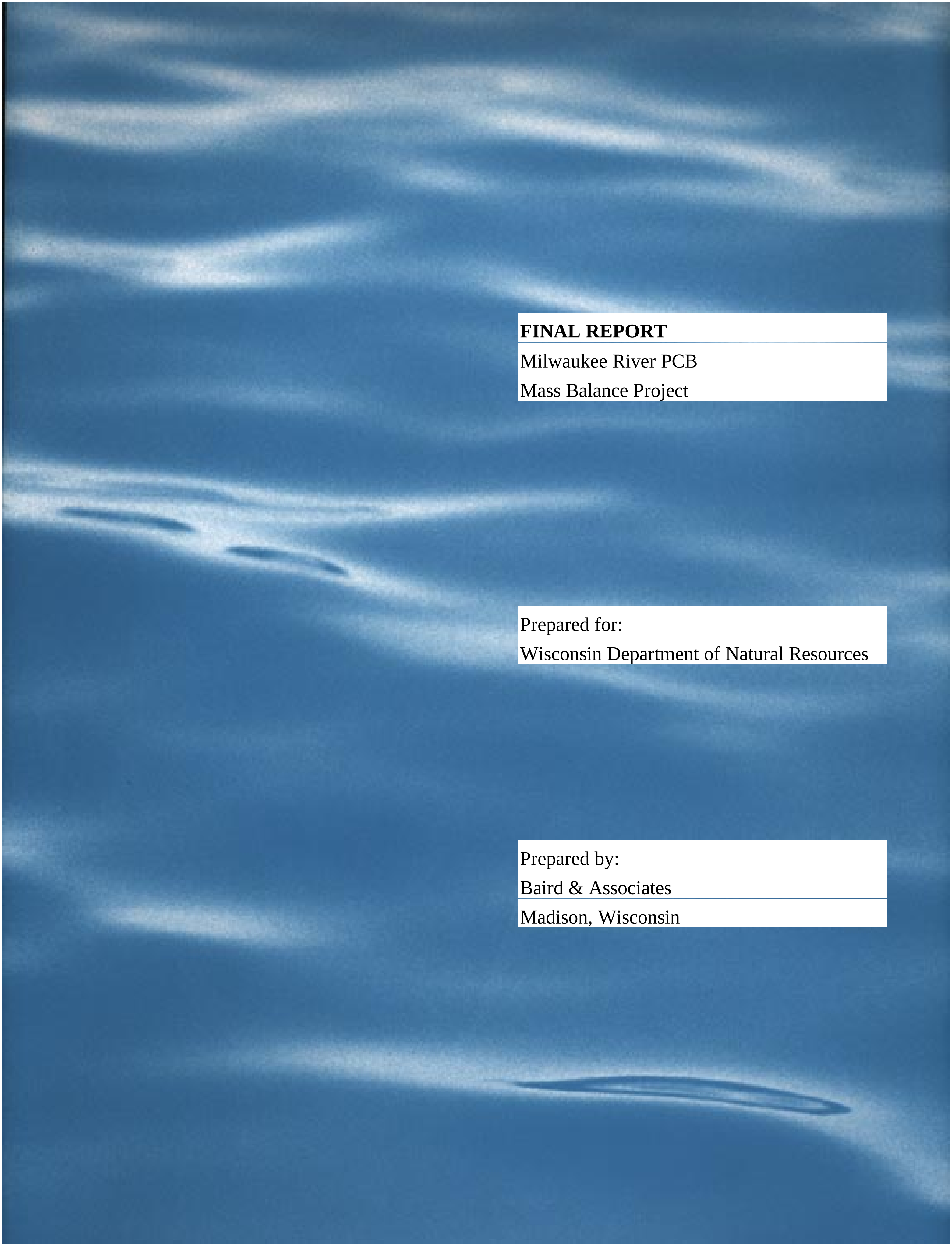

FINAL REPORT

Milwaukee River PCB

Mass Balance Project

Prepared for:

Wisconsin Department of Natural Resources

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1. EXECUTIVE SUMMARY

This project focused on tracking PCB transport in seven contaminated impoundments on Cedar Creek and the Milwaukee River. The point of this effort was to assist resource managers and responsible parties in targeting sites for further remediation within this system and to help articulate strategies to enhance the natural recovery of the system.

In order to analyze the transport of PCB in this system, hundreds of water and sediment samples were taken and analyzed and a PCB mass transport model was assembled. The model was used to evaluate a series of remediation scenarios that involved five of the seven impoundments.

The sample collection, data analysis and model development described in this report was conducted by staff of the Wisconsin Department of Natural Resources (DNR). Baird and Associates was retained by the DNR to gather together this work and produce the final report.

Summary of Results.

- The Cedar Creek system presently contributes an annual average PCB mass of about 5 kilograms to the Milwaukee River system. The annual PCB mass transported from Cedar Creek to the Milwaukee River is expected to drop to about 2 kilograms per year over the next 25 years as a result of Ruck Pond remediation.

- The Ruck Pond remediation removed a significant mass of PCB (between 350 and 700 Kg) from the Cedar Creek system. The mass removed represents between 30% to 45% of the PCB mass that was present in the Cedar Creek system before remediation of Ruck Pond.

- Mass removal of PCB, when performed in the right places within the system, enhances natural recovery significantly. This finding is based on model results.

Implications for Cedar Creek Remedial Strategy. Ruck Pond prior to remediation and Columbia Pond as it exists today together contained between 80%-85% of the total PCB mass within the Cedar Creek system. The model simulations show that mass removal of Ruck and Columbia Ponds will significantly enhance the natural recovery of the Milwaukee River system. The two other impoundments on the Cedar Creek system, Wire & Nail and Hamilton Ponds, have less impact on the Milwaukee River system with respect to mass transport and projected water column and sediment PCB concentrations.

This finding is consistent with the conclusions and recommendations made in Westenbroek (1993). Although not evaluated as part of this project, there may be other ecological or institutional reasons to conduct remediations on the Wire & Nail and Hamilton Ponds. Again, the expected benefit that accrues will be more difficult to gauge in terms of mass transport and projected downstream water column and sediment PCB concentrations.

One institutional reason to remediate Wire and Nail Pond may be the possibility of dam failure. This project did not evaluate the impacts of a catastrophic dam failure on PCB transport. Release of the 70 kilograms of PCB in such an event would be greater than the PCB transport from Cedar Creek projected over the next 25 years.

Implications for Milwaukee River Remedial Strategy. The Estabrook Impoundment is by far the largest contributor of PCB to the Milwaukee system. Remediation of the Cedar Creek system alone will not be as effective unless Estabrook Impoundment is addressed. It should be noted that the Estabrook Impoundment "hot spot" is clearly unrelated to the contamination on the Milwaukee River upstream. The source of Estabrook Impoundment sediments is unknown. Immediate, large reductions in PCB loadings and concentrations may be had when this impoundment is remediated.

2. SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

2.1 CONCLUSIONS

- The screening-level model presented here is an adequate tool for evaluating management options. Model projections are adequate in terms of estimating mass transport as a function of remediation, but the long-term fish tissue projections are simplistic and need additional refinement and calibration before using them quantitatively.

- The model can be used to help make management decisions, however, no attempt was made to simulate the effect of dam failure. A catastrophic dam failure at Wire and Nail Pond has the potential to release a mass of PCB greater than 25-years' worth of transport from Cedar Creek under normal conditions.

- The pattern of PCB transport in Cedar Creek and the Milwaukee River is in many ways similar to a simple series of completely-mixed reactors: the further one moves downstream from the source of contamination, Ruck Pond, the more dilute and dispersed is the pollutant. Similarly, remediation of the areas further downstream are projected to have diluted effects on the system. The most effective remediation strategies should focus on those areas where the mass and concentration of contaminant is highest.

- The Ruck Pond remediation reduced PCB transport in the Cedar Creek system, and dramatically enhanced the natural recovery of the system.

- Mass removal of all sediment in Columbia Pond will significantly reduce the transport of PCB and will enhance the natural recovery of the Cedar Creek system. The mass of PCB in Columbia Pond is greater than that calculated for Thiensville, Wire & Nail and Hamilton Ponds combined.

- Remediation of the Wire & Nail Pond is not likely to yield significant decreases in PCB mass export or water column concentrations. Institutional issues such as possible dam failure are beyond the ability to simulate accurately with this model. However, the release of a significant mass of PCB via a dam breach should be avoided. A dam break at Wire and Nail could redistribute and disperse the approximately 70 Kg of PCB, and would likely "recharge" downstream surficial sediment layers.

- Remediation of Hamilton Pond does not appear to offer significant system-wide benefits in terms of PCB mass export and projected fish tissue concentrations. Again, the model did not simulate the breach of the Hamilton Pond Dam, and is thus silent on the implications of sediment scour following dam failure.

- Remediation of Thiensville Impoundment may be impractical given its large surface area and relatively low PCB concentrations, and offers the lowest return on investment of any of the contaminated impoundments on the Milwaukee River System. Also, since the contamination only gets higher with increasing sediment depth, there is a real possibility that disturbing this sediment would make conditions worse, if only temporarily.

- Kletzsch Park Impoundment does not contain appreciable amounts of soft sediment and does not contain significant masses of PCB.

- Estabrook Impoundment contains nearly 4 times the mass of PCB as is contained in the remainder of the Cedar Creek / Milwaukee River System. Congener PCB results show that the PCB "hot spot" in the Estabrook Impoundment is unrelated to the PCB found in the remainder of the Milwaukee River. The source of Estabrook Impoundment PCB "hot spot" is unknown.

- Estabrook Impoundment contributes the greatest mass loading to the Milwaukee River and Milwaukee Harbor than all other Cedar Creek and Milwaukee River impoundments combined. Remediation of Estabrook Impoundment would greatly enhance the natural recovery of the system.

- Sediment trap results performed on Lincoln Creek were inconclusive, but suggest that current PCB transport from Lincoln Creek is low. Trap results also indicate that the original source or sources of the PCB "hot spot" in the Estabrook Impoundment were probably from within the reach bounded by 46^{th} Street upstream and Teutonia Avenue downstream. The trap results from Crestwood Creek suggest that no significant sources of PCB were located there.

- As stated before, the screening-level model performance is more than adequate to gauge the impact of remediation on the Cedar Creek and Milwaukee River systems. The following model enhancements would produce water column concentration PCB projections of greater accuracy and include the effect of catastrophic dam failure.

    - Model performance regarding elevated summertime water column concentrations may be improved by splitting the present single solids class into biotic and abiotic components, as was done in the upper Fox River modeling (WDNR, 1995).

    - Model performance simulating Estabrook Park sediment resuspension could be improved by using a 2-dimensional hydrodynamic and sediment transport model to better define current velocities and shear stresses under varied flow conditions.

    - Modeling of a few select congeners would aid in calibrating the Estabrook Park resuspension function, since the PCB congener profile is so different there than in the rest of the Milwaukee River.

    - A combined dam break analysis and 2-D sediment transport model would address issues surrounding possible dam failure.

2.2 RECOMMENDATIONS

- Columbia Pond should be the focus of immediate attention, based on the high resident PCB mass, the highest PCB flux in the system save for Estabrook Impoundment, and the projected enhanced natural recovery following remediation. Remediation of Columbia Pond will reduce long-term PCB transport dramatically and will lower the average long-term water column PCB concentrations in the Milwaukee River at Pioneer Road by over 50% as compared with the no action option at Columbia Pond.

- A performance-based cleanup criteria is suitable for application to Columbia Pond. Existing technologies will never meet the sediment quality criteria that are produced using the Ontario Sediment Quality Guidelines. Analysis of the Ruck Pond situation shows that although significant concentrations of PCB were left behind, water column and fish tissue concentrations will decrease significantly compared to the no action alternative.

- Estabrook Impoundment should be targeted for immediate additional work, including a source analysis similar to that which was originally done by Skip Baker for Ruck Pond on Cedar Creek. Additional sampling of the water column should be pursued to quantify the mass of PCB entering the impoundment from Lincoln Creek. Since the results of this project confirmed widespread PCB contamination within the Estabrook Impoundment, a remedial investigation/feasibility study (RI/FS) should be initiated with the goal of identifying ways to immobilize or remove the PCB "hot spot."

- The DNR should pursue and perfect the delivery of data electronically from the State Lab of Hygiene. Much time was spent on this project manipulating data files in order to summarize the results.

- DNR project managers should issue the field staff pre-printed lab slips, with critical information like the STORET number, site name, etc. filled in. Consistent entry of these parameters into the State Lab system helps tremendously when the results are manipulated electronically.

3. INTRODUCTION

The primary purpose of the Milwaukee River PCB Mass Balance Study was to consider the effects of present and future sediment remediation on water column PCB concentrations and PCB mass export in both Cedar Creek and the Milwaukee River.

This report presents a summary of water column and sediment data, documents mathematical model development and gives predictions based on various remediation scenarios.

3.1 Background

In the mid-1980s the Wisconsin Department of Natural Resources (DNR) detected polychlorinated biphenyl (PCB) in fish tissue samples from the impoundments on Cedar Creek, near Cedarburg, Wisconsin. Further investigation by the DNR showed high levels of PCB in sediment samples from four of five Cedar Creek impoundments (Wawrzyn and Wakeman, 1986).

Several subsequent studies documented the distribution of PCB within Cedar Creek sediments and examined the transport of PCB from Cedar Creek to the Milwaukee River (DNR, 1992; Westenbroek, 1993). In 1994, the Mercury Marine Corporation removed 7,500 cubic yards of sediment from Ruck Pond, the most highly contaminated of the five impoundments on Cedar Creek.

This project was designed as an extension of previous work, with the overall goal of examining the impact of PCB-contaminated sediment on the Cedar Creek / Milwaukee River system.

3.2 Site Description

The study area includes Cedar Creek from Highway 60 to its confluence with the Milwaukee River, the Milwaukee River from County Highway "T" to the Estabrook Park Dam, and Lincoln Creek in its entirety (see Figure 3.1).

Four continuous flow monitoring stations were operated by the U.S. Geological Survey (USGS) for most of the duration of this project. These sites include:

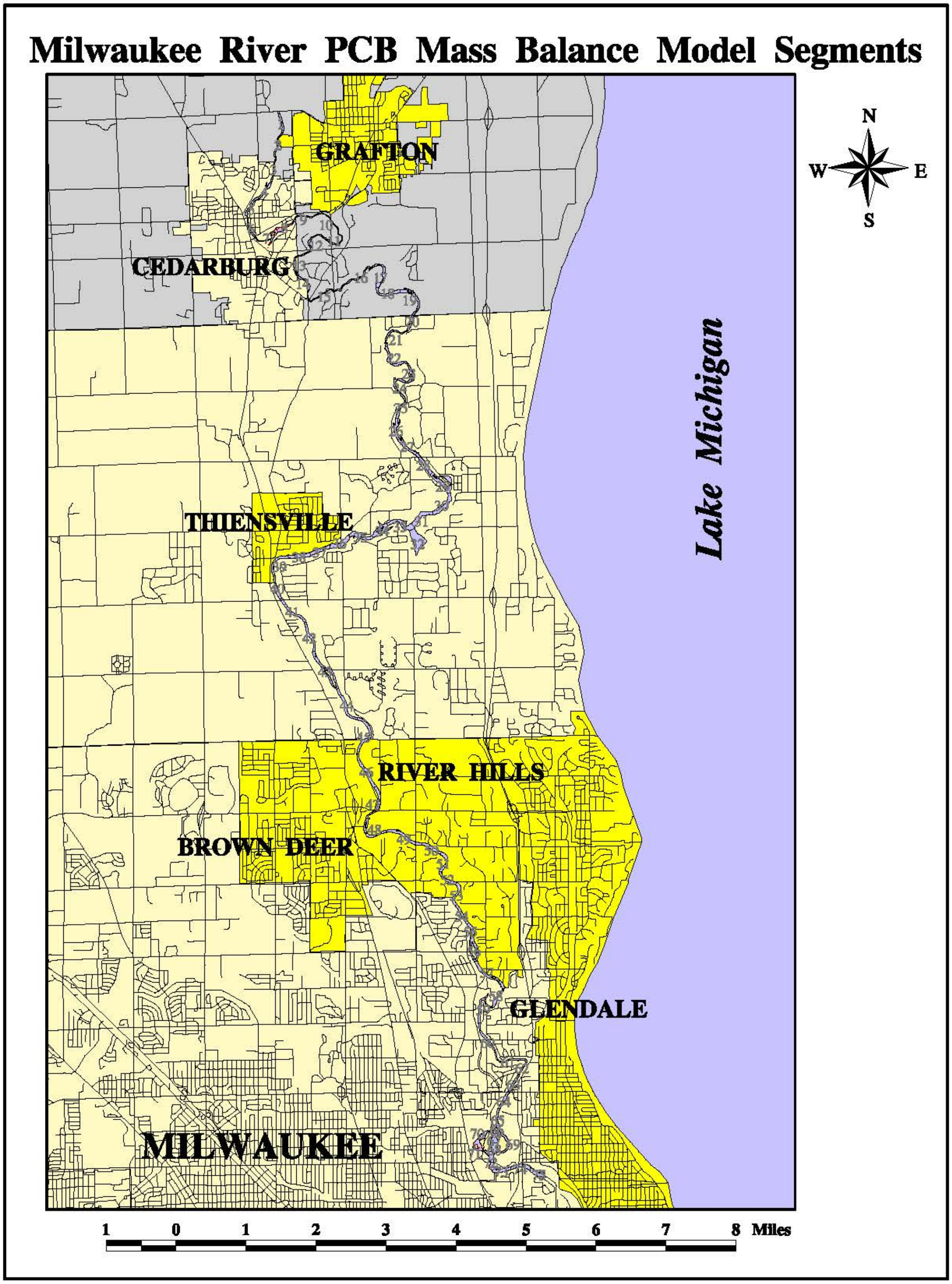
- Cedar Creek at Highway 60 (coincides with mode segment 1)
- Milwaukee River at Pioneer Road (coincides with model segment 20)
- Milwaukee River at Estabrook Park (coincides with model segment 75)
- Lincoln Creek at 47th Street

Water quality sampling was conducted by the USGS and DNR at the following sites:

- Cedar Creek at Columbia Road (Ruck Pond)
- Cedar Creek downstream of Highland Road (Columbia Pond)
- Milwaukee River at County Highway "T" (upstream background)
- Milwaukee River at Pioneer Road (first bridge downstream of Cedar Creek / Milwaukee River confluence)
- Milwaukee River at Highway 167 (below Thiensville Impoundment)
- Milwaukee River at Estabrook Park (below Estabrook Impoundment)

In addition, data presented in Westenbroek (1993) was used to supplement the data generated by this project. That study also sampled water from Cedar Creek downstream of the Wire and Nail Pond and Cedar Creek at Green Bay Road (downstream of Hamilton Pond).

FIGURE 3.1


Milwaukee River PCB Mass Balance Model Segments
N
W
E
S
GRAFTON
CEDARBURG
THIENSVILLE
RIVER HILLS
BROWN DEER
GLENDALE
MILWAUKEE
Lake Michigan
1 0 1 2 3 4 5 6 7 8 Miles

Because contaminated sediment tends to accumulate in soft sediment deposits behind dams, this study focused on characterizing the sediments behind dams on the Milwaukee River. Very little sediment is observed in the river reaches between impoundments: in general no more than 10 cm of sediment was found, and that was behind large boulders or in isolated pockets in these intermediate reaches. However, this study did not systematically sample or characterize the intermediate reaches.

Five impoundments included in the study are on the Cedar Creek system: Cedarburg (Woolen Mill) Pond, Ruck Pond, Columbia Pond, Wire & Nail Pond and Hamilton Pond. Ruck Pond was remediated in 1994 by the Mercury Marine Corporation. The Hamilton Pond Dam failed in the Spring of 1996, lowering the water levels by several feet. More complete description of these impoundments may be found in Westenbroek (1993) and Wawrzyn and Wakeman (1986).

The three Milwaukee River Impoundments included in the study area are Thiensville Impoundment, Kletzsch Park Impoundment and the Estabrook Park Impoundment. Wisconsin DNR staff performed sediment and water depth surveys in 1993 for Thiensville and Estabrook Impoundments. Figure 3.2 shows the distribution of water and sediment depths found in Thiensville and Estabrook Impoundments based on the 1993 surveys.

Backwater effects from the Thiensville Dam extend approximately 6 miles upstream. The impoundment is represented by water column segment numbers 30-38 in the model. The median water depth is about 1.8 meters (6 feet), with a maximum measured depth of 4 meters (13.1 feet). The median sediment depth is about 15 centimeters (0.5 feet), with a maximum of about 190 centimeters (6.2 feet).

The Kletzsch Impoundment was more or less ignored in this study after investigators found virtually no soft sediment deposits to speak of. The majority of the bottom sediments were well-armored, or consisted of cobbles or gravel.

The Estabrook Impoundment extends from the Estabrook Dam upstream to approximately Silver Spring Road. Estabrook Impoundment is represented by water column segments 66-75 in the model. The median water depth measured in 1993 is about 1.6 meters (5.2 feet), with a maximum of about 3 meters (9.8 feet). The median sediment depth is about 8 (0.25 feet) centimeters, with a maximum of about 170 centimeters (5.6 feet).

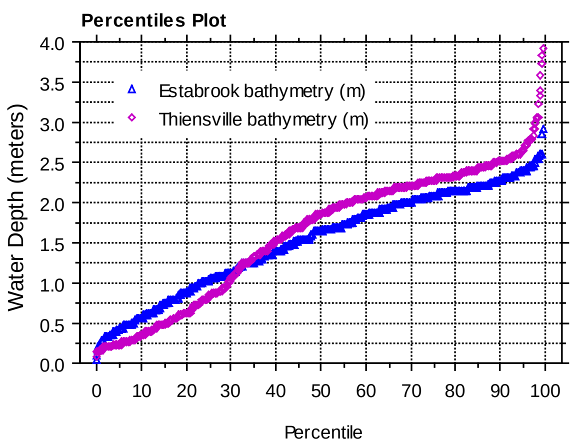
FIGURE 3.2 MILWAUKEE RIVER IMPOUNDMENT PHYSICAL CHARACTERISTICS

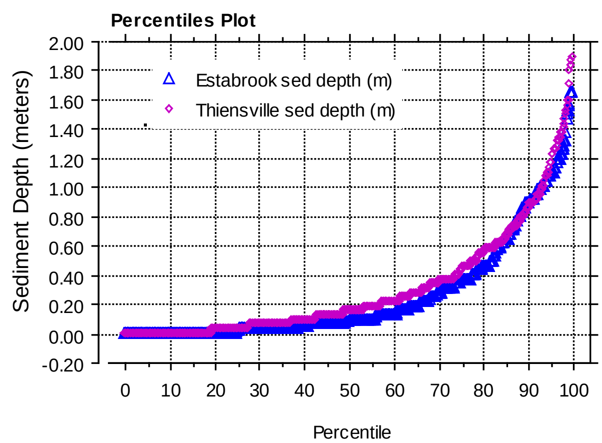
Percentiles

	Estabrook bathymetry (m)	Thiensville bathymetry (m)
10	.549	.305
25	1.006	.785
50	1.615	1.829
75	2.073	2.256
90	2.256	2.499

Percentiles

	Estabrook sed depth (m)	Thiensville sed depth (m)
10	0.000	0.000
25	.002	.030
50	.076	.152
75	.366	.427
90	.884	.853





3.3 Project Goals and Objectives

Specific objectives for this project were to:

- Expand the water column PCB database
- Define the horizontal and vertical extent of PCB contamination in the Estabrook Impoundment
- Determine whether Lincoln Creek represents a continuing source of PCB loading to the Milwaukee River
- Provide a *quantitative* estimate of PCB transport rates in the Milwaukee River
- Gauge the significance of the three large impoundments on the Milwaukee River in terms of PCB transport
- Predict the effect of various remediation alternatives on PCB mass transport rates and water column PCB concentrations

The overall goal for this project was to provide managers with information concerning the effectiveness of sediment remediation projects from a river-wide perspective.

