

ESTIMATION OF THE TOTAL PCB MASS IN THE HUDSON RIVER SYSTEM

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Abstract

Estimates of polychlorinated biphenyls (PCB) load to the Hudson river, PCB transport and fate and the total mass and spatial distribution of sediment-bound PCBs in the Hudson River Estuary vary significantly. A computation of total sediment-bound PCB mass using a comprehensive compilation and analysis of all published Hudson PCB data, sedimentation rates as a function of mile point and river surface yields a range of estimates of total amounts of PCBs in the river from 20 and 440 tons. These ranges result from different (plausible) choices of PCB concentrations and sedimentation rate as a function of milepoint. While the data needed to narrow down this range definitively is currently not available, a narrower range of 150-250 tons seems reasonable based on the available data and a qualitative analyses of the factors contributing to the calculation. The error bars on this computational result are appreciable but it is believed that the method developed in this study can provide a more accurate result as new data become available."

1.0 Introduction

The Hudson River Estuary is located in one of the most populated and industrialized portions of the United States and has been, and remains, subject to significant anthropogenic influence. One of the key questions which users and managers of the estuary face is how to assess the past and current effects of this influence. One of the major anthropogenic influences has been the release of Polychlorinated Biphenyls (PCBs) into the Hudson. Upriver discharges and loading from the New York metropolitan region have introduced significant amounts of PCBs into the Hudson, with estimates ranging from 150 to 680 metric tons (Bero and Gibbs 1990; Clearwater 1999). GE (reference here) quotes the 1994 EPA report as stating that the Fort Edwards Dam removal in 1973 resulted in some 1.1 million cubic yard of sediment moving downstream, resulting in 1.1 million lbs of PCB moving downstream (480 metric ton). (1 metric ton = 1000 kg = 2296 lbs).

The release of PCBs into the Hudson is accepted as fact, but the magnitude of this release (and the fate of PCBs) is the topic of intense discussions. As the water retention time in the estuary is on the order of several days at most, the PCBs that remain in the system are stored in the sediments. What is unclear – and what is sought to be resolved in this study – is the quantity of PCBs in the sediments.

Answering this question is far from trivial as the river is extremely heterogeneous and any kind of estimate based on a small number of datapoints is likely to be significantly inaccurate.

Therefore, it is necessary to base such an estimate on all possible data. In addition, any answer to this question should, where possible, be based on a number of clearly stated assumptions – thus

allowing the discussion on the total mass of PCBs to center on the assumptions, and from these assumptions derive an agreement on the final number.

In this paper, we provide an inventory of the currently available data on PCB concentration, river topography, sedimentation and hydrodynamic conditions in the Hudson. We formulate a straightforward formula to derive from these data a mass estimate, actually a range, for the total PCB mass currently present in the Hudson River System. While the final mass estimate that we arrive at seems plausible, there is a need for additional hard data on sedimentation rates and PCB concentrations in many parts of the river. This data is required to narrow the difference between the top and the bottom limits of our range.

2.0 Background

The purpose of this section is to outline the major characteristics of the Hudson River System and relate these attributes to the contamination problem. This is done by discussing the hydrodynamic properties of the Hudson and defining certain key concepts. The pollution history is addressed with emphasis on the sources, behavior, and fate of PCBs in the system. The background summary provided below sheds light on the important large-scale properties that are integral to the 'Analysis' section of this paper.

2.1 Hydrodynamics

The Hudson estuary drains an area of approximately 35,000 km². The drainage area of the Hudson estuary north of the Troy dam consists of two major rivers, the Upper Hudson River and the Mohawk River. Their annual sediment load to the Lower Hudson River is approximately 1x10⁶ metric tons of sediment annually (Bero and Gibbs 1990). Freshwater flow past the southern tip of Manhattan ranges between 60 m³ s⁻¹ during low river discharge and 1200 m³ s⁻¹ during periods of high river flow, with a mean discharge of 550 m³ s⁻¹ (Bero and Gibbs 1990; Gibbs 1994).

The Hudson River and Estuary can be divided into three broad areas (Figure 2.1), each with its own hydrodynamic properties that provide unique transport regimes for environmental pollutants and sediments. These areas have specific roles in the PCB balance of the system. The first area is the Inner Harbor. It extends from the Narrows to the George Washington Bridge and contains the part of the estuary that is saline throughout the year. Inner Harbor sedimentation rates can be as high as 20 cm yr⁻¹ (Bero and Gibbs 1990). The second area is the tidally influenced part of

the estuary above the harbor, which extends from the George Washington Bridge to the limit of the salt intrusion near Poughkeepsie, New York (milepoint 70). The sedimentation rates in this part of the system are typically an order of magnitude less than in the Inner Harbor, as sediment transport is dominant. The final area is the freshwater Hudson. This area extends north from Poughkeepsie. It is divided into the Lower and Upper Hudson by the dam at Troy, 248 km upstream from Battery Park, the southern tip of Manhattan (Bero and Gibbs 1990). Here, the river is perpetually fresh water and sedimentation rates are generally very low at approximately 0.1 to 0.2 cm yr^{-1} . It should be noted that according to [Analysis, 1999 #78] there is an agreement between EPA and GE data on sedimentation rates in the TIP area for 1997 and 1998 area of on the order of 0.8 cm year . It should be noted that these figures are averages: in each of the three areas there are locations of considerable erosion (negative sedimentation) or instances where the sedimentation rates differ significantly from the more broadly defined averages.

