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**QUANTIFICATION OF SEDIMENTATION IN
THE UPPER HUDSON RIVER**

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Prepared by:

HydroQual, Inc.
1 Lethbridge Plaza
Mahwah, New Jersey 07430

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SECTION 1

INTRODUCTION

Sedimentation plays a prominent role in the fate of hydrophobic contaminants in surface waters. The rate at which the surface sediment concentrations decrease is determined by the rate at which less-contaminated solids from the water column mix with and bury the contaminated surface sediments (i.e., sedimentation), the rate of loss of contaminant to the water column by diffusion and erosion, and the rate at which surface sediment contaminant is destroyed by degradation processes. For PCBs, degradation is typically not thought to be an important mass loss mechanism, although it may be a significant factor in altering the toxicity or bioaccumulation potential of the PCB mixture. Loss of PCBs to the water column due to erosion occurs at a slow rate because of the infrequency of high flow events. Diffusion of PCBs from the bed to the water column is also a minor loss mechanism because only a small fraction of sediment bed PCBs are in the dissolved phase and available for diffusion. Therefore, in most aquatic systems, burial of contaminated surface sediments by deposition of solids occurs at a much greater rate than losses to the water column.

The James River Kepone problem is a well-documented example of the significance of sedimentation in natural recovery. Following elimination of the Kepone source in the mid-1970's, surface sediment concentrations of Kepone in this aquatic system declined from about 0.15 ppm in the 1970's to less than 0.01 ppm in the late-1980's. A model of Kepone transport and fate in the James River indicated that the decline in sediment Kepone concentrations was mainly due to sedimentation (O'Connor et al., 1989).

Because sedimentation can control the rate of natural recovery, uncertainty of its magnitude can dominate uncertainty in attempts to predict the impact of natural recovery. For this reason it is critical that any effort to model the fate and

bioaccumulation of PCBs in the Upper Hudson River focus on data analysis and model calibration techniques that develop the best attainable estimate of sedimentation.

The primary objectives of this paper are: (1) review existing Upper Hudson River data that may be used to estimate sedimentation rates and (2) discuss the application of a solids mass balance model to this riverine system. Two different methods to estimate sedimentation rates in the Upper Hudson River will be presented in Section 2. EPA has proposed to develop and calibrate a solids mass balance model for the Upper Hudson River. Necessary model-data comparisons for adequate model calibration are discussed in Section 3. Conclusions resulting from the analyses and discussions presented in this paper are given in Section 4.

SECTION 2

QUANTIFYING SEDIMENTATION RATES IN THE UPPER HUDSON RIVER

This section will review two methods that can be used to quantify sedimentation rates in a river: (1) direct measurement and (2) solids mass balance. First, two direct measurement techniques (sediment core dating and bathymetric data analysis) that have been applied to the Upper Hudson River will be presented and the strengths, weaknesses and results of each technique discussed.

The solids mass balance method uses the principle of mass conservation to determine net sedimentation in a riverine system. During a specific time period, net sedimentation in a particular river reach is equal to the difference between the total sediment load input to the river and the amount of sediment transported out of the system at the downstream end of the reach. Because accurately determining sediment loading is a critical component of this approach, an analysis is presented that provides estimates of upstream and tributary loading to the Upper Hudson River. Data collected at two downstream locations, Stillwater and Waterford, are then used in conjunction with the sediment loading estimates to construct a simplified solids mass balance for two reaches of the river: (1) Fort Edward to Stillwater and (2) Stillwater to Waterford. The simplified solids mass balances were used to determine sedimentation rates, with order-of-magnitude accuracy, in these two reaches of the Upper Hudson River.

2.1 DIRECT MEASUREMENT

2.1.1 Sediment Core Dating

Sediment core dating has been widely used in marine and freshwater systems for geochronology analyses. Most applications have been in depositional environments, such as lakes, coastal areas and oceans (e.g., Robbins and Edgington,

1975; Christensen and Goetz, 1987; Allen et al., 1993). Geochronology analyses in more dynamic systems, such as rivers and estuaries, have also been conducted (e.g., Valette-Silver, 1993; Huntley, et al., 1995). These studies, and others, have shown that sediment core dating can be an extremely useful tool for determining the historical fluxes of contaminants to the sediment bed and estimating sedimentation rates. However, this type of analysis can be very difficult to do accurately, particularly in dynamic environments that are not purely depositional, e.g., riverine deposits that experience episodic resuspension and deposition.

The basic idea behind sediment core dating is to use environmental tracers, with a known time history of depositional flux to an aquatic system, to date the strata in a sediment core. One tracer that is typically used is cesium-137 (^{137}Cs) because of its known temporal history in the environment. This radioactive contaminant, which has a half-life of 30.2 years, was initially released into the atmosphere in 1954 during nuclear weapons testing and the peak release occurred in 1963 (Bopp et al., 1985). Time horizons in a sediment core can be determined from the depths of the first appearance of ^{137}Cs (1954) and its peak concentration (1963). An average sedimentation rate can then be estimated from this information.

An important assumption in this type of analysis is that sedimentation occurs at a steady, uniform rate, which is a valid approximation in certain situations, e.g., lakes and oceans. However, deposition in rivers tends to be episodic, as will be discussed in Section 3, and care must be taken when analyzing sediment cores from river systems, such as the Upper Hudson River. Episodic deposition, with possible periods of erosion, can significantly affect the accuracy of dating sediment cores from rivers or other dynamic aquatic systems.

Bioturbation in the surficial zone of the sediment bed can also complicate geochronology analyses. Biological activity in the upper layer of the bed, typically from 1 to 10 cm thick, mixes the sediments and causes contaminant concentrations

in this layer, called the well-mixed layer, to be approximately constant. Sedimentation rates are typically 1 cm/year or less in most systems, which means that between 1 and 10 years (or more) of contaminant deposition can be represented in the well-mixed layer. Variations in contaminant flux to the bed will be smeared in the well-mixed layer and, thus, obscure vertical profiles of contaminants and tracers in a sediment core. Errors can then be introduced into sedimentation rate estimates due to smearing of contaminant and tracer profiles caused by bioturbation.

Sediment cores collected from the Upper Hudson River in 1977, 1983 and 1991 have been analyzed by various researchers to determine sedimentation rates. Tofflemire and Quinn (1979) discussed a set of twenty-five cores collected during January 1977 between Fort Edward and Mechanicville. These cores were divided into one-inch sections and certain sections were analyzed for grain size distribution, PCB and ^{137}Cs concentration. Tofflemire and Quinn (1979, Figure 18) estimate sedimentation rates for only two of the cores (1.5 and 2.5 cm/yr). These cores were collected in high deposition, nearshore areas located near Thompson Island Dam and the Route 4 bridge.

Bopp et al. (1985) discussed sixteen cores collected in 1983 from the Upper Hudson and Mohawk Rivers. No quantitative analysis of sedimentation rates was reported, but it was remarked that "the low ^7Be activities in the surface samples of [all but one core] simply reflects the fairly low to moderate average sediment accumulation rates (≤ 1 cm/yr)" (Bopp et al., 1985, p. 15).

Bopp and Walsh (1992) reported ^{137}Cs concentrations in one core collected in May 1991 near river mile 188.6, which was close to the location of a core obtained in 1983. It was found that the shapes of the ^{137}Cs profiles in the two cores were quite similar, but the peak concentration of ^{137}Cs in the 1991 core was about 15 cm deeper than the 1983 peak concentration. This difference in the peak depths would

imply a sedimentation rate of about 1.9 cm/yr (15 cm/8 years) in this area. The report did not indicate if other cores had been collected in 1991.

Sediment core data for the cores collected in 1977, 1983 and 1991 have been reanalyzed in an attempt to verify, and possibly refine, previously reported results. Sedimentation rates were estimated using two approaches: (1) depth of first appearance of ^{137}Cs , which corresponds to 1954 and (2) depth of peak ^{137}Cs concentration, which corresponds to 1963. For example, if the depth of peak ^{137}Cs concentration was 10 cm for a core collected in 1983, then the sedimentation rate for that core would be estimated to be 10 cm/(1983 - 1963 years) or 0.5 cm/yr. Of the thirty-two cores for which ^{137}Cs data were available, only twelve cores could be analyzed using this methodology (three 1977 cores, eight 1983 cores and one 1991 core). The reason that the twenty rejected cores were not analyzed was that the depths of first appearance and peak ^{137}Cs could not be accurately determined; the vertical profile of ^{137}Cs in each of the cores was smeared due to a combination of flood effects (episodic deposition and erosion) and/or bioturbation.

For the twelve analyzed cores, the depth of first appearance method yielded sedimentation rates that ranged from 0.5 to 2.1 cm/yr. Using the peak ^{137}Cs approach, estimates of sedimentation were between 0.1 and 3.3 cm/yr. Most of the cores were obtained in the Thompson Island Pool, but spatial trends in deposition rate within this reach could not be identified because variability of estimated sedimentation rate was too great.

