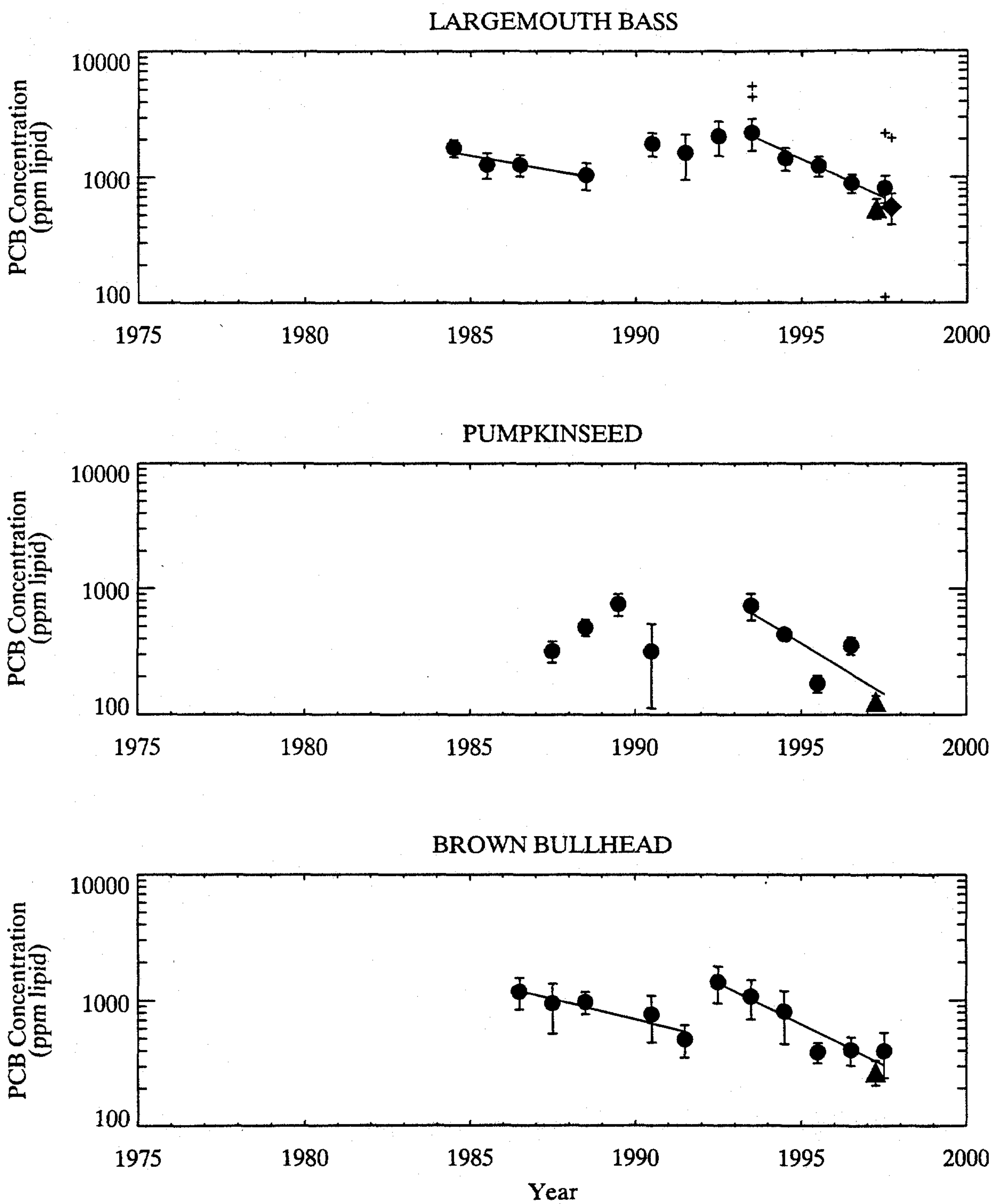
Solid lines represent logarithmic regressions of data.
Data are arithmetic means +/- 2 standard errors.
Circles = NYSDEC, Squares = NYSDOH, Triangles = Exponent, Diamonds = GE.
Crosses indicate values excluded from the annual averages.

Figure 5-8. Annual average PCB concentrations in resident fish of the Upper Hudson River. Lipid normalized, Stillwater Pool.



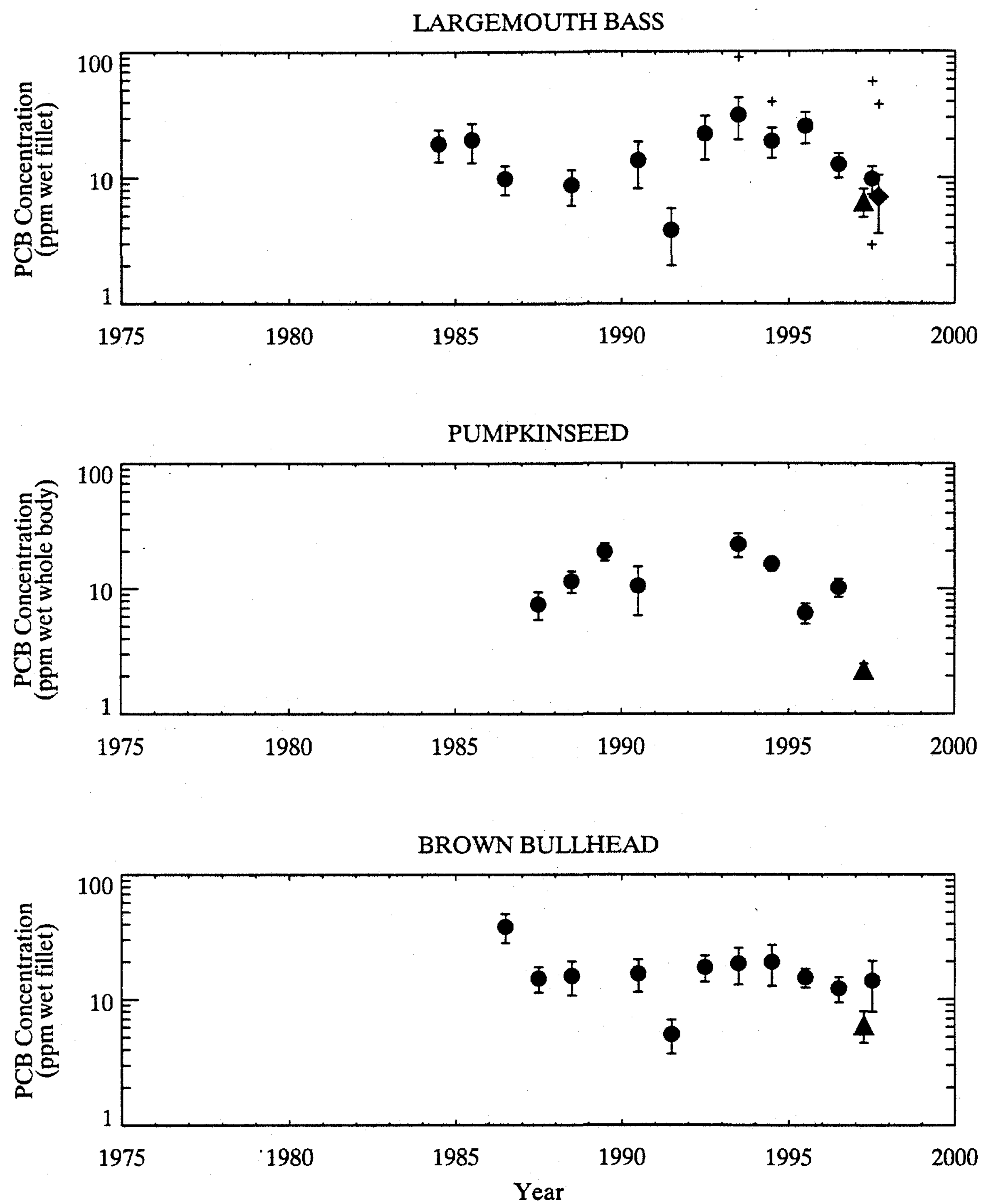
Data are arithmetic means +/- 2 standard errors.
Circles = NYSDEC, Squares = NYSDOH, Triangles = Exponent, Diamonds = GE.

Figure 5-9. Annual average PCB concentrations in resident fish of the Upper Hudson River. Wet-weight basis, Stillwater Pool.



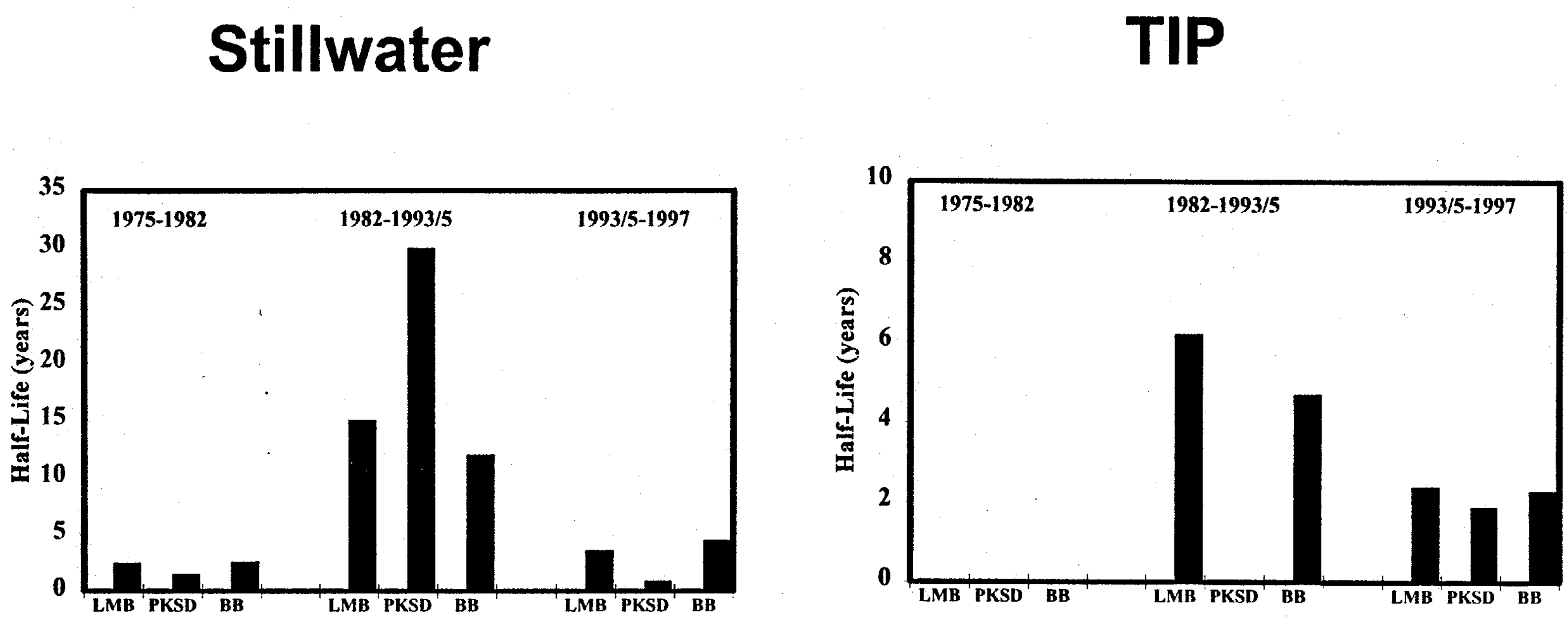
Solid lines represent logarithmic regressions of data.
Data are arithmetic means +/- 2 standard errors.
Circles = NYSDEC, Triangles = Exponent, Diamonds = GE.
Crosses indicate values excluded from the annual averages.
Crosses at top/bottom of axes represent values off of scale.

Figure 5-10. Annual average PCB concentrations in resident fish of the Upper Hudson River. Lipid normalized, Thompson Island Pool.



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

Figure 5-11. Annual average PCB concentrations in resident fish of the Upper Hudson River. Wet-weight basis, Thompson Island Pool.