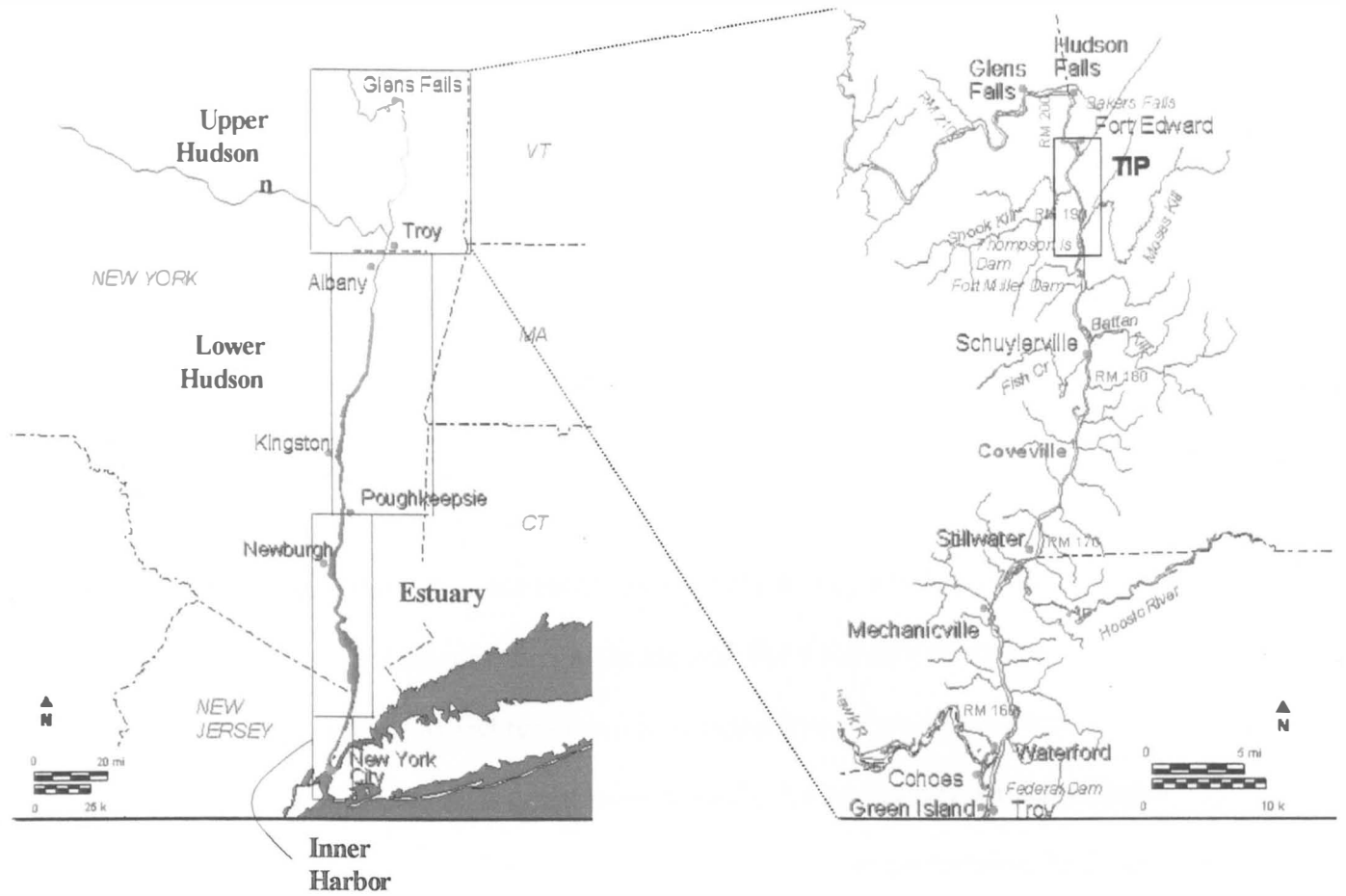


Figure 2.1. Study area and four broad areas of Hudson River. Figure on the right shows Thompson Island Pool (TIP)

2.2 Sedimentary Framework

Contaminants that enter the system either flush out to sea relatively quickly (on the order of days) or adhere to fine-grained sediments which are the primary carriers of organic and trace metal contaminants in river and estuarine systems. These sediments are of either natural or anthropogenic origin (e.g. sewage wastes, fly ash, oil, and dredge spoils). The subsequent fate of these sediments (i.e. their sedimentation and erosion behavior) will determine the fate of the contaminants.

Deposition and erosion in the system are controlled by a combination of diurnal and sporadic processes. The two main diurnal processes in the Hudson River Estuary are current-induced resuspension of bottom sediments and two-layered estuarine flow. Two-layered flow – the process by which small particles being swept downstream in the low salinity surface waters coagulate, settle, and fall into the high salinity bottom waters flowing upstream in the Inner Harbor – is a major factor in the regular sedimentation patterns of the estuary. At the head of the salt wedge (the location of the turbidity maximum) this upstream current fails and significant sedimentation occurs (Bero and Gibbs 1990).

The other type of transport mechanism is governed by irregularly occurring events, which can be either of a small or large scale. The main examples of natural events that occur in the Hudson system are storms and seasonal high flow. Seasonal high flow events account for the majority of sediment transport in a given year. For example, in 1977 more than half of the total yearly sediment load for the Hudson river (approximately 600,000 metric tons) was transported during a two-day period in March. In that same year, only 7 percent of the total sediment load was

transported during normal flow conditions (Bero and Gibbs 1990). Another major isolated event mechanism for moving sediment is dredging. Although it is not a natural phenomenon, it has significant impact on the sedimentary budgets of the Hudson River Estuary. In 1990, approximately 500,000 metric tons of sediment were removed from the harbor (Bero and Gibbs 1990). This process is profoundly affecting the sedimentation equilibrium within the estuary. As a result of dredging, large volumes of sediment are deposited in the lower estuary that would otherwise have ended up in the ocean (those with a provenance in the upper Hudson) or remained in the ocean (those sediments which are deposited in the lower estuary during storm surges)

In summary, while the sediment dynamics of the Hudson are fairly complex and only partly understood, the following components are roughly known:

- (1) the average sedimentation rates in the different areas of the system
- (2) the approximate amount of sediments entering the harbor
- (3) the dominant sediment transport mechanism (isolated events)

The analysis in this study uses the average sedimentation rates. A possible extension could use the other two factors; however, due to the uncertainty in exact sediment provenance and the complexity of factoring this information into an analysis, this information is not used here.

2.3 PCB Sources

The New York/New Jersey Harbor Estuary has among the highest PCB concentrations in the water, sediment, and biota along the coastal United States (Durell and Lizotte Jr. 1998). Over the past decades many studies have been conducted (Olsen, Simpson et al. 1978; Williams, Simpson et al. 1978; Bopp 1980; Bopp, Simpson et al. 1981; Mueller, Gerish et al. 1982; Olsen and al 1984; Rohmann and Lilienthal 1985; Ayres and Rod 1986; Rod, Ayres et al. 1989; Thomann, Mueller et al. 1989; Gibbs 1994; Feng, Cochran et al. 1998; US EPA 1998b , [Analysis, 1999 #78]) on the sources of pollution and the resulting PCB buildup in the Hudson. These studies agree on three current sources of PCBs to the Hudson's water column and food chain:

1. *Historical primary sources* – those PCBs input directly to the system, at some point in the past, due to a specific industrial activity.
2. *Current primary sources* – diffuse sources such as runoff or the discharge from water treatment plants.
3. *Second generation sources* – PCBs input from one of the above primary source categories which were removed from the system through sedimentation and subsequently re-enter the system through erosion/resuspension or biological activity (e.g. burrowing)

The chief historical primary source of PCBs into the river were plants from the General Electric Corporation (GE) which for nearly three decades, from the 1940s through the mid-1970s, disposed PCBs directly in the Hudson River at two capacitor manufacturing facilities in Glen Falls and Fort Edward, New York. There is some uncertainty as to the total amount of PCB released into the Hudson system by GE. Bero and Gibbs (1990) estimated that GE released more

than 150 metric tons of PCB while Durell and Lizotte cite the quantity to be greater than 250 metric tons (Durell and Lizotte Jr. 1998). The US Environmental Protection Agency (EPA) has estimated the number to be in the order of 500 metric tons. Clearwater Hudson River Sloop (an environmental organization/watchdog) states that during the period when they were used in manufacturing, GE legally dumped some 680 metric tons of PCBs into the Hudson River, and unknowingly saturated the bedrock beneath both sites with at least that much again (Clearwater 1999). A recent report by GE [Analysis, 1999 #78]) does not discuss numbers, but does seem to indicate an agreement with the higher estimates at least for the disposal in the Hudson River. In fact, using a combination of GE's and EPA's estimates for the sediment transported downstream and left upstream¹ as a result of the Fort Edwards Dam removal one arrives already at something close to 540 metric tons of PCB which was contained in the Fort Edwards Dam area, and obviously some amount of PCBs released prior to 1973 did not end up in the sediments. Note that figuring out the quantity of PCB disposed in the river and partitioning this between what ended up in the sediments and how these PCBs are remobilized is outside the scope of this thesis. However, it should be noted that (Thomann, Mueller et al. 1989) in their mathematical model from 1989 assume that a relatively small percentage of PCBs disposed in the river actually ended