It should be noted that these cores were collected from deposition areas with relatively high sedimentation rates. Therefore, the estimated sedimentation rates would be greater than the average rate for a particular reach. In addition, not all of the collected cores could be analyzed quantitatively because of considerable variation in the vertical profiles of ^{137}Cs . The depths of the peak and first appearance of ^{137}Cs could not be determined in those cores. This problem is common when attempting

to use sediment core dating techniques to estimate sedimentation rates in rivers. Many cores cannot be analyzed because the dynamic environment, with episodic deposition and resuspension, tends to produce non-uniform sedimentation, which violates the main assumption used in sediment core dating. Thus, geochronology analyses of riverine sediments may be useful for estimating upper limits of sedimentation rates within the Upper Hudson River. However, extrapolation of rates determined in deposition zones (where cores can be quantitatively analyzed) to the entire river bed (which contains zones of mixed resuspension and deposition, and unreadable cores) can produce erroneous results. Using sediment core dating to estimate sedimentation rates in the Upper Hudson River, and particularly the Thompson Island Pool, may be further complicated by unknown effects of past dredging activities and removal of the Fort Edward Dam in 1973.

2.1.2 Bathymetric Data Analysis

A second method for determining sedimentation rates in a riverine system is to analyze changes in bathymetry. The basic idea of this method is to collect sediment bed elevation data at two different times, with the period between measurements typically ranging from months to years. Average sedimentation, or erosion, rates throughout the system can then be determined by calculating the difference between the initial and final bed elevation at each measurement location and then dividing by the time between measurements.

While the underlying premise of this method is simple and straightforward, application to a riverine system, such as the Upper Hudson River, can be difficult due to measurement error. The primary problem is establishing the location of each measurement site in the system so that sediment bed elevation data can be accurately collected during the initial and final surveys. The horizontal position, e.g., latitude and longitude, of a sampling location must be precisely known, generally within 5 meters or less. Permanent surveying monuments or Global Position System (GPS) equipment

are needed to establish repeatable horizontal locations with this degree of accuracy. A vertical datum must be established, e.g., a specific elevation (119' above sea level), that can be used as a reference for all bed elevation measurements. Finally, depth measurements should be made using an acoustic depth finder, which typically produces measurement errors of ± 3 cm.

This procedure has been used to estimate sedimentation rates in the Thompson Island Pool. Bathymetric surveys were conducted in this reach of the Upper Hudson River in 1977, 1982 and 1991. The 1977 survey was carried out by Normandeau Associates with bed elevations measured along 165 transects between Fort Edward and Troy, about 40 of the transects were in the Thompson Island Pool. Depth soundings were made at approximately 44,000 locations in the Thompson Island Pool during the 1982 survey, which was run by Raytheon. General Electric conducted two bathymetric surveys in 1991. One survey collected depth soundings at about 107,000 points in the Thompson Island Pool, while the other survey measured bed elevations along the same transects used in the 1977 survey.

Analyses of these data sets were performed in an attempt to estimate reach-average bed elevation changes in the Thompson Island Pool during the 14-year period between 1977 and 1991. A major difficulty encountered during this work was determining a common vertical datum that could be used as a reference for data collected during the three surveys. Adequate documentation for the 1977 survey allowed that data set to be compared with the 1991 measurements; 1.17 feet was added to the 1977 datum so that the 1977 and 1991 surveys were referenced to a common datum. At the present time, the vertical datum used in the 1982 survey is uncertain, which precludes use of that data set in the current analysis. Thus, only the 1977 and 1991 data sets were used to estimate sedimentation rates in the Thompson Island Pool.

Two different methods were used to compare bed elevations measured in 1977 and 1991. One approach used a standard civil engineering method, called cut and fill, to calculate average bed elevations along transect locations. Sedimentation, or erosion, rates were then calculated along each transect and an average sedimentation rate for the Thompson Island Pool was determined using the transect rates. This method yielded an average sedimentation rate of 0.24 cm/yr. The second technique determined the average bed elevation in 1977 and 1991 for the Thompson Island Pool, using all of the available data from each of those surveys. The reach-average sedimentation rate was then calculated to be, using the 1977 and 1991 average bed elevations, 0.57 cm/yr.

2.2 SOLIDS MASS BALANCE

Estimates of sedimentation rates in the Upper Hudson River by direct measurement methods, see Section 2.1, were found to have a wide range of values, from 0.24 cm/yr to more than 3 cm/yr. Sediment core dating produces information at selected locations in the river and it was shown to only be reliable in depositional zones. Thus, this method cannot be used to determine reach-average sedimentation rates, e.g., the Thompson Island Pool. Analysis of bathymetric data can provide good estimates of reach-average bed elevation changes, if horizontal and vertical datums have been accurately determined. Data sets available for the Thompson Island Pool (1977 and 1991 surveys) yielded estimates of the reach-average sedimentation rate that varied by about a factor of two (0.24 to 0.57 cm/yr).

Variability and uncertainty in these results indicate that direct measurement methods must be supplemented by additional analysis to improve quantification of sedimentation rates in the Upper Hudson River. The direct measurement data can be used to provide limits on sedimentation rates in the Upper Hudson River. Sediment core dating provides an upper bound on localized deposition rates. Bathymetric data

analyses can be used to narrow the range of reach-average sedimentation rate in the Thompson Island Pool to between 0.24 and 0.57 cm/yr.

A sediment mass balance approach can produce additional information about sedimentation rates throughout the Upper Hudson River, which cannot be realized using the direct methods described in Section 2.1. The first step in constructing a mass balance for solids in the Upper Hudson River is to determine the solids loading to the system, and a loading analysis is discussed in the following sub-section. A method is then presented for completing the mass balance and estimating net sedimentation in the system. This approach uses available data at Fort Edward, Stillwater and Waterford to construct simplified mass balances and calculate order-of-magnitude average sedimentation rates for the Fort Edward to Stillwater and Stillwater to Waterford reaches.

2.2.1 Estimating Watershed Sediment Loads

Tributary sediment loading will have a major impact on net sedimentation in the Upper Hudson River. Any attempts to predict past, present or future sedimentation rates in this riverine system using a quantitative framework, e.g., a numerical model, will thus require accurate estimates of annual sediment loading to the system. Because very few direct measurements exist for solids loadings from Upper Hudson River tributaries, a method is proposed in this section to address this requirement.

Suspended sediments are transported into the Upper Hudson River between Fort Edward and Waterford from two sources: (1) the upstream limit on the Hudson River at Fort Edward and (2) eight primary tributaries (see Table 2-1). Sufficient historical data exists at the Fort Edward location to adequately estimate the average annual sediment load in the Upper Hudson River at that point. Various groups, e.g., USGS, have collected total suspended solids (TSS) concentration data at Fort Edward between 1977 and the present. These data, along with corresponding flow rate

measurements made at the USGS gaging station at Fort Edward, can be used to develop a rating curve which relates TSS to flow rate.

$$C_{fe} = \begin{cases} 3.5 & , Q_{fe} \leq 10,000 \\ 5.53 \left(\frac{Q_{fe}}{10,000} \right)^{2.1} & , Q_{fe} > 10,000 \end{cases} \quad (2-1)$$

where C_{fe} is TSS at Fort Edward (mg/l) and Q_{fe} is flow rate at Fort Edward (cfs). This relationship was used to estimate the average annual sediment load at Fort Edward in the following way. For each day during the 15-year period from 1977 to 1992, the daily average TSS concentration at Fort Edward was calculated by using the measured daily average flow rate in Equation (2-1). The annual sediment load for each year during this period was then calculated using estimated TSS and measured flow rates. The average annual sediment load at Fort Edward between 1977 and 1992 was thus determined to be 30,500 metric tons/yr.

Sediment loading data for tributaries to the Upper Hudson River between Fort Edward and Waterford are sparse. Few suspended sediment concentration measurements have been made on the eight primary tributaries in this region. Virtually no tributary data has been collected during floods, which is of primary importance for accurately determining annual sediment loads. Therefore, an approximate method has been used to develop sediment loading from the eight tributaries along this reach.

Knowledge about the watershed in this area is helpful in developing estimates of tributary sediment loads. The Upper Hudson River drainage basin encompasses an area of 4620 mi² upstream of Waterford, with 61% of that area (2817 mi²) located upstream of Fort Edward. The mean flow rate at Fort Edward is 5230 cfs and it increases to 8150 cfs at Waterford, which is a 56% increase.

The surficial geology (soil types) and land use in this watershed changes just north of the Fort Edward area. In the Adirondack region north of Fort Edward, soils are primarily composed of sandy tills and a low fraction of the land has been developed for agricultural use. A transition to different soil types and greatly increased agricultural use occurs in the vicinity of Fort Edward. A large portion of the watershed between Fort Edward and Waterford contains two types of soils: glacial till and lacustrine silt/clay. Glacial till is composed of a poorly sorted mixture of clay and silt that was deposited underneath glacier ice in thicknesses ranging from 1 to 50 m. The glacial till deposits are mainly located east of the Upper Hudson River. The lacustrine silt and clay deposits were formed in Glacial Lake Albany, which was formed about 15,000 years ago. These laminated deposits can be up to 100 m thick and are generally found within 3 miles of the river, except for a large deposit northeast of Fort Edward.

The Soil Conservation Service (SCS) has studied the erosional characteristics of many watersheds in New York state, including the eight tributaries considered here. Estimates of gross soil erosion, on an annual basis, from these watersheds have been made by SCS (1974). These estimates are presented in Table 2-1.