3.4 Scope of Work

Extensive field sampling, data analysis and numerical modeling were the primary activities carried out for this project. This section describes the work conducted as part of this project.

It should be noted that Baird's scope of work was limited to the compilation and synthesis of the data and modeling results provided by the DNR.

3.4.1 SAMPLE COLLECTION

Sediment samples

Approximately 222 sediment samples were taken as part of this study between October of 1993 and December of 1995. The sediment samples were analyzed for PCB Aroclors and total organic carbon. Particle grain size and bulk density analyses and were also performed on the majority of samples. Approximately 10% of samples were analyzed for PCB congeners.

A subset of samples was analyzed for polynuclear aromatic hydrocarbons (PAHs), with the goal of providing context for the PAH sampling conducted further downstream as part of Remedial Action Plan activities. These results are included in the appendix.

Sediment samples generated by this project were distributed as follows:

- 7 sediment grab samples from Ruck Pond, on Cedar Creek, following Ruck Pond Remediation
- 53 sediment core samples from Columbia Pond, on Cedar Creek
- 58 sediment core samples from Thiensville Impoundment, on the Milwaukee River
- 4 sediment core samples from Kletzsch Park Impoundment, on the Milwaukee River
- 87 sediment core samples from the Estabrook Impoundment, on the Milwaukee River
- 13 sediment trap samples from Lincoln Creek

Water samples

Approximately 103 water column samples were analyzed for particulate and dissolved PCB congeners between June of 1993 and August of 1995. In addition, water samples were collected and analyzed for total suspended solids (TSS), volatile suspended solids (VSS), chlorophyll a, chloride, particulate organic carbon (POC) and dissolved organic carbon (DOC).

Figure 3.1 shows how water column samples were distributed by location.

TABLE 3.1

Location	Waterbody	Number of Water Column PCB, POC, DOC, Chl-a Samples	Number of TSS and VSS Samples (MMSD)
Ruck Pond	Cedar Creek	11	---
Columbia Pond	Cedar Creek	13	251
County Highway "T"	Milwaukee River	5	---
Pioneer Road	Milwaukee River	27	771
Thiensville Impoundment	Milwaukee River	16	677
Estabrook Impoundment	Milwaukee River	31	844
TOTAL		103	2292

3.4.2 NUMERICAL MODEL DEVELOPMENT

A 320-segment contaminant mass balance model was developed as part of this project. The numerical framework used is the IPX model, which is based on the U.S. EPA's WASP model framework (Velleux *et al*, 1994).

The model includes 75 water column segments extending from Cedar Creek at Highway 60 to the Estabrook Park Dam. Underneath each of the water column segments is a stack of at least 3 sediment segments used to represent sediment deposits in the model. Model segmentation is discussed in greater detail elsewhere in this document.

The model was calibrated using data collected as part of this study as well as data collected by the Milwaukee Metropolitan Sewerage District and the data collected as part of the Cedar Creek PCB Mass Balance Study (Westenbroek,1993).

3.4.3 ANALYSIS OF REMEDIATION SCENARIOS

A primary objective for this project was to analyze and project the effect of various remediation scenarios on PCB concentrations and PCB mass transport in the Milwaukee River. In order to accomplish this, the numerical model was run for a combination of remediation alternatives.

A series of remediation scenarios was developed and simulated using the numerical model. Simple bioconcentration factor-based projections of fish tissue concentrations were made based on the projected water column concentrations.

The modeled remediation scenarios were compared by examining PCB mass export and water, fish tissue and sediment concentrations over time.

4. SAMPLE COLLECTION, DATA ANALYSIS AND INTERPRETATION

4.1 Sample Collection Methods

Field methods and lab procedures are described in the workplan that was prepared in an earlier phase of this project. The workplan is included as an appendix to this document.

4.2 Quality Control / Quality Assurance

The data quality objectives for this project are documented in the quality assurance project plan (Westenbroek and Wawrzyn, 1995), and include both quantitative and qualitative measures of the following:

- Precision
- Accuracy
- Completeness
- Detectability
- Representativeness
- Comparability

The data quality objectives for this project were met with one exception: the level of completeness of the Lincoln Creek sediment trap samples.

Lincoln Creek is a highly urbanized stream, and it responds quickly to rainfall events. Peak velocities observed during high flow events approach 10 feet per second (as estimated by gauging the velocity of a *sofa* traveling downstream). As a result, one sediment trap assemblage was lost completely, and at other sites, sediment trap bottles were often lost or broken, presumably after being hit by objects carried downstream during peak events.

Due to the loss of sediment trap assemblages, it is not possible to state with certainty that Lincoln Creek is or is not a *continuing* source of PCB to the Milwaukee River. The data suggests that Lincoln Creek is no longer a continuing source, but further study is needed to verify this.

The sections that follow briefly summarize the results of quality control samples.

4.2.1 QA/QC: WATER COLUMN PCB SAMPLES

Blanks

Six field blanks were prepared and analyzed for dissolved and particulate PCB congeners. Blank water was obtained from Naturally Pure Water in Milwaukee, which obtained the water from a spring in Little Rock, Arkansas (Jeff Steuer, personal communication). The blank water was transported in the sample van to the field site and processed using the same equipment as was used in the field sampling.

The blank results are displayed alongside the field results in the next section. The maximum PCB level detected in a blank sample was 1.3 ng/L, all of which was in the dissolved fraction.

Jeff Steuer of the U.S. Geological Survey notes that numerous congeners (5/8, 16/32, 26, 33, 49, 44, 37/42, 41/64, 70/76, 66/95, 84/92, 101, 99, 87, 77/110, 149, 132/152) were detected in field blanks, but not in the upstream background (Milwaukee River at HY "T") site. This may be evidence of low-level contamination in the field blank water.

As is shown in the next section, the amount of PCB detected in blank water samples is well below the levels detected elsewhere in the Milwaukee River field samples, with the exception of the upstream background samples.

Field Duplicates

Five field duplicates for water column PCBs were collected during the study. The field duplicates of the operationally dissolved fraction varied by an average of 11%. The field duplicates of the particulate PCB fraction varied by an average of 14% (Jeff Steuer, personal communication).

The measured variation falls well below the field duplicate precision control limits specified in the QAPP.

Upstream Background

Five upstream background samples were obtained and analyzed from the Milwaukee River at Highway "T", upstream of the confluence of Cedar Creek. The purpose of these samples was to determine quantitatively the level of PCB present in the Milwaukee River system upstream from Cedar Creek. It had been assumed that this level was near zero given the extremely low levels of PCB in fish tissue samples from fish taken above Grafton.

There were a few particulate PCB congeners detected (Σ [dissolved+particulate] < 1 ng/L) in the upstream background samples that may indicate a small, historical source upstream from Grafton, or perhaps even reflect atmospheric deposition. Typically when "clean" blank water is run through the system, dissolved congeners are most often detected, not particulate congeners. Therefore, it appears that the low levels of PCB present in the upstream background samples reflect environmental conditions, not cross-contamination of equipment.

Despite the presence of a few particulate PCB congeners in the upstream background samples, the PCB load carried by the Milwaukee River system upstream of Cedar Creek is effectively zero.

4.2.2 QA/QC: SUSPENDED SOLIDS SAMPLES

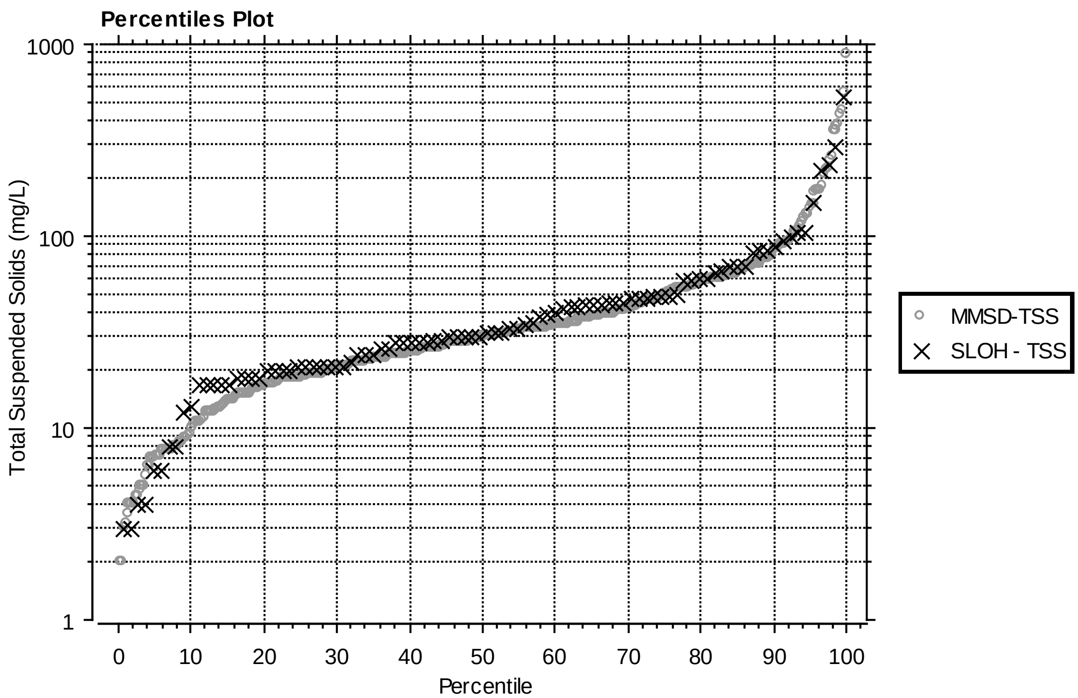
Two different labs were used to generate the suspended solids record used for this project: the State Lab of Hygiene (SLOH), and the Milwaukee Metropolitan Sewerage District (MMSD). Both labs used the same method, based on the State Lab of Hygiene's Method 340.1 (SLOH, 1992).

As was done for the Fox River PCB Mass Balance, the filter normally used for this method was switched from a Whatman GF/A (1.6 micron) to a Whatman GF/F (0.7 micron) glass fiber filter.

The distributions of data generated by the two labs are nearly identical, indicating no substantial difference between laboratories. Figure 4.1 below displays the two suspended solids distributions developed for Estabrook Park. Note that the two data sets cover the same period in time, although the datasets are not paired.

The comparisons between field data and model output in the next few sections identify which lab performed the suspended solids analysis .

FIGURE 4.1 COMPARISON OF SUSPENDED SOLIDS RECORDS AT ESTABROOK IMPOUNDMENT



4.3 DATA SUMMARY

This section summarizes the analytical results of field samples collected as part of this project.

4.3.1 WATER COLUMN DATA

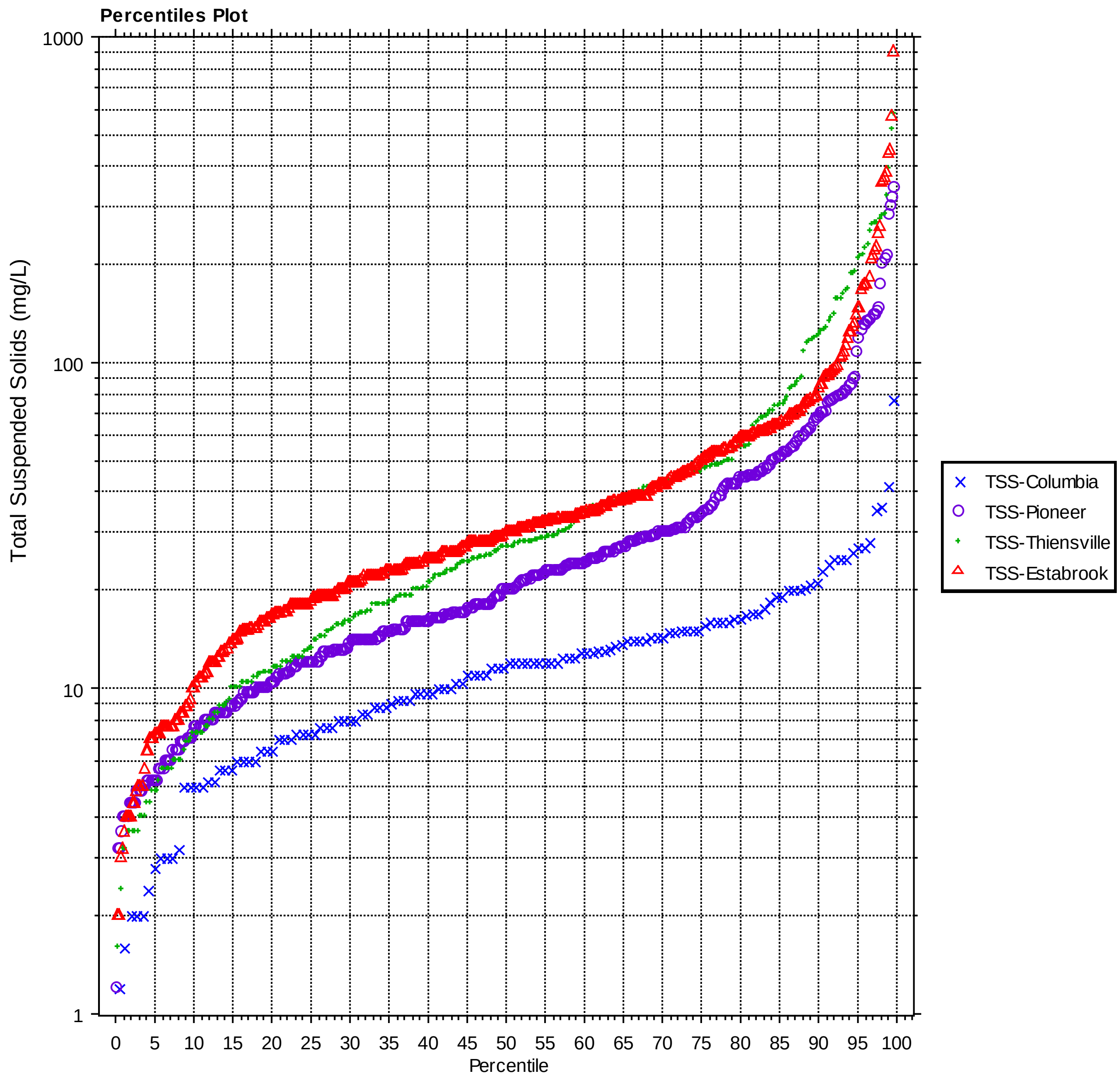
Over 2200 suspended solids and volatile suspended solids samples were collected and analyzed as part of this project. Time series plots comparing this data to model output for selected locations may be found in section 6 of this document.

Figure 4.2 below gives the cumulative probability distribution for suspended solids as derived from the MMSD data collected for this project.

FIGURE 4.2 SUSPENDED SOLIDS CONCENTRATIONS

Percentiles (mg/L)

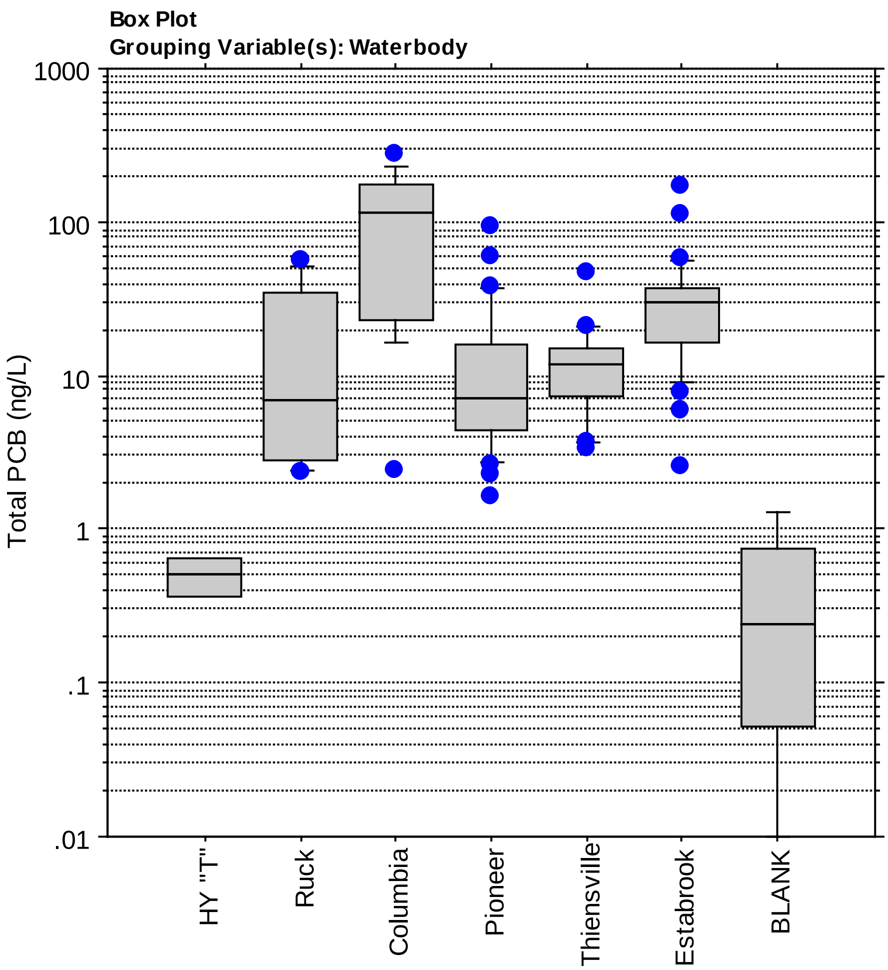
Percentile	TSS-Columbia	TSS-Pioneer	TSS-Thiensville	TSS-Estabrook
10	5.000	7.180	7.140	9.760
25	7.200	12.000	13.200	18.200
50	11.800	20.000	27.000	29.800
75	15.300	34.000	46.000	49.500
90	21.540	67.640	120.300	80.500



Estabrook Impoundment registers the highest median suspended solids levels, while Columbia Pond suspended solids levels were generally significantly lower. The distribution of solids concentrations and, thus, the solids load, generally increases as one move downstream.

Total water column PCB results are presented in Figure 4.3 below. Median water column PCB concentrations in Columbia Pond are an order of magnitude higher than anywhere else in the system save for Estabrook Impoundment.

FIGURE 4.3 WATER COLUMN PCB CONCENTRATIONS



The median value for Columbia Pond (1994-1995) is somewhat higher than that calculated from 1990-1991 data (Westenbroek, 1993), while the range is consistent with those data.

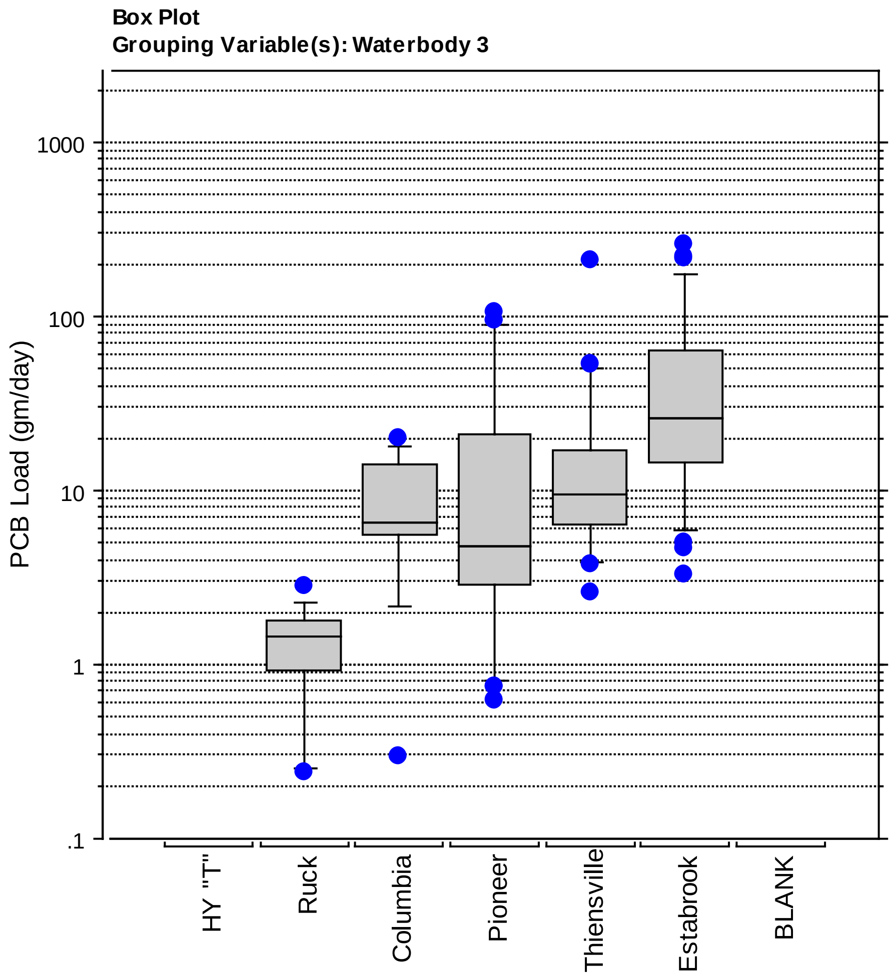
The median value for Ruck Pond (1994-1995, post Ruck remediation) is about 40% lower than that median determined in the 1990-1991 sampling, and the maximum value is about 25% less than the maximum recorded during 1990-1991.

> *Note that in Figure 4.3 above and in the box plots that follow, the horizontal bar bisecting the box represents the 50th percentile (median value), while the top and bottom of the box represents the 75th and 25th percentiles, respectively. The horizontal bars at the end of the "whiskers" represent the 90th and 10th percentiles, while the dots above or below the bars represent data points above the 90th or below the 10th percentiles.*

Note that the Milwaukee River background samples ("HY "T") are within the range of values detected in blank samples. The background sample result may represent contamination, albeit at extremely low levels, possibly from atmospheric deposition or a historical PCB source upstream from Grafton. As is noted elsewhere, it is the mix of particulate PCB congeners present in the background samples versus the blank samples that makes the Highway "T" samples appear to be due to more than simple cross-contamination of equipment.

Figure 4.4 below shows the distribution of calculated PCB loads at various points in the Cedar Creek / Milwaukee River system.

FIGURE 4.4 CALCULATED DAILY PCB LOADS



The PCB load jumps the most between Ruck and Columbia Ponds on Cedar Creek, then essentially levels out until one reaches Estabrook Impoundment, where the load may be seen to increase significantly.

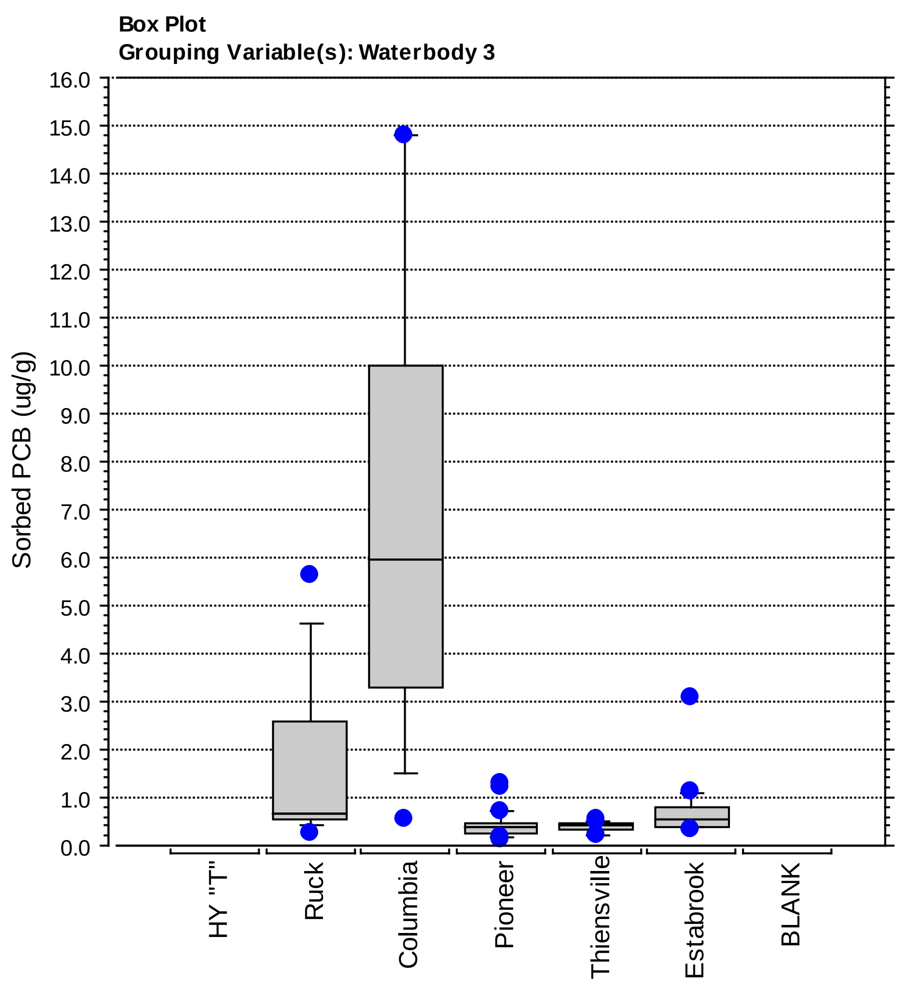
The calculated median PCB load from Ruck Pond following remediation is about 40% lower than the load calculated from the 1990-1991 data.