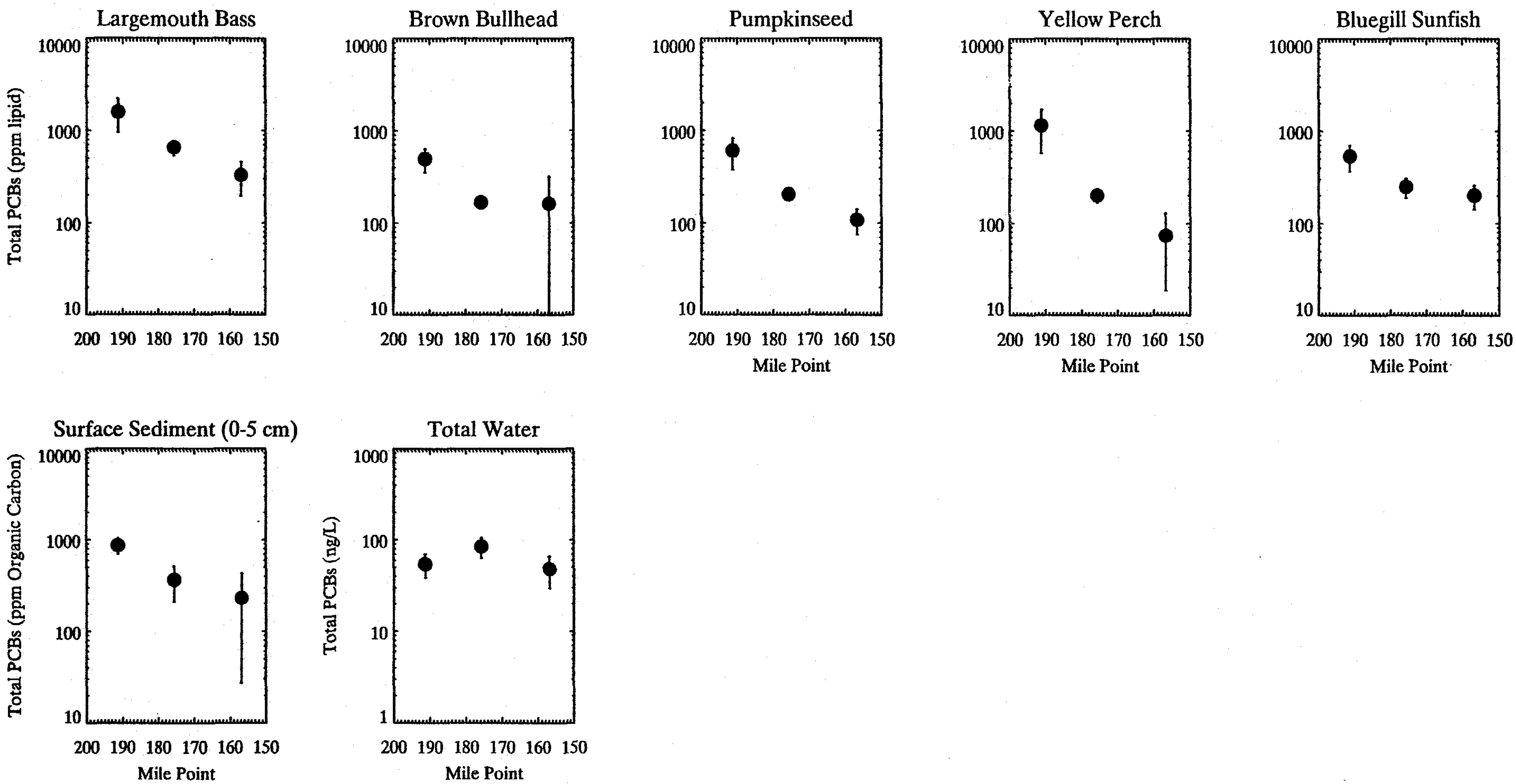


LMB: Largemouth bass

PKSD: Pumpkinseed

BB: Brown bullhead

Figure 5-12. Half-lives computed from trends in lipid-based total PCB concentrations measured in fish from the Upper Hudson River.



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Annual Averages +/-2 Standard Errors
Surface sediment data: GE, 1991; PCB_{3+}, 0-5 cm.
Water data: GE, June-Sept., 1991; PCB_{3+}, whole water.
Fish data: NYSDEC, 1991; Total PCBs;

Figure 5-13. Spatial gradients in PCB concentrations in surface sediments, water, and fish.

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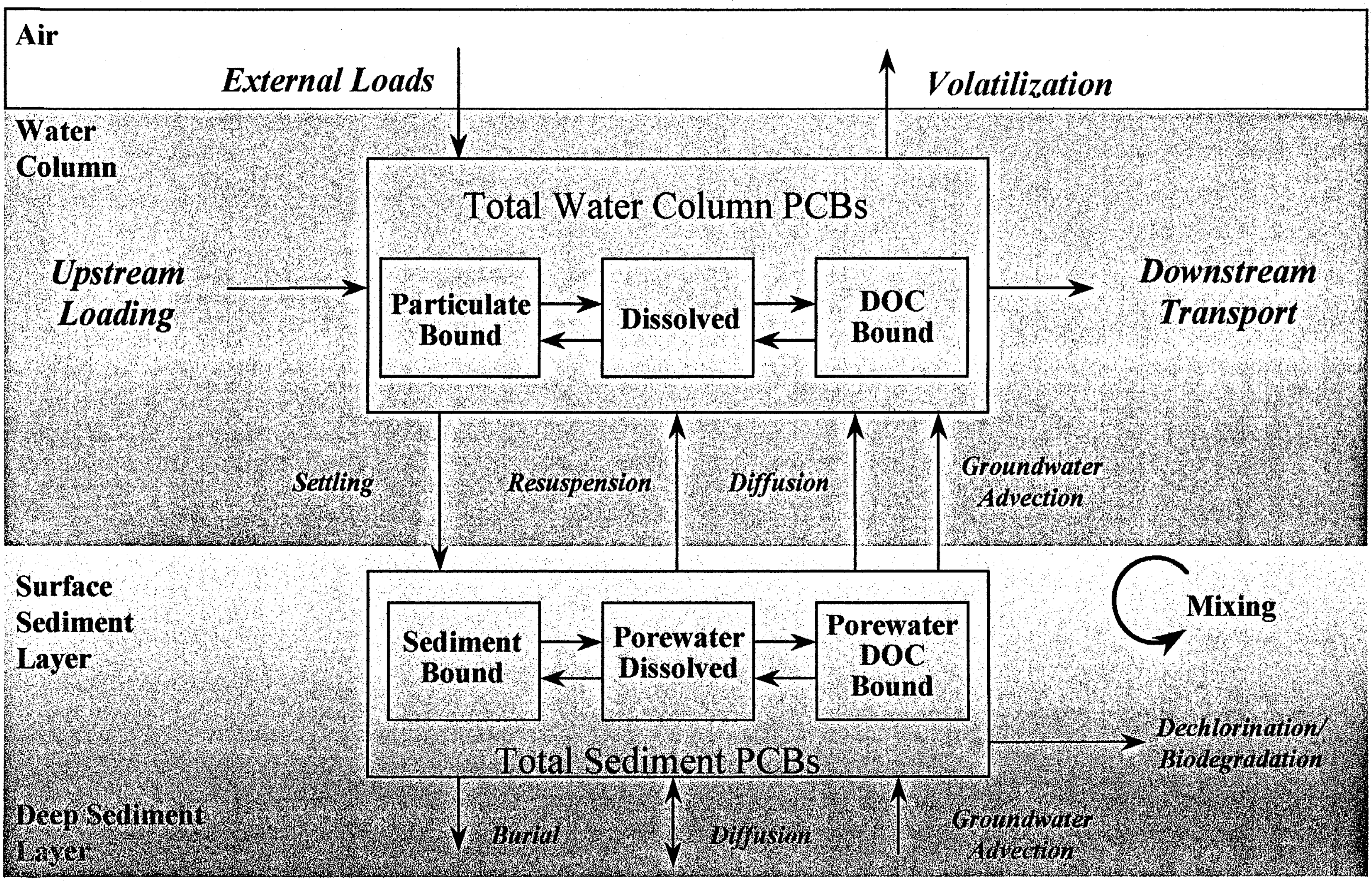

Figure 5-14. Processes affecting PCB fate and transport in the Upper Hudson River.

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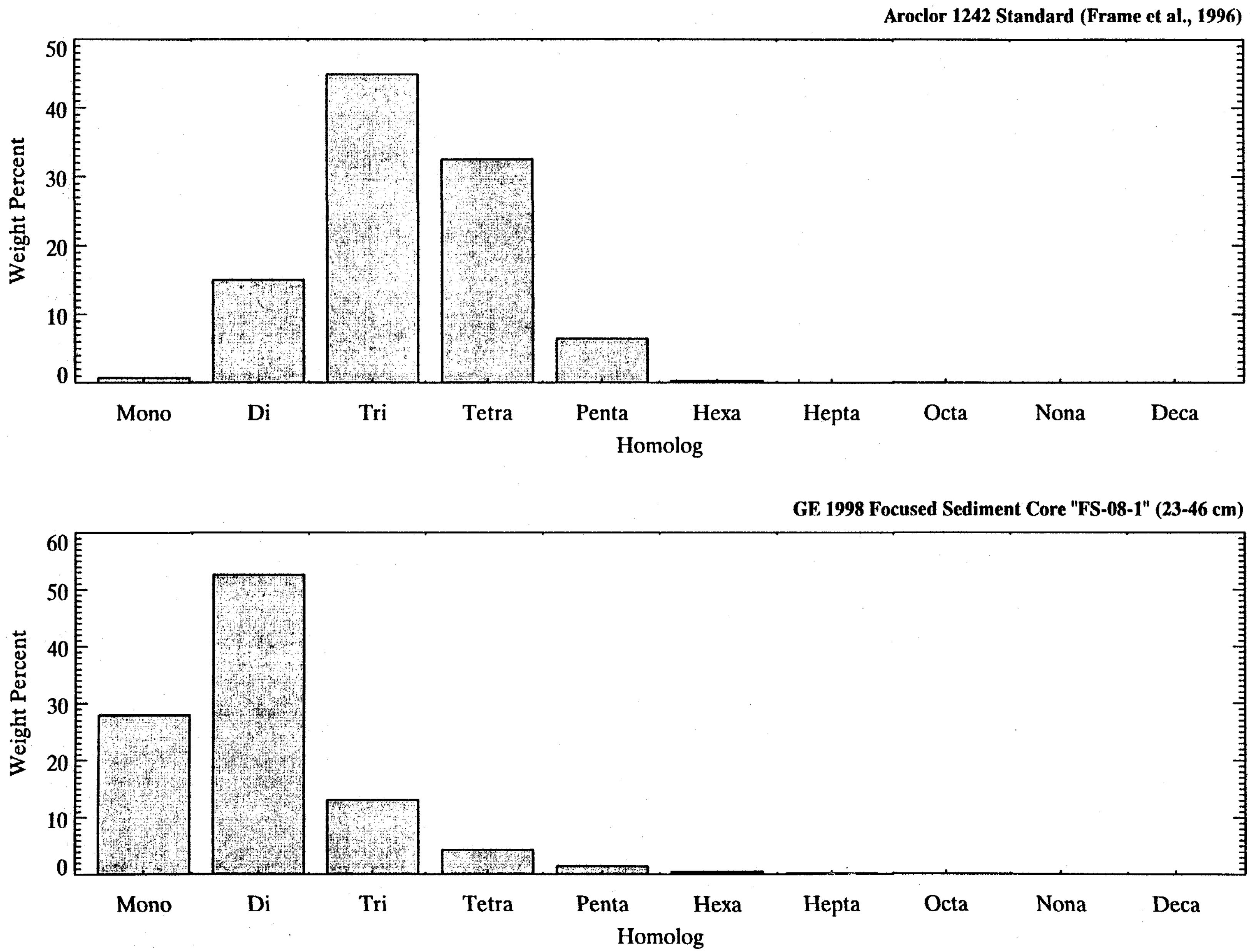

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Figure 5-15. Observed changes in Aroclor 1242 composition as a result of PCB dechlorination within Upper Hudson River sediment.