¹ assuming a remnant deposit density of 2 grams/cubic centimeter some 55.5 metric tons of PCBs would currently be contained in some 380 thousand cubic yards of remnant deposits (remnant deposits being the deposits which remained upstream of Fort Edwards Dam following the dam removal and subsequent scour events). Note here that for river sediments we assume a density of .5 gram/cubic centimeter – however the remnant deposits are exposed and likely have a somewhat larger density.

up in the sediments. The Thomann model had some other assumptions which make it hard to extrapolate these numbers to the numbers given here – however, the highest currently published estimates of PCB released to the river by GE may well be significant underestimates.

Urban runoff (non-point source pollution, sewer overflows), discharge from wastewater treatment facilities and leaks from the bedrock around the GE Hudson Falls Plant site are the three main current primary sources of PCBs to the Hudson system. The amount of PCB removed from the influent to wastewater treatment plants ranges broadly from 20 percent in the most inefficient cases to over 90 percent (Durell and Lizotte Jr. 1998). Durell and Lizotte estimate that the annual PCB contribution from the 26 water pollution control plants discharging to the New York/New Jersey Harbor Estuary is roughly 88 kg, with only a small portion (3%) diverted directly to the estuary during precipitation events (Durell and Lizotte Jr. 1998). The amount contributed by urban runoff is unknown. With regards to the bedrock sources there are a number of bedrock seeps of PCB. The magnitude of these seeps has decreased as a result of remediation efforts undertaken by GE, however the seeps are still active. The exact magnitude and number of these seeps is not known, but from measured seeps and GE's monitoring effort it seems likely that the total PCB release through these seeps is in the order of some hundreds of lbs of PCB per year.

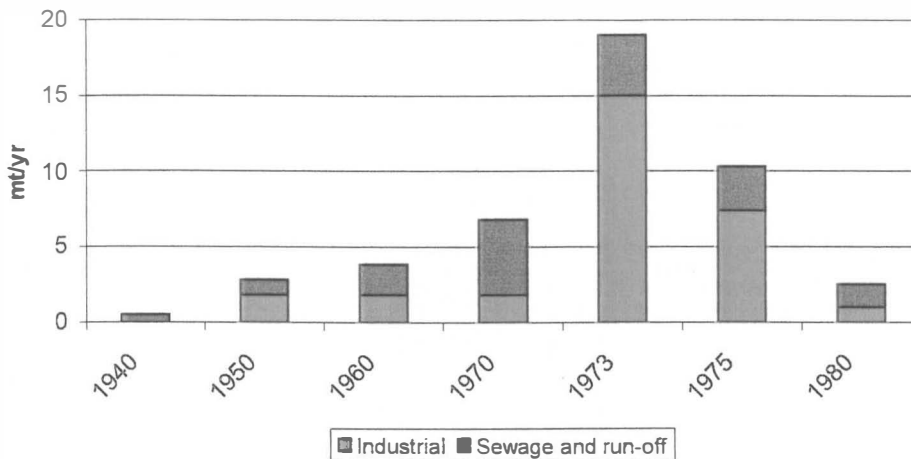


Figure 2.2 Estimated PCB Loading in Hudson River with time (Ayres and Rod 1986)

Both Ayres (1986) and Thomann (1989) estimated historical PCB loading from primary sources. Ayres' numbers are a tabulation of historical data while Thomann derives his data from a predictive model. Figures 2.2, 2.3, and 2.4 show the Ayres and Thomann estimates separately, while Fig. 2.5 provides a comparison of the two sets of data. Note that the datasets are in general agreement in the trends even though the numbers from Ayres are roughly 30 % less than the numbers from Thomann. Also note that the latest figures indicate significantly higher total releases than the data shown by either Thomann or Ayres.

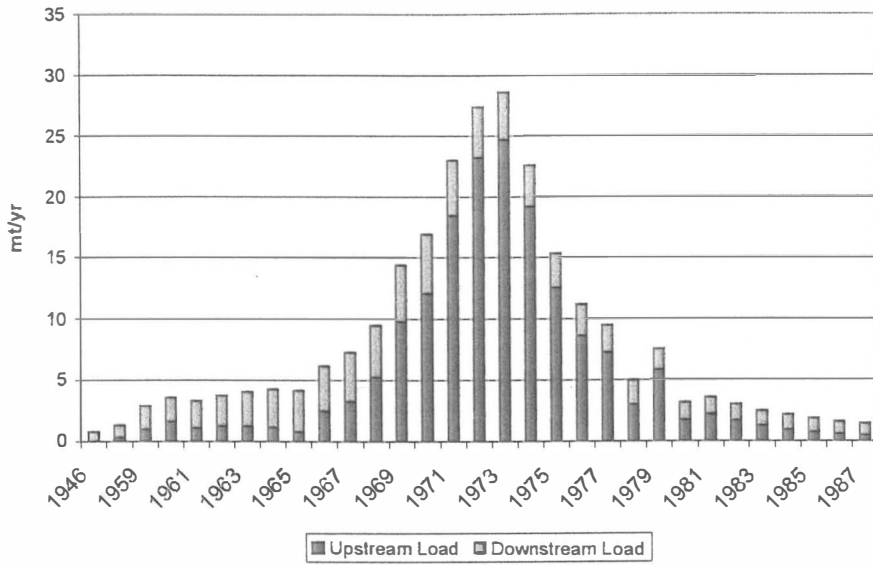


Figure 2.3 Estimated PCB Loading in Hudson River with time
 (Thomann, Mueller et al. 1989)