TABLE 2-1. ESTIMATED SEDIMENT LOADING FROM TRIBUTARIES ON THE UPPER HUDSON RIVER				
TRIBUTARY	REACH	DRAINAGE AREA (mi ²)	GROSS SOIL EROSION* (tons/yr)	ANNUAL SEDIMENT LOAD (tons/yr)
Snook Kill	8	122	66,000	9,900
Moses Kill	8	69	62,900	9,400
Batten Kill	5	450	151,300	22,700
Fish Creek	5	230	86,200	12,900
Flatly Brook	5	85	68,700	10,300
Hoosic River	4	700	263,900	39,600
Anthony Kill	3	67	26,900	4,000
Deep Kill	2	68	35,000	5,300
*Soil Conservation Service estimate				

Not all of the soil eroded in these watersheds will be transported to the Upper Hudson River, as discussed previously. The delivery ratios for the eight tributaries cannot be determined from available data and have been estimated as follows. As a first approximation all tributaries on the Upper Hudson River have been assumed to have the same delivery ratio. Data from watersheds in others regions of the United States have indicated that delivery ratio decreases as drainage basin area increases (Vanoni, 1975). These data, generally obtained from Midwestern rivers, suggest that delivery ratios for watersheds between 50 and 500 mi² range between approximately 20% and 5%. The two largest tributaries on the Upper Hudson River (Hoosic River and Batten Kill) flow through relatively steep topography suggesting that these larger tributaries would have higher delivery ratios than would normally be expected given the drainage basin size. This fact, along with the uncertain relationship between drainage basin size and delivery ratio in this region, is the basis for assuming that delivery ratios in this reach of the Upper Hudson River are independent of drainage basin size. Finally, the delivery ratio for these tributaries has been assumed to be 15%. This relatively high value was chosen because of the soil types, land use and topography in this region.

Using this delivery ratio, annual sediment loads to the Upper Hudson River from the eight tributaries can be calculated using the SCS soil erosion estimates (Table 2-1). The estimated annual loads range from 4,000 to 39,600 metric tons/yr. The total tributary load is 114,100 metric tons/yr, which is considerably larger than the annual load at Fort Edward of 30,500 metric tons/yr. Thus, the total estimated sediment load to the Upper Hudson River between Fort Edward and Waterford is 144,600 metric tons/yr.

Tributary loads are very important to the total sediment loading to the system and, hence, net sedimentation in the Upper Hudson River. The eight tributaries are estimated to bring about 79% of the total annual sediment load into the system. The results of this approximate method for determining tributary loads are consistent with observed changes in land use and surficial geology near Fort Edward. Upstream of Fort Edward, the watershed generally contains forested land with sandy till which generates relatively low sediment loading to the river. Downstream of Fort Edward, agricultural use increases

greatly and large portions of the watershed contain loosely consolidated clay and silt deposits. The nearly five-fold increase in estimated sediment load between Fort Edward and Waterford is consistent with these changes in watershed characteristics. As noted earlier, mean flow rate in the Upper Hudson River increases by 56% in the reach under consideration, with the sediment load increasing by 475%. Thus, TSS concentrations in the river would be expected to be significantly higher at Waterford than Fort Edward, especially during high flow events. Examination of available TSS data at Fort Edward and Waterford indicates that this trend exists, see Figure 2-1, which provides additional support to the validity of this analysis.

2.2.2 Simplified Solids Mass Balance

The sediment loading information presented in the previous sub-section has been used to construct a simplified mass balance for solids in the Upper Hudson River. In addition to upstream and tributary sediment loading information, data were analyzed to estimate solids loading at downstream locations during the time period under consideration. The net sediment deposition rate in a particular reach can be calculated using the following equation:

$$M_{\text{dep}} = M_{\text{up}} + M_{\text{trib}} - M_{\text{down}} \quad (2-2)$$

where M_{dep} is sediment deposition rate; M_{up} is upstream solids loading rate; M_{trib} is tributary solids loading rate; and M_{down} is downstream solids rate. All of the loading rates in Equation (2-2) are in mass/unit time, e.g., metric tons/year. Average values of M_{up} and M_{trib} have already been estimated. Completing the mass balance, and determining M_{dep} , thus requires an estimate of M_{down} .

Sediment rating curves, similar to Equation (2-1), at Stillwater and Waterford were developed from available data:

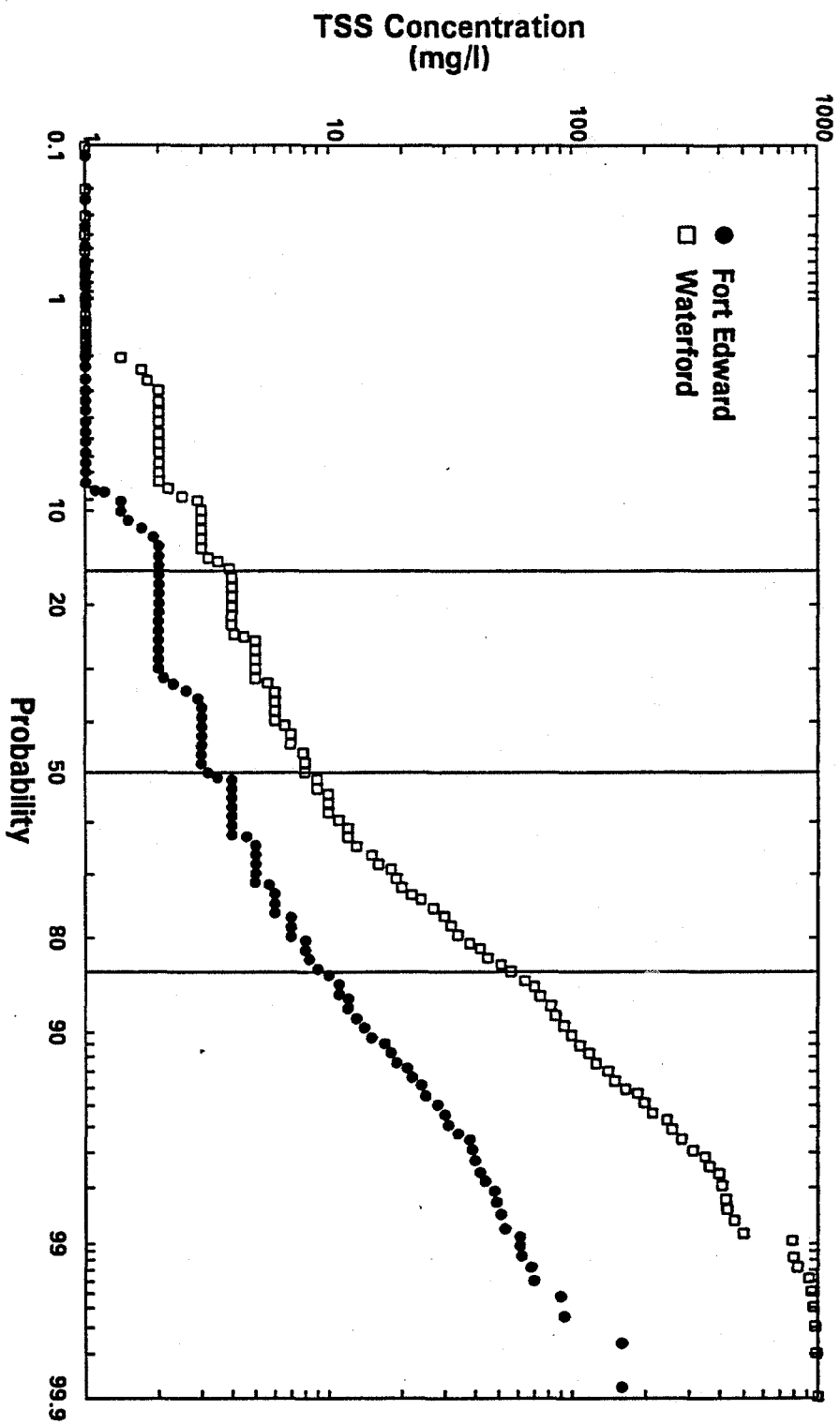


Figure 2-1. Frequency distributions of TSS data collected at Fort Edward and Waterford.

$$C_{st} = \begin{cases} 4 & , Q_{st} \leq 10,000 \\ 11.9 \left(\frac{Q_{st}}{10,000} \right)^{1.58} & , Q_{st} > 10,000 \end{cases} \quad (2-3)$$

and

$$C_{wat} = \begin{cases} 6 & , Q_{wat} \leq 15,000 \\ 4.55 \left(\frac{Q_{wat}}{10,000} \right)^{2.40} & , Q_{wat} > 15,000 \end{cases} \quad (2-4)$$

where C_{st} is TSS at Stillwater (mg/l); Q_{st} is flow rate at Stillwater (cfs); C_{wat} is TSS at Waterford (mg/l); and Q_{wat} is flow rate at Waterford (cfs). Daily average TSS concentrations at Stillwater and Waterford were calculated using measured daily average Q_{st} and Q_{wat} for each day during the 15-year period from 1977 to 1992. This information was then used to estimate that the average annual sediment loading rates at Stillwater and Waterford (M_{down}), between 1997 and 1992, were approximately 80,100 and 145,600 metric tons/yr, respectively.