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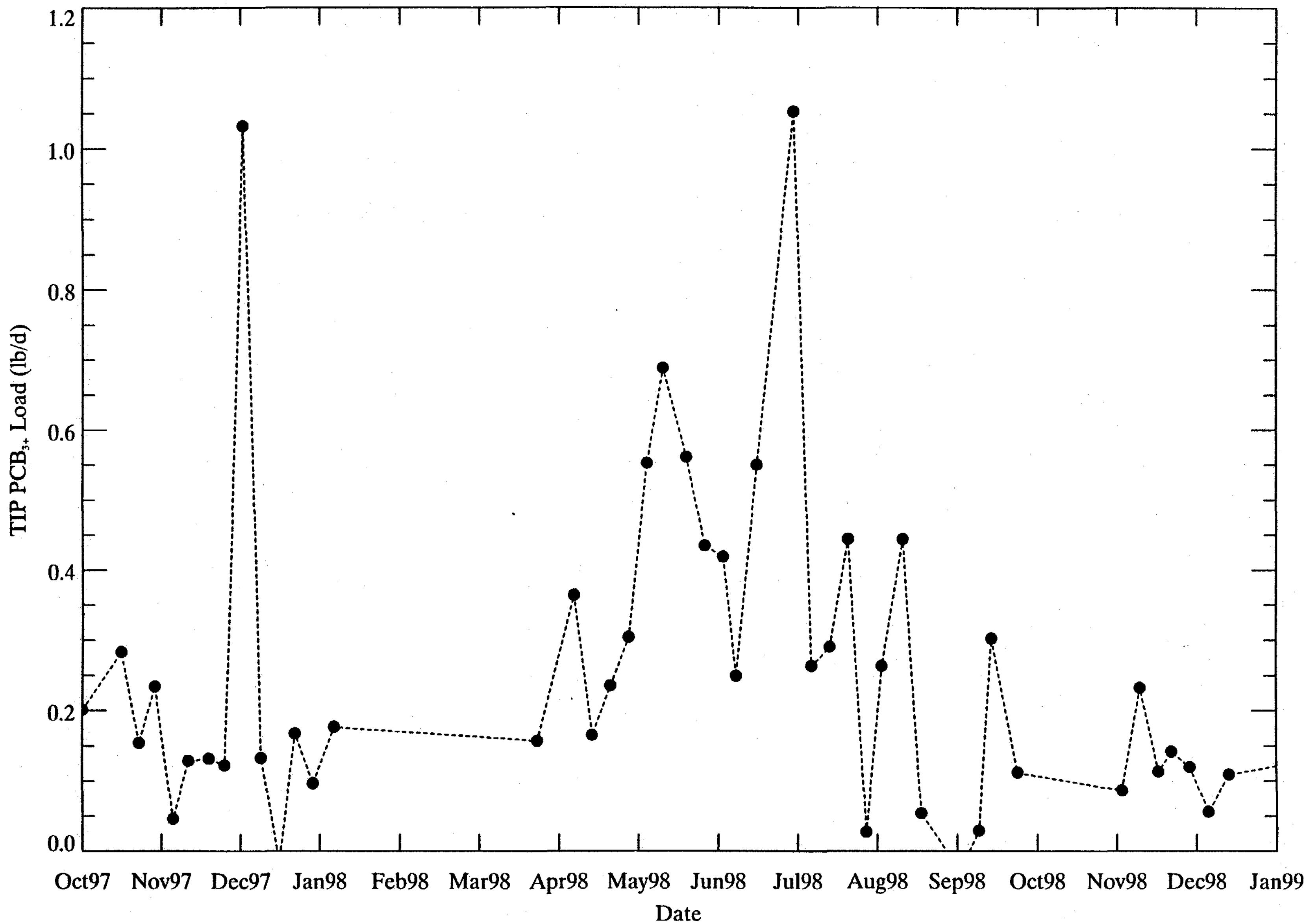
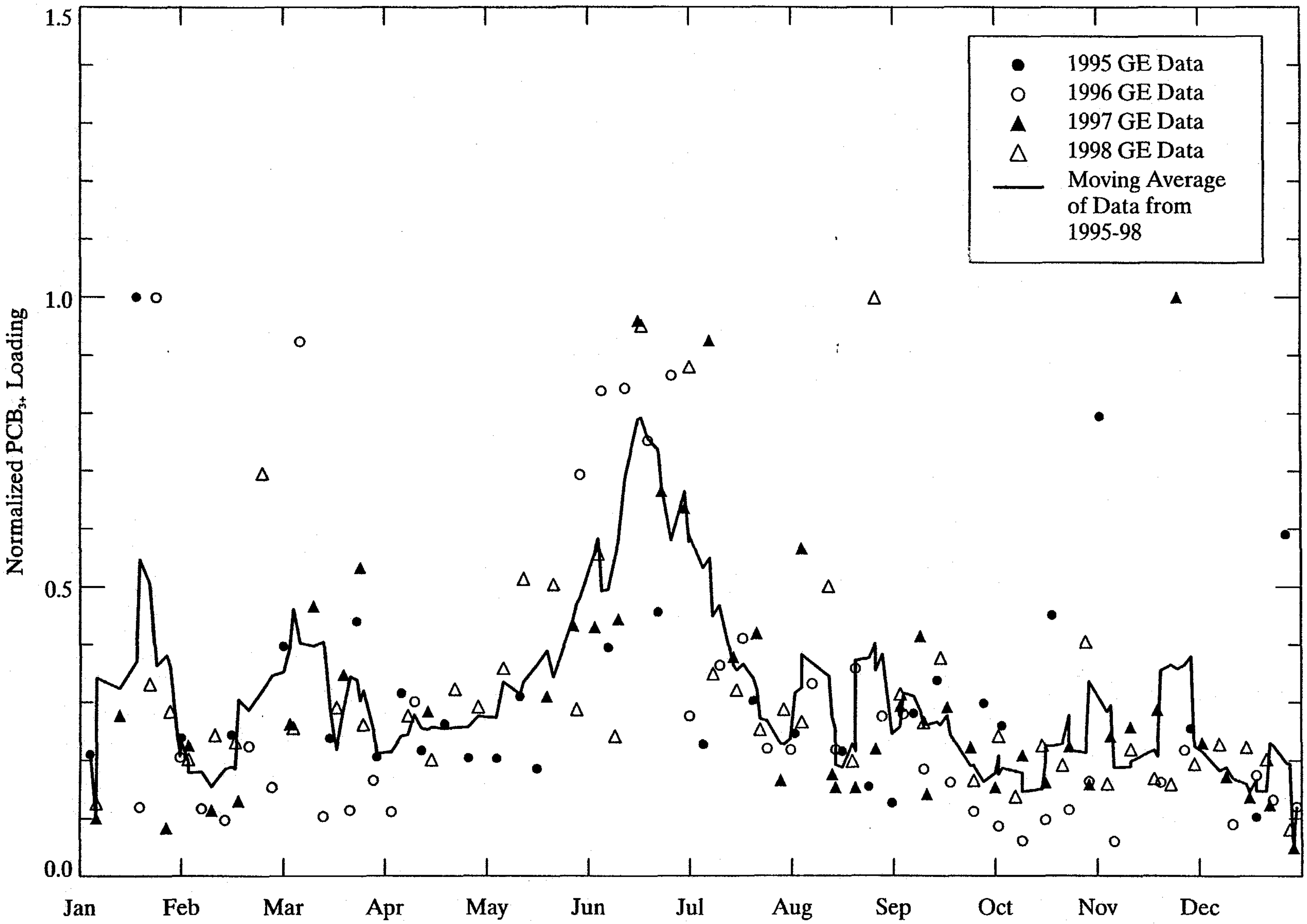


Notes: TIP loading is calculated as the difference between the loadings at Fort Edward and Thompson Island Dam. Low flow (< 10,000 cfs) data only. August, 1998 outlier removed (~3 lb/day).

Figure 5-16. Seasonal trends in PCB_{3+} loading for the Thompson Island Pool region of the Upper Hudson River.



Notes: Loading normalized to the highest observed for a single calendar year. Low flow defined as less than 10,000 cfs at Fort Edward.

Figure 5-17. Seasonal trends in low flow PCB_{3+} loading observed at Thompson Island Dam.

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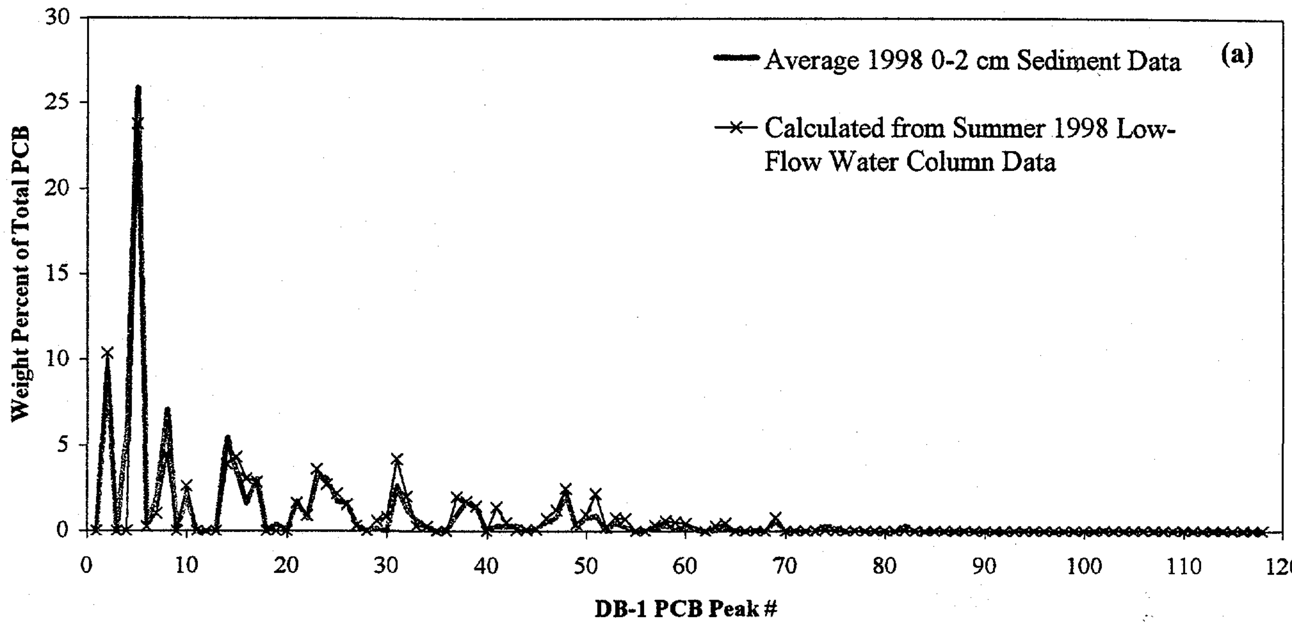

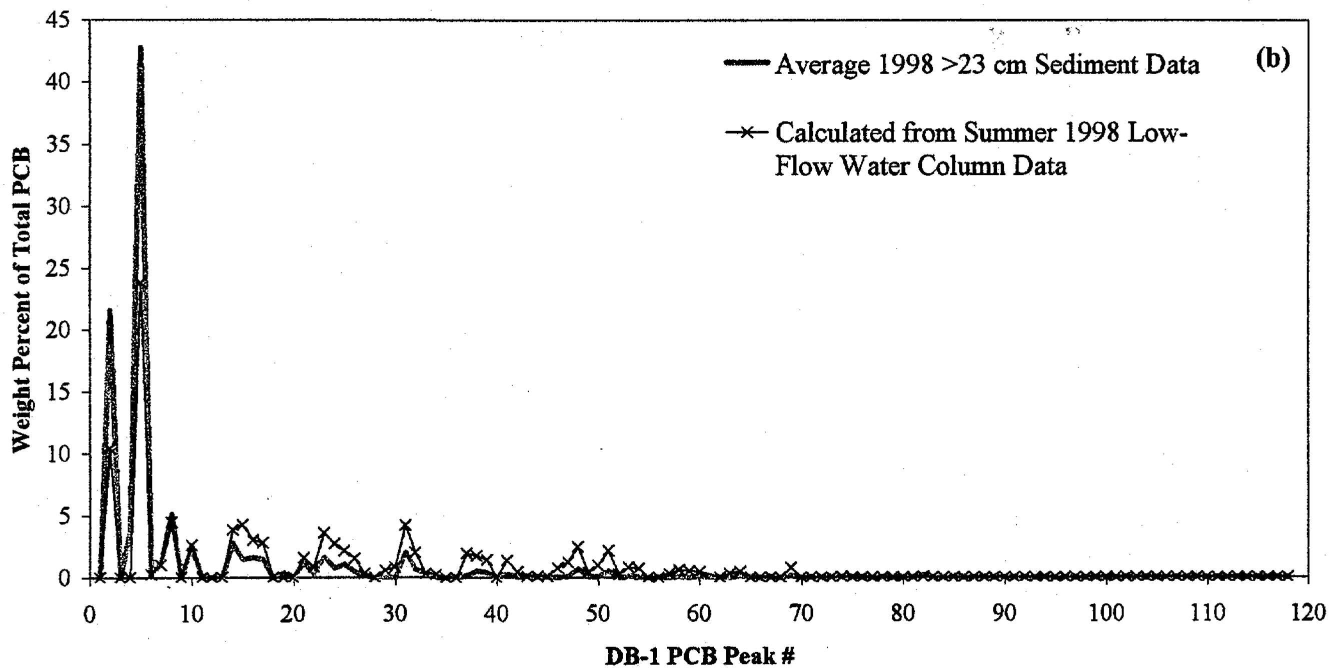

Notes: DB-1 Peaks are groupings of 1-3 PCB congeners, with chlorine level generally increasing with increasing DB-1 Peak #. Sediment data with concentrations less than 5 ppm were excluded from the > 23 cm average.

Figure 5-18. Comparison of the PCB congener composition of the particulate phase sediment source required to produce observed water column PCB loadings across the TIP with (a) surface sediment (0-2 cm) and (b) deep sediment (>23 cm) PCB congener composition.