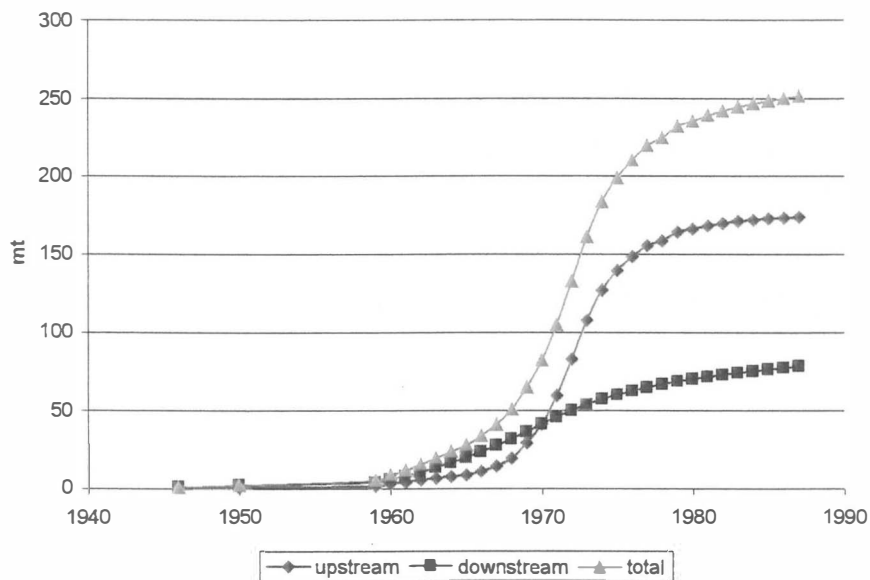


Figure 2.4 Cumulative PCB input from upstream, downstream and total values from data shown in Fig 2.3. Note continued input from downstream sources past late 80's. Also note that according to this data the total upstream PCB release is roughly 170 mt.
 (Thomann, Mueller et al. 1989)

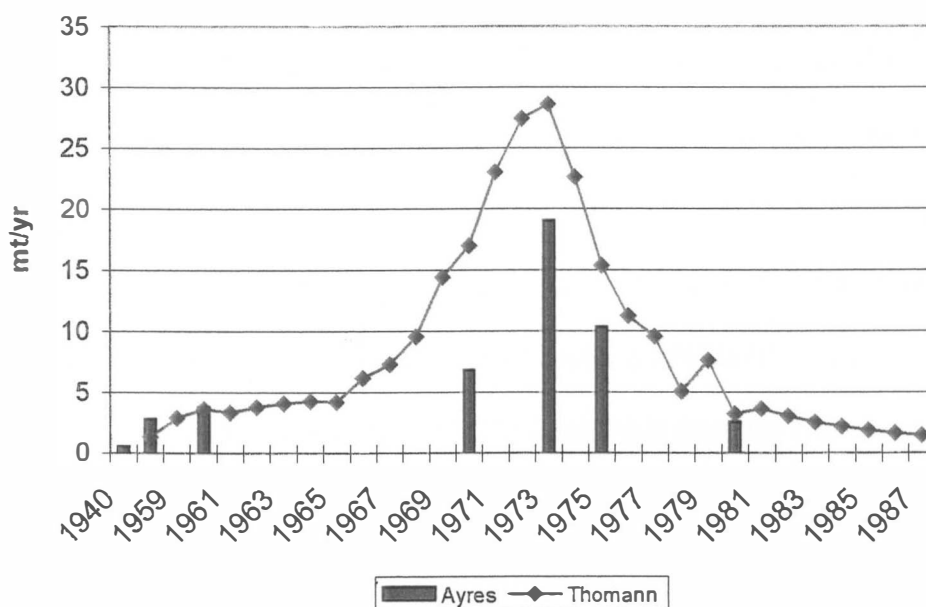


Figure 2.5 Combined Ayers and Thomann data on Total Loading with time
 (Ayers and Rod 1986; Thomann, Mueller et al. 1989)

The sediment reservoir is the only second generation source of PCBs to the water column. The industrial releases mentioned above, in conjunction with the traces found in runoff and municipal discharge, have resulted in a PCB buildup in the river's sediment to the degree that it is now felt that this sediment reservoir is the largest source of PCBs to the water column.

Estimates on the magnitude of this reservoir vary widely but have in general increased over the years. (Bopp, Simpson et al. 1981) estimated that 76 metric tons of PCBs are associated with the tidal Hudson sediments. (Bopp and Simpson 1988) stated that New York Harbor was the major repository, holding approximately 23 metric tons in its sediments. Other hotspots, or areas of significant local concentration, are located upstream of the harbor. The river widens between mile points 85 and 93, and this stretch is thought to contain about 21 metric tons of PCB in its sediment reservoir (Bopp and Simpson 1988). The Thompson Island Pool (TIP), which is probably the single largest PCB source to the Lower Hudson, is stated to contain between 19.6 and 23.2 metric tons (US EPA 1997). The remnant deposits contain some 55 metric tons of PCB (assuming a sediment density of 2 grams/cubic centimeter). The wide range of estimates in total PCB contained in these sediments is again noteworthy. Associated with the wide range of estimates in PCBs in the sediment is a wide range of estimates on PCBs which are released to the system. It has been estimated that the amount of PCB discharged from the Upper Hudson sediment reservoir has decreased from $\sim 2 \text{ ton yr}^{-1}$ in the 1980's to $\sim 1 \text{ ton yr}^{-1}$ today (Feng, Cochran et al. 1998). This issue is addressed in greater detail below.

2.4 PCB Fate

The two core questions surrounding the PCB contamination in the Hudson is the total amount of PCB present in the sediment and the manner in which these sediments release the PCBs – in particular the mechanism and the time frame. It has been theorized that the PCB release out of sediments (sediment flux) is 2-100 times greater than the flux of dissolved PCBs traveling downstream at some points (Achman, Brownawell et al. 1996). There are several possible mechanisms for PCB transfer from the sediments to the water column. The first mechanism, porewater exchange, is the transport of PCBs to the water column via the interstitial water found within the river sediments. The EPA study demonstrated that this mechanism is a viable source of water column PCBs and that the sediments with low levels of dechlorination are the likely candidates (US EPA 1997). Another mechanism is thought to be resuspension of sediments and this was also shown to be capable of yielding the water column patterns observed in EPA study discussed below.

The above core question on PCB fate is driving the EPA study of the Hudson River PCB Superfund site, and the reassessment of its interim 'No Action' decision made in 1984. One of the principal discoveries of the EPA investigation was the determination that the area upstream of the Thompson Island Dam (TID) represents the primary source of PCBs to the freshwater Hudson (US EPA 1997). This area, nearly 330 km (200 miles) north of the Battery, includes the GE Hudson Falls and Fort Edward facilities, as well as the 10 km (6 mile) stretch of water between Fort Edward and TID, that is commonly referred to as the Thompson Island Pool (TIP).