Another diagnostic parameter of use in problems involving hydrophobic organic compounds is the solid phase toxicant concentration. This may be calculated by dividing the particulate PCB concentration by the total suspended solids concentration.

The level of "sorbed" PCB represents the PCB concentration on the average suspended particle, which, in turn, is related to the local surficial sediment concentration, the influx of uncontaminated suspended solids from tributaries as well as the flux of sorbed PCB from upstream.

Figure 4.5 gives the calculated sorbed PCB concentrations for various sites in this project.

FIGURE 4.5 SORBED PCB IN THE WATER COLUMN



The level of sorbed PCB is significantly higher in Columbia Pond, with 75% of the calculated values falling above all values calculated for any of the Milwaukee River impoundments. Although there are many factors that determine the sorbed PCB concentration, the discrepancy between the values at Columbia Pond and the rest of the system indicates that the average suspended sediment particle at

Columbia Pond will carry far more PCB than the average suspended sediment particle from one of the downstream impoundments.

Figure 4.6 below shows the fraction organic carbon content (f_{oc}) of solids in the water column. The f_{oc} for the Cedar Creek impoundments is significantly higher than for the Milwaukee River. Because the f_{oc} is a function of a number of different parameters, it is difficult to say whether the differences between f_{oc} are attributable to differences in algal productivity, watershed characteristics or other factors.

FIGURE 4.6 FRACTION ORGANIC CARBON CONTENT ON SOLIDS IN THE WATER COLUMN

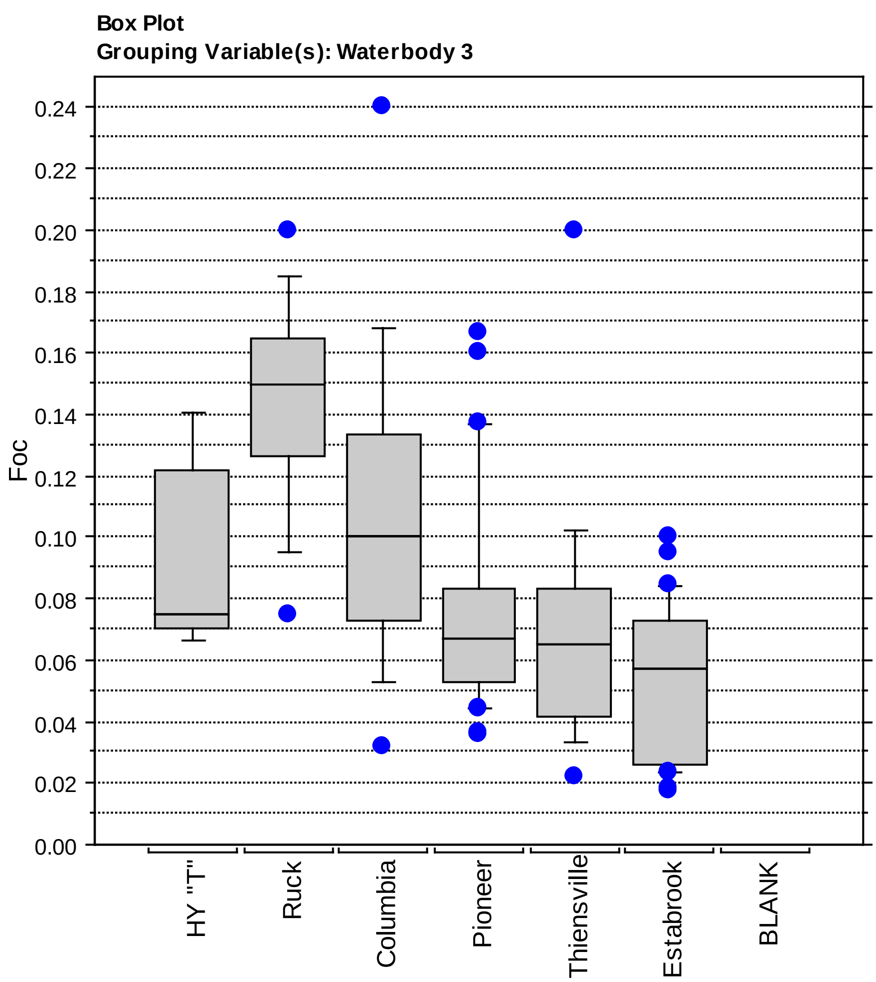
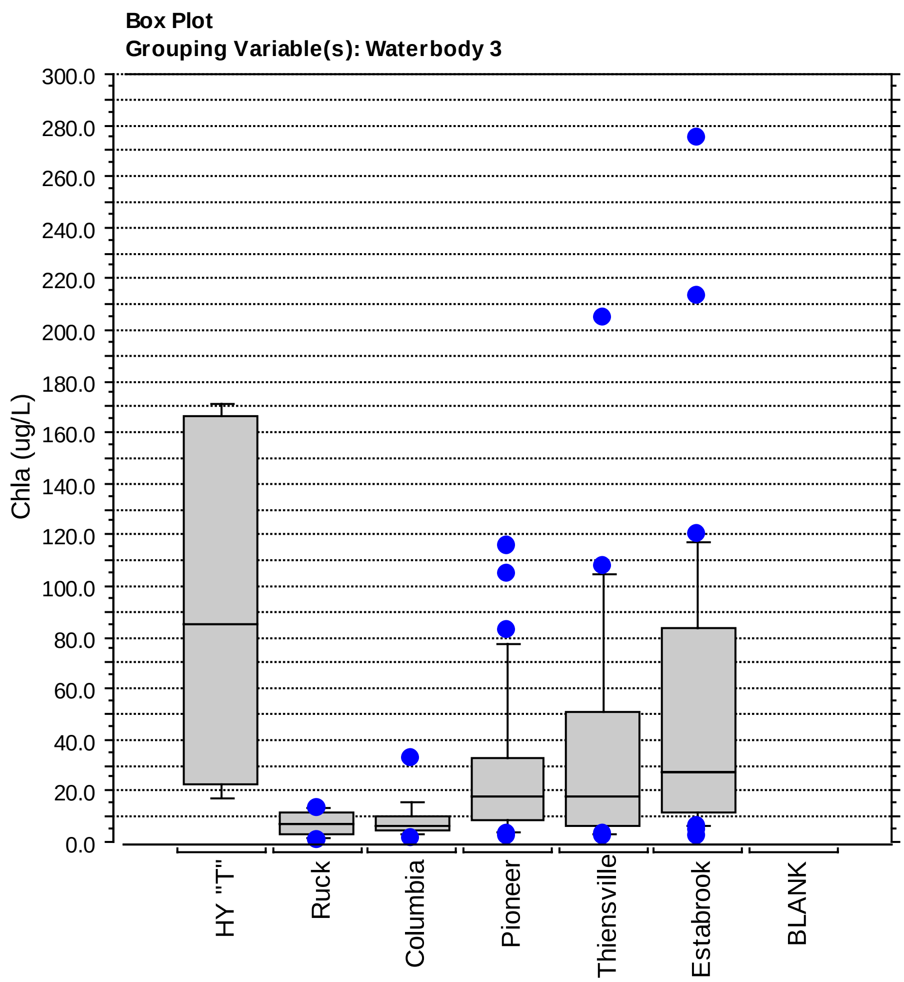


Figure 4.7 below presents chlorophyll a data for Cedar Creek and Milwaukee River sites. Again, we see a significant difference between Milwaukee River sites and Cedar Creek sites. This data is consistent with historical data from the Milwaukee Metropolitan Sewerage District Ambient Monitoring Program, and Westenbroek (1993).

FIGURE 4.7 WATER COLUMN CHLOROPHYLL A CONCENTRATIONS



4.3.2 SEDIMENT DATA

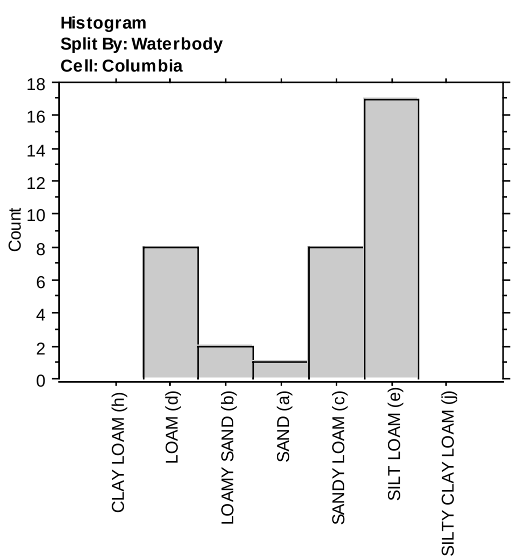
Approximately 222 sediment samples were obtained as part of this project, with the primary goal of characterizing the Milwaukee River Impoundments.

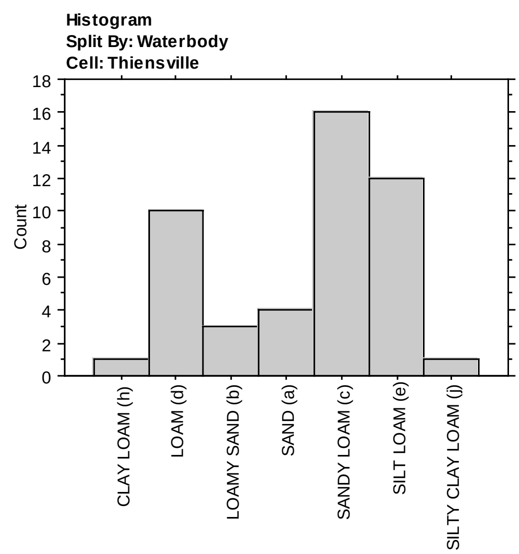
Figure 4.8 below summarizes the distribution of sediment particle sizes as defined by the U.S. Department of Agriculture textural classification.

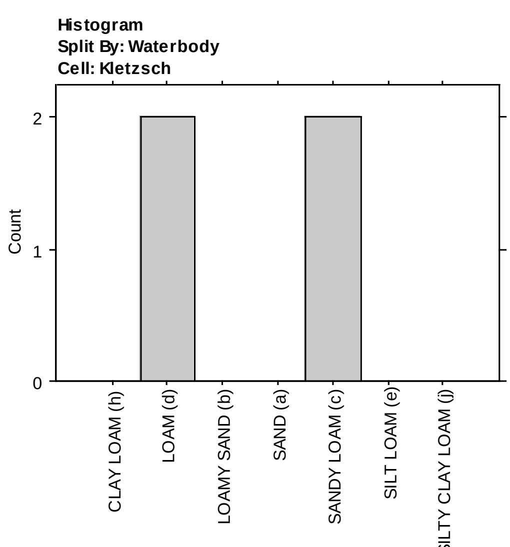
FIGURE 4.8

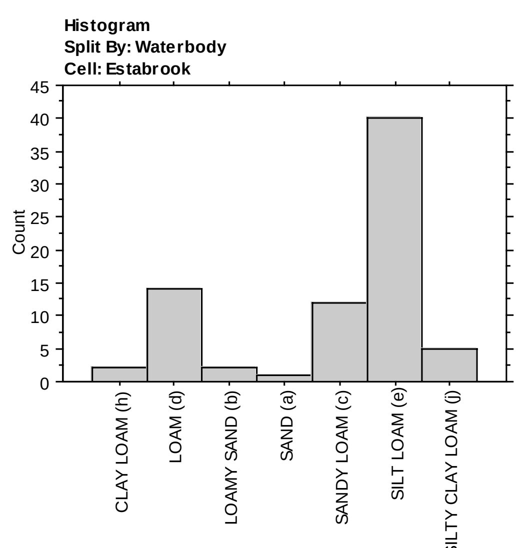
Frequency Distribution for Soil Texture
Split By: Waterbody

	Total Count	Columbia Count	Thiensville Count	Kletzsch Count	Estabrook Count
CLAY LOAM (h)	3	0	1	0	2
LOAM (d)	34	8	10	2	14
LOAMY SAND (b)	7	2	3	0	2
SAND (a)	6	1	4	0	1
SANDY LOAM (c)	38	8	16	2	12
SILT LOAM (e)	69	17	12	0	40
SILTY CLAY LOAM (j)	6	0	1	0	5
Total	163	36	47	4	76





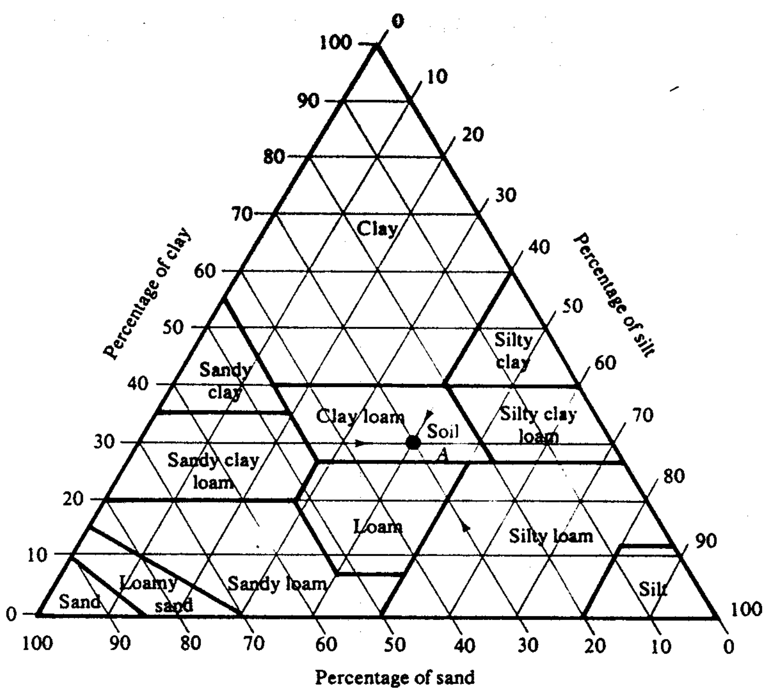




Under the USDA system sand silt and clay are defined as follows:

- SAND: 2.0 - 0.05mm diameter
- SILT: 0.05 - 0.002mm diameter
- CLAY: < 0.002mm diameter

For reference, the USDA soil textural classification is shown below.



The most common classification for the Cedar Creek and Milwaukee River sediment samples is that of "silty loam", which, as the name implies, is dominated by silt-size particles.

Figure 4.9 presents the calculated sediment bulk densities for the sediment samples. The calculated bulk densities increase as one moves downstream, with the maximum bulk densities calculated for sediments from Estabrook Park Impoundment.

The Estabrook Impoundment bulk density may be higher because of the operation of the dam. Every fall, the impoundment is drained, dewatering and exposing the shallow mudflats. In spring, the Estabrook Impoundment is reflooded.

This action compacts the Estabrook Impoundment sediments. In fact, sampling efforts in the late fall had to be abandoned simply because the compressed mudflats were impenetrable using standard sediment coring equipment.

FIGURE 4.9 CALCULATED SEDIMENT BULK DENSITIES

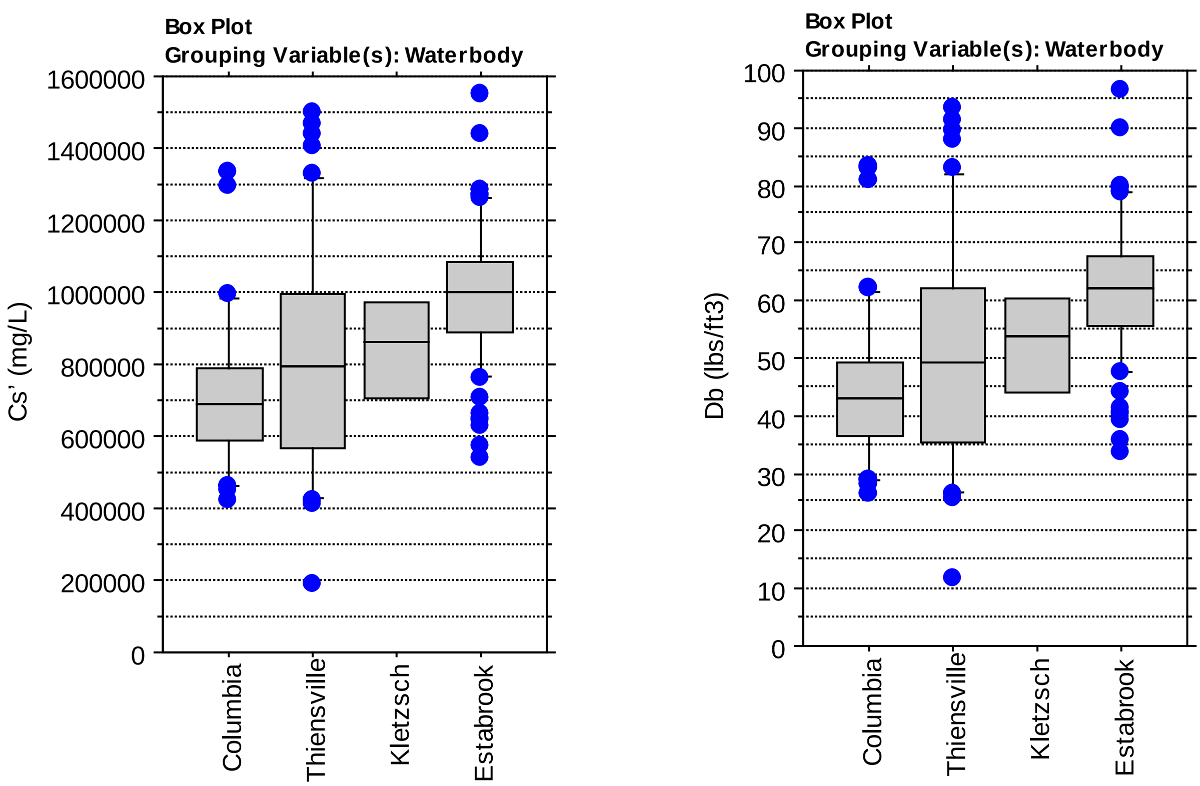
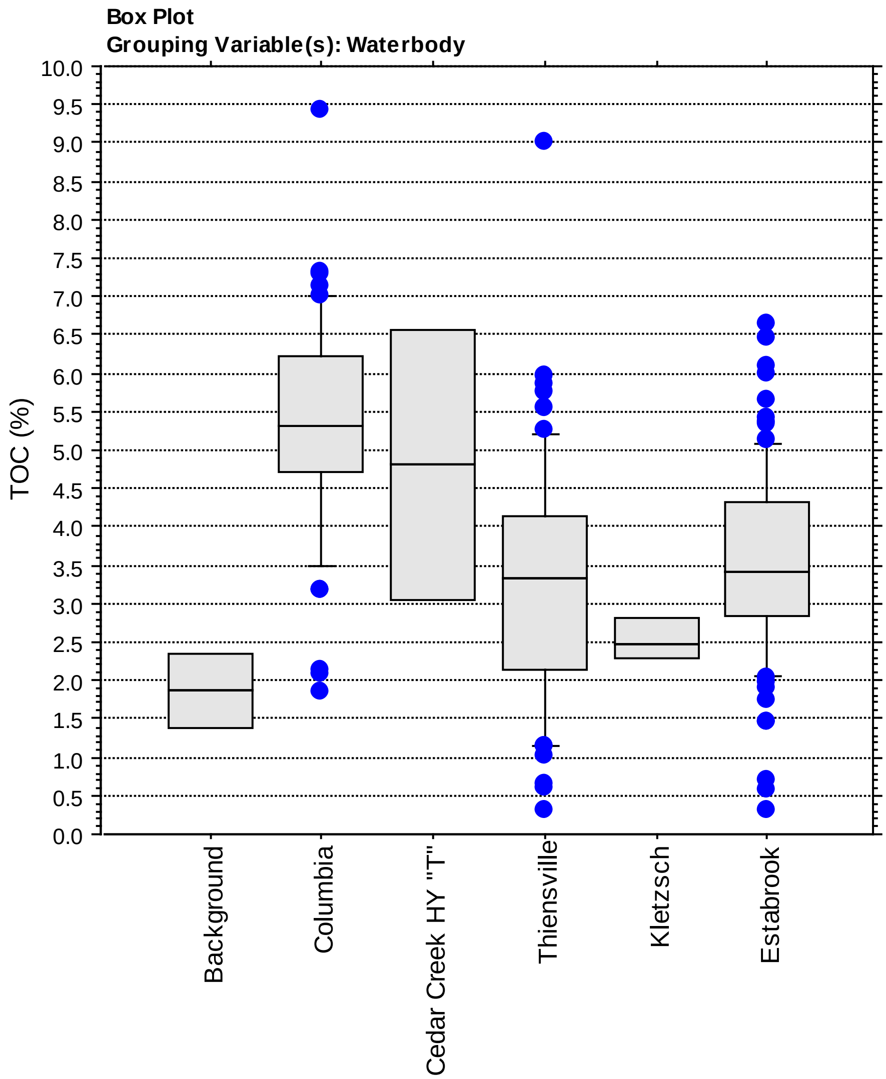


Figure 4.10 below summarizes the total organic carbon content of sediments from the sampled impoundments.