The deposition rates in the Fort Edward to Stillwater and Stillwater to Waterford reaches can now be calculated using Equation (2-2). Net deposition occurred between Fort Edward and Stillwater at the average rate of 15,600 metric tons/year. This deposition rate can be converted to an average sedimentation rate as follows

$$T_{dep} = 100 \frac{M_{dep}}{\rho_s A} \quad (2-5)$$

where T_{dep} is sedimentation rate (cm/yr); ρ_s is bulk density of bed sediments (g/cm^3); and A is sediment bed area (m^2). Sediment bed property data indicates that the average value of ρ_s for this reach is approximately $0.88 g/cm^3$. The area of the sediment bed between Fort Edward and Stillwater is about $8.46 \times 10^6 m^2$. The resulting net sedimentation rate

is 0.21 cm/yr, which compares favorably with sedimentation rates determined by direct measurement methods in sections of the reach between Fort Edward and Stillwater.

Temporal changes in the vertical distribution of PCB sediment bed concentrations provide additional support that net sedimentation is occurring in this segment of the Upper Hudson River. Average PCB sediment concentrations for the reach between Fort Edward and Stillwater, in the 0-5 cm, 5-10 cm and 10-25 cm layers of the bed, in 1977 and 1991 are presented on Figure 2-2. These vertical profiles indicate that net sedimentation is occurring because average PCB concentrations have decreased in all three layers of the bed, with the greatest decline being found in the surficial (0-5 cm) layer. If net erosion had occurred in this segment of the river, 1991 surficial bed concentrations would not have decreased because PCB levels in 1977 increased with increasing depth in the bed. Erosion (scouring) of the sediment bed between 1977 and 1991 would have exposed higher concentrations of PCBs at greater depth, which is not indicated by average surficial bed concentrations in 1991.

The mass balance between Stillwater and Waterford yielded net erosion at the average rate of -16,600 metric tons/yr. The average bulk density for this reach is 0.92 g/cm³ and the bed area is approximately 6.27×10^6 m². Thus, the net erosional rate was estimated to be -0.29 cm/yr between Stillwater and Waterford. Direct measurement analyses have not been extended to this area of the Upper Hudson River, so the validity of this result cannot be evaluated at the present time using direct measurement data.

Similar to what was observed in the Fort Edward to Stillwater reach, significant decreases in PCB bed concentration between 1977 and 1991 indicate that net sedimentation is occurring between Stillwater and Waterford. Figure 2-3 shows that PCB levels have decreased significantly in surface sediments (0-5 cm and 5-10 cm layers) between 1977 and 1991. These declines in surficial concentration, coupled with the high sediment PCB levels remaining in the 10-25 cm layer, indicate that net sedimentation is occurring between Stillwater and Waterford and not sediment erosion.

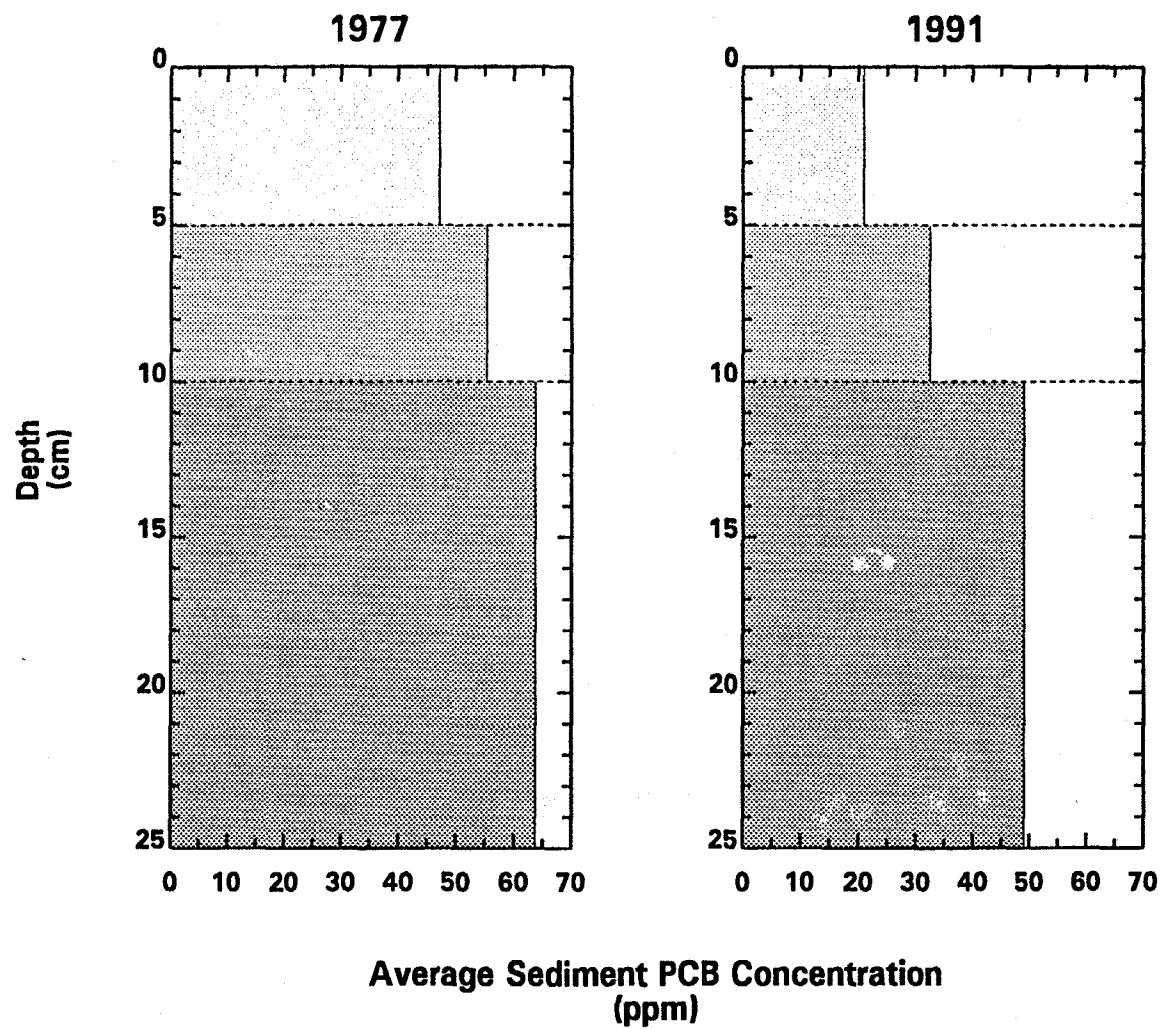


Figure 2-2. Average PCB sediment bed concentrations in 1977 and 1991 for the reach between Fort Edward and Stillwater.

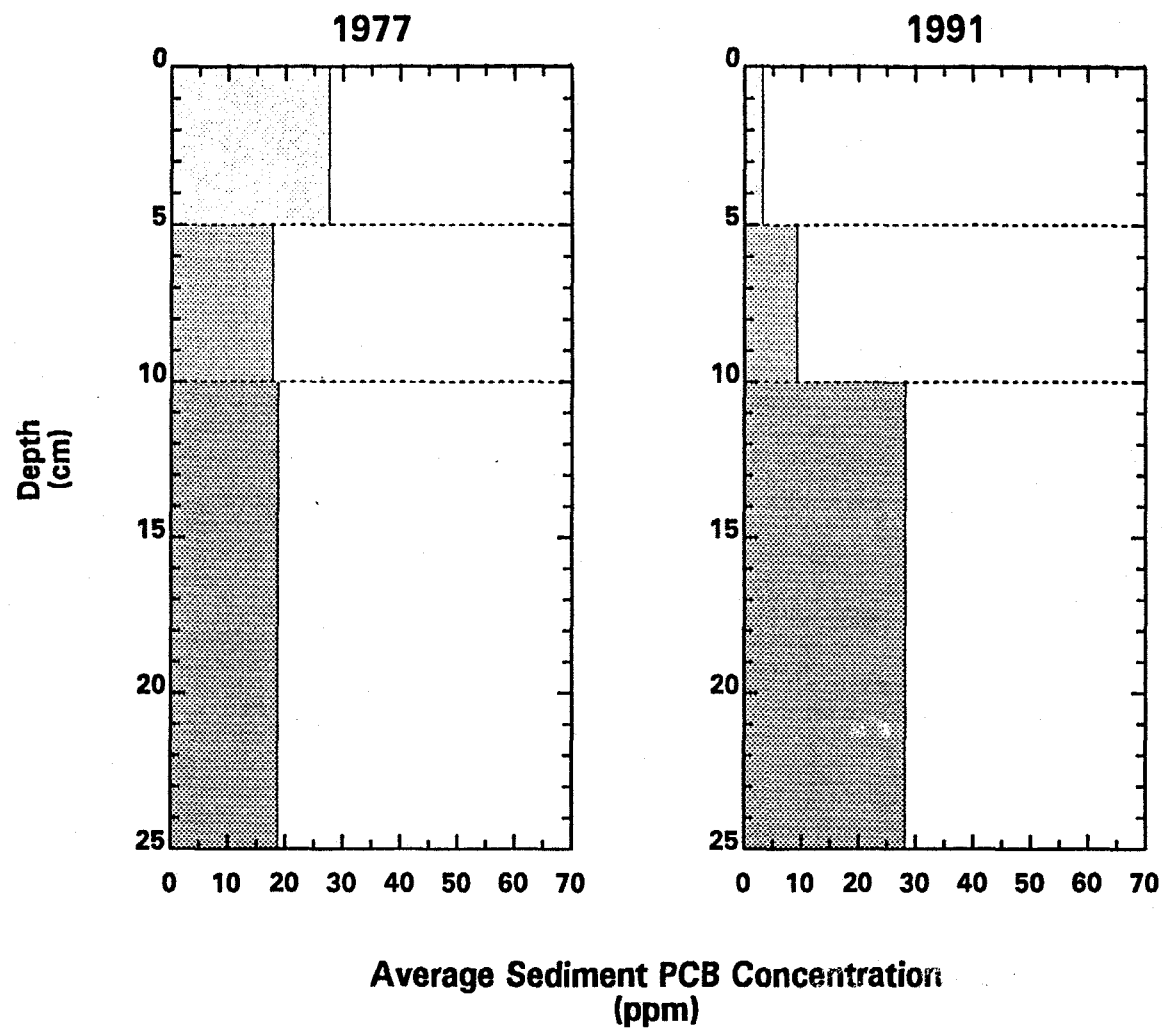


Figure 2-3. Average PCB sediment bed concentrations in 1977 and 1991 for the reach between Stillwater and Waterford.