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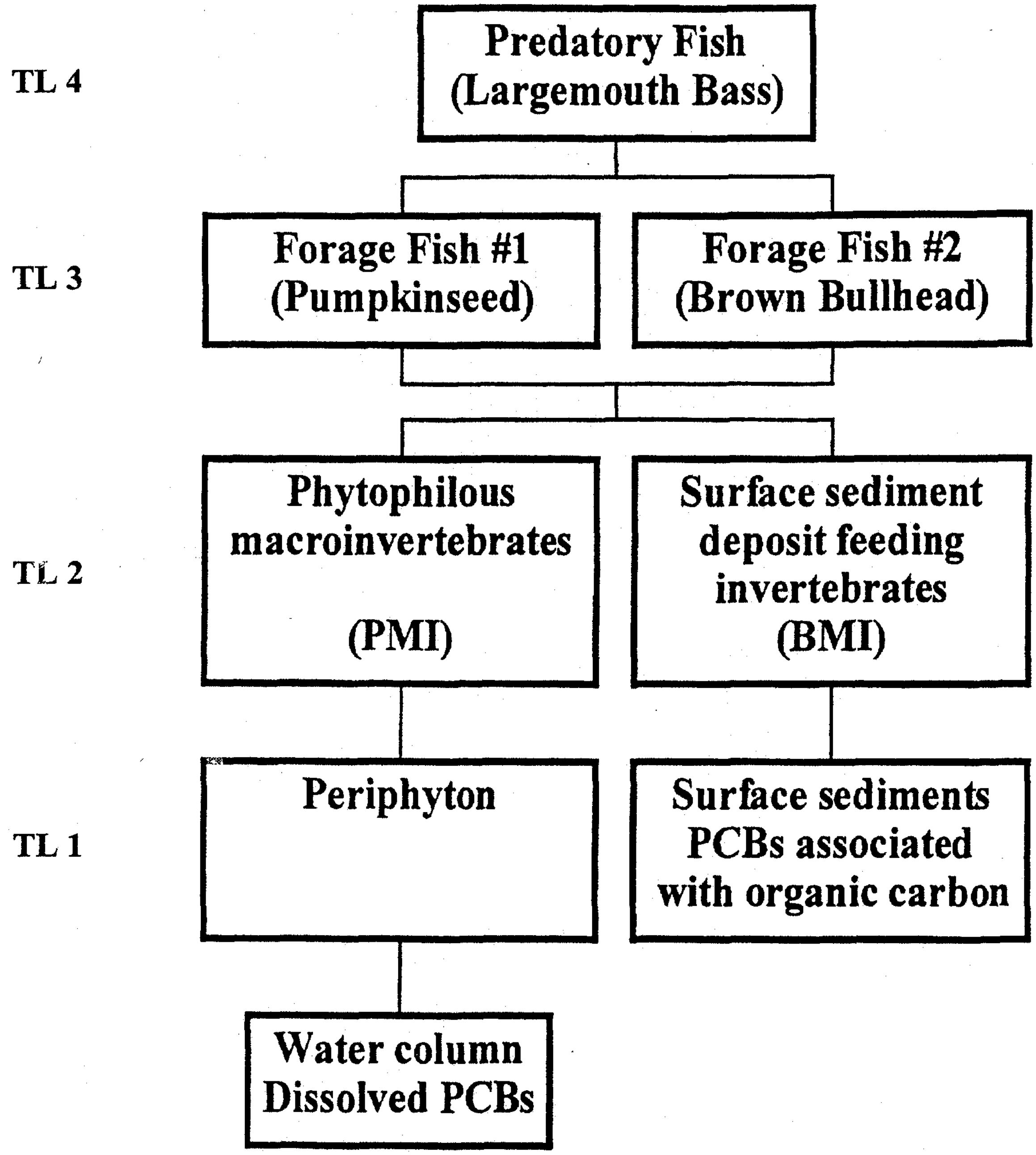

Note: TL = Trophic Level

Figure 5-19. Simplified food web structure of the Upper Hudson River.

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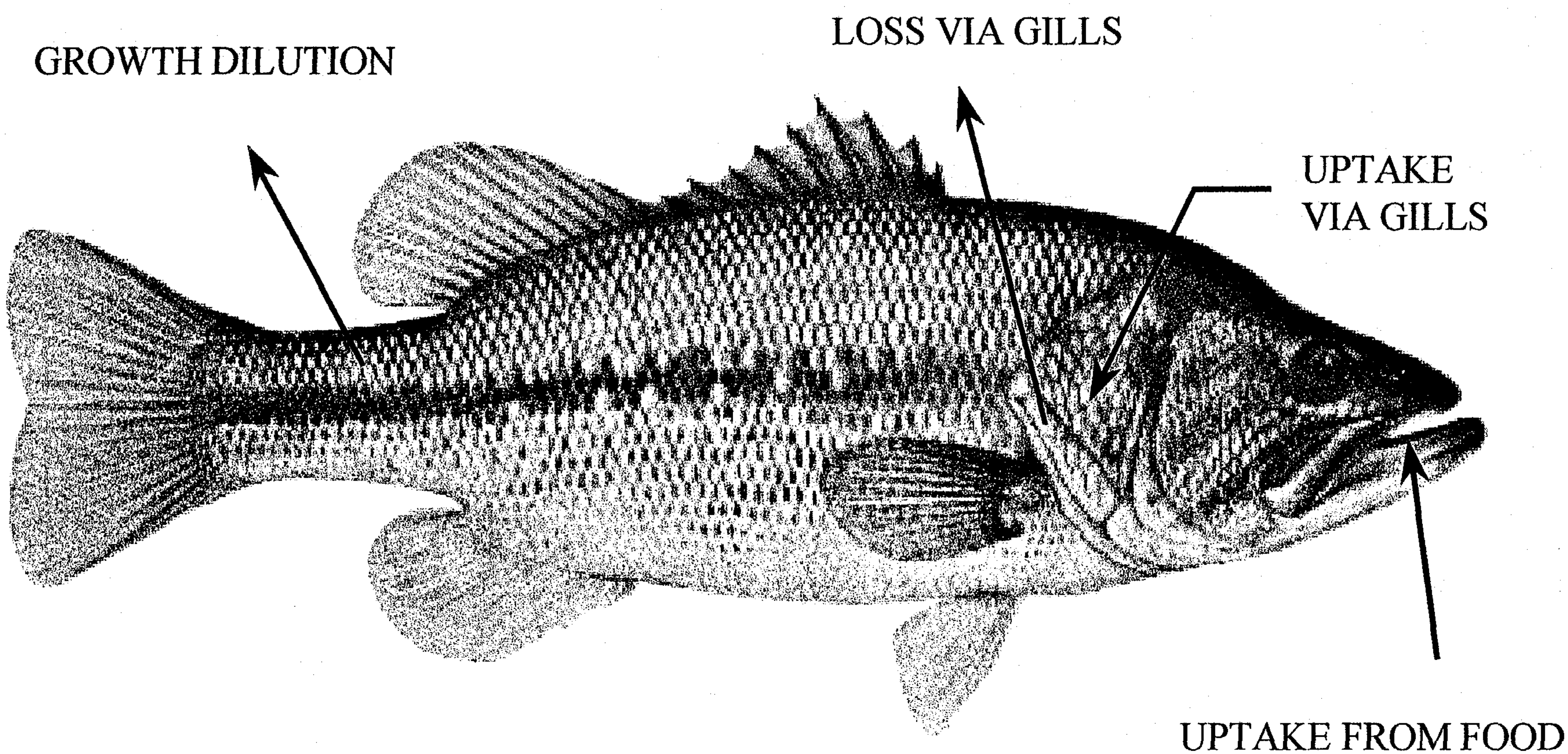

Figure 5-20. Major processes controlling PCB bioaccumulation in fish.

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Quantitative Environmental Analysis, LLC

GENhud 131

May, 1999

Section 6

Sources and Sinks of PCBs in the Upper Hudson River

Quantitative Environmental Analysis, LLC

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SECTION 6
SOURCES AND SINKS OF PCBs IN THE UPPER HUDSON RIVER

The data collected from the Upper Hudson River provide clear evidence that PCBs are not a static feature of the river. Concentrations in the water column, the surface sediments and the fish have declined significantly since the first comprehensive study in the late-1970's. These declines and the spatial patterns of the PCBs are the net result of the host of processes discussed in earlier sections of this report. In many ways, the data for water, sediment and fish are akin to a monthly bank statement that tells the current state of an account, but is not sufficient to interpret changes over time. Just as it is necessary to review the deposits and withdrawals noted in many months of statements to begin to understand the account, it is necessary to review the various sources and sinks of PCBs to understand the temporal and spatial patterns of PCBs in the Upper Hudson River.

For example, lack of a change in PCB concentration may indicate an absence of significant PCB fluxes or it may indicate that numerous fluxes are approximately balanced. The difference between these interpretations is of critical importance. The first interpretation implies that control of sources at upstream locations will significantly reduce concentrations everywhere. The second interpretation implies that upstream sources are only partially responsible for downstream concentrations and the response to controls at upstream locations is unknown. Knowledge of the PCB sources and sinks provides a means to overcome the ambiguity of the data and a stronger scientific basis for remedial decision-making. This knowledge can be developed from a combination of data analysis and modeling.

Among the original sources of PCBs in the Upper Hudson River were the two GE plants that used the material for 30+ years. All the PCBs discharged into the river did not flow down the river; instead, PCBs were sequestered in the Upper Hudson River sediments. These sediment PCBs and residual discharges from the vicinity of the GE plants have been continuing sources to the river. From the perspective of the river water, the sinks for PCBs include transfer to the sediment in association with settling particles, transfer to the atmosphere *via* volatilization and the transport out of the study area with water flowing over the Troy Dam. From the perspective of the surface sediment, the transfer from the water column *via* settling is a source and transfers to the water column *via* erosion and diffusion from pore water are sinks. Other withdrawals or sinks include burial below the bioavailable zone and destruction by biotransformation.

The sources and sinks of PCBs were identified from studies of PCB congeners, their abundance and concentration in the water column, sediment and fish, and from studying the physical, biological and chemical processes that affect PCBs over time and within the varied river environments. These data and processes were used to develop the Upper Hudson River model that is presented in Volume 2.

Because earlier measurement techniques did not properly account for PCBs containing one or two chlorine atoms, it is not possible to estimate the historical sources and sinks of this component (see Section 5 and Volume 2). For this reason, the evaluations that follow consider only the fraction of the PCBs that contain three or more chlorine atoms, i.e., PCB_{3+}.

6.1 SOURCES OF PCB_{3+} TO THE RIVER

PCBs that entered the Upper Hudson River from upstream were derived from discharges to the river occurring along the shoreline in the vicinity of Hudson Falls, and, prior to their remediation, from the Remnant Deposits. The best estimate of the magnitude of the inputs comes from the monitoring data collected at Rogers Island in Fort Edward. Analysis of these data, described in Volume 2 of this report, yields annual estimates that range from about 1,500 pounds in 1979 down to about 100 pounds in 1997. In general, the inputs have continuously dropped over time, as shown in Figure 6-1. The variation around the general trend has several causes, the most important of which appears to be river flow. Years of elevated river flow had elevated PCB inputs because of greater erosion of unstabilized Remnant Deposit material and re-suspension of any PCB oil from the Hudson Falls area that had accumulated at the river bottom. A second factor is the uncontrolled release of PCBs from the Allen Mill that resulted in elevated inputs in the period from 1991 to 1993. Finally, an increase in PCB input between 1997 and

1998 is observable in Figure 6-1; this may be related to remedial actions at Hudson Falls during 1998 (Section 3.3.3, QEA 1999). Overall, about 17,000 pounds of PCBs entered the Upper Hudson River between 1978 and 1998. GE's remediation of the Remnant Deposits and at Hudson Falls has successfully eliminated most of the input, as evidenced by the minimum value of about 100 pounds in 1997.

PCBs have also entered the river water from the surface sediments; both continuously from pore water and intermittently *via* sediment erosion. As discussed in Volume 2, the continuous flux from pore water was estimated from 1998 data. The flux in other years was calculated using the 1998 number, assuming that the flux is proportional to the surface sediment concentration. The surface sediment concentrations in each year between 1978 and 1998 were obtained from results of the Upper Hudson River model, which compared favorably with data from the various sampling programs. The annual flux has declined through time from about 1,200 pounds in 1978 to about 200 pounds in 1998 (Figure 6-2). Although loading from continuous flux from pore water appears similar in magnitude to the input from upstream, direct comparison is not appropriate. The upstream inputs enter the study area at Rogers Island, whereas the flux from pore water enters gradually over the length of the river. Thus, as one moves downstream, the relative importance of these two inputs changes. Initially, the upstream input is much more important. Moving downstream, the relative contribution of the pore water flux increases.

The PCB input to the water *via* erosion was determined from estimates of the sediment erosion rate and the PCB concentration on the eroding solids. Sediment erosion rates were estimated using measurements of the erosion potential of the river sediments, equations that describe erosion in rivers and river velocities; all integrated within the Upper Hudson River model. The annual input, which principally comes from non-cohesive sediments, varied from year-to-year in response to the frequency and magnitude of high flow events, with a general downward trend due to the decline in surface sediment PCB concentration (Figure 5-7). Estimated values for input from erosion range from about 2,600 pounds in 1979 down to about 250 pounds in 1997. They are generally larger than the inputs from upstream and from sediment pore water. As with the continuous pore water flux, input from erosion occurred over the entire river and is not directly comparable to upstream inputs.

6.2 SINKS OF PCB_{3+} WITHIN THE RIVER

As the river water traverses the Upper Hudson River and receives PCBs from the sediment, it loses PCBs to the sediment *via* settling and to the atmosphere *via* volatilization. The settling loss is closely coupled to the erosion source because of the relationship between erosion and water column suspended solids concentration and because a portion of the solids and associated PCBs that are eroded redeposit on the sediment. Estimates of the settling losses were made using the Upper Hudson River model. They have ranged from about 2,100 pounds in 1979 down to about 200 pounds in 1997 (Figure 6-3).

The sink due to volatilization is proportional to the PCB concentration in the river water and dependent on several physical processes (Section 5.2.3). Equations developed to describe this process were incorporated in the Upper Hudson River model. These equations indicate that volatilization is a minor sink that resulted in losses ranging from about 290 pounds in 1978 to about 50 pounds in 1997 (Figure 6-4).

PCBs that entered the water column and were not lost due to settling or volatilization were transported over the dam at Troy to the Lower Hudson River. Again, the Upper Hudson River model provides estimates of the magnitude of this sink. As with the other sinks, the annual fluxes have declined over time from a high of about 2,600 pounds in 1979 to a low of about 300 pounds in 1997 (Figure 6-5). Year-to-year variation around the general decline occurred because of variation in the erosion source. High flow years had relatively high fluxes and low flow years had relatively low fluxes. During the period from 1978 to 1998, a total of about 24,000 pounds was estimated to have been transported from the Upper Hudson River to the Lower Hudson River.