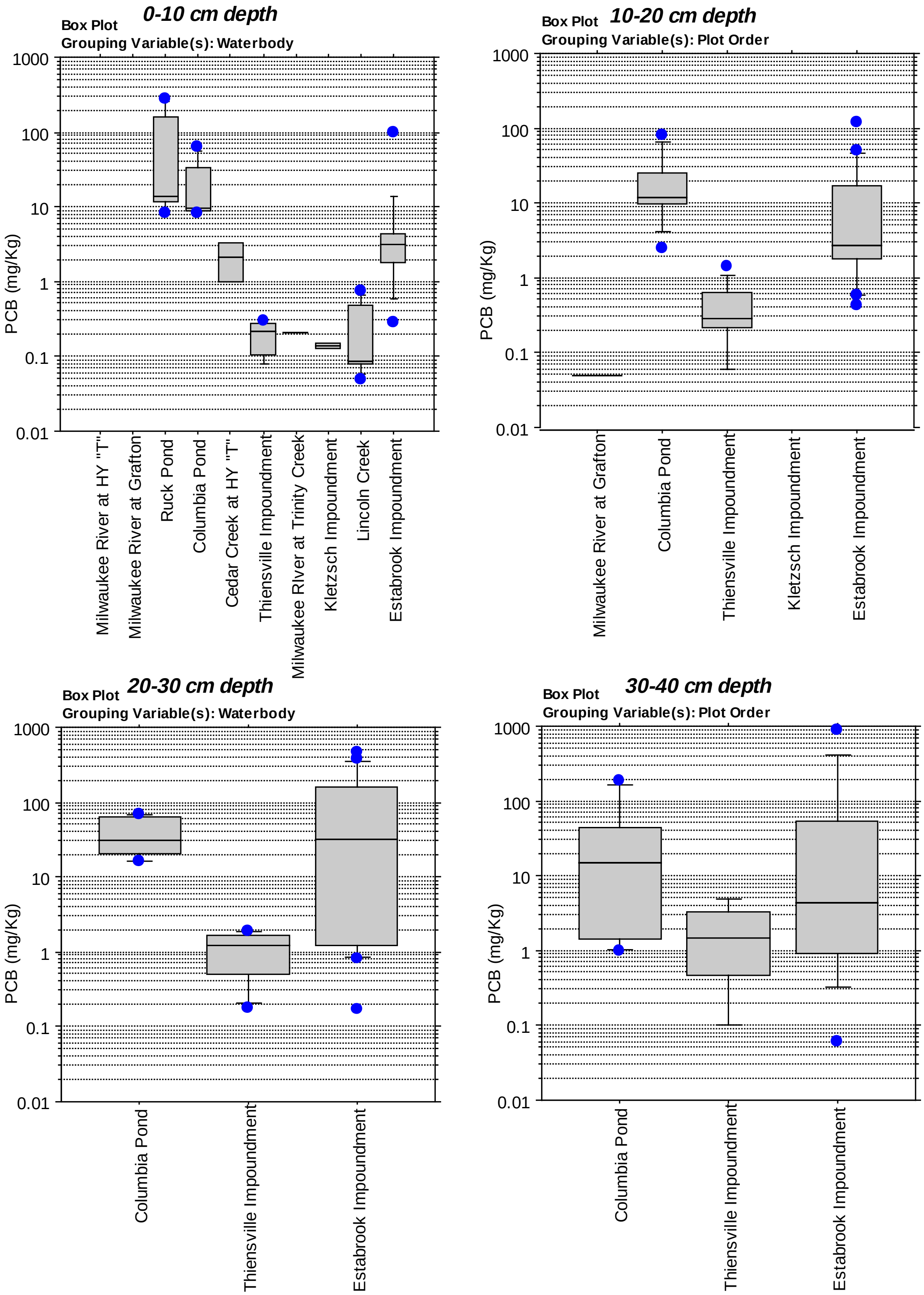
FIGURE 4.10 SEDIMENT TOTAL ORGANIC CARBON CONTENT



Sediments from Columbia Pond yield substantially higher levels of total organic carbon than do the impoundments on the Milwaukee River. It is assumed that this is a reflection of the higher f_{oc} exhibited on suspended particles from the Cedar Creek system relative to the Milwaukee River system.

Figure 4.11 below summarizes the horizontal and vertical distribution of PCB in sediment samples as part of this project. Note that the sediment results given are from samples obtained during 1993-1995. Ruck Pond surficial samples were obtained following Ruck Pond remediation.

FIGURE 4.11 DISTRIBUTION OF SEDIMENT PCB CONCENTRATIONS



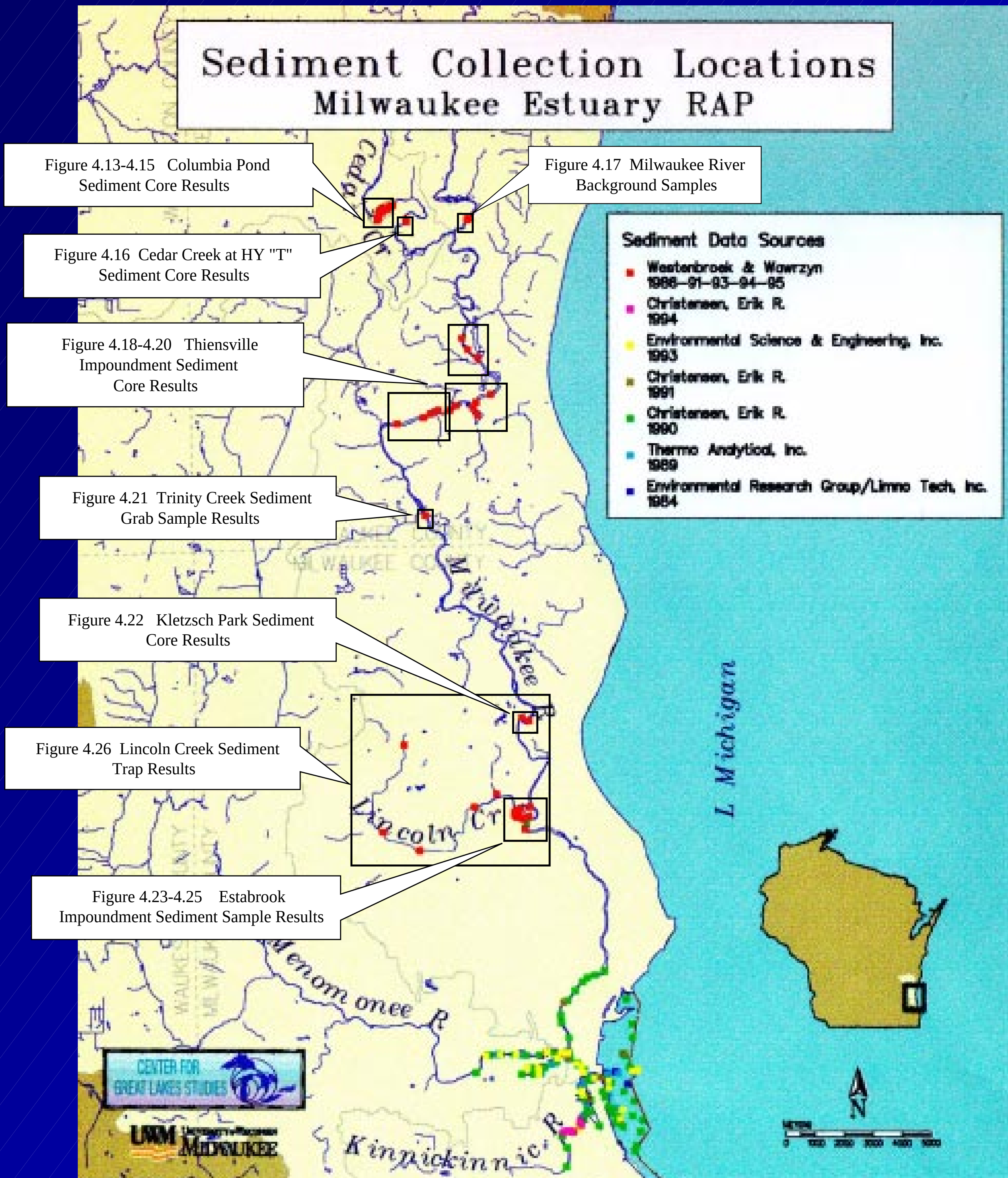
A few generalizations may be made based on Figure 4.11 and other information:

- Columbia Pond sediments are generally at least one order of magnitude or more higher than sediments found in the Milwaukee River, with the exception of the Estabrook Impoundment.
- Columbia Pond and Estabrook Impoundment sediments increase in concentration with depth, with the greatest concentrations found between 20 and 30 cm of depth. Thereafter, concentration decreases with depth. Congener results are given in the appendix.
- The Estabrook Impoundment sediment deposits are largely unrelated to the transport of PCB from Cedar Creek. The predominant Aroclor mixture at Estabrook Impoundment is Aroclor 1242; throughout Cedar Creek and the Milwaukee River upstream of Estabrook, the predominant Aroclor is Aroclor 1260.
- Thiensville Impoundment sediment concentrations increase with depth, with a median concentration of about 0.2 mg/Kg in the top 10 cm, increasing to a median value a little over 1 mg/Kg between 20-30 cm of depth. Generally, there is little detectable PCB below 40 or 50 cm of sediment depth, although there are exceptions.

On the pages that follow are the complete results of PCB analyses run on sediment samples from this project.

Figure 4.12 on the following page gives an overview of all sediment sampling activity.

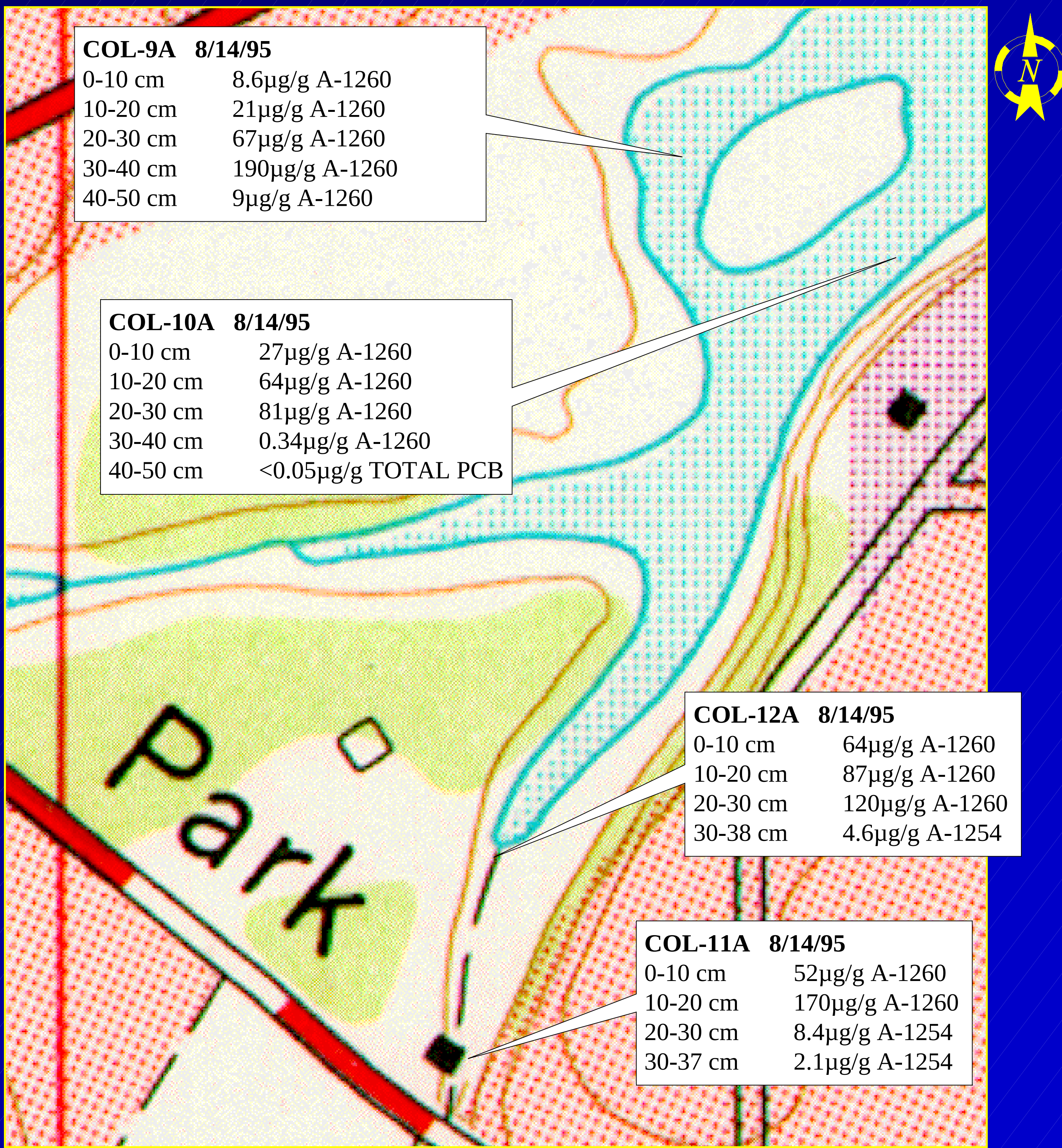
Figure 4.12 Overview of Sediment Sampling Locations



Basemap: Milwaukee Sediment Geographic Information System, 1996

Figure 4.13 Sediment Sample Results

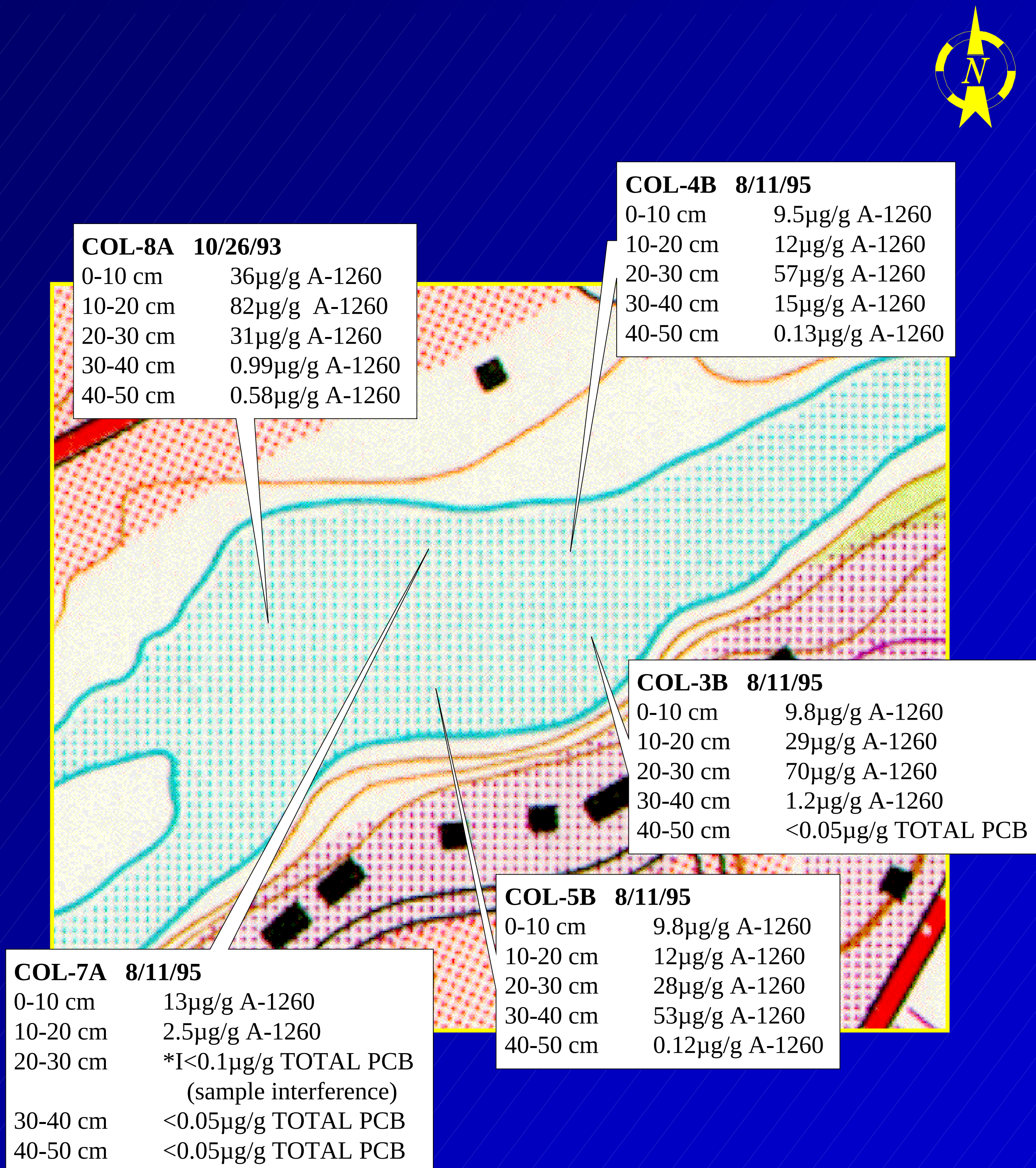
Cedar Creek at Columbia Pond



Basemap: Cedarburg, Wisconsin 7.5 minute quadrangle, USGS, photorevised 1971 and 1976

Figure 4.14 Sediment Sample Results

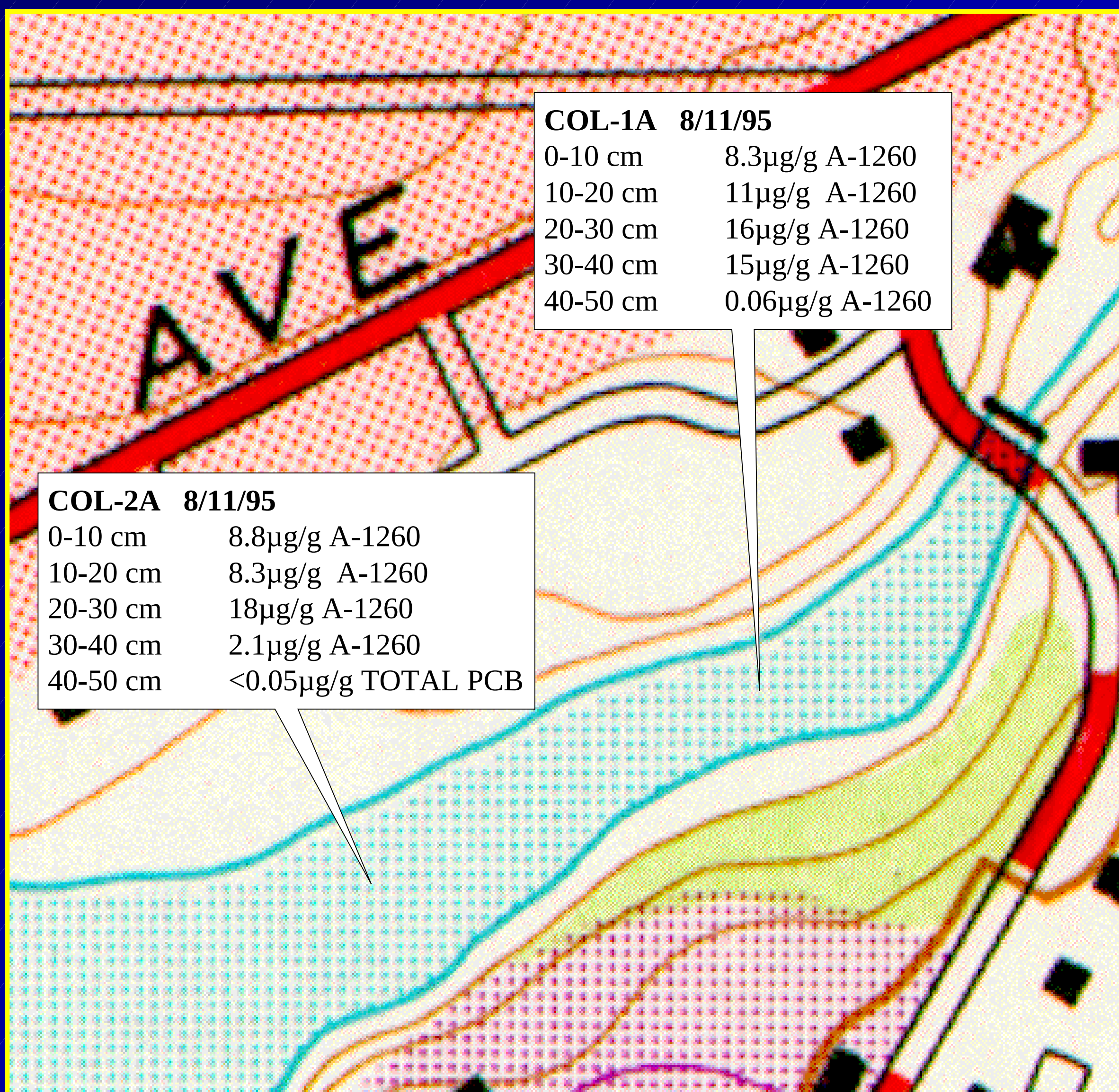
Cedar Creek at Columbia Pond



Basemap: Cedarburg, Wisconsin 7.5 minute quadrangle, USGS, photorevised 1971 and 1976

Figure 4.15 Sediment Sample Results

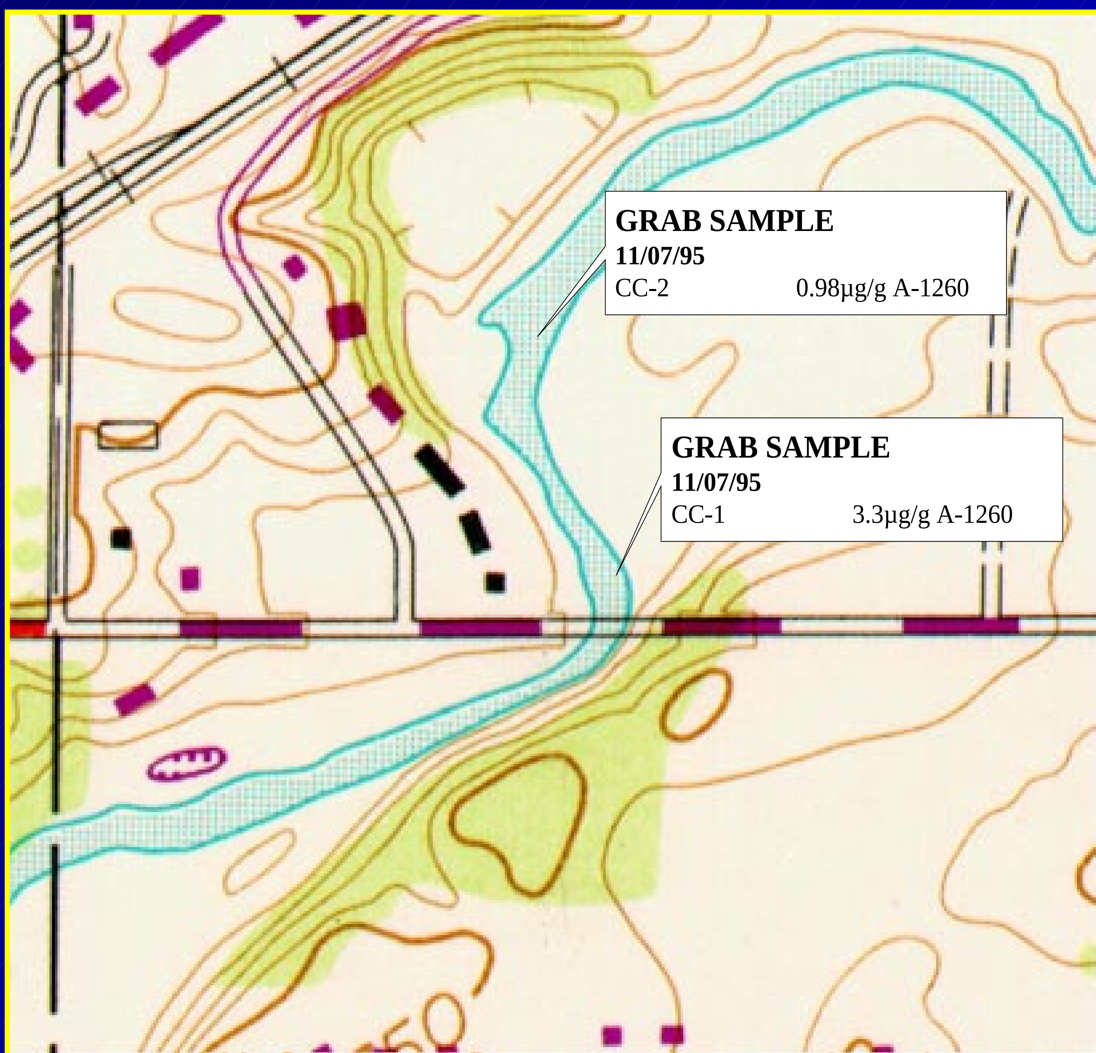
Cedar Creek at Columbia Pond

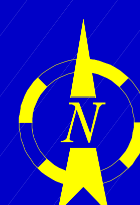


Basemap: Cedarburg, Wisconsin 7.5 minute quadrangle, USGS, photorevised 1971 and 1976

Figure 4.16 Sediment Sample Results

Cedar Creek at County Highway "T"