Based upon the above analysis, it appears that the Upper Hudson River is a net sediment sink and has an average sedimentation rate that ranges between 0.2 and 0.5 cm/yr. The estimated sedimentation rate yielded by the simple mass balance approach between Fort Edward and Stillwater is consistent with sedimentation rates estimated from direct measurements. However, the estimate of net erosion between Stillwater and Waterford does not appear to be supported by other data and suggests that the sediment loading estimates for the tributaries in this segment of the river are uncertain. This uncertainty in estimating the net sedimentation rate in the Upper Hudson River is primarily due to a lack of direct data on the amount of sediment delivered by the tributaries to the Upper Hudson River. In particular, the SCS erosion estimate and the assumed delivery ratio of 15% are difficult to validate based only on the existing data. Given the importance of net sedimentation as a natural recovery process, and the uncertainty in the sedimentation rate estimates that are currently available, further work is needed to better understand this phenomenon in the Upper Hudson River.

There are at least two methods for reducing this uncertainty. The first approach is to collect data directly on the sediment loading from the tributaries. Total suspended solids (TSS) or turbidity data, in conjunction with measured flow rates, would need to be collected from the eight primary tributaries, see Table 2-1. The tributary sampling program would have to be properly designed so that adequate data are collected during high flow events (see Section 3.1 for a discussion of the importance of episodic solids loading). This sampling program would also need to be conducted over a period of time that is long enough to develop tributary loading estimates over a wide range of hydrological conditions. It is probable that a multi-year monitoring program would be necessary.

Another approach that can be used to determine sedimentation rates in the Upper Hudson River utilizes calibration of dynamic solids and PCB mass balance models to the full suite of existing field data. Proper application of such models is a credible technique for estimating sedimentation rates in the Upper Hudson River. Such an approach is possible using models similar to those proposed by EPA (LimnoTech, 1993). Section 3 of this paper describes more fully how this may be accomplished.

SECTION 3

APPLICATION OF A SOLIDS MASS BALANCE MODEL

Estimates of sedimentation rates in the Upper Hudson River developed using direct measurement data or a simple solids mass balance have significant uncertainty. As the PCB sediment bed data discussed in Section 2.2.2 suggest, other available, indirect data may provide valuable insights related to sediment deposition or erosion in the Upper Hudson River. Given the complex transport processes of PCBs in the Upper Hudson River, integrating all of the relevant data together to estimate sedimentation rates utilizing simple techniques is problematic. However, solids mass balance models that realistically simulate sediment resuspension and deposition processes in rivers are available. Proper application of this type of model in conjunction with a PCB fate model would allow use of the Upper Hudson River data base to better understand the processes that affect natural recovery in the Upper Hudson River, including sedimentation.

A brief discussion of the primary factors that control sedimentation in a river will be presented in the next sub-section. The purpose of this review is to highlight the key points that must be addressed when developing and applying a solids mass balance, or sediment transport, model to the Upper Hudson River. The modeling approach that has been proposed by EPA is then reviewed. The primary objective of this review is to emphasize the importance of adequate model-data comparisons during the model calibration and validation process.

3.1 DETERMINANTS OF SEDIMENTATION RATE

Sedimentation in a riverine system is controlled by the amount of sediment delivered to the river from the surrounding watershed and subsequent deposition of sediment onto the river bed. Factors determining the amount of sediment transported into a river from its tributaries will be presented in this subsection. The importance of high flow events, i.e., floods, on controlling net sedimentation in a river will also be discussed.

Soil erosion processes in the drainage basin of a river determine the amount of sediment that is delivered to the river, either by direct runoff or by tributary transport. Many factors affect soil erosion in a particular watershed, including: soil types (surficial geology); land use; annual precipitation; climate; and topography.

Not all of the eroded soil in a watershed will be transported into the river; the watershed will retain a large fraction of the eroded soil by trapping it in many different ways before the sediment reaches the river. The percentage of eroded soil that actually is transported into the river is called the delivery ratio for that particular watershed. Delivery ratios typically range from less than 5% to about 50%, i.e., 5 to 50% of the gross amount of annual soil erosion in the watershed will be transported into the river. Delivery ratios have been found to be correlated with drainage basin area; delivery ratios tend to decrease as drainage basin area increases (Vanoni, 1975).

Floods are of critical importance when considering sediment loading from the tributaries of a riverine system. Analysis of data from a wide range of rivers has shown that sediment loading is episodic with a major fraction of the annual sediment load being delivered from the watershed during a few high flow events each year (Walling et al., 1992). This phenomenon occurs in the Upper Hudson River drainage basin. Results of an analysis of sediment loading data collected at 42 U.S. Geological Survey (USGS) sediment discharge stations located in the eastern United States, including stations at Stillwater and Waterford, illustrate this point (Figure 3-1).

The deposition and resuspension of fine-grained, cohesive sediments, i.e., clays and silts, significantly affect net sedimentation in a river. Considerable work has been done over the last 30 years to investigate cohesive sediment dynamics (e.g., Krone, 1962; Partheniades, 1965; Parchure and Mehta, 1985; Burban et al., 1990; Lick et al., 1995). One result of experimental work on cohesive sediment resuspension has been quantification of the phenomenon referred to as bed armoring, which is the observation that only a finite amount of sediment can be resuspended from a cohesive bed at a specific shear stress (Parchure and Mehta, 1985; Tsai and Lick, 1987; Graham et al., 1992). An

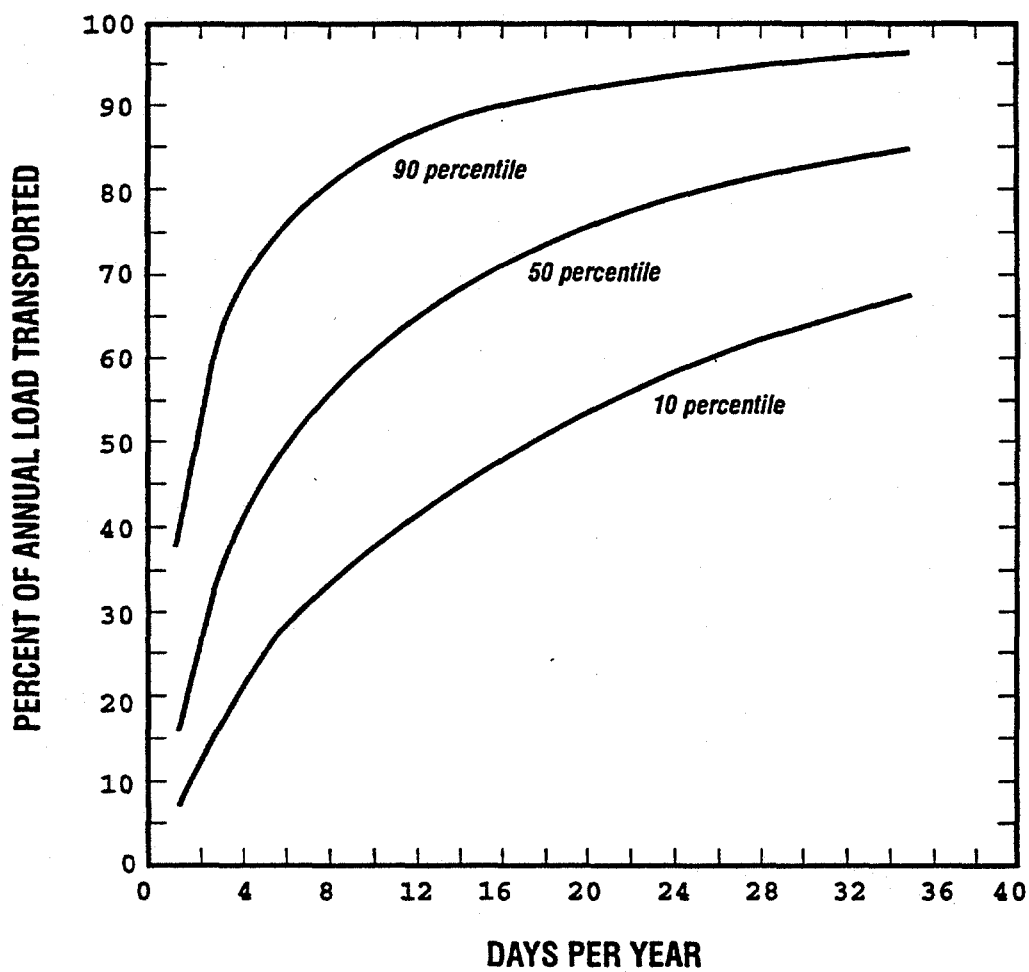


Figure 3-1. Portion of annual sediment load transported during a specific number of days per year. Variability in sediment loading is indicated by 10, 50, and 90 percentile lines. A total of 721 years of data from 42 rivers were used in the analysis.

important finding from this research was that erosion of cohesive sediments is a highly non-linear process in a river; small increases in river velocity, or flow rate, cause large increases in resuspension (Ziegler and Connolly, 1995).