The biota of the river are not exposed to all of the PCBs in the sediment. Rather, they only come in contact with PCBs that may be transported to the surface by hydrodynamic forces and the activities of benthic animals. Based on the Upper Hudson River model, the layer in which such transport occurs includes the top 10 cm in cohesive (fine) sediments and the top 3 cm in non-cohesive (coarse) sediments. Sediment PCBs become sequestered from the biota if sediments accumulate and bury the PCBs below this surface mixing layer. Conversely, sequestered PCBs become available to the biota if erosion occurs and mixing is extended into the buried PCBs. Thus, net burial or net erosion represents a sink or source of PCBs. The Upper Hudson River model indicates that PCBs have been lost from the active system *via* net burial that ranges from about 3,600 pounds in 1979 down to about 50 pounds in 1998 (Figure 6-6). The mass of PCB buried declined over time as the surface sediment concentration declined. As with the other processes related to sediment transport, the year-to-year variation around the general decline is attributable to variations in solids loading to the river associated with variations in river flow. Burial rates differed between cohesive and non-cohesive sediments (Figure 6-7). Burial was the primary mechanism for the decline in PCB concentration in cohesive sediments. In contrast, burial was a minor mechanism in non-cohesive sediments.

6.3 MASS BALANCE FOR THE RIVER

Taken as a whole, the Upper Hudson River received PCB_{3+} inputs that have ranged from about 5,000 pounds in 1979 to about 600 pounds in 1997. The sinks offset these inputs. The Upper Hudson River model (Volume 2) provides estimates of all the sinks and a basis for estimating an overall mass balance of PCB_{3+} within the river.

The model-generated mass balance for the Upper Hudson River water from Rogers Island to the Troy Dam is shown in Figure 6-8. Between 1978 and 1998, about 17,000 pounds entered the Upper Hudson River from upstream. An additional 10,000 pounds entered from the sediments, in annual fluxes that ranged from about 1,400 pounds in 1979 to about 250 pounds in 1997. Of the 27,000 pounds that entered the water over the 21-year period examined, 24,000 pounds were transported to the Lower Hudson River and 3,000 pounds were volatilized.

The estimated 10,000 pounds of PCB_{3+} that entered the water from the sediment came mostly from the non-cohesive sediments *via* continuous flux from sediment pore water (Figure 6-9). The settling and erosion fluxes have been closely balanced, yielding a net flux from the water column to cohesive sediments of about 1,300 pounds and a net flux from non-cohesive sediments to the water column of about 300 pounds. The continuous flux from sediment pore water contributed 1,600 pounds from cohesive sediments and 9,100 pounds from non-cohesive sediments.

The surface sediments of the TIP were an important component of the total input to the water from sediment, but the majority of this input came from sediments downstream of the TID. The TIP sediments contributed about 3,300 pounds of PCB_{3+} to the water. In other words, they were responsible for about one-third of the total input from sediment. Most of that input came from non-cohesive surface sediments largely due to the greater surface area represented by these sediments (Figure 6-10). Non-cohesive sediments accounted for 2,400 pounds, which was the net of 6,200 pounds entering the water *via* continuous flux from sediment pore water and erosion and 3,800 pounds leaving the water and entering the sediments *via* settling. The cohesive sediments contributed about 900 pounds to the water; the result of 4,100 pounds moving to the water from the sediment and 3,200 pounds moving to the sediment from the water.

As indicated in Figure 6-8, about 16,000 pounds of PCB_{3+} were buried below the surface sediment layer between 1978 and 1998. This loss occurred entirely in the cohesive sediments. The Upper Hudson River model estimates that almost 17,000 pounds were buried in the cohesive sediments and about 1,000 pounds was brought into the surface layer from buried sediments in the non-cohesive sediments (indicated as upward burial flux in Figure 6-9). About one-third of burial was predicted to have occurred within the TIP, where about 5,600 pounds were buried in cohesive sediments and about 150 pounds were brought in to the surface layer in non-cohesive sediments (Figure 6-10).

The mass balance analysis further indicates that burial was primarily responsible for the decline in PCB_{3+} observed in the cohesive sediments. Over the entire study area, the 17,000 pounds that were buried dwarf the net flux at the sediment surface to the water column due to settling, resuspension and non-erosion exchange of about 300 pounds (Figure 6-9). Within the TIP, the conclusion is the same, although the comparison is not quite as dramatic. Fifty-six hundred pounds were buried, whereas 900 pounds were transferred to the water column (Figure 6-10). The flux to the water column is larger in the TIP than in the Upper Hudson River because settling flux to the sediment is higher downstream of the TIP as a result of the higher water column PCB_{3+} concentrations at downstream locations.

In contrast to the cohesive sediments, the mass balance indicates that the declines observed in non-cohesive sediments are principally due to PCB_{3+} flux to the water column. Within the surface layer, no burial has occurred in non-cohesive sediments over the study area (Figure 6-9) or within the TIP (Figure 6-10).

6.4 CONTRIBUTIONS OF THE VARIOUS PCB_{3+} SOURCES TO DOWNSTREAM PCB_{3+} FLUX

The Upper Hudson River model reproduces the spatial patterns observed in the water column PCB_{3+} data. For example, in August of 1993, the model computes an increase in PCB_{3+} concentration from about 30 ng/L at Fort Edward to about 60 ng/L at the TID and 70 ng/L at Schuylerville, Stillwater and Waterford. The limited spatial gradient below TID does not mean that the TIP sediments are the primary PCB source at the downstream stations. Mass balance analyses conducted with the model indicate that the TIP sediments have been a minor contributor to the PCB_{3+} flux from the Upper Hudson River to the Lower Hudson River, as indicated by the PCB_{3+} flux passing Waterford (Figure 6-11). These sediments have accounted for about 13 to 26% of the flux, depending on the year examined. The upstream source (PCBs entering with water passing Fort Edward) has contributed amounts about equal to the TIP sediments, except during the period of high upstream releases from the plant site area when the upstream source dominated (e.g., 1992, Figure 6-11). The major contribution to the PCB_{3+} flux came from sediments between the TID and Waterford.

The model indicates that PCBs originating from TIP sediments (or the upstream source) are lost due to settling and, to a lesser extent, volatilization as water moves downstream. These PCBs are replaced by PCBs fluxing to the water column from downstream sediments. Overall, the contribution of PCB within sediments in any specific region of the Upper Hudson River to the flux to the Lower Hudson River is a function of the sediment PCB concentration and the distance between the region and the Federal Dam in Troy (the upstream boundary of the Lower Hudson River).

6.5 SOURCES OF PCBs TO THE BIOTA

The spatial and temporal trends in fish PCB levels are a response to trends in water column and surface sediment PCBs (Section 5.3). In general, biota trends reflect relative PCB concentrations in organic matter at the base of the food web.

The dose to the food web, which is approximated as the consumption rate of particulate organic carbon times the concentration of PCBs on the particles, is likely to have been dominated by sediment-associated PCBs. Although gut contents indicate that both sediment and water column particles are sources of organic matter to forage fish (Exponent 1998b), PCB_{3+} concentrations on surface sediment particles have been approximately one order of magnitude greater than concentrations on water column particles (USEPA 1997). This conclusion is supported by the observation that PCB_{3+} concentrations in fish and sediment follow a similar spatial trend - declining from Thompson Island Pool to Waterford - whereas water column levels do not exhibit as strong a gradient (Figure 5-13). That is, lower PCB levels in the downstream sediments lead to less PCB accumulation by the downstream fish, indicating that the sediments are the dominant source. The Upper Hudson River bioaccumulation model presented in Volume 2 indicates that surface sediments have comprised an average of 80% of the dose of PCBs to the largemouth bass in Thompson Island Pool and 50% of the dose in Stillwater since 1980.

The specific source of sediment PCBs entering the food web could be anywhere within the top 10 cm sediment, or so. Benthic invertebrates are capable of burrowing many centimeters into the bed. However, based on published literature, the majority of the feeding seems to occur within the top few centimeters (e.g., Millbrink 1973). This estimate of the depth of bioavailable material was refined with the two additional analyses presented below.

Buried PCBs are generally dechlorinated in the Upper Hudson River sediments (Section 5.2.1). Because dechlorination does not occur to an appreciable degree within fish, the PCB composition of the fish gives an indication of the dechlorination status of their exposure sources. Fish exposed to dechlorinated PCBs are enriched in lower chlorinated congeners relative to fish exposed to fresh PCBs. Ratios of selected PCB congener concentrations provide a measure of dechlorination. For example, analysis of data from USEPA's High Resolution Coring (USEPA 1997) has indicated that congener 56 (2,3,3',4' tetrachlorobiphenyl) is dechlorinated relatively rapidly, while congener 49 (2,2',4,5' tetrachlorobiphenyl) is dechlorinated to a much lesser degree. Both congeners have similar partitioning and bioaccumulation properties. Therefore, a ratio of the concentrations of the two congeners provides a measure of dechlorination: a high value is characteristic of undechlorinated PCBs, and a low value indicates the PCB source has been dechlorinated. The value of this congener ratio in sediments within the top 5 cm of the sediment bed is high and similar to the value in Aroclor 1242 (Figure 6-12) and decreases with depth. The value of this ratio is also relatively high in fish and similar to values observed in sediments within 5 cm of the surface. This suggests that the fish are exposed to relatively undechlorinated PCBs that originate within the top 5 cm of the bed.

A steady-state homolog bioaccumulation model based upon the calibrated PCB_{3+} model was used to provide additional evidence regarding the source of PCBs to fish. In the model, forage fish (pumpkinseed) were exposed to sediments containing PCBs with three levels of dechlorination, as represented by PCBs in TIP surface sediments collected by USEPA (1997) and GE (1993e), and TIP buried sediments collected by USEPA (1997). The model showed that fish exposed to surface sediments (0-2 cm or 0-5 cm) containing relatively undechlorinated PCBs resulted in computed homolog distributions that were most similar to measured distributions (Figure 6-13). In contrast, the model predicted pumpkinseed PCB homolog distributions were quite dissimilar to measured distributions when buried dechlorinated PCBs were used as the route of PCB exposure. This analysis indicates that the upper two to five centimeters of sediment have been the most likely exposure source for PCBs in fish.

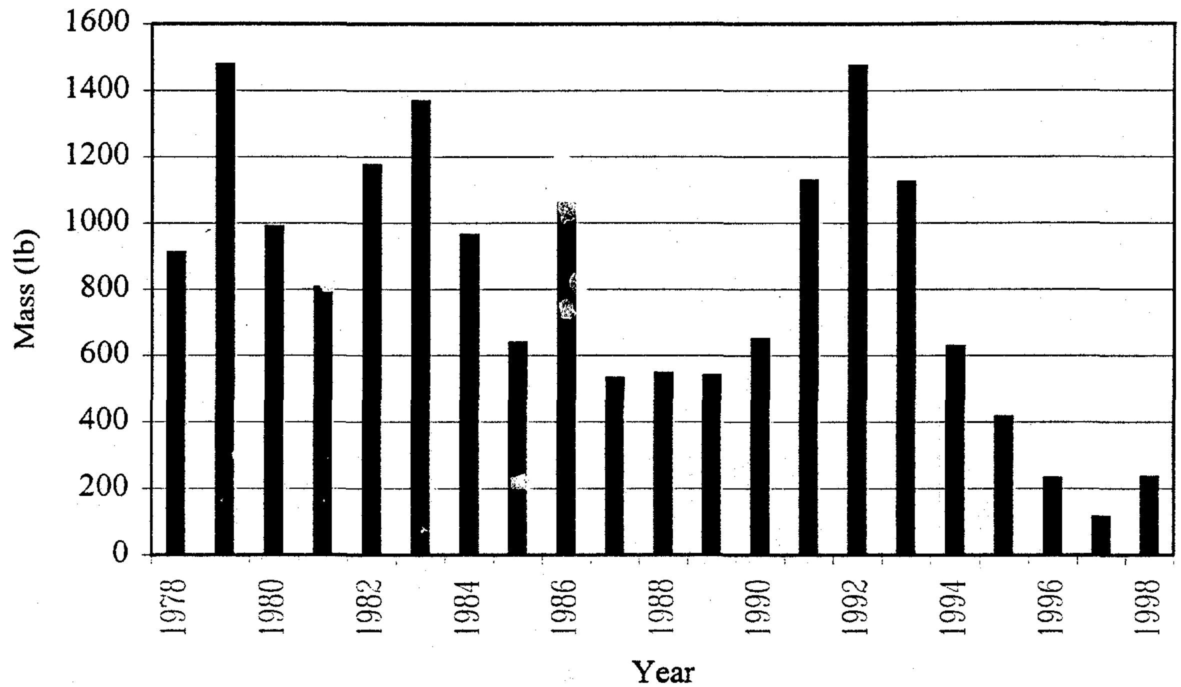

Figure 6-1. Estimated annual average PCB_{3+} load passing Rogers Island for the period from 1978 to 1998. Values are from Upper Hudson River PCB fate and transport model presented in Volume 2.