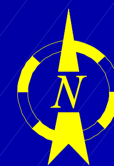


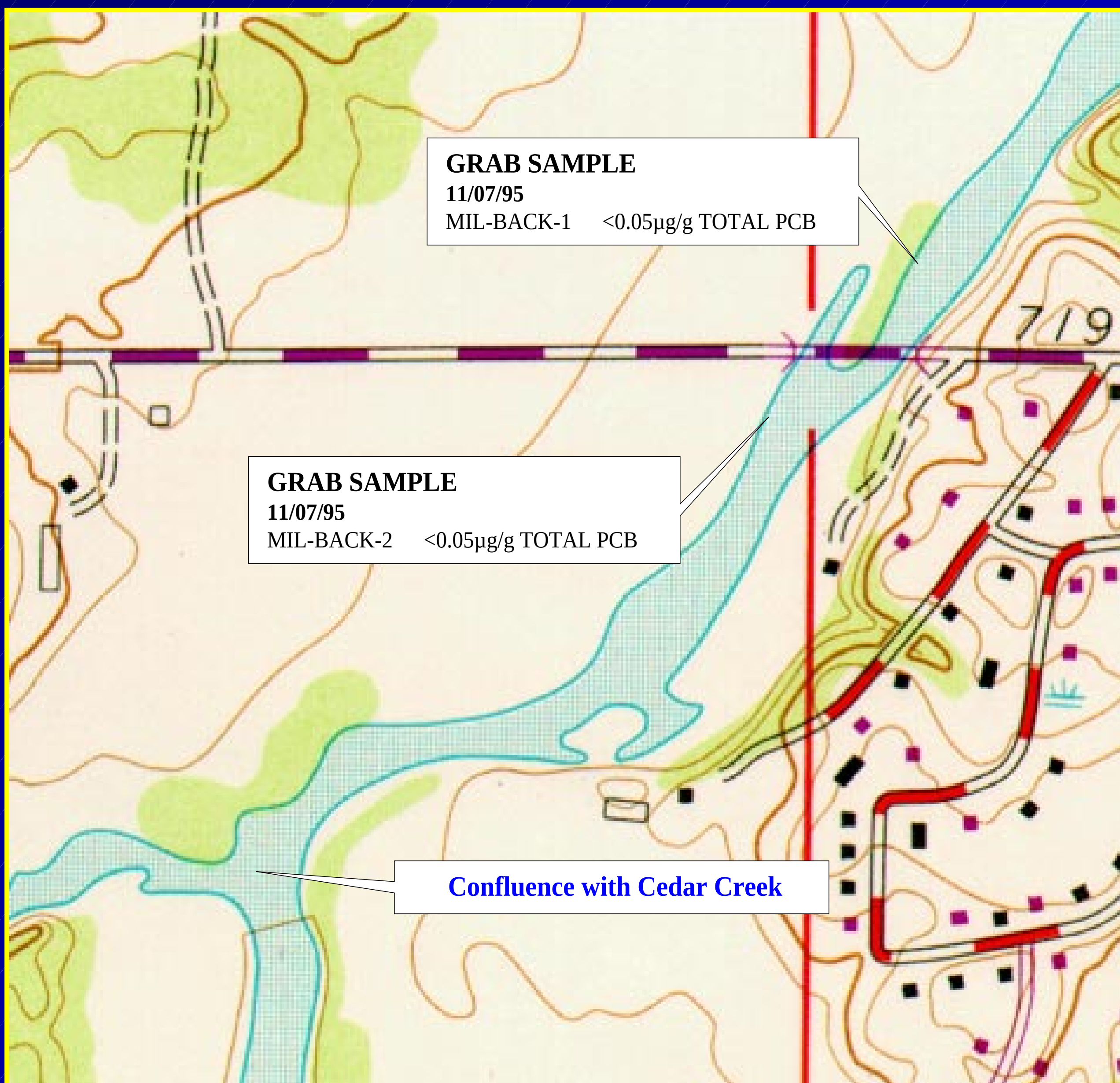


Basemap: Cedarburg, Wisconsin 7.5 minute quadrangle, USGS, photorevised 1971 and 1976

Figure 4.17 Sediment Sample Results

Milwaukee River at County Highway "T"

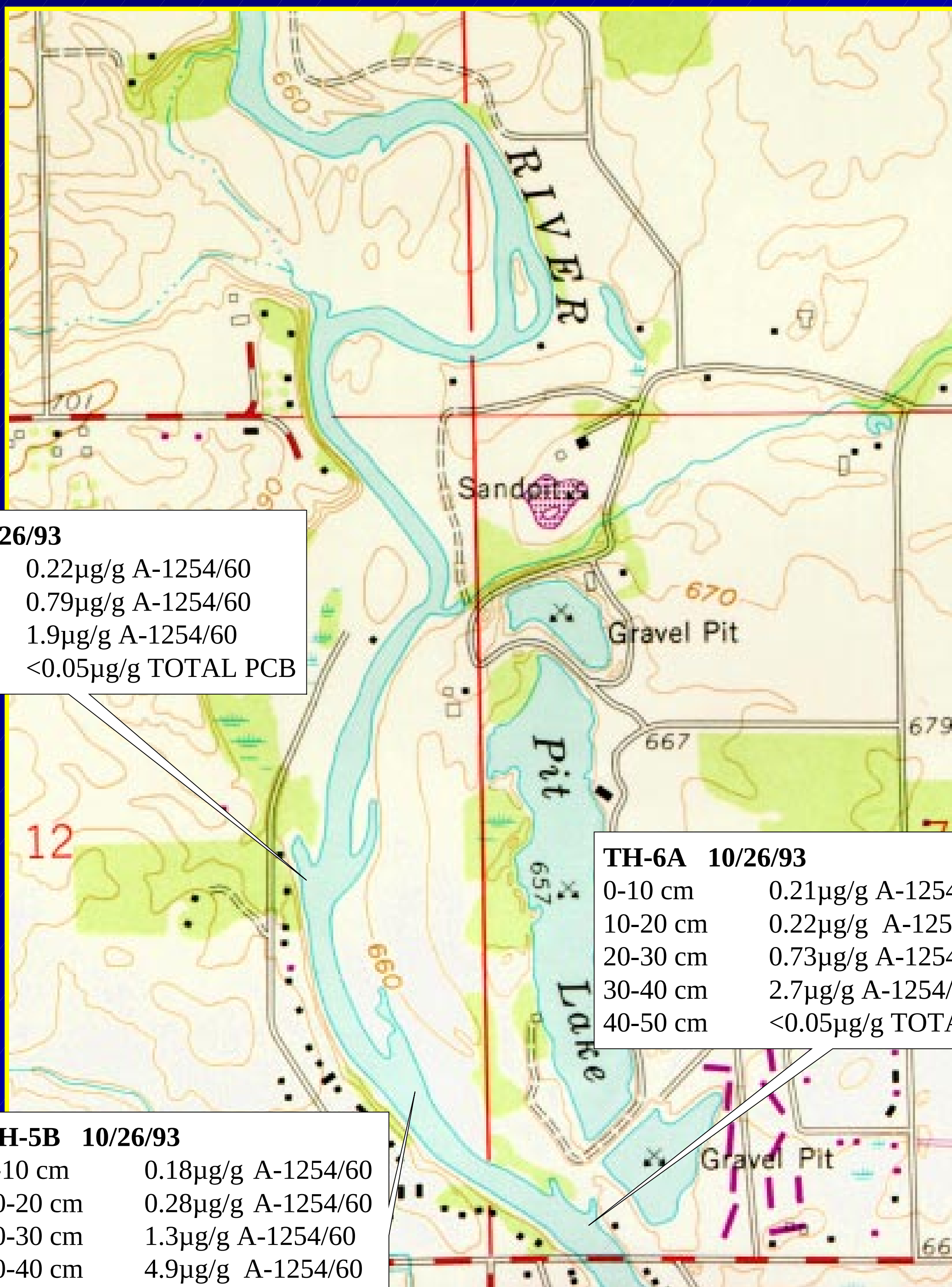




Basemap: Cedarburg, Wisconsin 7.5 minute quadrangle, USGS, photorevised 1971 and 1976

Figure 4.18 Sediment Sample Results

Milwaukee River, Thiensville Impoundment



TH-4B   10/26/93

0-10 cm	0.22µg/g A-1254/60
10-20 cm	0.79µg/g A-1254/60
20-30 cm	1.9µg/g A-1254/60
30-40 cm	<0.05µg/g TOTAL PCB

TH-6A   10/26/93

0-10 cm	0.21µg/g A-1254/60
10-20 cm	0.22µg/g A-1254/60
20-30 cm	0.73µg/g A-1254/60
30-40 cm	2.7µg/g A-1254/60
40-50 cm	<0.05µg/g TOTAL PCB

TH-5B   10/26/93

0-10 cm	0.18µg/g A-1254/60
10-20 cm	0.28µg/g A-1254/60
20-30 cm	1.3µg/g A-1254/60
30-40 cm	4.9µg/g A-1254/60
40-48 cm	0.73µg/g A-1260

Basemap: Cedarburg, Wisconsin 7.5 minute quadrangle, USGS, photorevised 1971 and 1976

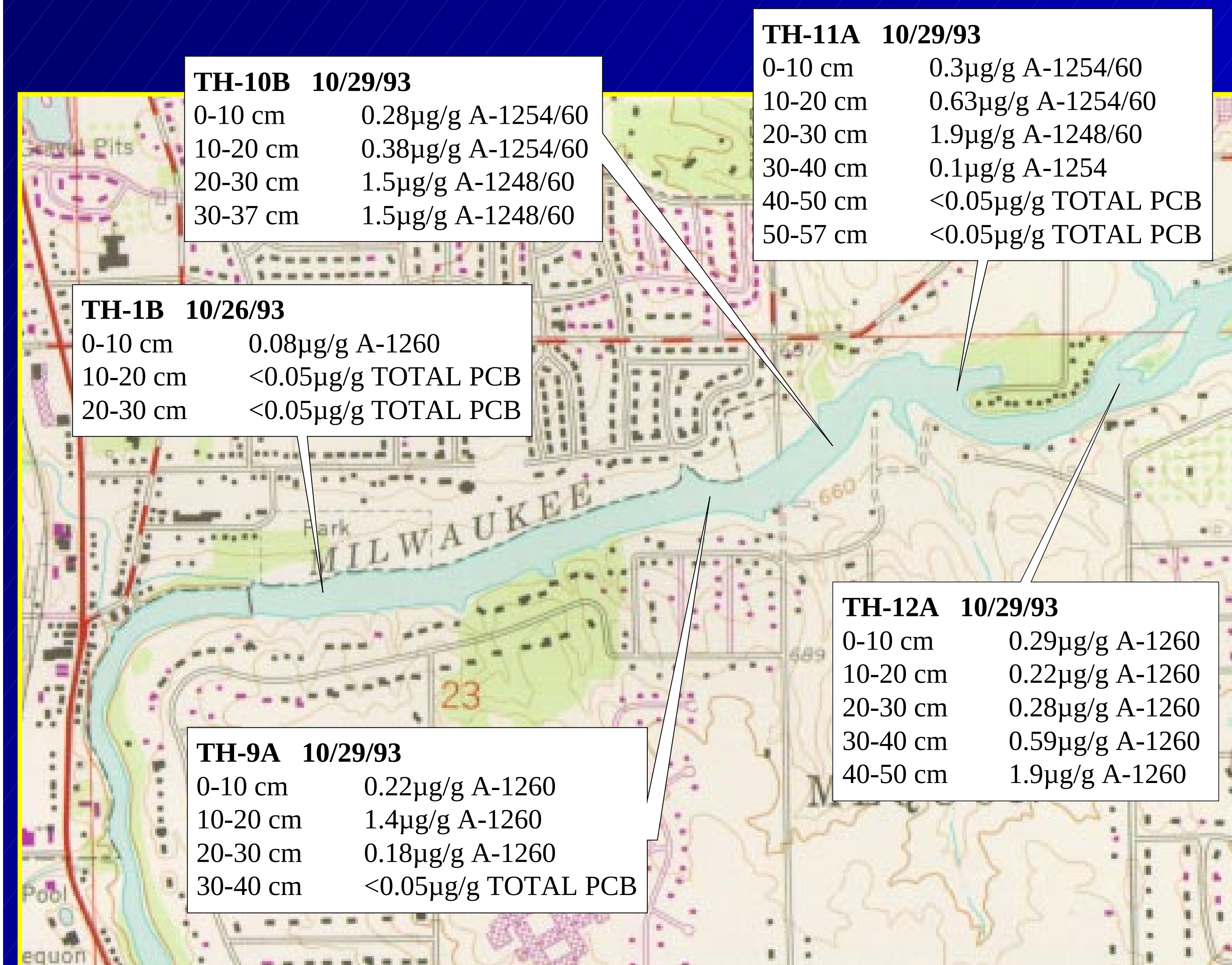
Figure 4.19 Sediment Sample Results

Milwaukee River, Thiensville Impoundment

Basemap: Thiensville, Wisconsin 7.5 minute quadrangle, USGS, photorevised 1971 and 1976

Figure 4.20 Sediment Sample Results

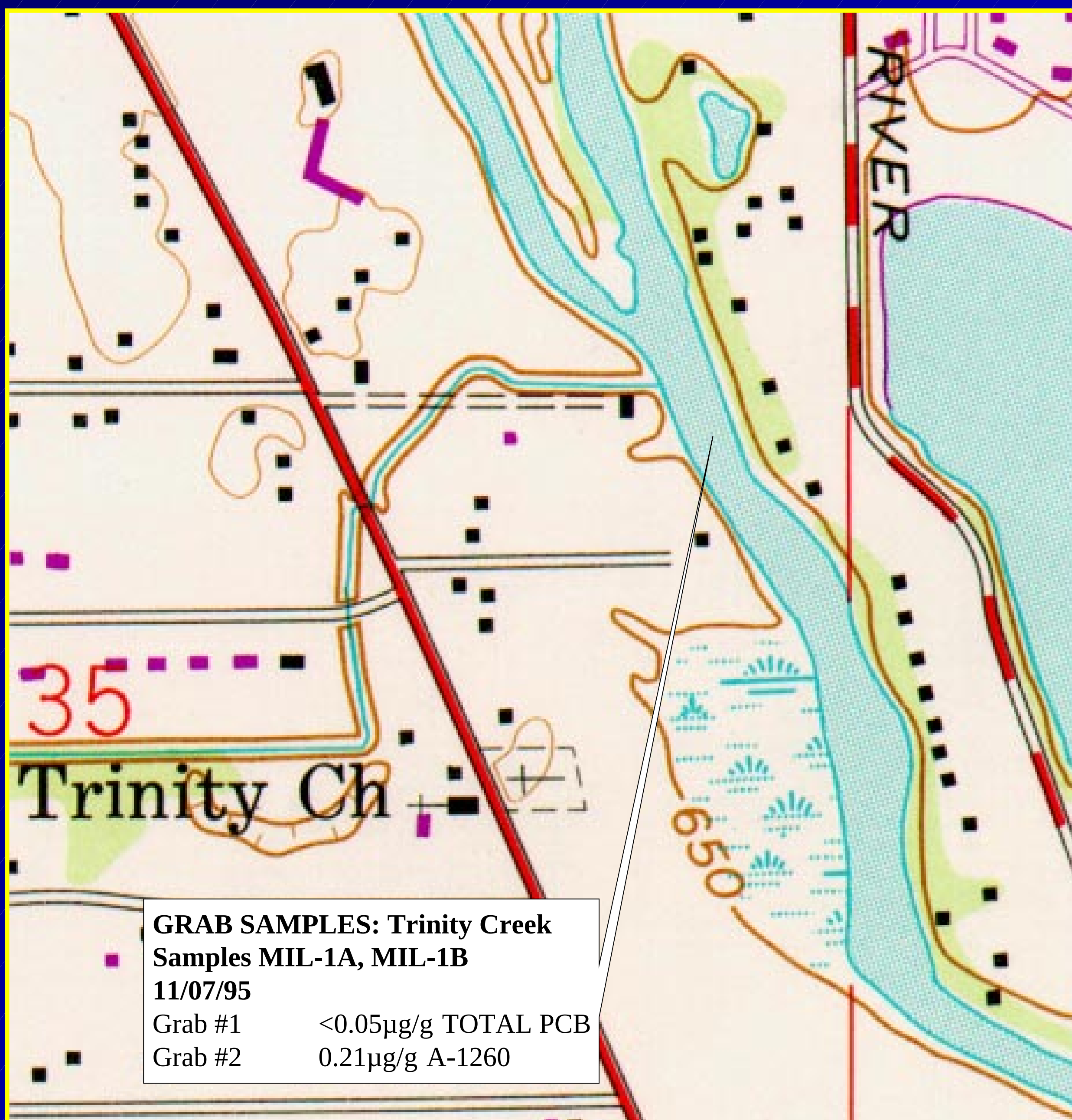
Milwaukee River, Thiensville Impoundment



Basemap: Thiensville, Wisconsin 7.5 minute quadrangle, USGS, photorevised 1971 and 1976

Figure 4.21 Sediment Sample Results

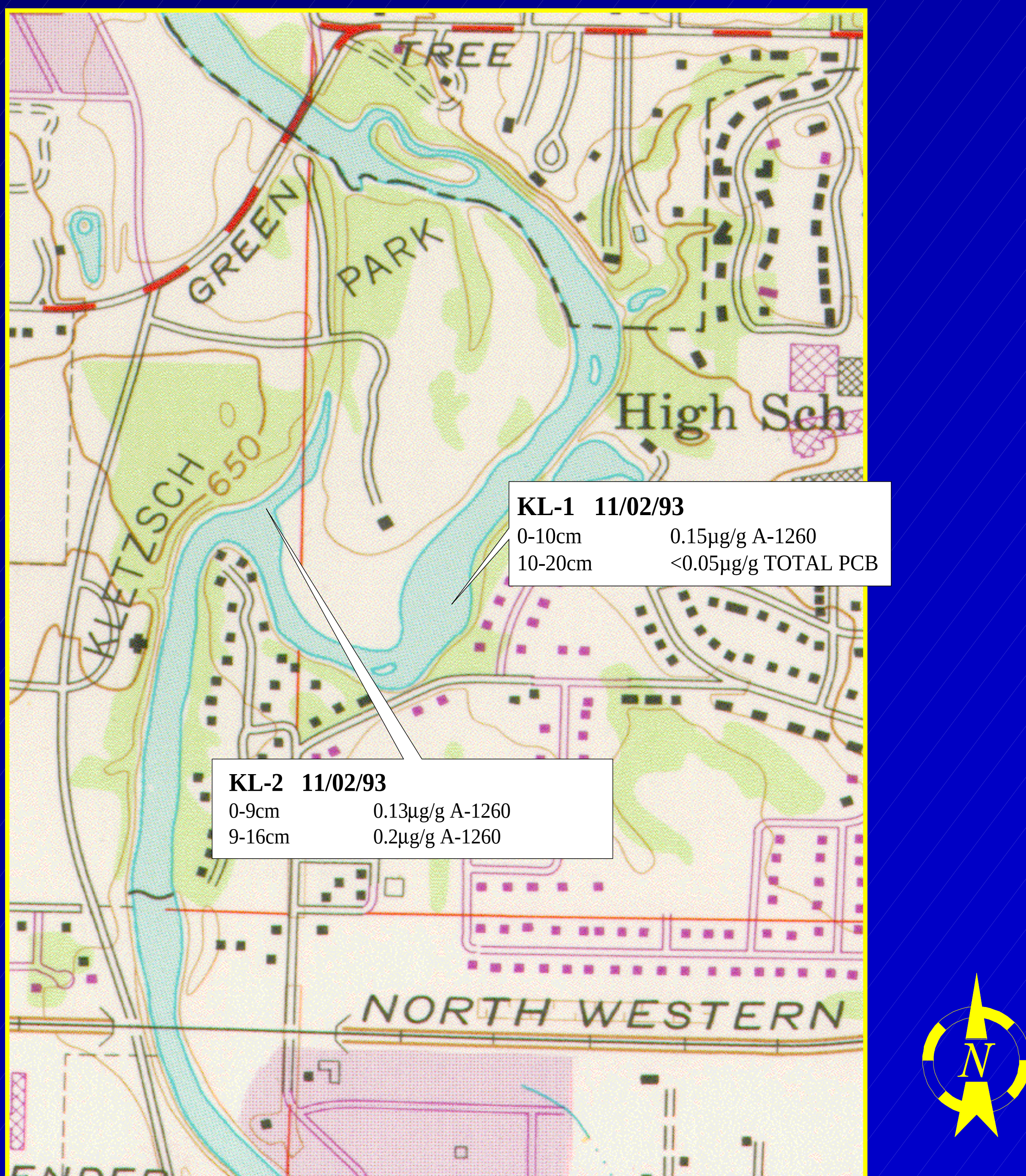
Milwaukee River downstream of Trinity Creek



Basemap: Thiensville, Wisconsin 7.5 minute quadrangle, USGS, photorevised 1971 and 1976

Figure 4.22 Sediment Sample Results

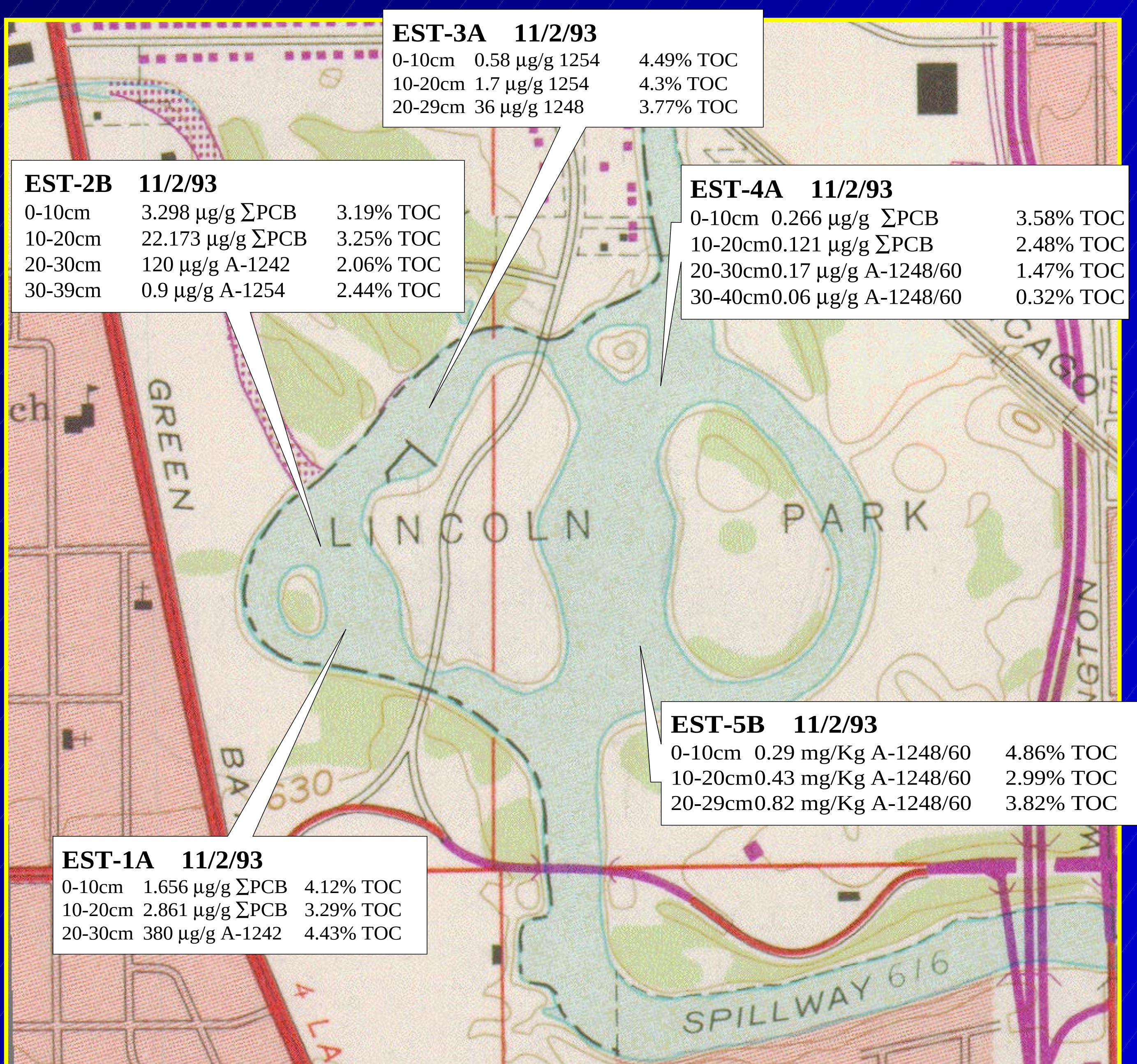
Milwaukee River at Kletzsch Park



Basemap: Thiensville, Wisconsin 7.5 minute quadrangle, USGS, photorevised 1971 and 1976