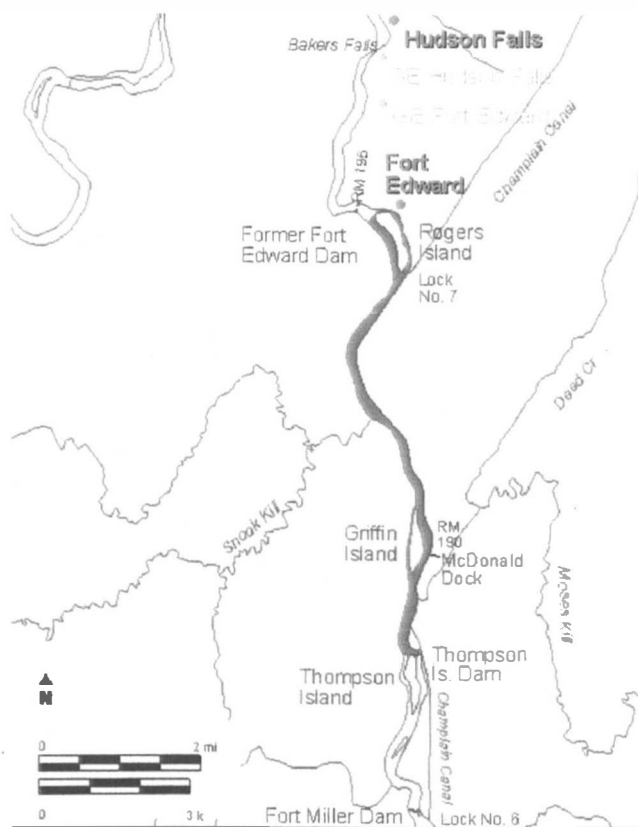


Figure 2.6 Thompson Island Pool

This conclusion was based on a number of various techniques, one being the identification of a unique homologue pattern, or ‘fingerprint,’ for PCBs originating from this area. Based on calculations combining the homologue patterns from the TIP with those of other potential sources, over 75 percent of the congener content in downstream cores was attributable to this one area (US EPA 1997). This suggests that the Upper Hudson is responsible for at least 75 percent of the PCB sediment burden and water column load downstream. Only when the EPA coring reached New York/New Jersey Harbor were other significant PCB types detected. In cores taken

from the Inner Harbor, the Upper Hudson load represented roughly half of the total PCBs in the sediments (US EPA 1997).

GE has claimed that PCB levels in the fish and sediments of the Upper Hudson have declined dramatically as a direct result of their cleanup program (The General Electric Corporation 1999, [Analysis, 1999 #78]). In their research programs, GE scientists and consultants conclude that more fresh sediment enters the Upper Hudson River than leaves it. This “net gain” in fresh sediment covers the river bottom and, along with GE’s cleanup program, is said to be a significant contributor to the river’s robust natural recovery (The General Electric Corporation 1998). GE agrees that some PCBs disappear from the upper river each year through the processes of erosion and diffusion. However, they claim that these processes mostly affect the surficial sediments and not the old, buried deposits. Based on the GE analysis of water, sediment, and fish data, the buried deposits are not a significant source of PCBs to the river system; furthermore, GE feels that little loss would be expected because these deposits are located in depositional areas of the Upper Hudson.

On the other hand, the EPA investigation found little evidence of burial of PCB-contaminated sediment by clean sediment in the TIP. Although burial was observed at some sites, most core sites displayed a loss of PCB inventory (US EPA 1998a). The EPA found that from 1984 to 1994 there had been a net loss of approximately 40 percent of the PCB inventory from the highly contaminated sediments in the TIP (US EPA 1998a). Typical hot spot sediments, those with Total PCB inventories greater than 10 g m^{-2} , exhibit a statistically significant loss. Some specific sites experienced losses from 50 to 80 percent. This loss could be either to the overlying water

column or dechlorination. The extent of dechlorination, however, is limited. Probably less than 10 percent mass loss can be attributed to the dechlorination process (US EPA 1997). This conclusion seems to be agreed with by GE ([GE, 1999 #80], 4-15)

Feng et al (1998), in their comprehensive investigation of the lower 100 km of the Hudson River, collected a large number of sediment core samples. They determined that sediment concentration of Total PCBs shows a decreasing trend down-estuary to New York Harbor where the concentrations increase due to local source inputs in the lower estuary (Feng, Cochran et al. 1998). The contaminant distribution and subsequent analysis led them to conclude that PCBs are partly controlled by upriver sources and are being transported downstream. The high concentration of PCB and other contaminants in New York Harbor sediments indicate that this area serves as a reservoir for particle associated contaminants (Feng, Cochran et al. 1998).

3.0 Data Synthesis

A large number of studies aimed at estimating PCB levels in the Hudson Estuary (either locally or systemwide) have been undertaken by a range of scientific groups (local, state, and federal agencies, universities, consulting firms, environmental organizations). An essential component of this study to establish a PCB mass estimate was to synthesize as much of the gathered data as possible into a format which would allow for data analysis in a geospatial format. The approach used in this study was to enter this data into a Geographic Information Systems (GIS) database, which also contains bathymetry and other relevant information. The following published reports were used as sources:

(Bopp, Simpson et al. 1981; Bopp and Simpson 1988; US Army Corps of Engineers 1991; US Army Corps of Engineers 1993; Achman, Brownawell et al. 1996; Feng 1997b; Feng, Cochran et al. 1998; US EPA 1998b; US EPA 1998c).

The references of US EPA 1998c and both of the US Army Corps of Engineers sources actually include numerous datasets. For instance, the EPA database contains data from their 1992 high-resolution coring campaign, their 1994 low-resolution coring campaign, and sediment samples from the NYDOH from 1984. The present study used several key pieces of information from the above sources: (1) Total PCBs, (2) sample location, (3) sample depth, and (4) sample date.

Although the various studies listed above displayed their data in different ways or emphasized different contaminants and PCB congeners, in most cases it was possible to manipulate the data into a common form for comparison purposes. The form used was the total PCB concentration. In the majority of studies, concentration was expressed in parts per billion ($\mu\text{g PCB kg}^{-1}$)

¹sediment). PCB concentrations were often tabulated separately for each congener in a particular study, but in all cases except one (EPA 1998b) the authors combined their data into a value for Total PCBs. In the EPA 1998b, the authors listed the separate concentrations of each of the various PCB congeners analyzed and provided a simple formula for calculating the Total PCBs. In section 2.7.1 of the EPA report, it is stated that Total PCBs were the sum of the concentrations of the 20 congeners in Table 2-3 multiplied by 2.0.

Figure 3.1 is a map of the Hudson River basin showing the locations of the sediment core data incorporated into the GIS database (Arcview 3.1). The circles indicate data utilized in this particular study. Sediment information from the Upper Hudson, Lower Hudson, Estuary, Harbor, and Raritan Bay was incorporated.

The Bathymetry data were obtained from the National Geophysical Data Center and from digitization of NOAA maps and USGS quadrangle maps. For significant parts of the river (above milepoint 160) no bathymetry is currently available. For this part of the river a digitization of the coastline from USGS quadrangle maps was used to at least have a correct surface estimate. After assembling, georeferencing, and tabulating the sediment data, a GIS was utilized to combine several layers of information in creating a chart detailing the concentration of PCBs in the estuarine and riverine sediments as a function of distance along the river's axis (milepoint or km point). Figure 3.2 shows this distribution of PCBs in Hudson sediments. It is interesting to note that there is both a wide range in measured concentrations and a sparsity of data in the middle part of the river