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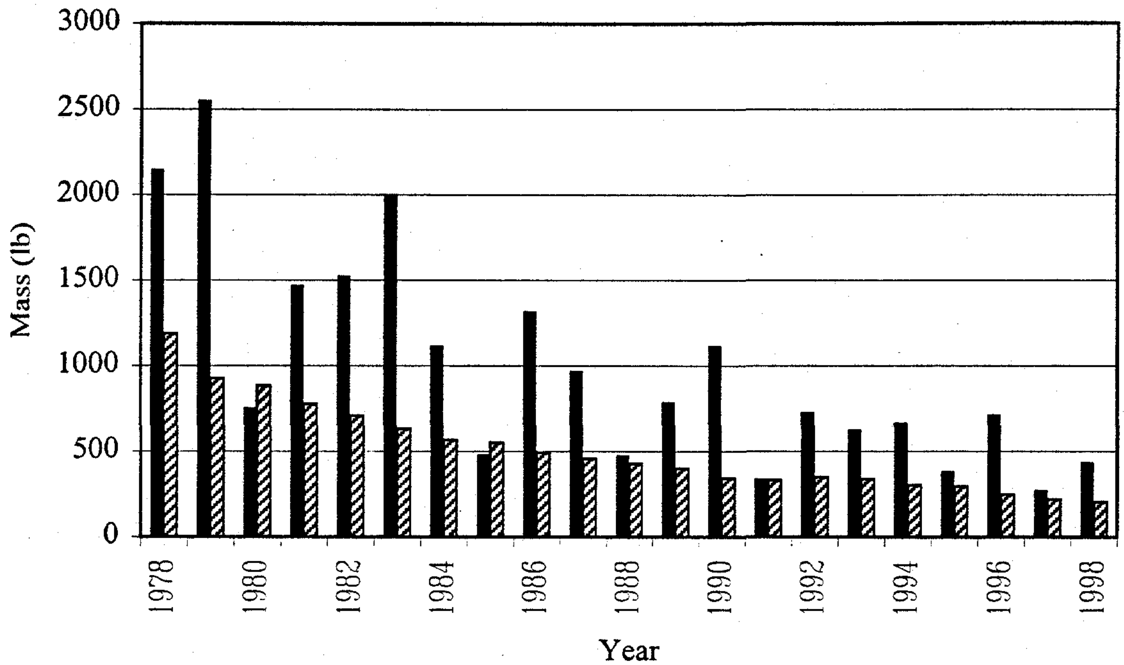

Figure 6-2. Estimated annual average flux of PCB_{3+} to the Upper Hudson River water column from surface sediments between Rogers Island and the Troy Dam for the period from 1978 to1998. Light bars indicate the continuous flux due to migration from pore water. Dark bars indicate the intermittent flux due to erosion. Values are from Upper Hudson River PCB fate and transport model presented in Volume 2.

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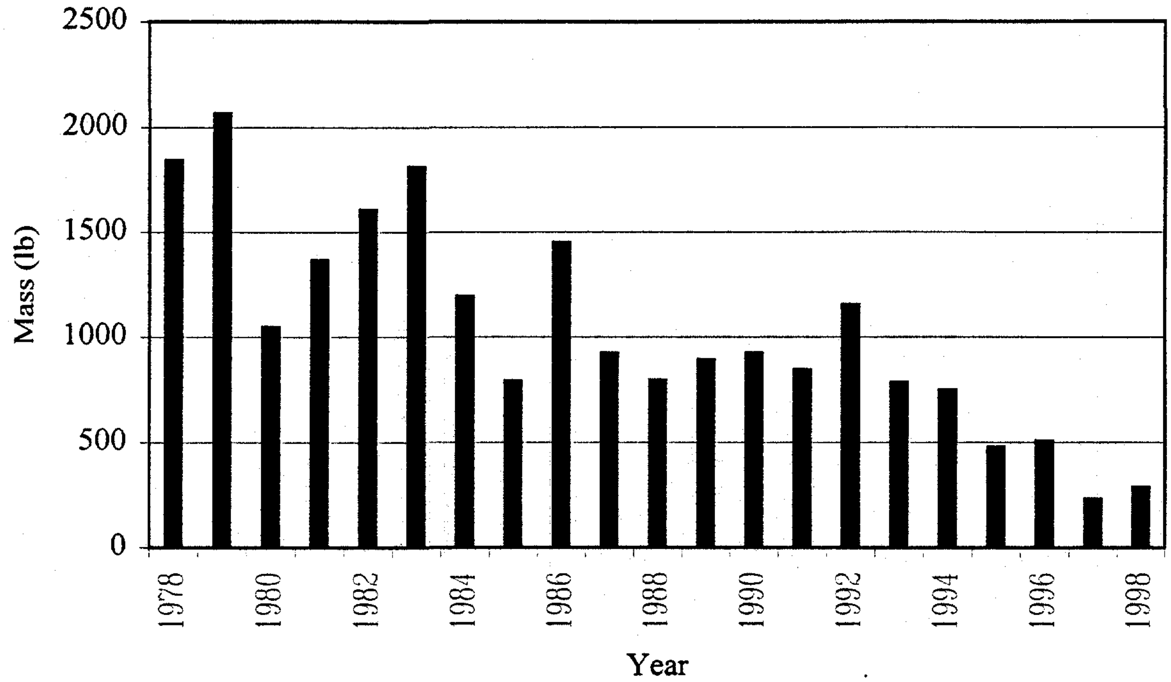

Figure 6-3. Estimated annual average flux of PCB_{3+} to the Upper Hudson River surface sediments between Rogers Island and the Troy Dam for the period from 1978 to 1998 *via* settling. Values are from Upper Hudson River PCB fate and transport model presented in Volume 2.

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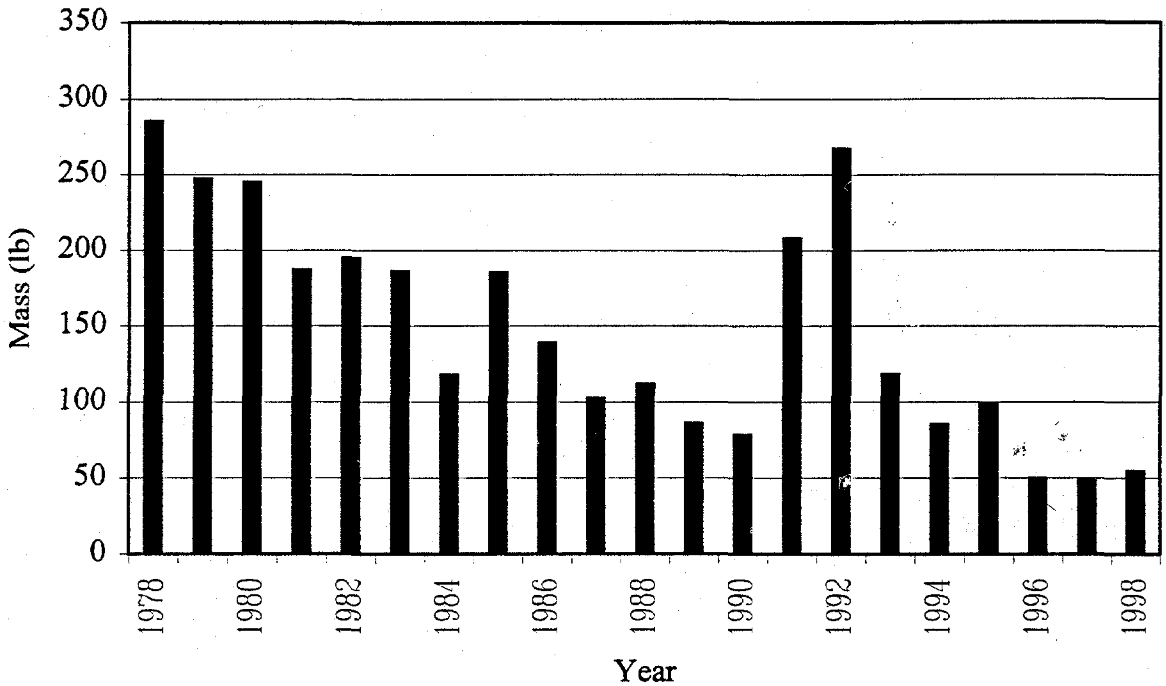

Figure 6-4. Estimated annual average loss of PCB_{3+} from the Upper Hudson River between Rogers Island and the Troy Dam for the period from 1978 to 1998 *via* volatilization. Values are from Upper Hudson River PCB fate and transport model presented in Volume 2.

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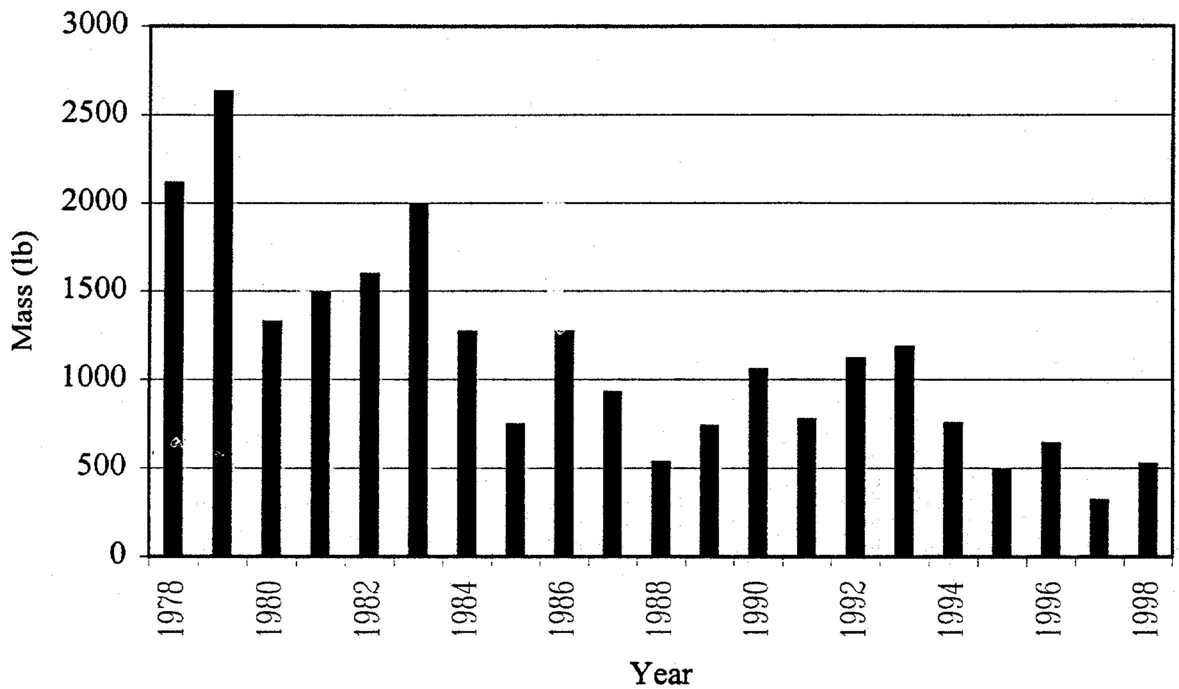

Figure 6-5. Estimated annual average flux of PCB_{3+} from the Upper Hudson River to the Lower Hudson River for the period from 1978 to 1998. Values are from Upper Hudson River PCB fate and transport model presented in Volume 2.

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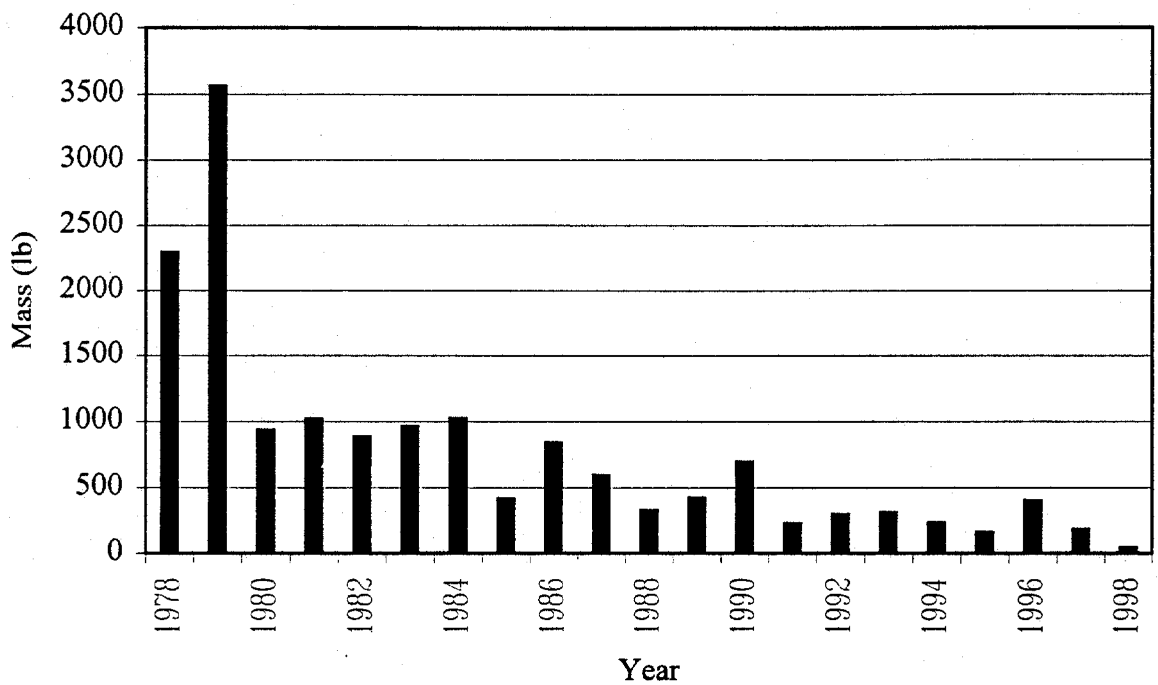

Figure 6-6. Estimated annual average flux of PCB_{3+} from surface sediments to buried sediments in the Upper Hudson River between Rogers Island and the Troy Dam for the period from 1978 to 1998. Values are from Upper Hudson River PCB fate and transport model presented in Volume 2.