Figure 4.23 Sediment Sample Results

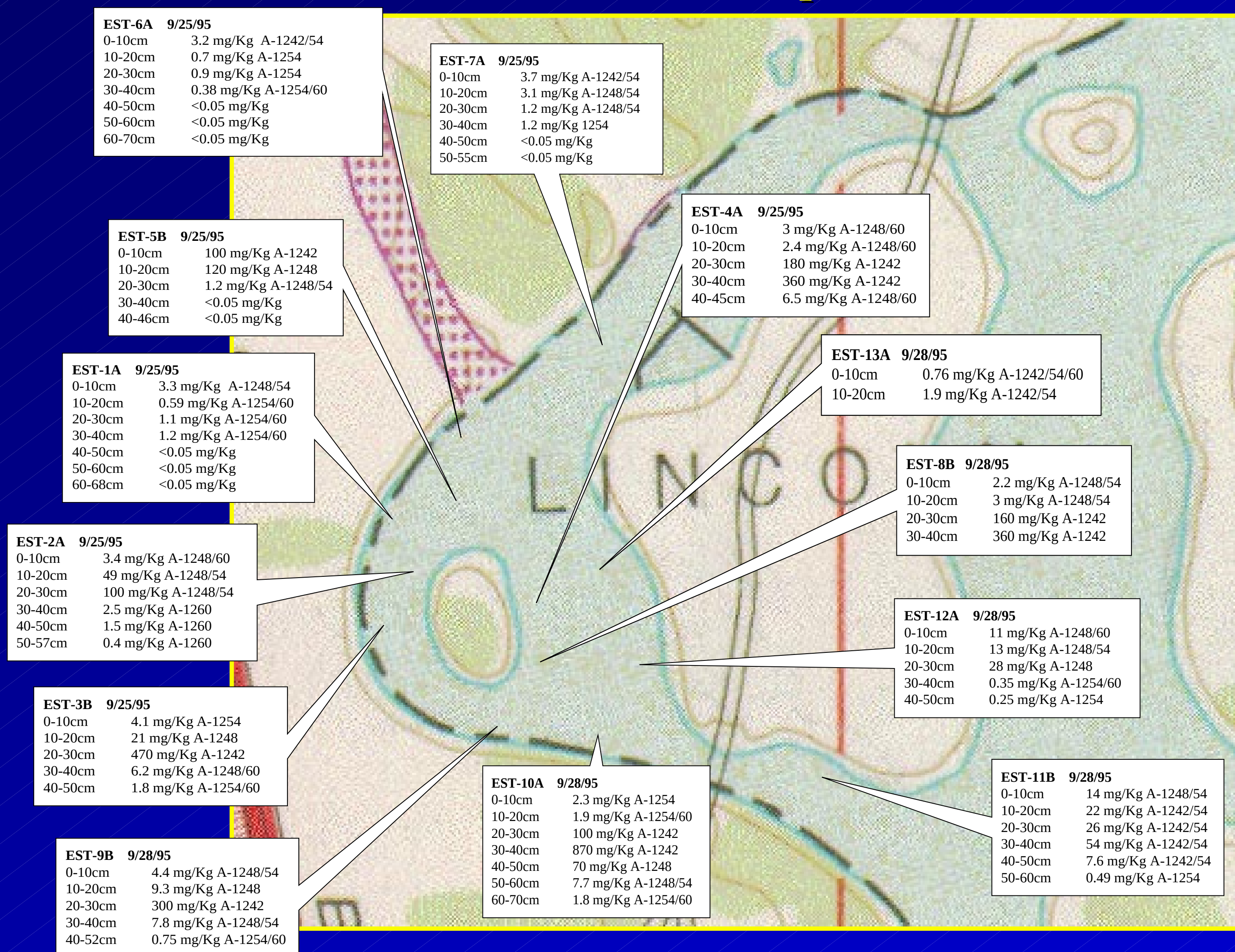
Milwaukee River, Estabrook Impoundment - 1993



Basemap: Milwaukee, Wisconsin 7.5 minute quadrangle, USGS, 1958, photorevised 1971

Figure 4.24 Sediment Sample Results

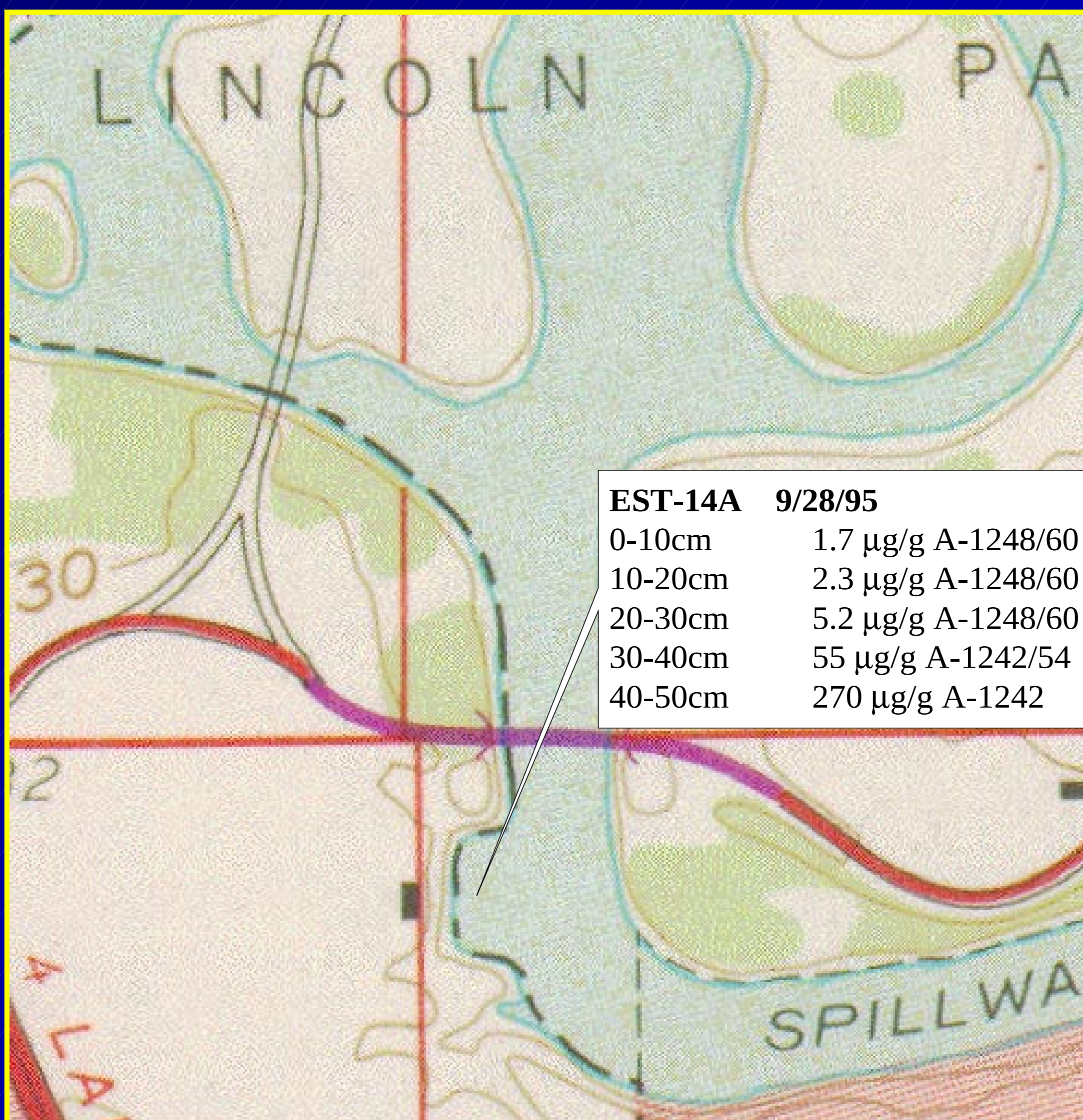
Milwaukee River, Estabrook Impoundment - 1995



Basemap: Milwaukee, Wisconsin 7.5 minute quadrangle, USGS, 1958, photorevised 1971

Figure 4.25 Sediment Sample Results

Milwaukee River, Estabrook Impoundment - 1995

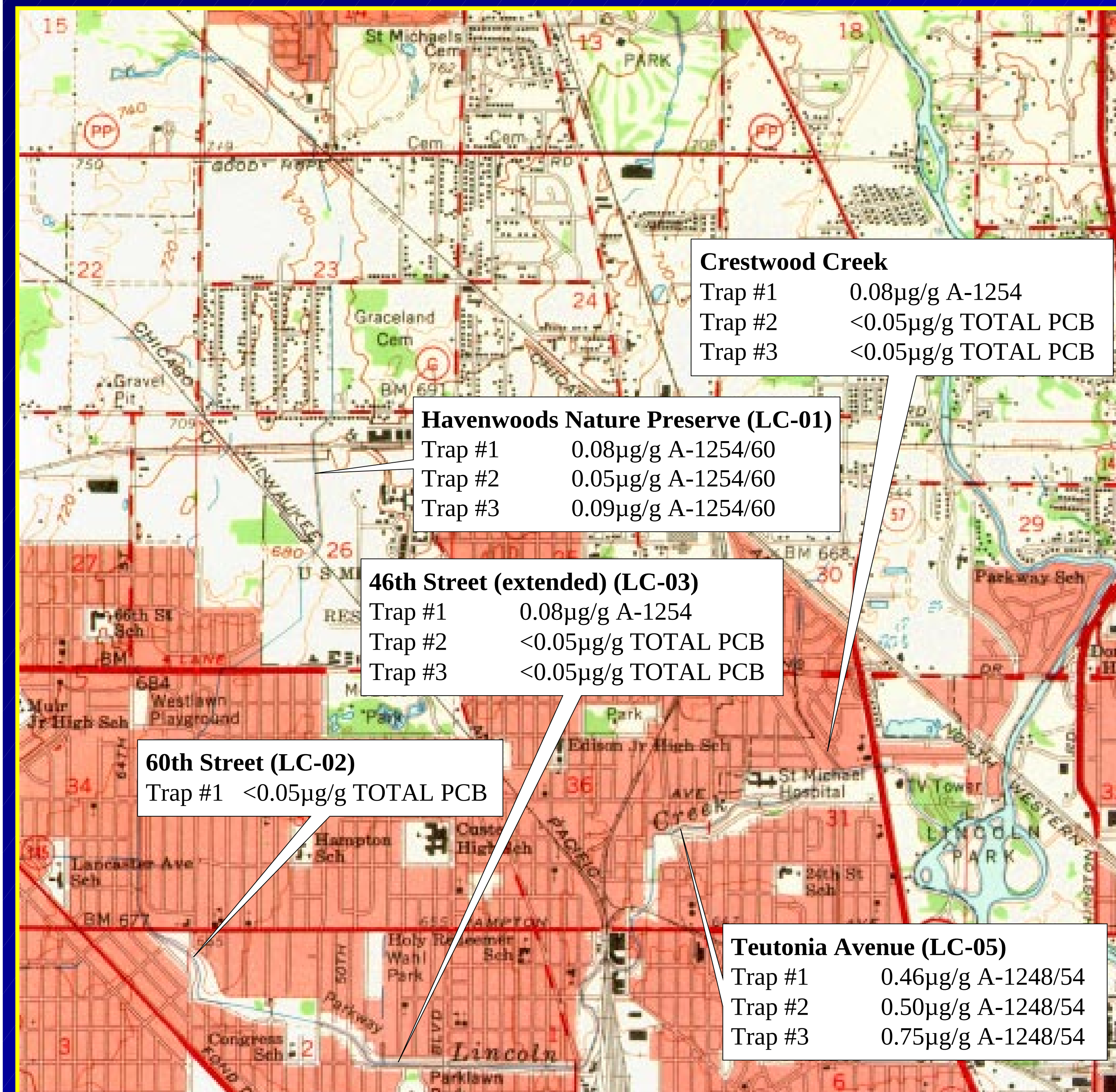


EST-14A	**9/28/95**
0-10cm	1.7 µg/g A-1248/60
10-20cm	2.3 µg/g A-1248/60
20-30cm	5.2 µg/g A-1248/60
30-40cm	55 µg/g A-1242/54
40-50cm	270 µg/g A-1242

Basemap: Milwaukee, Wisconsin 7.5 minute quadrangle, USGS, 1958, photorevised 1971

Figure 4.26 Sediment Sample Results

Lincoln Creek Sediment Traps



Basemap: Milwaukee, Wisconsin 15 minute quadrangle, USGS, 1958, photorevised 1971

5. MODEL DEVELOPMENT

This section describes how the Cedar Creek / Milwaukee River PCB Mass Balance model was put together, and includes a brief description of the model framework and parameterization.

5.1 MODEL FRAMEWORK

The Milwaukee River PCB Mass Balance Model is based on the IPX Model framework, which was developed by staff at the EPA's Large Lakes Research Station (LLRS). The framework has been applied successfully to a number of large river systems, including the Buffalo River in New York and the Lower Fox River in Green Bay, Wisconsin (Velleux *et al*, 1994). The IPX framework is itself a modification of the EPA's Water Quality Analysis and Simulation Program (WASP) model. The IPX framework includes a subroutine that simulates the settling and resuspension of cohesive sediments.

Horizontal Segmentation

The Milwaukee River PCB Mass Balance Model consists of 75 water column segments stretching from Cedar Creek at Highway 60 to the Estabrook Impoundment Dam, a distance of approximately 26 miles. Water column segment volumes were selected in order to minimize the differences between segment volumes. Minimizing the difference between volumes is important to ensuring a stable numerical solution.

Table 5.1 below gives the model segment numbers that correspond to the major impoundments on the Cedar Creek / Milwaukee River system.

TABLE 5.1

Model Segment Number	Waterbody Name
Segment 6	Ruck Pond
Segment 7 and 8	Columbia Pond
Segment 9	Wire & Nail Pond
Segment 14	Hamilton Pond
Segments 30-38	Thiensville Impoundment
Segment 58 and 59	Kletzsch Park Impoundment
Segments 66-75	Estabrook Impoundment

The following three figures show the horizontal model segmentation. Segment 1 is at the upstream end, on Cedar Creek at Highway 60, while segment 75 is downstream, on the Milwaukee River at Estabrook Impoundment Dam.

FIGURE 5.1

Cedar Creek IPX Model Segments

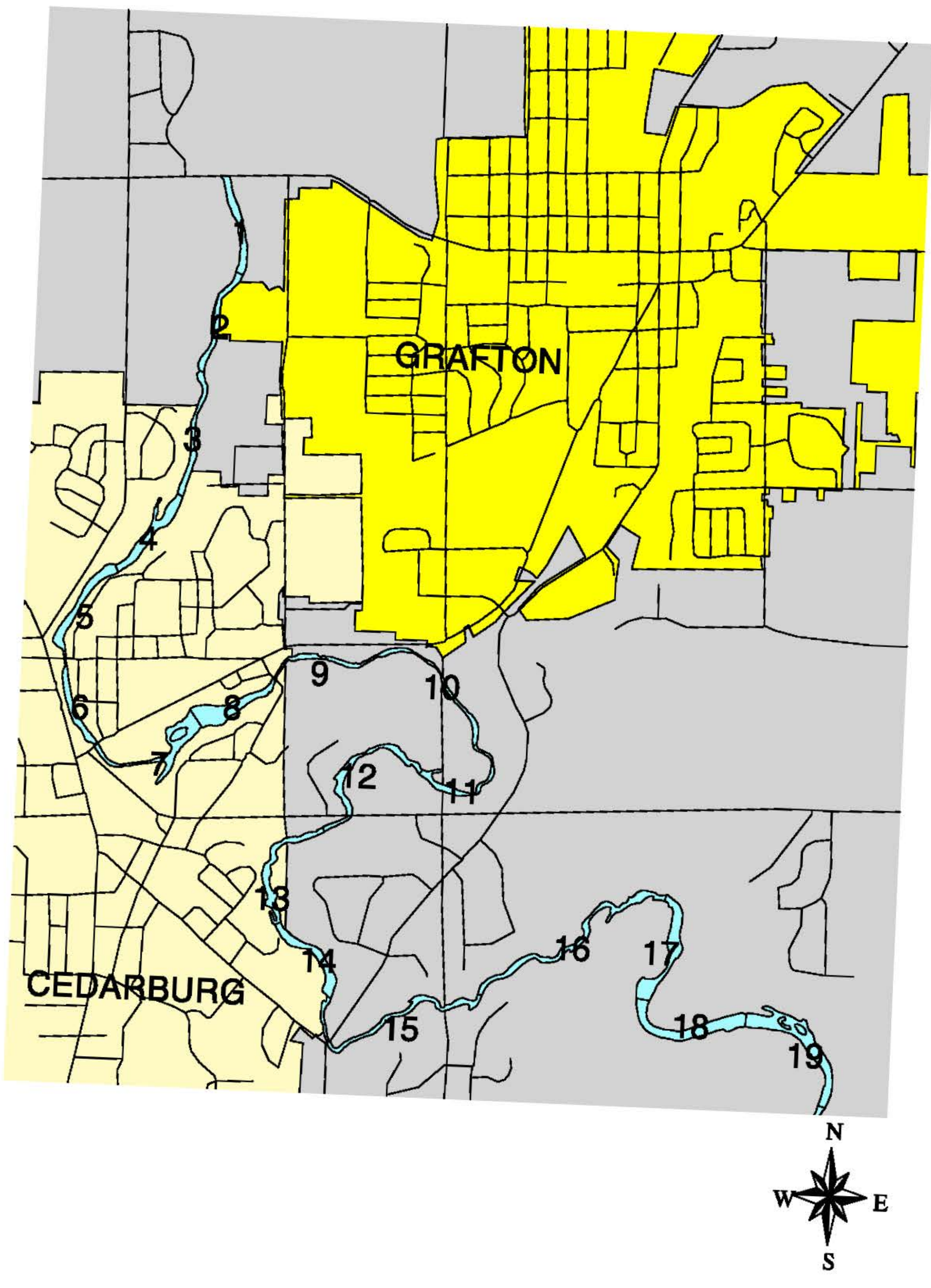


FIGURE 5.2

Milwaukee River IPX Model Segments - Upstream

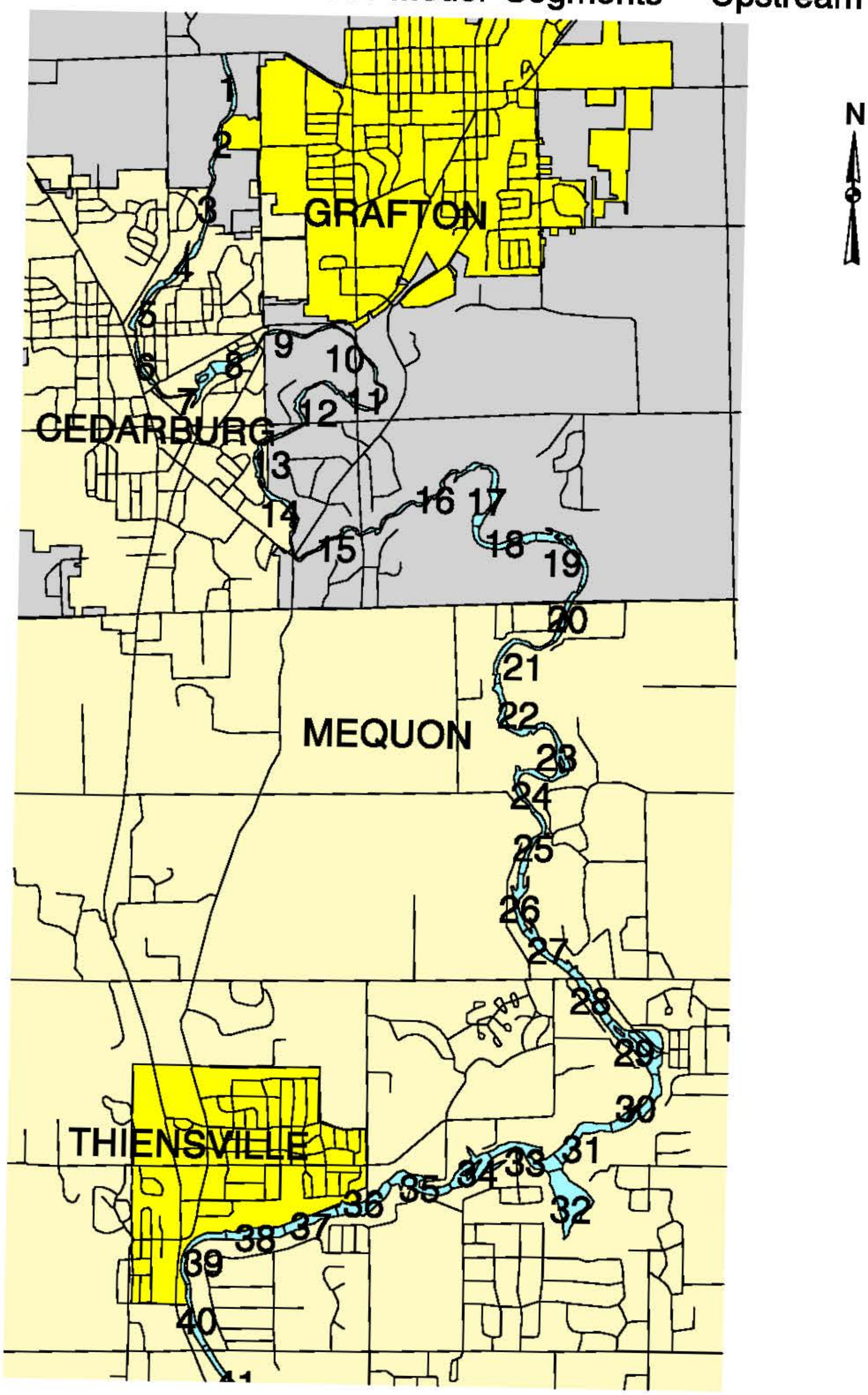
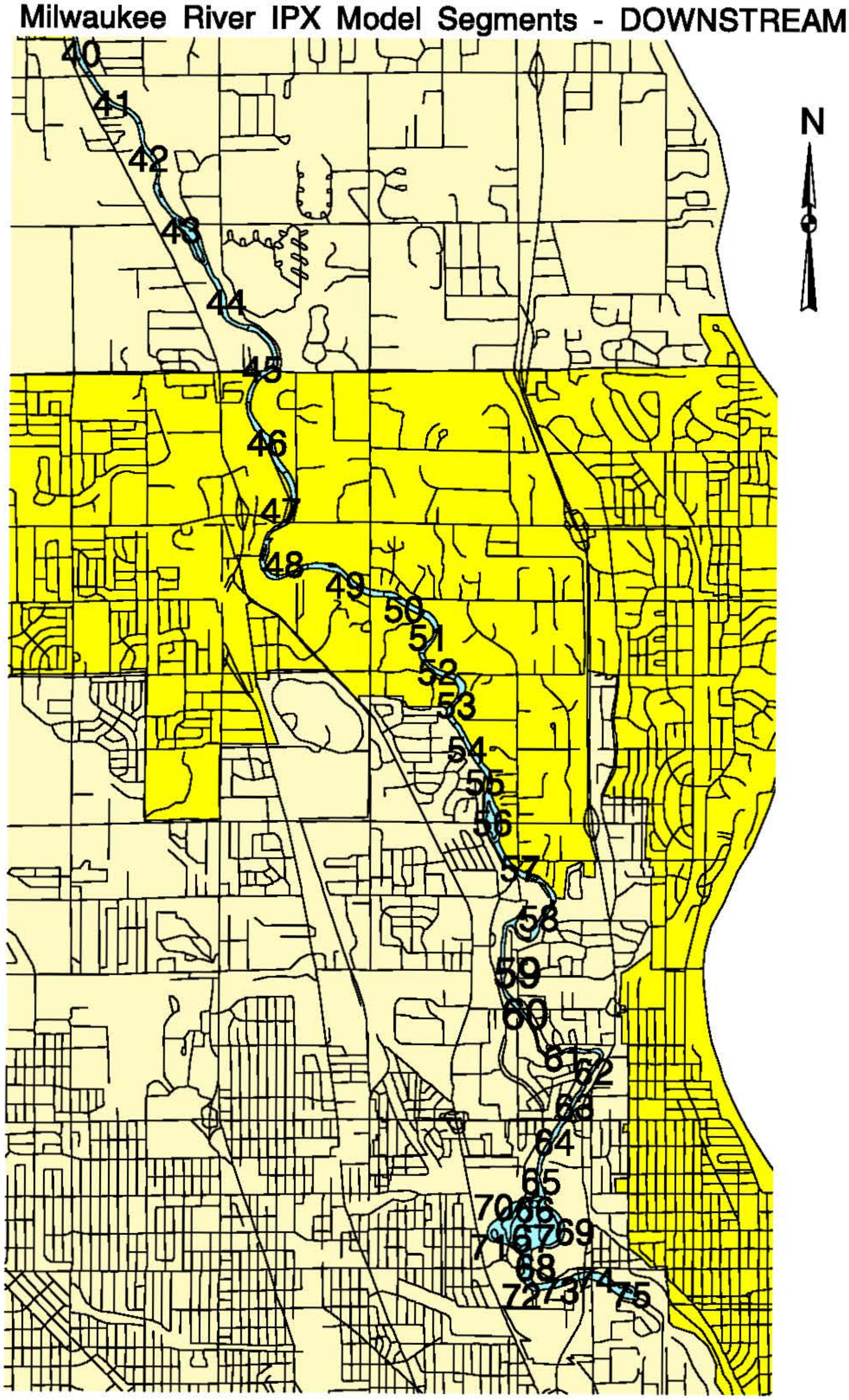