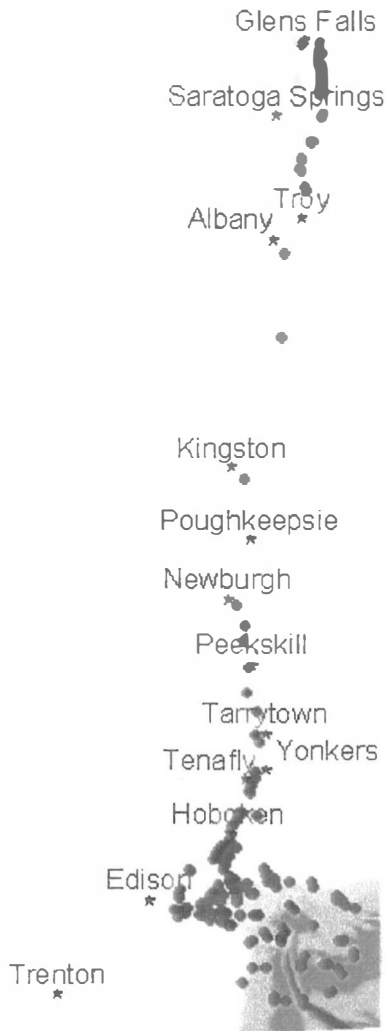


Figure 3.1 Location of study area and distribution of PCB samples

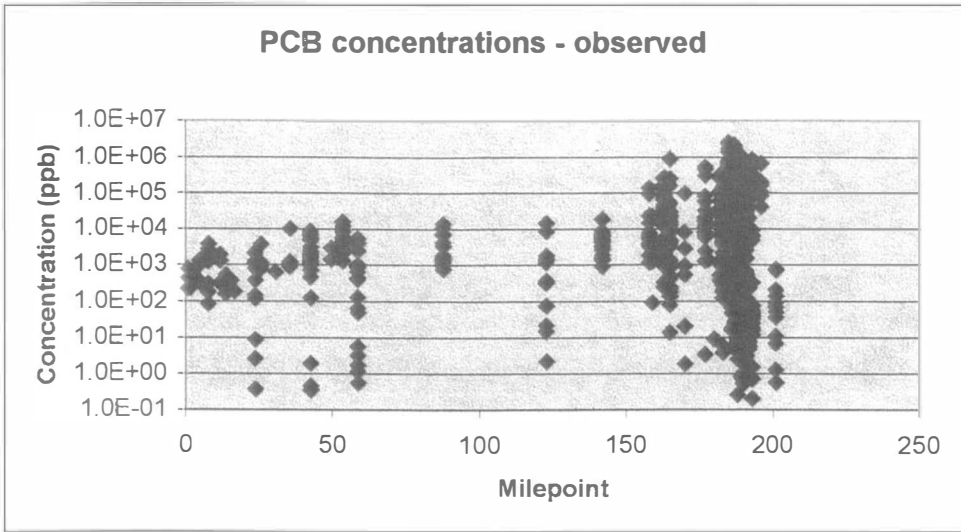


Figure 3.2 PCBs in Hudson Sediments – geographical location and measured values. Milepoint -20 is Sandy Hook, 0 is the Battery, 190 is TIP area. Note both the spread in measured values and the sparsity of data between milepoints 60 and 150.

The question at hand is now how to extract meaning from the PCB distribution shown in figure 3.2. This should take into account the various factors involved in the transport and fate of these contaminants. Primary among these are flow rate and tidal level, sedimentation rate, river depth, and relationships such as river depth to width. The significance of these variables is discussed below.

4 Data Analysis

4.1 Methodology

To estimate the total mass of PCBs locked into the sediments of the Hudson River Estuary we need to know the following parameters:

- Total sedimentation in the river occurring over the past 40 years (approximately the length of time PCBs have been in the Hudson system)
- Current PCB concentration in the sediments deposited over the last forty years
- Density of river sediments
- River bottom surface

If we can quantify these parameters for each point in the river it is possible to obtain the total PCB volume for the river by integrating over the river surface and multiplying by the density, the PCB concentration, and the sediment thickness. The problem is, of course, that we do not have this information. Specifically, we do not have the first two parameters and so our calculation will have to make assumptions on the concentration of PCBs and sedimentation rates. Depending on the values chosen -- and there are a range of choices that can be defended -- total calculated PCBs can vary wildly. We do have the river bottom surface (from river bathymetry and a digitization of the shoreline) and we can make an educated guess as to the density of river sediments (somewhere between .5 and 1).

In our calculation we use a straightforward approach where one value for both PCB concentration and sedimentation rate is assigned to each milepoint of the river. This is done for a number of different PCB and sedimentation rate models. In reality this is of course a gross oversimplification which will be addressed in subsequent work – however the aim of this thesis

was the development of an approach as well as the establishment of a baseline range; the more advanced efforts necessary to refine this calculation falls outside this thesis. However, I do indicate what would be required for this refinement.

The integration outlined above can be separated in a step to determine the total sedimentation in a specific area occurring over the past 40 years (approximately the length of time PCBs have been in the Hudson system). This value is based on integrating the sedimentation rate over the area of the section and then multiplying by the total length of time. A sample calculation below details the method.

$$\textit{Total Sedimentation} = \{area\} * \{sedimentation\ rate\} * \{time\} \quad (4.1)$$

The next step is to determine the total mass of PCBs stored in the sediments of the area in question. This is done by combining the total sedimentation with estimates of PCB concentration and sediment density.

$$\textit{Total PCB} = \{\rho_{sediments}\} * \{total\ sedimentation\} * \{PCB\ concentration\} \quad (4.2)$$

The calculation above can use the basic area element (a 30 x 30 m block of the river). It requires making estimates on total PCB concentration and sedimentation rates. Note that this calculation ignores the division in shallow and deep areas (and the different sedimentation rates associated with it). It also ignores the fact that we have different concentration rates for PCB for different

years (cf. the GE report showing a time dependence of the PCB in cores), and the fact that our data has different ages (so that in the case of PCB loss from the sediments we overestimate the amount of PCBs in the sediments)

4.2 Additional Considerations

While we do not use them explicitly it is useful to investigate the various components of transport and sedimentation when attempting to gain an understanding of the phenomena that influenced PCB fate. Due to the fact that PCBs and other contaminants are transported downstream mostly via suspended solids in the river channel, flow rate (and the sedimentation which is directly correlated to this) is a primary factor in contaminant transport. In addition, whether the river is tidally influenced (and how much) also has a large influence on contaminant transport. North of the dam at Troy (~milepoint 150), the Hudson River is not tidally influenced.

The amount of river with a specific depth, and the volume of water which flows over a specific depth (Figure 4.1) should provide a useful insight into areas which could experience either sedimentation or erosion. In Fig. 4.2 these characteristics are normalized and the relationship becomes more evident. This analysis was performed for the section of the estuary from the Battery north to approximately 42° 15". The available digital bathymetry data necessary for this analysis did not extend any further north than this.