Deposition of fine-grained sediments is affected by the settling characteristics of these sediments, changes in composition of the suspended load, and turbulence near the sediment-water interface. Flocculation of cohesive particles in the water column has been shown to have a significant impact on the settling speed of flocs (Burban et al., 1990). Suspended sediment composition data collected in various rivers suggests that the fraction of coarse sediment in the suspended load increases during floods (Walling and Moorehead, 1989). Turbulence effects in the bottom boundary layer, combined with flocculation effects on settling speeds and load composition changes, causes fine-grained sediment deposition to be a non-linear process.

Thus, net sedimentation is an episodic process in rivers due to: (1) episodic sediment loading from tributaries and (2) non-linearity of fine-grained sediment resuspension and deposition. A relatively few high flow events each year can then be responsible for most of the annual sedimentation in a river. Geologists and geomorphologists have recognized the impact of episodic deposition on the geologic record (Ager, 1981; Dott, 1983), which lends support to the above observation. Lick (1992) has also discussed the importance of extreme events on sediment loading and deposition in rivers and lakes. These factors need to be considered in the development and calibration of a solids transport model for the Upper Hudson River. Neglect of episodic sedimentation processes in the application of a model to this river may produce results of questionable value.

3.2 CALIBRATION REQUIREMENTS FOR A SOLIDS TRANSPORT MODEL

Solids mass balance, or sediment transport, models have been successfully applied to other riverine systems, including: Fox River in Wisconsin (Gailani et al., 1991), Pawtuxet River in Rhode Island (Ziegler and Nisbet, 1994), Saginaw River in Michigan

(Cardenas et al., 1995), Watts Bar Reservoir in Tennessee (Ziegler and Nisbet, 1995) and Buffalo River in New York (Gailani et al., 1995). The solids transport modeling approach that EPA has proposed to use on the Upper Hudson River is similar to these past studies (LimnoTech, 1993). Proper application of a mass balance model to this system by EPA could produce a credible tool for predicting sedimentation rates in the Upper Hudson River.

The two critical tasks that must be successfully completed if EPA is to develop a solids mass balance model that can accurately quantify sedimentation in the river are: (1) specification of external solids loadings (from upstream and tributary sources) and (2) model-data comparisons to demonstrate that the model has been adequately calibrated and validated. The impact of upstream and tributary sediment loads, and methods to determine those loads, on sedimentation in the Upper Hudson River has been examined in Section 2 and will not be discussed further.

The ability of a solids mass balance model to realistically and accurately predict sedimentation rates in a river can only be evaluated by rigorous comparisons between model results and data. Sufficient model-data comparisons must be made by EPA to demonstrate that the Upper Hudson River solids transport model has been adequately calibrated and validated. Successful calibration and validation of the model will indicate that the solids mass balance model is realistically simulating resuspension and deposition of sediments and that external solids loadings have been accurately specified.

Four primary types of model-data comparisons need to be conducted by EPA during calibration and validation of the Upper Hudson River solids transport model, see Table 3-1. Other model-data comparisons could be made, but those listed in Table 3-1 are of critical importance for evaluating model performance. Failure to adequately simulate system response in any of these four areas would indicate that the solids transport model is improperly calibrated and reduce confidence in the predictive capabilities of the model.

TABLE 3-1. NECESSARY MODEL-DATA COMPARISONS	
Purpose	Comparison of calculation and data ⁽¹⁾
Evaluate the ability of the model to account for all sources of suspended solids and their long-term average transport	Annual average solids loading passing Schuylerville, Stillwater and Waterford
Evaluate the ability of the model to capture the variability of suspended solids caused by variations in loading and net solids flux across the sediment-water interface	a. Temporal distribution of TSS during flood events b. Long-term comparison of observed and calculated TSS (e.g., 1977 to 1994)
Check that the sedimentation rate, in combination with other loss mechanisms, properly accounts for the observed long-term changes in PCB concentration at all locations within the sediment column	Change in surface and subsurface sediment PCB concentration between 1977 and 1991
Evaluate the ability of the model to account for the relative contributions to TSS coming from resuspension of contaminated solids and external loading of clean solids.	Water-column PCB levels during flood events that occur nearly each year of the 17-year record (1977 to 1994)
⁽¹⁾ Data are available for each of these comparisons	

The EPA solids mass balance model can be used to predict annual average solids loadings at Schuylerville, Stillwater and Waterford, as was done with the simplified mass balance model in Section 2.2.2. These predicted loading rates can be compared with estimated annual average loadings, using available TSS and flow rate data, at these three locations. The importance of this model-data comparison is to evaluate the model's ability to account for all sources of suspended sediment and the long-term average transport of those solids.

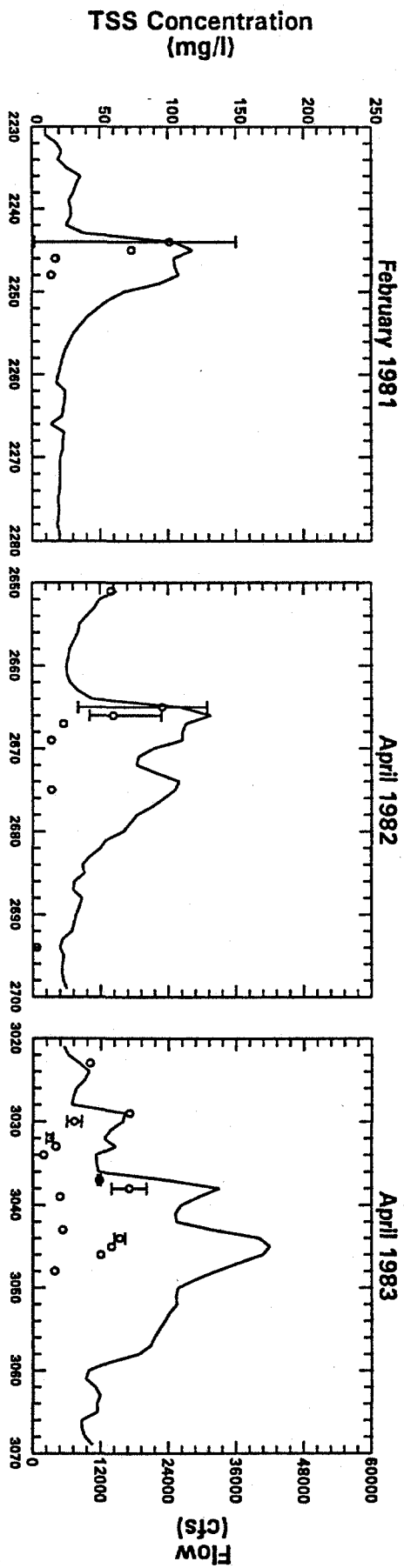
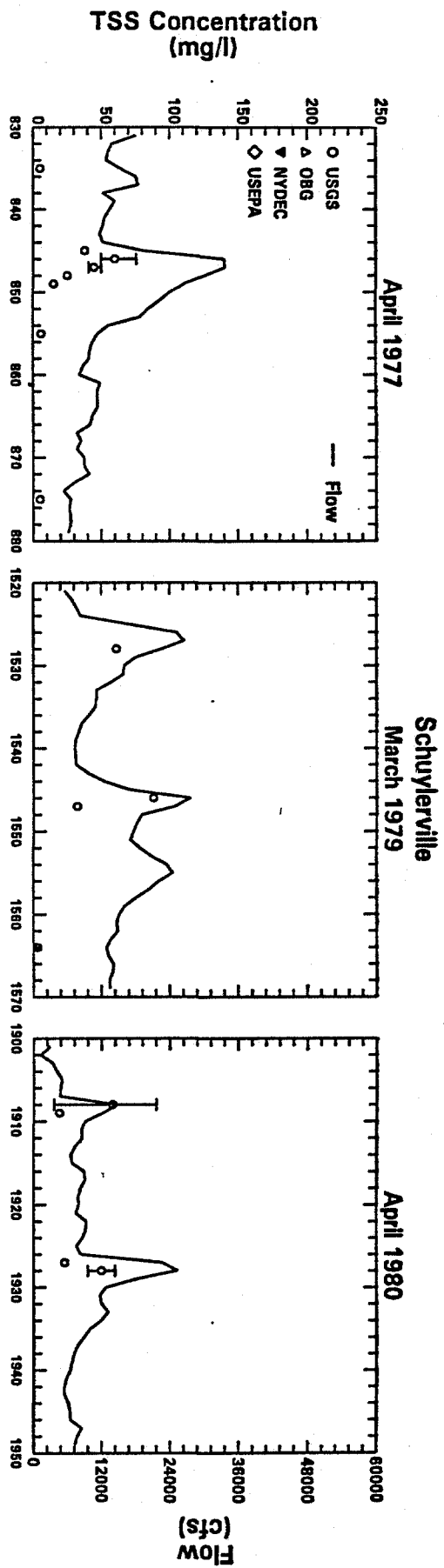
Correctly simulating temporal variations in TSS, at several locations on the river, over a wide range of flow rates and tributary loadings is also a necessary requirement for successful calibration of the model. Comparisons of predicted and observed TSS, on a daily average basis, need to be done over relatively long periods. Upper Hudson River TSS data are available from 1977 to 1994, making a 17-year long comparison possible. This

portion of the calibration process is needed to demonstrate that the solids transport model can simulate temporal variability of suspended solids caused by external loading variations and net sediment flux across the sediment-water interface.