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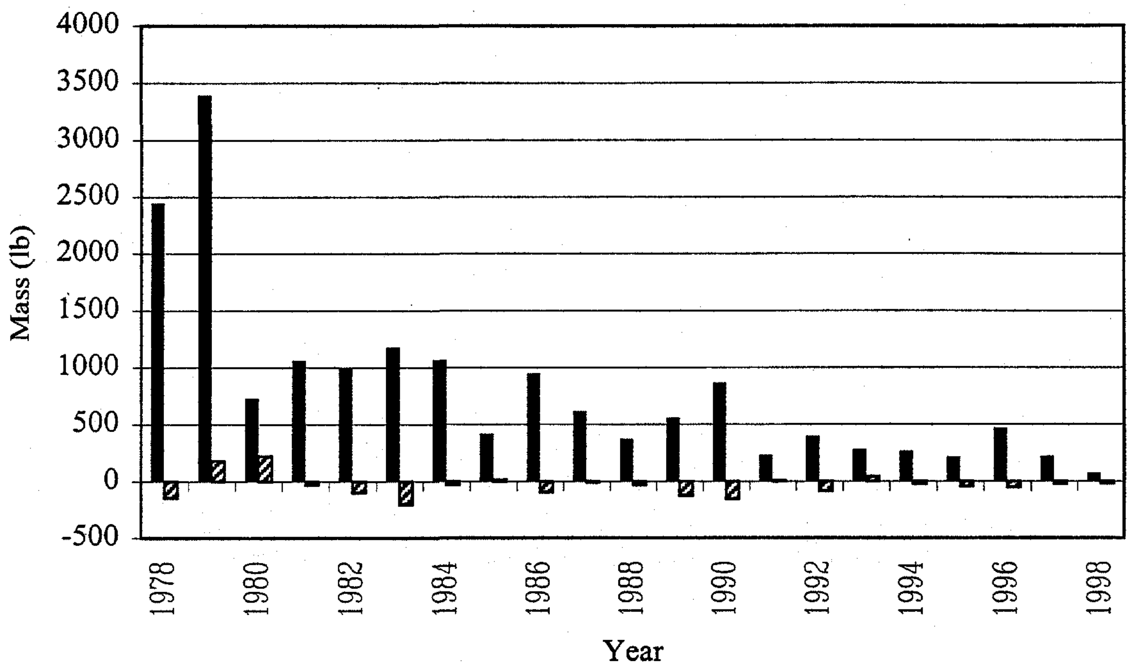

Figure 6-7. Estimated annual average flux of PCB_{3+} from surface sediments to buried sediments in cohesive (dark bars) and non-cohesive (light bars) sediments of the Upper Hudson River between Rogers Island and the Troy Dam for the period from 1978 to 1998. Values are from Upper Hudson River PCB fate and transport model presented in Volume 2.

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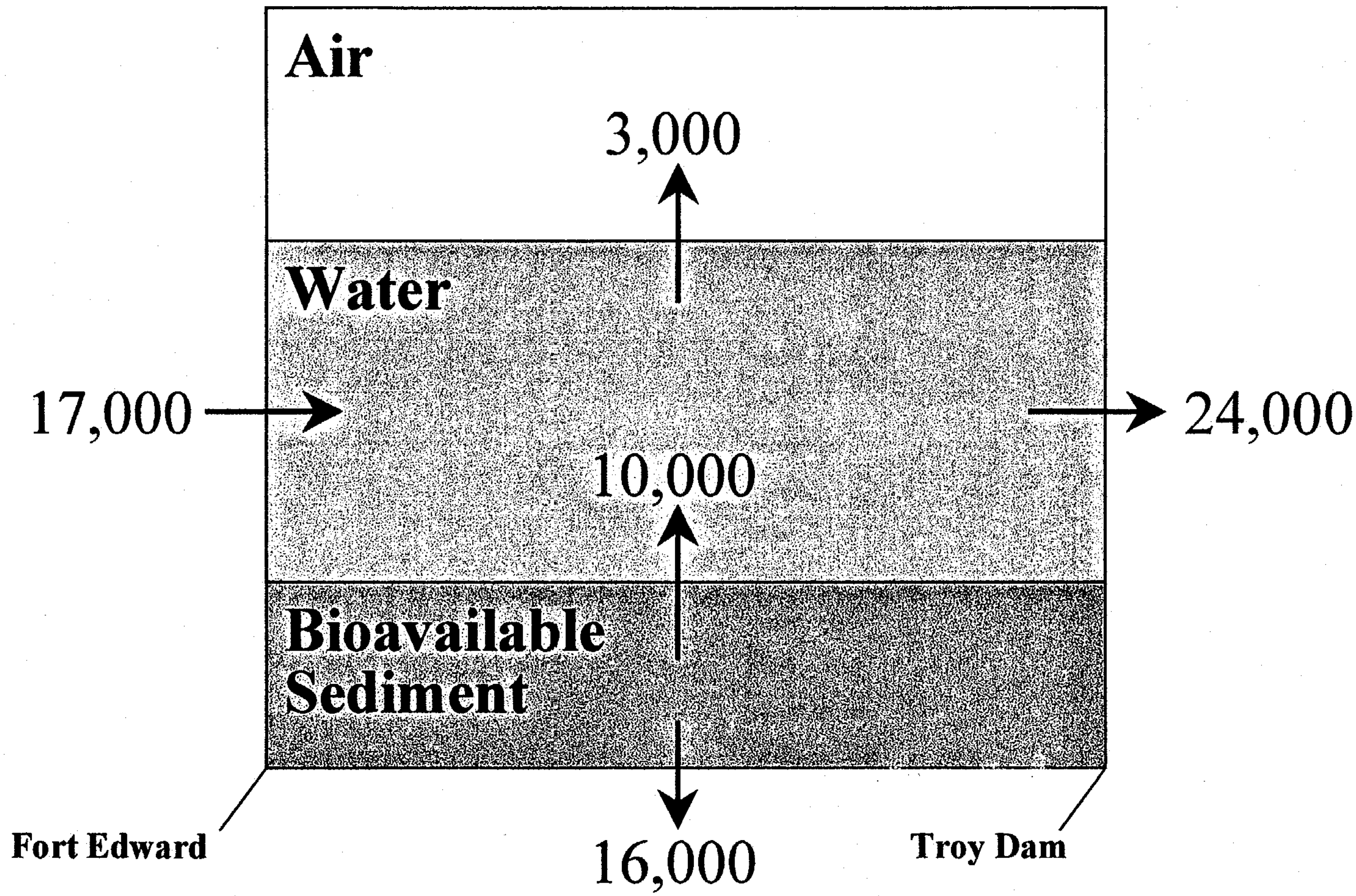

Figure 6-8. Estimated mass balance for PCB_{3+} in the water and surface sediments of the Upper Hudson River between Rogers Island and the Troy Dam for the period from 1978 to 1998. Number are in units of pounds.

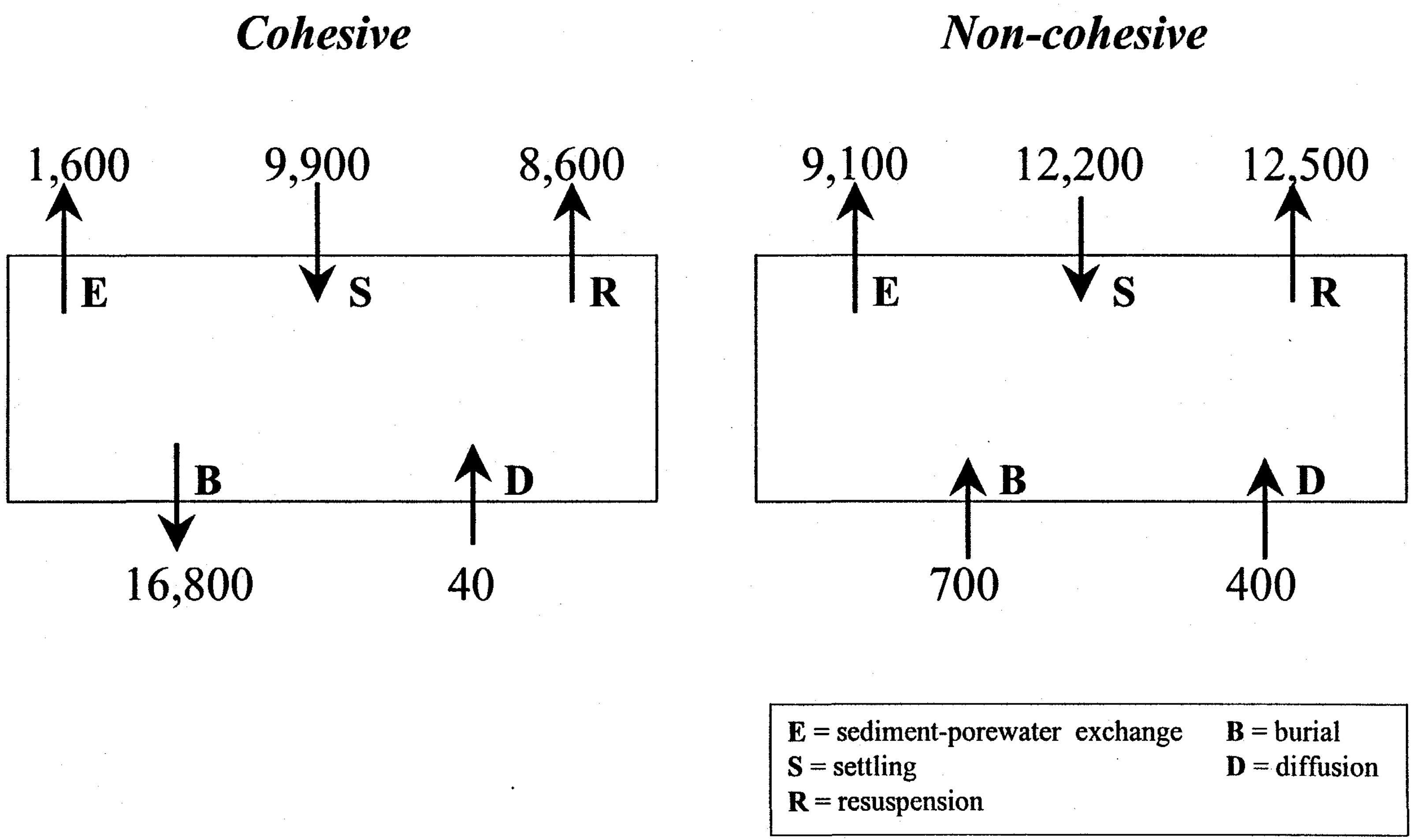

Figure 6-9. Estimated mass balance for PCB_{3+} in the surface cohesive and non-cohesive sediments of the Upper Hudson River between Rogers Island and the Troy Dam for the period from 1978 to 1998. Numbers are in units of pounds.

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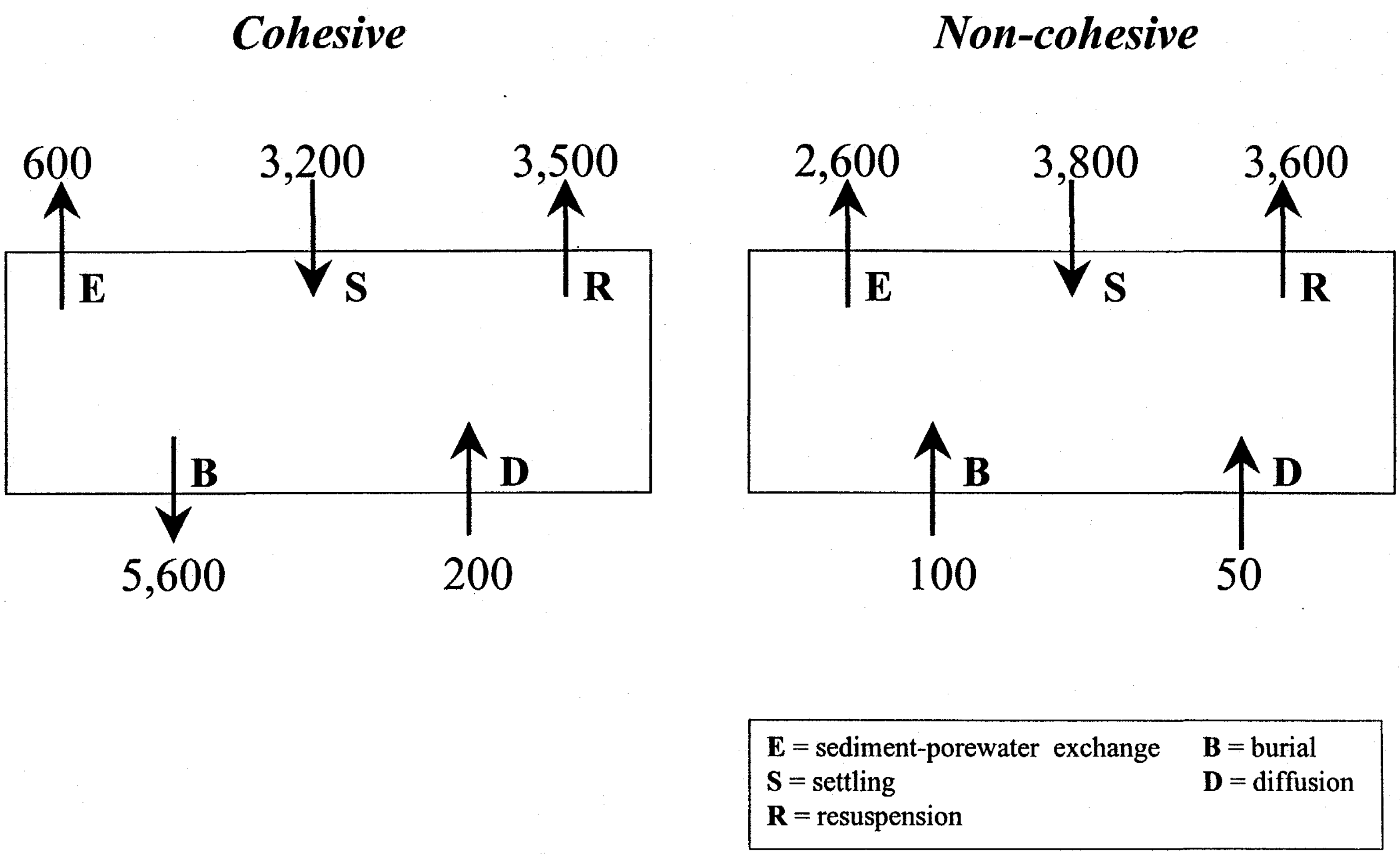

Figure 6-10. Estimated mass balance for PCB_{3+} in the surface cohesive and non-cohesive sediments of the TIP for the period from 1978 to 1998. Numbers are in units of pounds.