FIGURE 5.3


Milwaukee River IPX Model Segments - DOWNSTREAM
N
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75

Vertical Segmentation

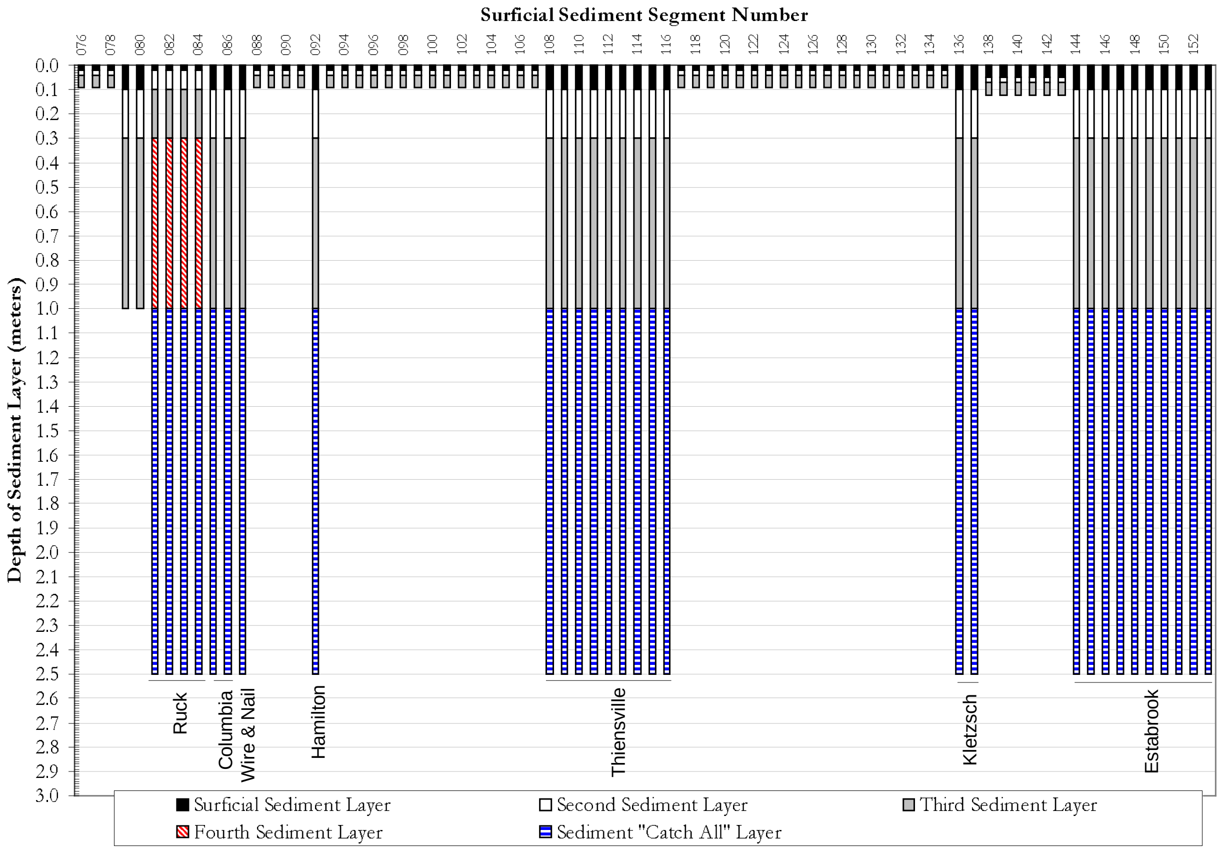
Sediments in the Milwaukee River PCB Mass Balance Model are treated as a series of stacked, constant-volume reservoirs, as shown in Figure 5.4 In general, the sediment segments correspond directly to their overlying water column segments (i.e. one surficial sediment segment for one water column segment).

The exception to this is Ruck Pond prior to remediation. Ruck Pond sediment PCB concentrations varied from below detection to 155,200 mg/Kg prior to remediation, and exhibited many orders of magnitude of difference both horizontally and vertically. Therefore, Ruck Pond sediments were broken down into four separate "stacks" of sediment underlying a single water column segment to represent the following:

- Ruck hot spot- adjacent to the stormwater outfall (150 m^2 surface area)
- River LEFT[1] average (3045 m^2)
- River RIGHT average (3045 m^2)
- "Uncontaminated"- relatively uncontaminated zone upstream from the rail trestle (7330 m^2)

[1] River LEFT: left side of the river looking DOWNSTREAM

FIGURE 5.4 VERTICAL SEDIMENT SEGMENT CONFIGURATION



Note that the figure above depicts "catch all" sediment layers 1.5 meters thick underlying each of the impoundments. The inclusion of such "catch all" segments does not imply that such a layer really exists in the field. Rather, the 1.5 meter "catch all" layers serve as extremely large reservoirs into which PCB is effectively buried over time. The initial condition specified for these segments is zero. The real purpose of the segments is to allow for full accounting of PCB mass over the course of a 25-year simulation.

5.2 Internal Model Parameterization

This section discusses how values were assigned to processes internal to the model boundaries, including model initial conditions.

5.2.1 INITIAL CONDITIONS

Initial conditions for the model are based on the results of the field sampling program.

The initial solids concentration in sediments was universally set to 500,000 mg/L. This concentration falls within the normal range of solids concentrations, and falls slightly below the range of solids concentrations calculated from field data. Previous work using the IPX model framework shows that model results are relatively insensitive to this number (Mark Velleux, personal communication).

The fraction organic carbon content (f_{oc}) of sediments was uniformly assigned the value 0.06; f_{oc} of solids particles in water was uniformly assigned the value 0.12.

The initial conditions for PCB concentration in sediment were determined by calculating an average sediment PCB concentration from all available field data for each applicable segment. In cases where little or no data existed, such as the miles of river between the major impoundments, a rough interpolation was performed between adjacent model segments.

No attempt was made to segregate sediment data by the year in which it was collected. Even though this project collected a large number of samples from the Milwaukee River system, data was still too scarce to be able to throw out even the oldest of the data, collected in 1986. The oldest, and therefore, most questionable data is from the Hamilton and Wire & Nail Impoundments, which represent the smallest PCB reservoirs on the Milwaukee River system.

Figure 5.5 below shows how the initial conditions for surficial sediment segments compare to the average sediment PCB concentrations calculated from field data. The units are given as mg/L because the IPX framework accepts mg/L as input. Multiply the results by two to obtain the concentrations in mg/Kg.

Note how the surficial sediments for pre-remediation Ruck Pond vary by more than 3 orders of magnitude (Segments 81-84).

FIGURE 5.5 MODEL INITIAL CONDITION COMPARED TO FIELD DATA - SURFICIAL SEDIMENTS

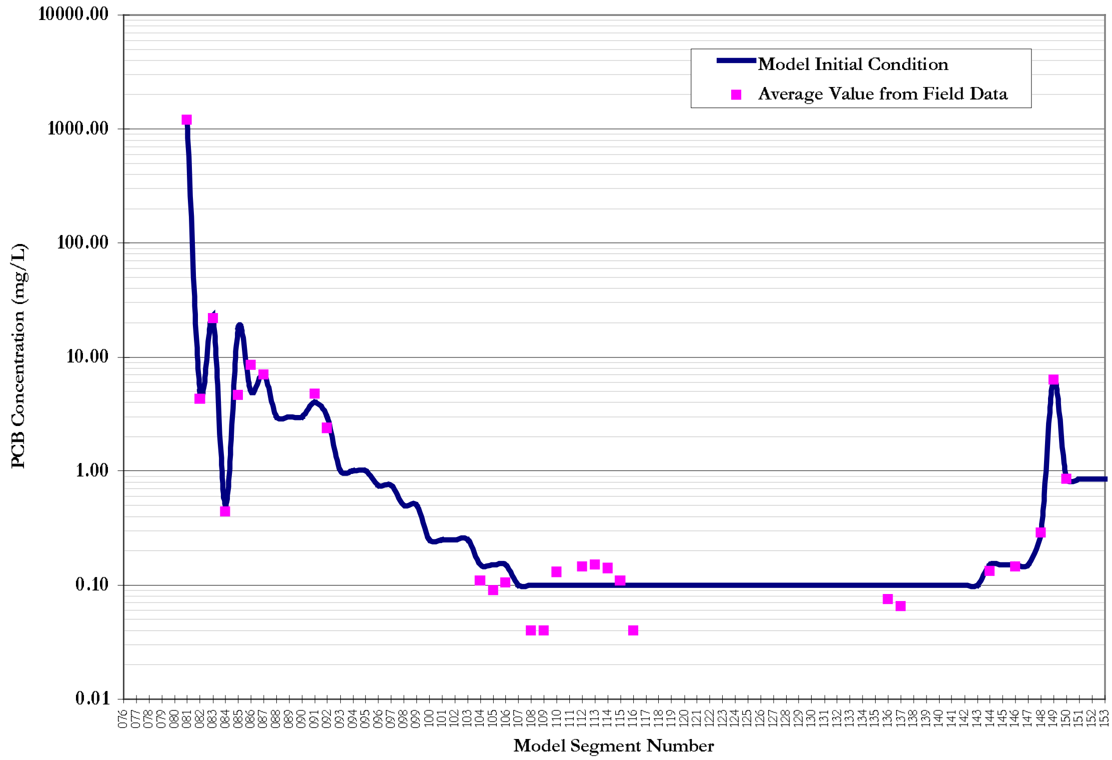
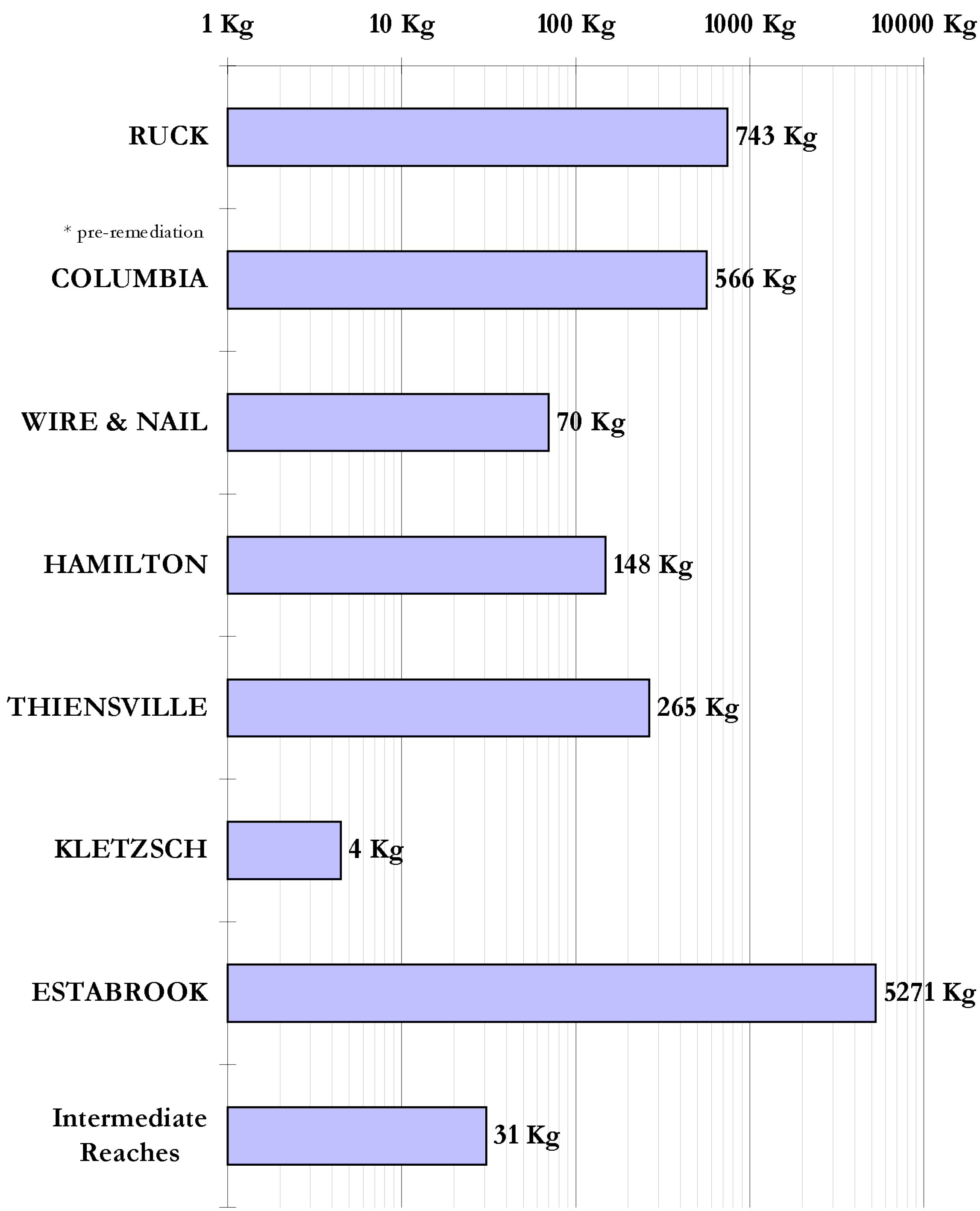


Figure 5.6 below shows the initial masses assumed at the beginning of the 5-year model run. The mass shown for Ruck Pond is pre-remediation.

FIGURE 5.6 INITIAL MODELED PCB MASS BY IMPOUNDMENT



5.2.2 RESUSPENSION AND SETTLING TIME FUNCTIONS

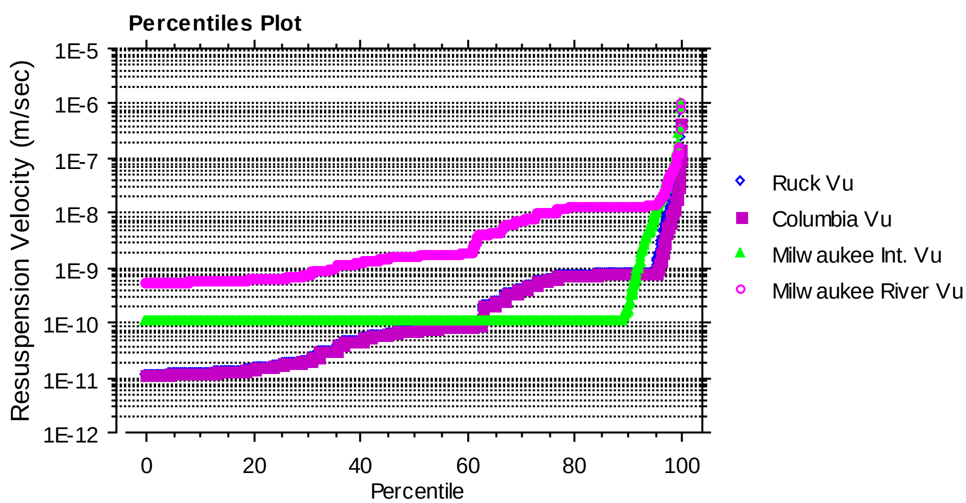
Resuspension and settling time functions were generated using both standard and modified versions of the preprocessors described in the IPX user's guide (Velleux *et al*, 1994). The only significant modification to the RESUSPND program was that the velocity calculation was changed such that it is now consistent with the method used in the IPX framework (i.e. $v=aQ^b$).

The distribution of *raw* resuspension velocities is given in Figure 5.7 below.

FIGURE 5.7 DISTRIBUTION OF RAW RESUSPENSION VELOCITIES FOR VARIOUS REACHES

Percentiles

	Ruck Vu	Columbia Vu	Milwaukee Int. Vu	Milwaukee River Vu
10	1.140E-11	1.140E-11	1.000E-10	5.220E-10
25	1.570E-11	1.570E-11	1.000E-10	6.100E-10
50	6.900E-11	6.900E-11	1.000E-10	1.510E-9
75	5.670E-10	5.480E-10	1.000E-10	9.460E-9
90	7.490E-10	7.440E-10	1.499E-10	1.235E-8



"Ruck Vu" was applied to both the Woolen Mill and Ruck Ponds. "Columbia Vu" was applied to both Columbia and Wire & Nail Ponds.

It should be noted that the actual resuspension within the model is also affected by the sediment age. The empirical sediment age constant, Z, is used to modify the resuspension velocities shown above to reflect the effects of sediment aging. Due to a variety of processes, sediment becomes less likely to resuspend over time.

The IPX framework tracks seven separate sediment age classes and modifies the raw resuspension velocities according to sediment age. The empirical sediment age constant varied between 1 and 49, beginning with 1 on the first day. Each day, the Z value was increased by 7, so that sediments in the 7-day old class would have a Z value of 49 (i.e. the resuspension velocity shown in Figure 5.7 would be divided by 49 prior to being applied in the model).

Background resuspension was varied by season ("summer": May-Sept, inclusive, "winter", all other times). In addition, the background resuspension rate during summer was assumed directly proportional to temperature (and thus, algal productivity). Resuspension rates were increased during the summer months in order to simulate the presence of a highly resuspendable layer of dead algal material observed commonly during field sampling and cited in literature.

In addition, the IPX framework contains provisions that allow for resuspension of "freshly deposited" sediments. Although this option was needed on larger systems such as the Fox River (Wisconsin), on the Milwaukee River system it did not appear justified. The "fresh resuspension" routine is designed to continue resuspending sediments after the peak of the hydrograph has been reached. For this application, the fresh resuspension option was disabled by "zeroing out" the values of a_0 and τ_{crit} for fresh resuspension.

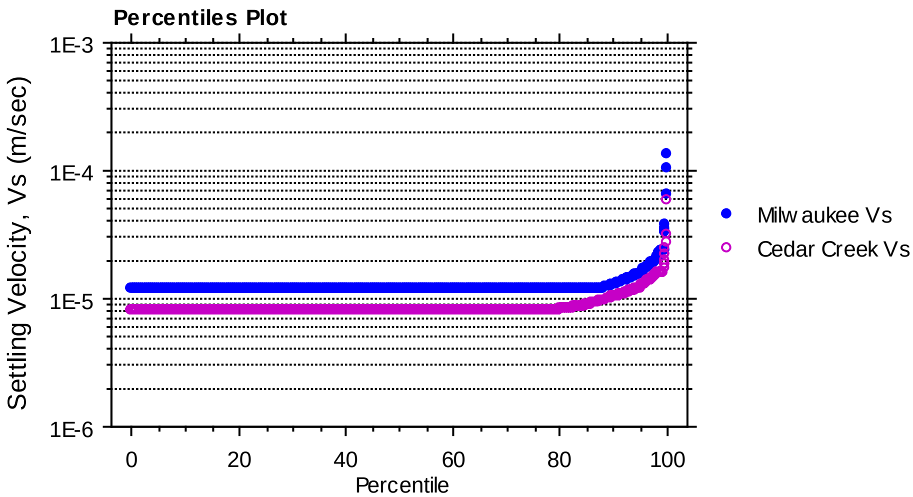
Settling velocities were calculated using the SETTLE preprocessor described in Velleux *et al* (1994). The settling velocity is essentially constant save for extreme high flow events, where the presumed higher proportion of sands in suspension settle more quickly.

Figure 5.8 shows the distribution of settling velocities used in the Milwaukee River model.

FIGURE 5.8 DISTRIBUTION OF SETTLING VELOCITIES FOR VARIOUS REACHES

Percentiles

	Milw aukee Vs	Cedar Creek Vs
10	1.200E-5	8.000E-6
25	1.200E-5	8.000E-6
50	1.200E-5	8.000E-6
75	1.200E-5	8.000E-6
90	1.284E-5	1.023E-5



5.3 EXTERNAL MODEL PARAMETERIZATION

5.3.1 HYDROGRAPHS

During development the model was run for a simulated "5-year" period beginning on September 13, 1990, the first day of resumed operation of the Cedar Creek Highway 60 gaugehouse. The simulated 5-year period ends with September 30, 1995.

The model application runs simulate a "25-year" time period. The model runs simulate the time period from October 1, 1995 to September 29, 2021.

Hydrographs Used in 5-year Simulations

The hydrographs used in the 5-year simulations were based on hydrographs recorded at four gauging stations that were operating during the model calibration period: Lincoln Creek at 47th Street, Cedar Creek at Highway 60, Milwaukee River at Pioneer Road and Milwaukee River at Estabrook Park.