The focus of the TSS model-data comparison task should be on high flow events, as was done during similar studies on the Fox River (Gailani et al., 1991) and the Pawtuxet River (Ziegler and Nisbet, 1994). Focusing on model performance during floods is critical because, as discussed previously, a major fraction of the annual erosion, deposition and transport of sediment in a river occurs during a few high flows each year. Compilation of available TSS data for the Upper Hudson River indicates that sufficient data exists to calibrate and validate the EPA solids transport model under flood conditions. Some of the TSS data available at Schuylerville, Stillwater and Waterford during floods that have occurred since 1977 are presented on Figures 3-2 to 3-4.

Further validation of the ability of the solids transport model to accurately simulate net sedimentation in the Upper Hudson River should be done through model-data comparisons of water column and sediment bed PCB concentrations in the river using the chemical fate and transport component of EPA's modeling framework (LimnoTech, 1993). Comparisons need to be made between predicted and observed sediment bed PCB concentrations throughout the Upper Hudson River over a sufficiently long period, e.g., 1977 to 1991. As was discussed in Section 2.2.2, significant decreases in bed PCB concentrations have occurred during this 14-year period, see Figures 2-2 and 2-3. The purpose of this model-data comparison is to show that the predicted net sedimentation rate, in combination with other PCB loss mechanisms, properly accounts for observed long-term changes in sediment bed PCB concentrations.

Finally, comparisons between predicted and measured water column PCB concentrations during floods should be made, similar to the solids transport calibration discussed earlier. Favorable agreement between predicted and observed water column PCB concentrations, as well as suspended solids, during floods would be a strong indication that the solids transport model is properly simulating sediment bed erosion and



Julian Date
(Day 1 = January 1, 1975)

Figure 3-2. Flow rate and TSS data collected at Schuylerville during some floods that have occurred since 1977.

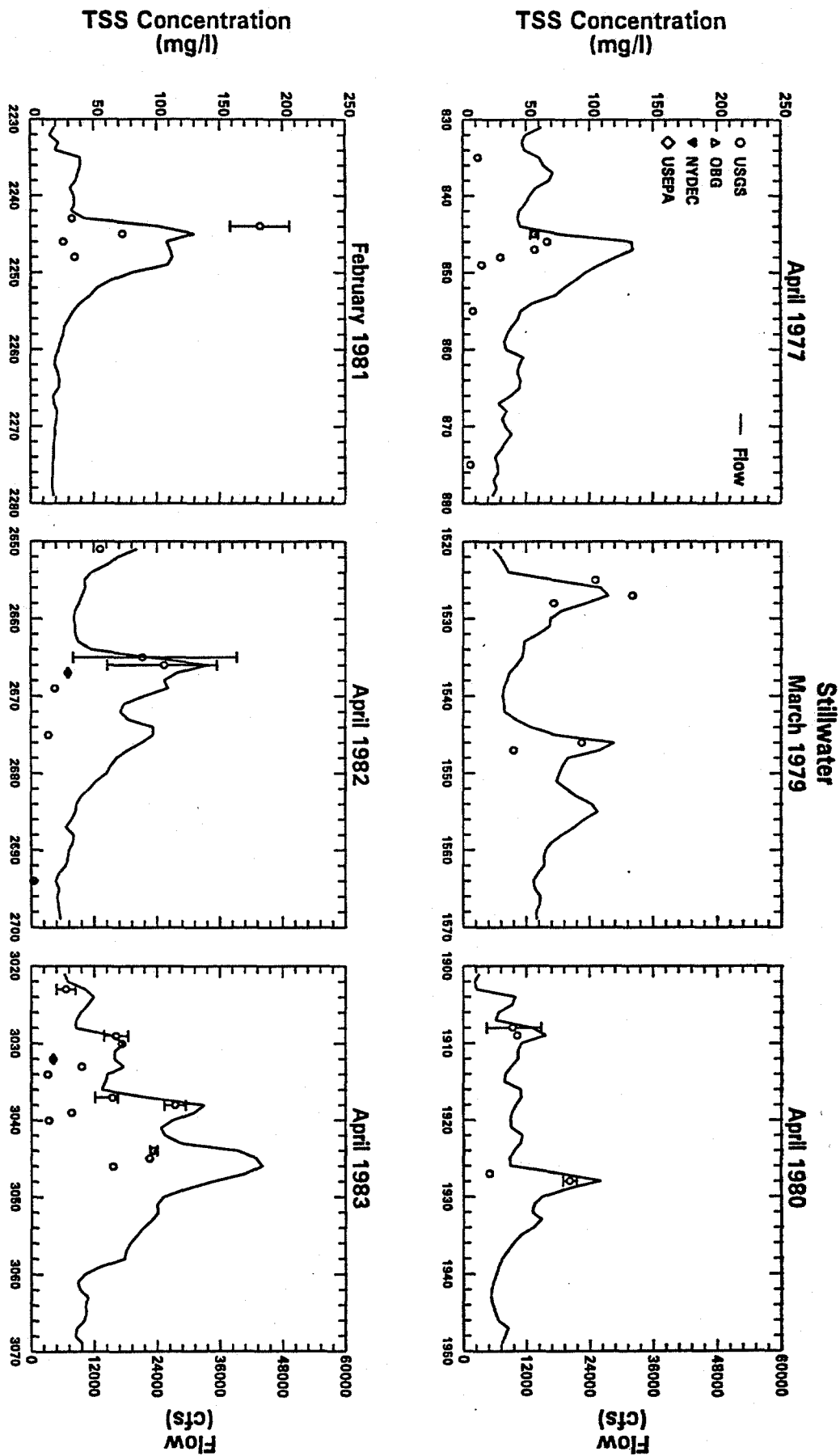


Figure 3-3. Flow rate and TSS data collected at Stillwater during some floods that have occurred since 1977.

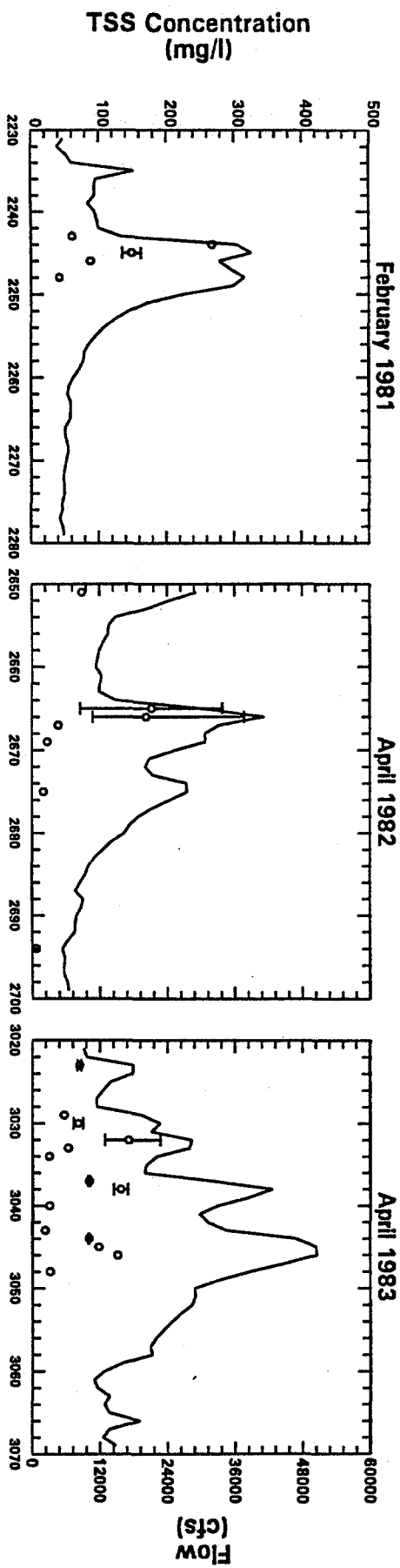
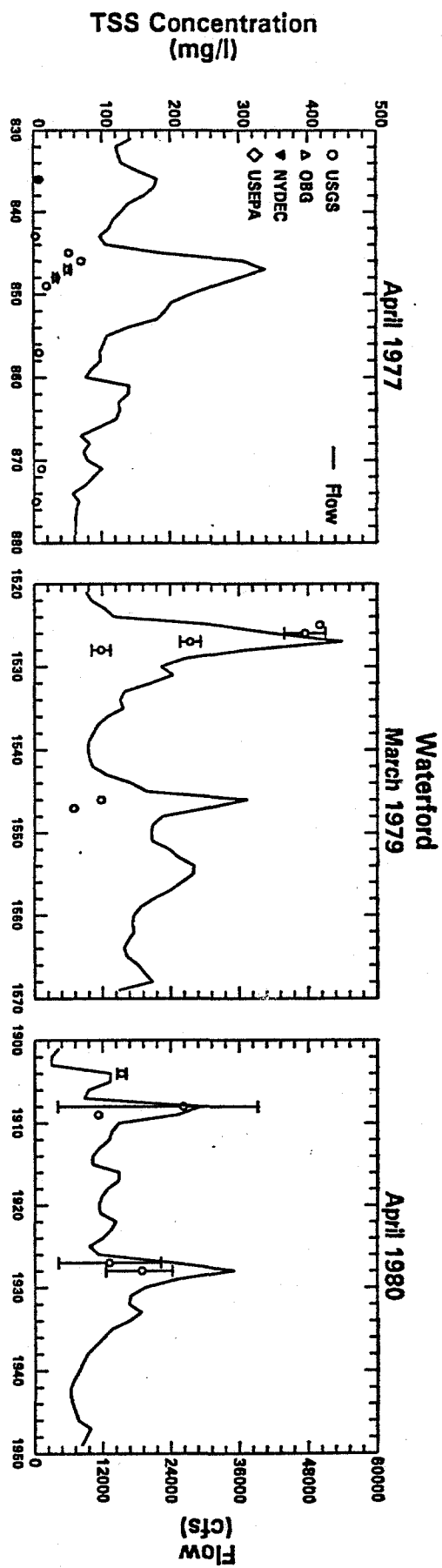