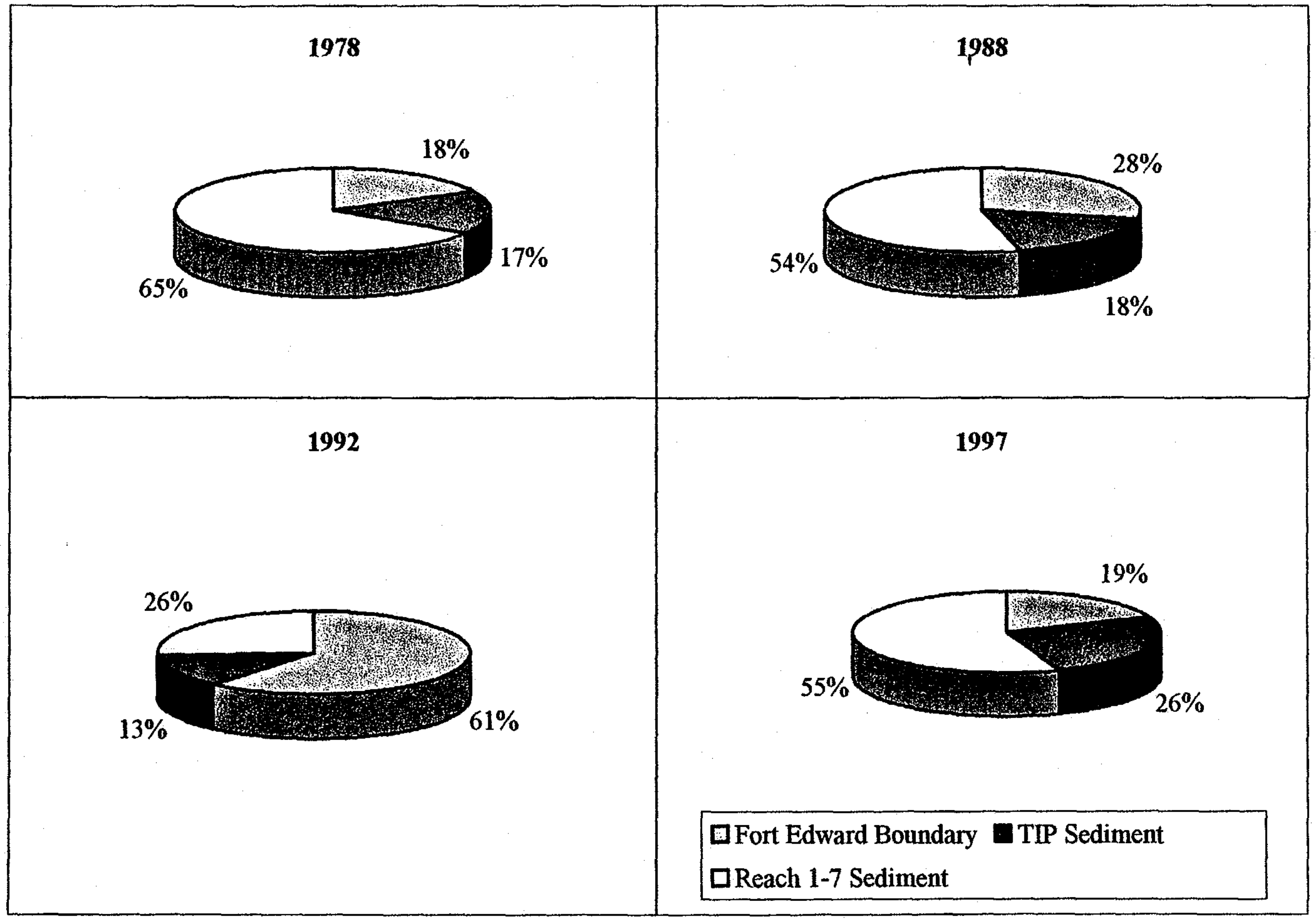

Figure 6-11. Estimated relative contribution of upstream sources, TIP sediments and Reaches 1 through 7 sediments to the PCB_{3+} flux passing over Troy Dam.

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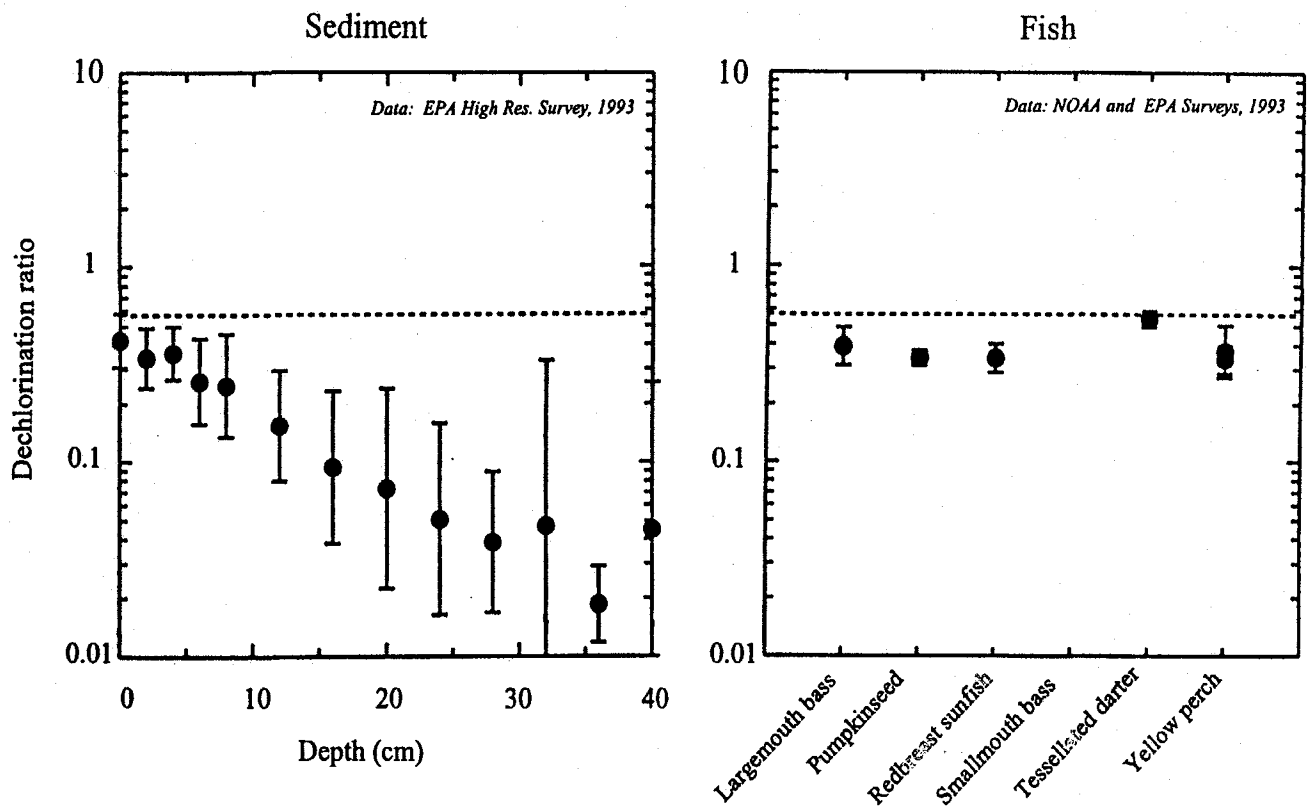

Note: Dashed lines represent Aroclor 1242

Figure 6-12. Dechlorination ratios in fish and sediments of the Thompson Island Pool. The ratio of BZ 56 to BZ 49 is plotted in sediments against depth and for each species of fish.

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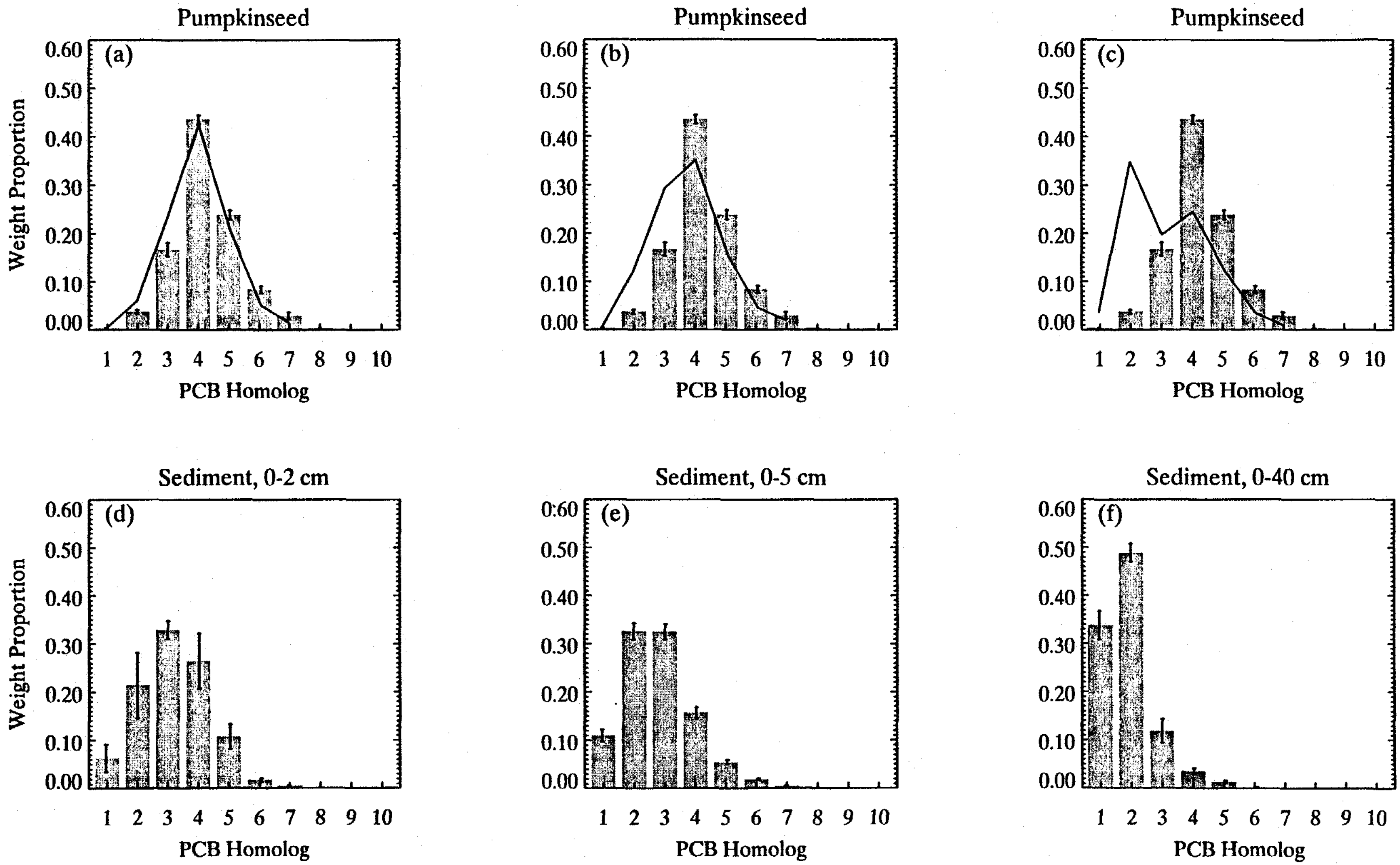

Fish Data : mean +/- 2 std errors, USEPA (1995, includes data from USEPA, NOAA, Law Environmental and OBG), Exponent (1995) (panels a, b and c).
Sediment Data: USEPA (1997) (panels d and f) and GE (1993e) (panel e).
Panel f: Samples with < 2.5 chlorines per biphenyl only.

Figure 6-13. Food web homolog bioaccumulation model. Comparisons of PCB composition data for TIP forage fish (Pumpkinseed) with model predictions for different assumed sediment PCB exposure compositions.

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