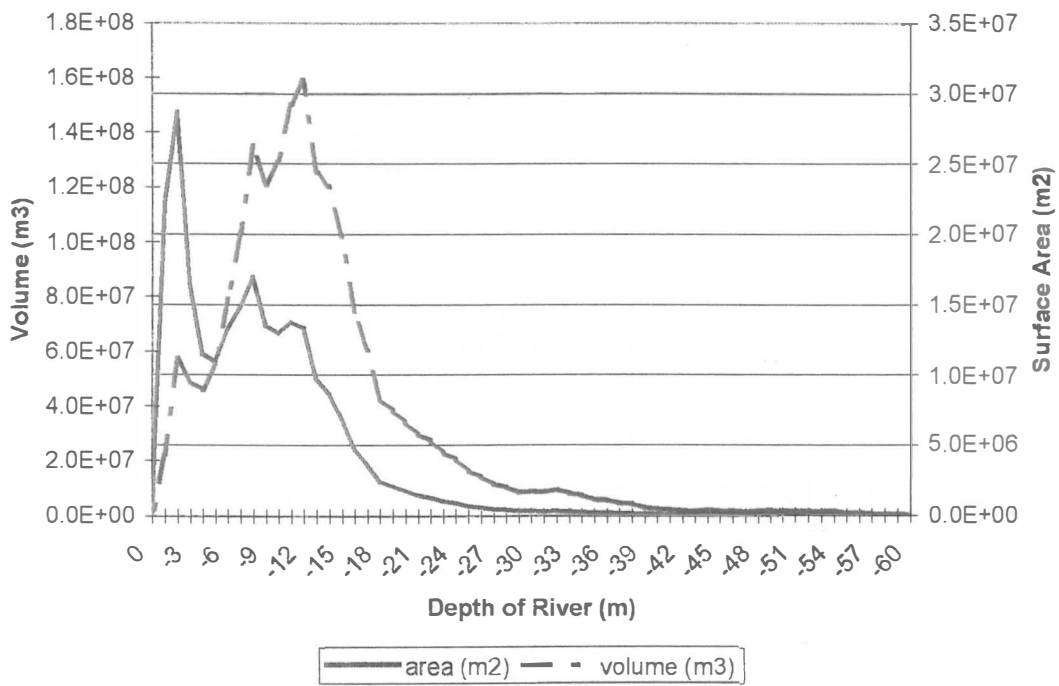


Figure 4.1 Integrated River Volume and Depth
 (Battery north to 42°15" – extent of available bathymetry data)

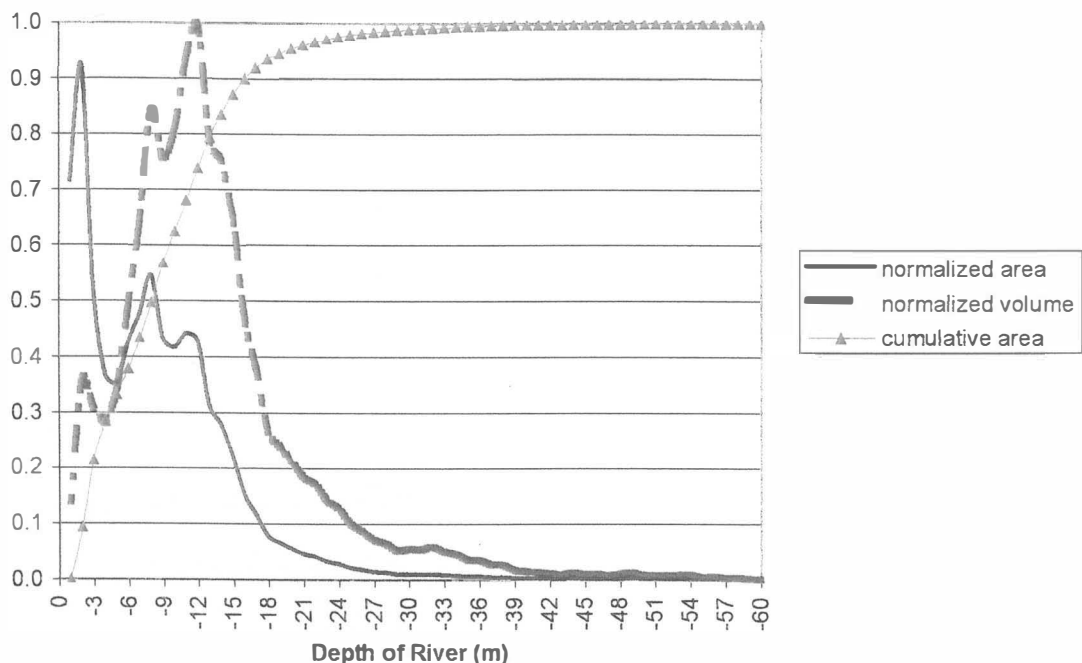


Figure 4.2 Normalized Area and Volume
 (Battery north to 42°15" – extent of available bathymetry data)

The above plots clearly show that fully 90% of this stretch of the river is below 18 meters depth. They also reaffirm the intuitive notion that the shallow sections (3m or less) have large surface areas and the deep sections have small surface areas. The volume, or sediment carrying capacity, reaches its maximum in the 12 to 15 meter depth range. As depth increases beyond 18 meters, the two parameters decrease proportionally. Perhaps most interesting is the fact that the largest river volumes do not correspond to the largest areas; therefore determining areas of sedimentation is not a simple matter but a first effort might be to assume higher sedimentation rates in areas where the river volume is high, and low sedimentation rates in area where the river volume is low. Finally, our estimates do not take the effect of dredging into account. Over the past forty years the shipping channel up the Hudson has been maintenance dredged and some of

the PCBs in the system have been removed through dredging. Finally, we use a constant multiplication number to go from “PCB in a year’s worth of sediments” to “Total PCBs”.

Note that a large part of the problem with these estimates is the poor quality of the data. What we need for this calculation is high resolution coring data for a statistically meaningful number of sites for a range of different waterdepths in conjunction with information on generalizability of sedimentation rates (information which could be obtained by geophysical subbottom mapping efforts). It is puzzling that notwithstanding the expenditure of several tens of millions by a range of organizations the data needed to solve this essential question has not been collected. Hopefully the current effort underway by CARP will remedy this situation.

4.3 Estimates on sedimentation rates and PCB concentrations

For the purposes of this study, a rough estimation on sedimentation rates for the Hudson River system was made. We realize that these sedimentation estimates are based on broad assumptions but they are in fair agreement with the literature (Olsen and al 1984; Bopp and Simpson 1988; Bero and Gibbs 1990; Gibbs 1994; Robideau 1997; Feng, Cochran et al. 1998) and should be suitable for a large-scale study such as ours. Note that the sedimentation rate for the TIP area is given by GE as about 1 cm/yr (an order of magnitude above the value listed here). We use five different sedimentation rate models (shown in figure 4.3). Our PCB concentration rates are based on three different models, which represent low, mid and high values (Figure 4.4).