Figure 3-4. Flow rate and TSS data collected at Waterford during some floods that have occurred since 1977. Note that the TSS scale has changed from that on Figures 3-2 and 3-3.

that the tributary sediment loads have been estimated with reasonable accuracy. This point is important because if the relative contributions of the predicted bed erosion and estimated tributary loading to the total sediment load in the river were significantly in error, then EPA's chemical fate and transport model would tend to greatly over or under predict water column PCB concentrations during floods.

The above recommendations will hopefully be useful in EPA's efforts to develop, calibrate and validate a solids mass balance model of the Upper Hudson River. This type of model can be an important tool in quantifying sedimentation in the river, which in turn impacts predictions of the long-term fate of PCBs in the system. However, the scientific credibility of EPA's solids transport model must be demonstrated through extensive model-data comparisons, similar to those discussed above.

SECTION 4

CONCLUSIONS

Burial of PCB-contaminated sediments in the Upper Hudson River is a natural remediation process that decreases surface sediment PCB concentrations and, hence, decreases the bioavailability of PCBs in this river system. Determining the effects of burial on PCB levels in the sediment bed, either past, present or future, requires a reliable methodology to accurately quantify sedimentation rates in each reach of the Upper Hudson River. Two approaches that can be used to quantify sedimentation have been discussed in this paper: direct measurement and simplified mass balance. Direct measurement techniques were shown to yield uncertain sedimentation rates, e.g., a factor of two variation (0.24 cm/yr to 0.57 cm/yr) for reach-average sedimentation in the Thompson Island Pool. Although these results are insufficient for quantitative analyses of PCB fate in the river, the direct measurement results are qualitatively consistent and useful. Sediment core dating and bathymetric data analyses both indicated that net sedimentation is occurring in the river, suggesting that natural recovery due to burial is happening in the Upper Hudson River.

Further evidence that net sedimentation is occurring in the Upper Hudson River was provided by construction of simplified mass balances. Average net sedimentation, at the rate of 0.21 cm/yr, was calculated for the reach between Fort Edward and Stillwater using this simplified solids balance approach. While this result can only be considered an order-of-magnitude estimate, it is consistent with and compares favorably with sedimentation rate estimates derived using direct measurement methods. The simplified mass balance between Stillwater and Waterford indicated that net erosion was occurring in this reach. However, this result is inconsistent with observed changes in sediment bed PCB concentrations in this portion of the river between 1977 and 1991, see Section 2.2.2. Thus, the simplified mass balance constructed for the lower portion of the river is not a reliable method, at the present time, for estimating net sedimentation.

Temporal changes in PCB concentrations of surficial sediments throughout the Upper Hudson River are consistent with the above observations concerning net sedimentation. Significant decreases of reach-average PCB concentrations, using surface-layer sediment data, were observed between 1977 and 1991 in all eight reaches of the river, see Figure 4-1. Various loss mechanisms, e.g., volatilization and downstream transport, have contributed to this decrease in sediment PCB levels. However, based upon the analyses presented in this report, it must be concluded that sedimentation has a major impact on the decline of PCB concentrations in the Upper Hudson River.

Understanding sedimentation patterns in the Upper Hudson River will be critical to predicting the course of natural recovery in the river. As discussed in this paper, estimates of sediment deposition rates using direct measurement data or simple solids mass balances produced results for which the uncertainty is too great to yield meaningful predictions of the Upper Hudson River recovery rate. However, EPA does have an opportunity to develop more refined estimates of sedimentation rates in the Upper Hudson River through application of a solids mass balance model. Adequate calibration of the solids mass balance model is critical, however, and specific model-data comparisons have been suggested in this paper. Through this calibration process, it should be possible to assess whether the remaining uncertainty in the model predictions, which results from an imperfect knowledge of sediment transport processes in the Upper Hudson River, justifies the collection of additional field data in order to increase our knowledge of the actual sedimentation rates in the river.

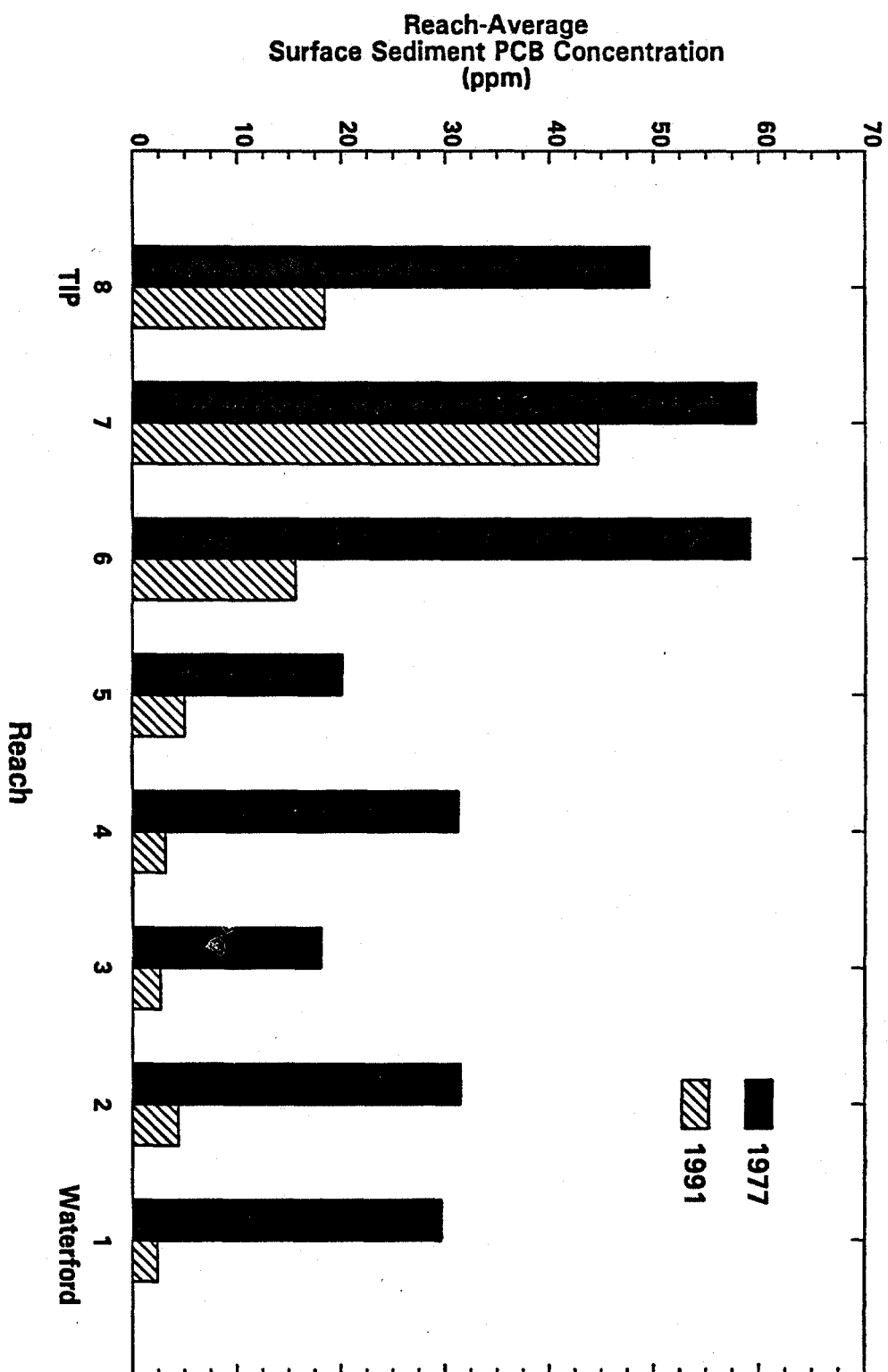


Figure 4-1. Reach-average PCB concentrations in the surficial sediment layer (0-5 cm) in 1977 and 1991.

SECTION 5

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