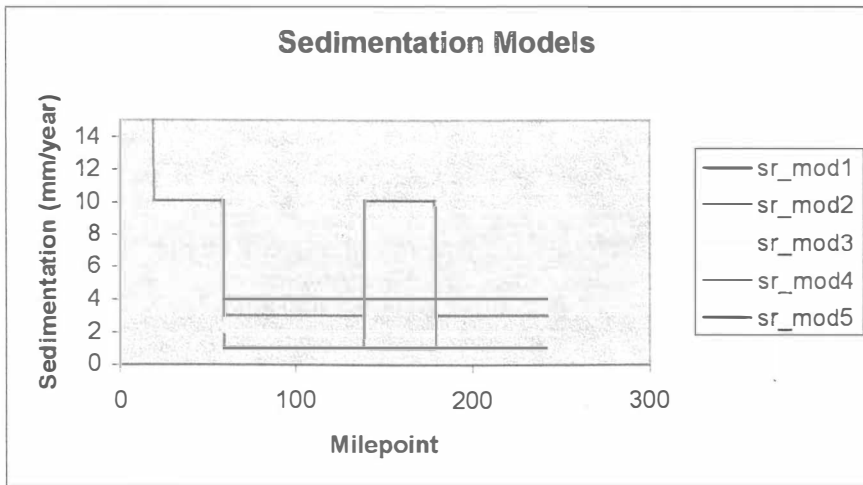


Figure 4.3 Five different sedimentation models used in calculations. All models have 50 mm/year in Inner Harbor area. Models 2 and 5 have 10 mm/year in Thompson Island Pool area

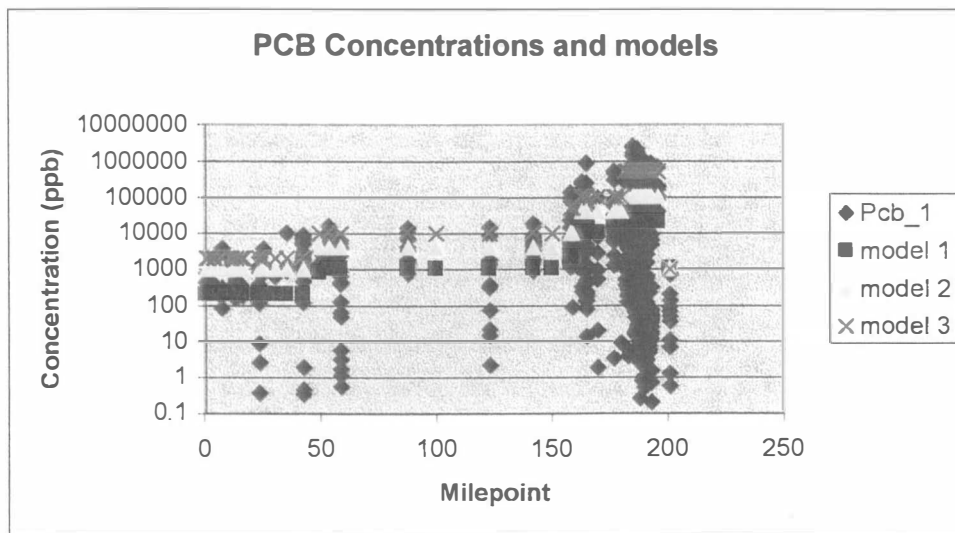


Figure 4.4 Three different models for PCB concentrations in the Hudson river. Pcb_1 is the field data

4.4 Calculation of total PCBs in river

Once we have the sedimentation rates in the river and the PCB concentrations the next step is the calculation of the total PCBs. This can be done in the simplest way by using Arcview. We first create grids of the sedimentation and PCB rates. These grids have cells with a size of 30 x 30 meters. In Arcview we multiply the sedimentation rate grid by the PCB concentration grid. This gives at each grid point a value, which has the units $\text{ppb} \times \text{mm}$. As the grid size is 30 x 30 meters we can multiply this grid by .9 to get to the units $\text{ppb} \times \text{m}^3$. Subsequent to this we can divide this grid by 1E9 to come to cubic meters of PCB. Multiplying this with the density of sediment (we assume 1 here) gives the tonnage of PCB in a gridcell.

We can now sum this tonnage over all the gridcells, which gives us table 4.1 of PCB for each of the 15 combinations of sedimentation and PCB models. This PCB volume is effectively a one year value, i.e. the amount of PCB which is present in one year's worth of sediments.

	SR Model 1	SR Model 2	SR Model 3	SR Model 4	SR Model 5
PCB Model 1	1.01	1.01	1.22	1.46	1.87
PCB Model 2	4.88	6.34	5.72	6.72	8.37
PCB Model 3	8.37	15.39	13.64	16.83	21.99

Table 4.1 Total tons of PCB in the river for a one year layer of sediment using the different sedimentation/PCB models shown in figures 4.3 and 4.4

We now have to go from a one year value to a multi year value. This step is of course extremely open for discussion: while we have had release of PCBs into the Hudson for some forty years we can not just multiply the numbers in table 4.1 by a factor of forty – even though the numbers as we used them are in many cases PCB concentration in the whole contaminated core. Barring any more detailed data a factor of twenty seems a reasonable number. The result of using this number for the total amount of PCB in the river is shown in table 4.2

	SR Model 1	SR Model 2	SR Model 3	SR Model 4	SR Model 5
PCB Model 1	20.28	20.28	24.38	29.27	37.31
PCB Model 2	97.61	126.81	114.37	134.37	167.36
PCB Model 3	167.36	307.83	272.74	336.52	439.83

Table 4.2 Range of estimates for models shown in figures 4.3 and 4.4 of total tons of PCB in Hudson River Sediments

5 Discussion and conclusions

The results shown in table 4.2 show a range of 20 to 440 metric tons of PCB locked in Hudson River Sediments. These numbers were calculated in a straightforward fashion using some relatively simple approximations. The question is now which model is most realistic.

An in depth discussion on this falls outside the true scope of the thesis. In essence the answer is that we do not have enough data to answer this question, and that we probably will have to mix these models and make them more complex (e.g. incorporate different sedimentation rates as a function of bathymetry, riverflow, tidal influence etcetera). However, the argument can be made that a lot of these factors will tend to average out so that we can take a “middle of the road” range as most plausible - some 150 –200 metric tons of PCB. Arguments to choose the higher or lower numbers (based on some of the elements discussed before) can and should of course be made. Thus, the main results of this work are the following:

1. We can do a quick calculation and comparison of the results of different sedimentation and PCB concentration models in terms of total PCB in the river. By having the calculation done in a standardized way we can now concentrate on getting better data.

2. There is a discrepancy between the data that we need and the data that we have. Note that there is a large stretch of the river (some 100 miles) for which we have only a few PCB concentration points. For others we have wildly varying numbers. Sedimentation rates in the river and facies maps are not available to map out zones of erosion and sedimentation. Obviously, the fact that some of the data does not have accurate positioning and depth information makes it less useful.
3. There is still a significant amount of PCB in the river. Our estimates are along the lines (in terms of order of magnitude) of other estimates.
4. Refinement of this methodology is conceptually simple: we can introduce flow and depth dependent sedimentation rates, we can refine our PCB model (which is especially relevant in the area south of TIP where we have known hotspots) and we can introduce time dependent concentration and sedimentation numbers. All of these steps can and should be open to discussions. By focusing on each individual steps and by determining errorbars for each step we should be able to refine the range of estimates arrived at here
5. New sampling efforts should be model driven. A simple statistical approach (in which we take cores at random locations) is not going to provide us with the information we need. High resolution coring in areas with different sedimentation rates and patterns is necessary.

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