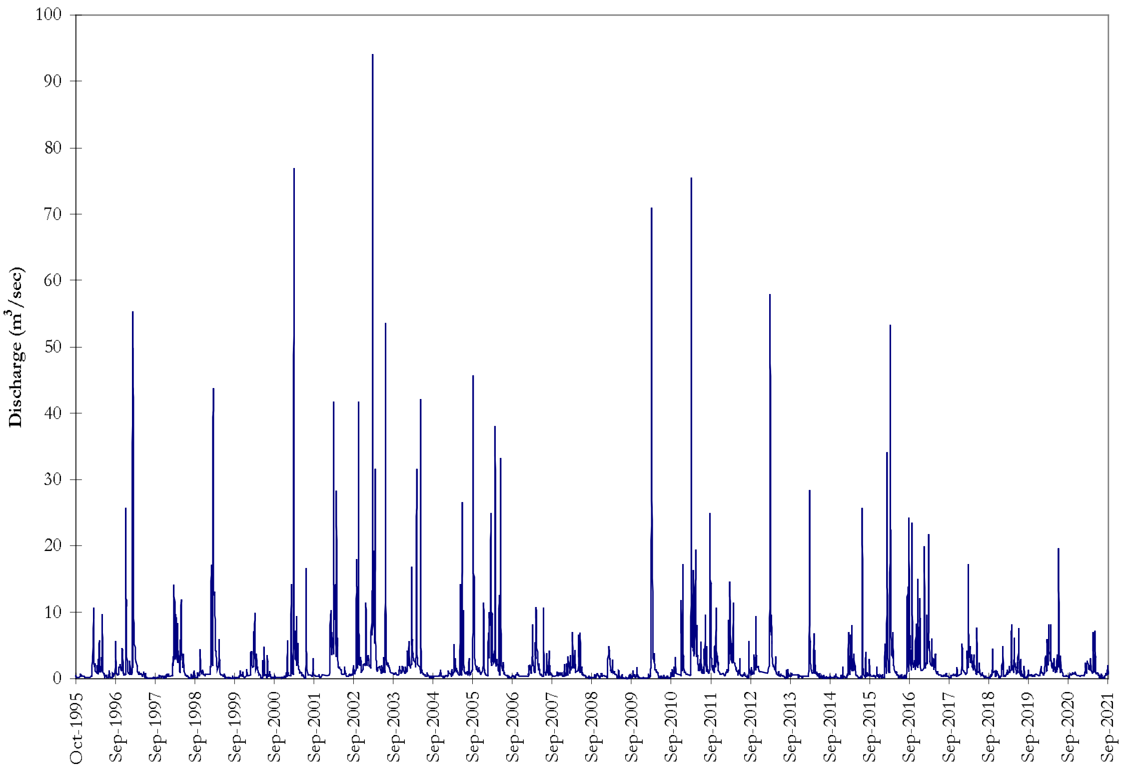
Hydrographs Used in 25-year simulations

The hydrographs used in the long-term model simulations are based directly on actual measured hydrographs for Cedar Creek and the Milwaukee River. For Cedar Creek, the 25-year hydrograph represents the actual hydrograph from the period of October 1, 1944 through September 30, 1970, measured in Cedar Creek at Highway 60[2].

Figure 5.9 below shows the hydrograph applied at the upstream boundary on Cedar Creek for the 25-year model runs.

[2] The period of record 10/1/44-9/30/70 actually represents a 26-year period of record; this report makes reference to the "25-year" model runs regardless, since that was the length of model simulation originally planned for during model formulation.

FIGURE 5.9 25-YEAR HYDROGRAPH: CEDAR CREEK AT HIGHWAY 60



The hydrograph applied at the upstream boundary of the Milwaukee River is based on the hydrograph recorded at the Estabrook Park USGS gaugehouse, between October 1, 1944 and September 30, 1970. Values were adjusted to the Pioneer Road location by using the watershed area ratio between sites (607 $mi^2/696mi^2$). The value applied at the Milwaukee River upstream boundary was obtained by subtracting the value at the Cedar Creek Highway 60 site from the value calculated for the Pioneer Road site.

Figure 5.10 shows the hydrograph applied to the Milwaukee River upstream boundary for the 25-year model run.

FIGURE 5.10 25-YEAR HYDROGRAPH: MILWAUKEE RIVER AT UPSTREAM BOUNDARY

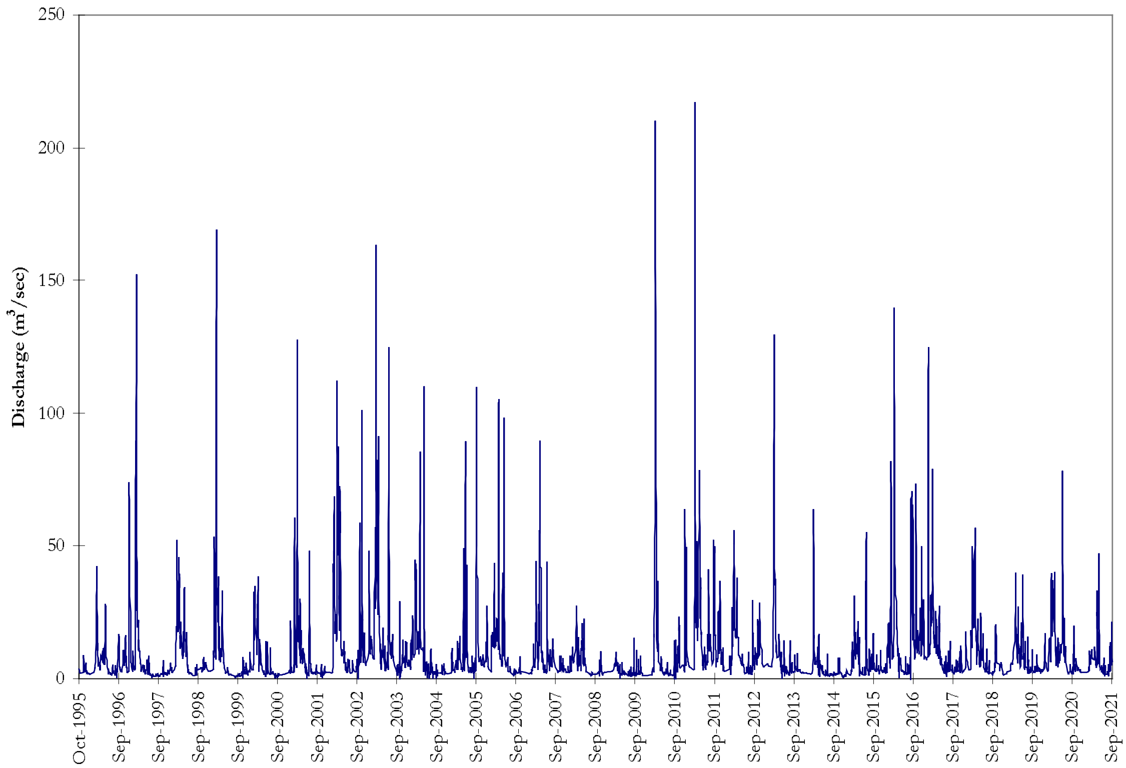


Figure 5.11 below shows the flow-duration curves for the hydrographs used in the 25-year run.

FIGURE 5.11 FLOW-DURATION PLOTS FOR THE 25-YEAR MODEL HYDROGRAPHS

Percentiles

	Cedar Creek	Milwaukee River
10	.227	1.730
25	.425	2.740
50	1.133	5.660
75	3.200	13.400
90	7.929	32.100

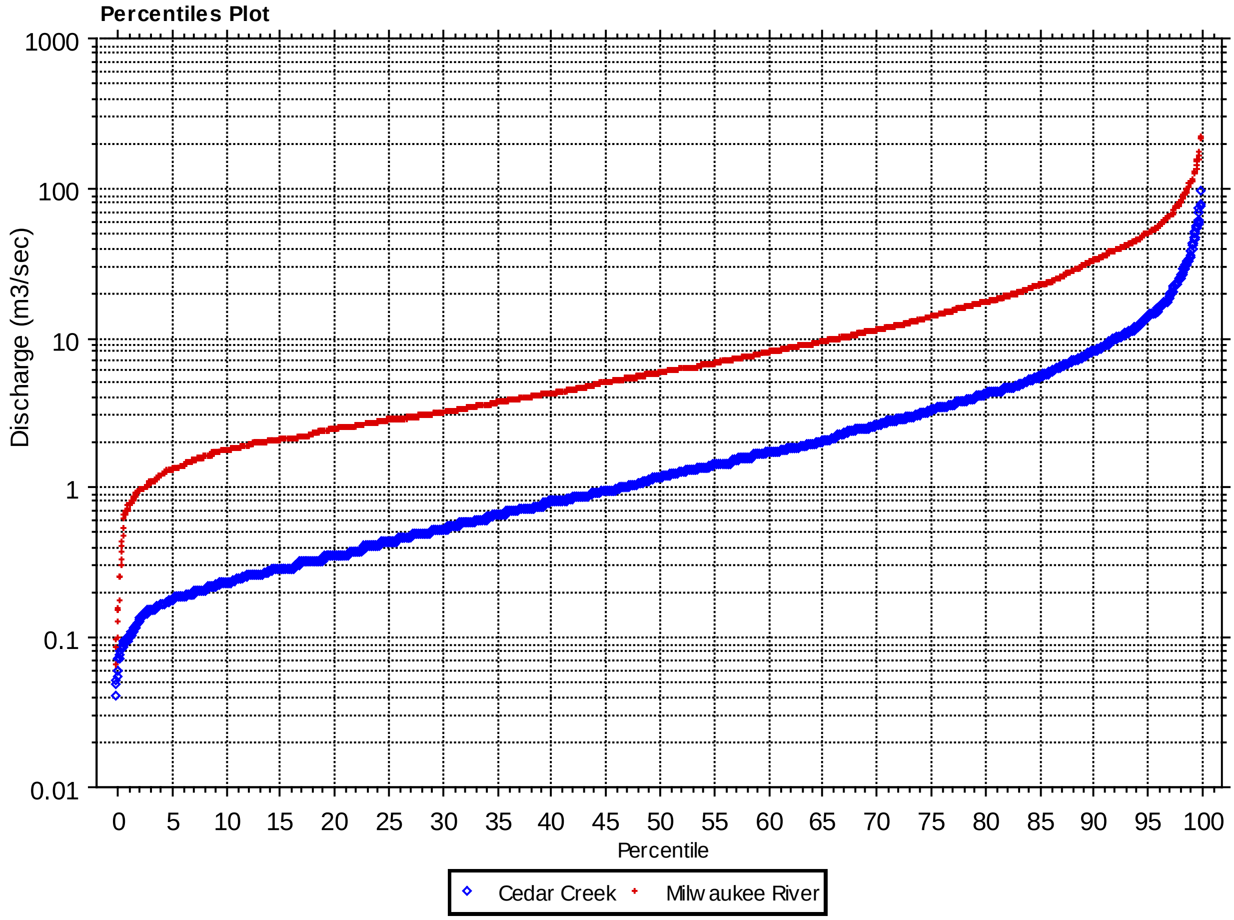


Table 5.1 below gives the flood frequency characteristics for the Milwaukee River and for Cedar Creek. The hydrographs used in the 25-year simulation have maximum flows slightly over the level calculated for the 25-year recurrence interval.

TABLE 5.2 FLOOD FREQUENCY CHARACTERISTICS OF CEDAR CREEK AND THE MILWAUKEE RIVER

Recurrence Interval[3] (years)	Discharge: Cedar Creek at HY 60 (m^3/sec)	Discharge: Milwaukee River at Waubeka (m^3/sec)
2	26.9	59.75
5	52.7	100.0
10	73.6	120.4
25	103.9	163.4
50	129.4	190.0

For the 25-year model runs, Lincoln Creek flows were defined as three-tenths the value of the difference between the measured value at Estabrook Park and the calculated value at Pioneer Road. The three-tenths ratio is roughly equivalent to that portion of the difference between watershed areas at Estabrook Park and Pioneer Road that is attributable to the Lincoln Creek watershed.

A number of alternative methods of hydrograph generation were tried, including the generation of a synthetic hydrograph based on summary statistics from the existing gaugehouse at Pioneer Road. In the end, simulation hydrographs were based on recorded hydrographs because long, coordinated hydrographs existed and were judged superior to synthetic hydrographs.

5.3.2 BOUNDARY CONDITIONS

The primary boundary condition in the application of the IPX model to this site is the function used to specify suspended solids loads at each upstream model boundary. The boundary conditions for particulate and dissolved PCB are defined as zero in the modeling, an assumption supported by the field monitoring discussed elsewhere.

The solids relationships shown on the next few pages were developed from a variety of data sources. The Cedar Creek (segment 1) relationship is derived from data included in Westenbroek (1993).

Cedar Creek Suspended Solids

[3] U.S. Geological Survey. Water Resources Investigations Report 91-4128, "Flood-Frequency Characteristics of Wisconsin Streams."

Figure 5.12 shows the assumed relationship between discharge and suspended solids during summertime at the segment 1 boundary. Figure 5.13 shows the same relationship during wintertime.

FIGURE 5.12 RELATIONSHIP BETWEEN DISCHARGE AND SUSPENDED SOLIDS IN CEDAR CREEK: SUMMERTIME (JUNE-SEPTEMBER, INCLUSIVE)

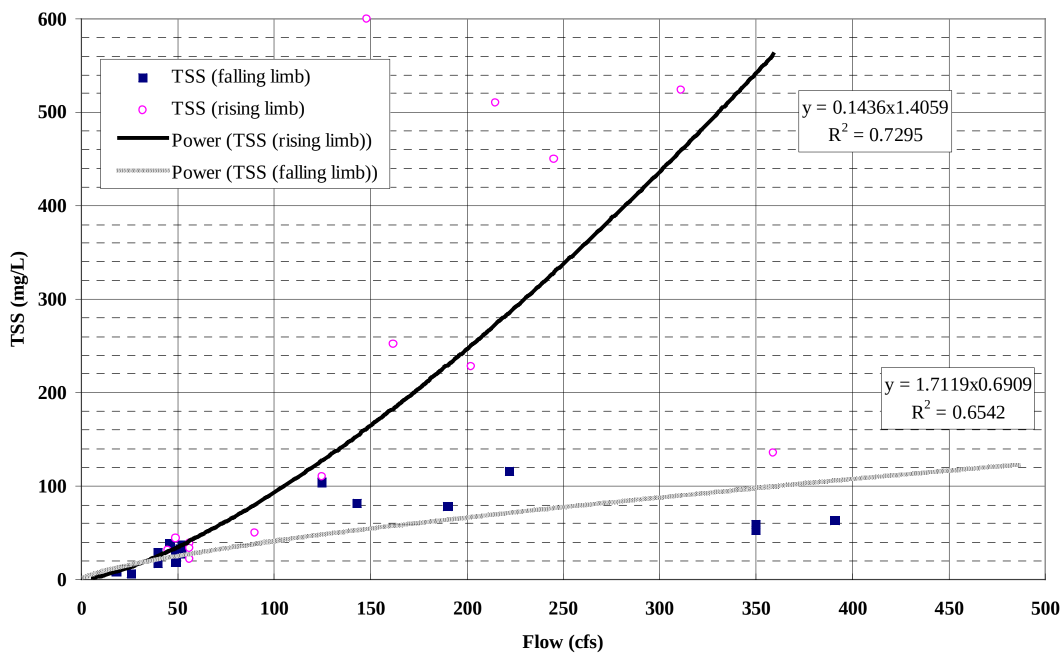


FIGURE 5.13 RELATIONSHIP BETWEEN DISCHARGE AND SUSPENDED SOLIDS IN CEDAR CREEK: WINTERTIME (OCTOBER-MAY, INCLUSIVE).

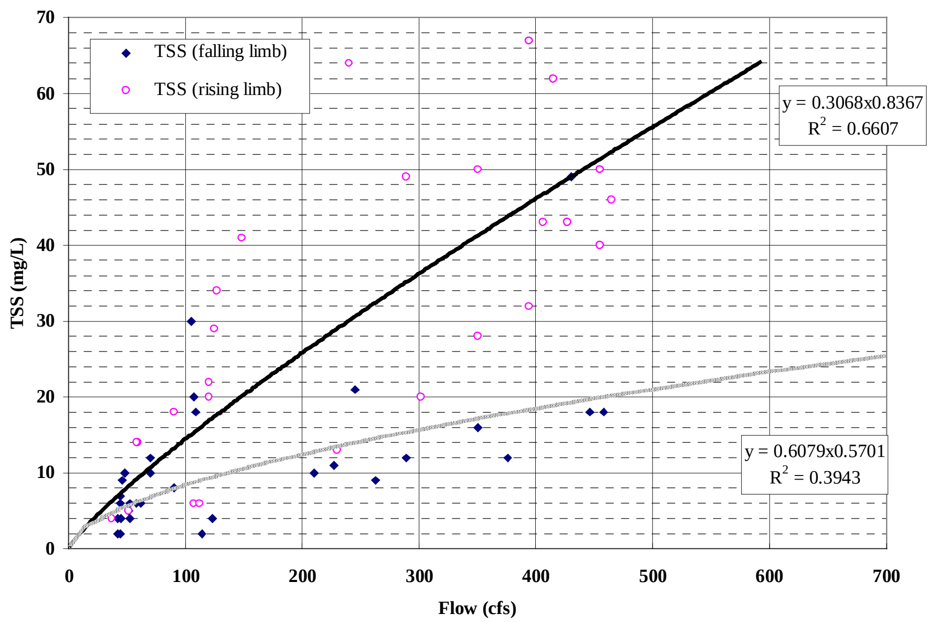


Table 5.3 below summarizes the relationships used to generate boundary conditions during both the 5-year and 25-year model runs.

TABLE 5.3 RELATIONSHIPS USED TO SUMMARIZE CEDAR CREEK SUSPENDED SOLIDS LOADS

	Rising Limb of Hydrograph	Falling Limb of Hydrograph
Summer	$0.1436*Q_{cedar}^{1.4059}$	$1.7119*Q_{cedar}^{0.6909}$
Winter	$0.3068*Q_{cedar}^{0.8367}$	$0.6079*Q_{cedar}^{0.5701}$

Milwaukee River Suspended Solids

Figure 5.14 shows the assumed relationship between discharge and suspended solids during summertime at the segment 17 boundary (i.e. confluence of Milwaukee River and Cedar Creek). Figure 5.15 shows the same relationship during wintertime.

FIGURE 5.14 RELATIONSHIP BETWEEN DISCHARGE AND SUSPENDED SOLIDS IN THE MILWAUKEE RIVER AT PIONEER ROAD: SUMMERTIME (JUNE-SEPTEMBER, INCLUSIVE)

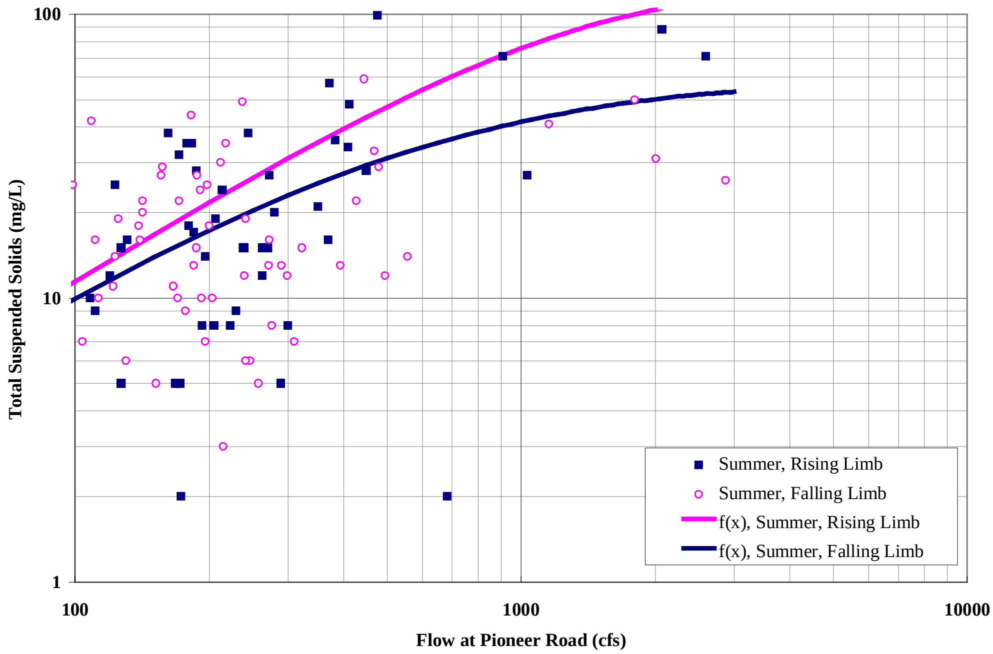


FIGURE 5.15 RELATIONSHIP BETWEEN DISCHARGE AND SUSPENDED SOLIDS IN THE MILWAUKEE RIVER AT PIONEER ROAD: WINTERTIME (OCTOBER-MAY, INCLUSIVE)

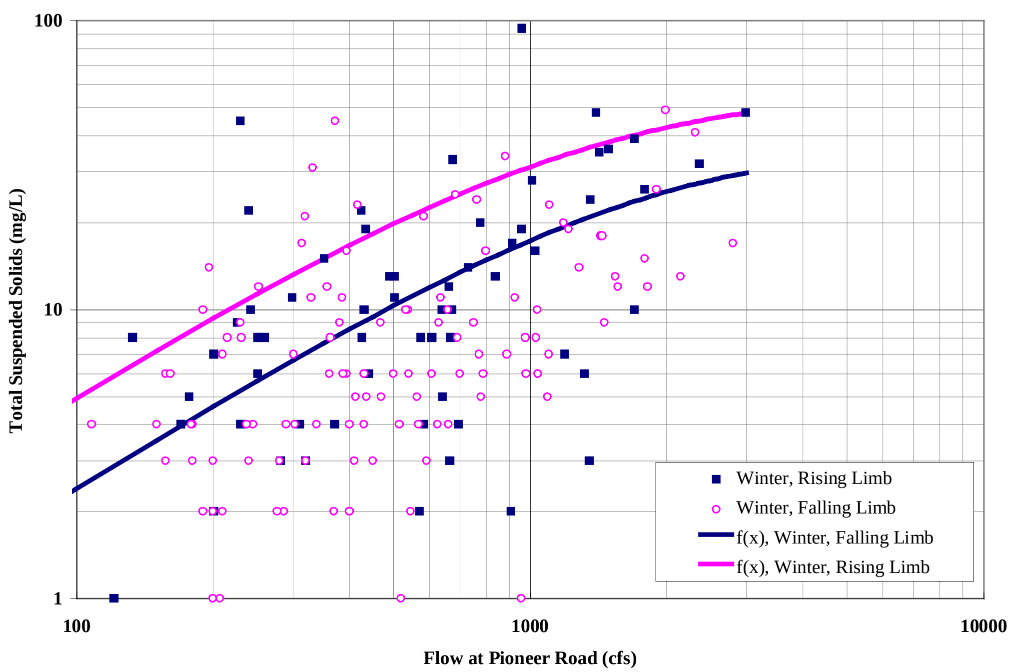


Table 5.4 summarizes the relationships used to establish the solids load at Pioneer Road. Note that the daily load calculated for Cedar Creek was subtracted from the daily result calculated using the relationships below to arrive at the boundary condition function for segment 17.

TABLE 5.4 RELATIONSHIPS USED TO REPRESENT MILWAUKEE RIVER SUSPENDED SOLIDS AT PIONEER ROAD

	Rising Limb of Hydrograph	Falling Limb of Hydrograph
Summer	$120(1-e^{-0.001Q})$	$35(1-e^{-0.001Q})+20(1-e^{-0.004Q})$
Winter	$30(1-e^{-0.0005Q})+25(1-e^{-0.0015Q})$	$20(1-e^{-0.0005Q})+15(1-e^{-0.001Q})$

Lincoln Creek Suspended Solids

Lincoln Creek boundary conditions are based on several years of monitoring conducted by DNR's urban nonpoint source program. This relationship is adequate, but the solids balance of the model could doubtless be improved if a more robust set of solids data were to be collected.

The equation below was used to characterize the Lincoln Creek solids load for both the 5-year and 25-year model runs:

$$\textit{Lincoln Creek TSS} = -0.0021Q^2 + 2.0531Q$$

6. MODEL VERIFICATION

6.1 COMPARISON OF MODEL RESULTS TO TIME SERIES DATA

The Milwaukee River PCB Mass Balance model does a good job of replicating the trends in PCB and suspended solids in response to river flows. The following subsections compare model predictions to data for suspended solids and water column PCB.

6.1.1 SUSPENDED SOLIDS

This section compares time series data to model output. Note that the data from Westenbroek (1993) is included as supplemental data to that generated as part of this project.

Figures 6.1-6.4 show model versus observed suspended solids for select locations.

FIGURE 6.1 PREDICTED AND OBSERVED TSS - CEDAR CREEK AT COLUMBIA POND (1990-1995)

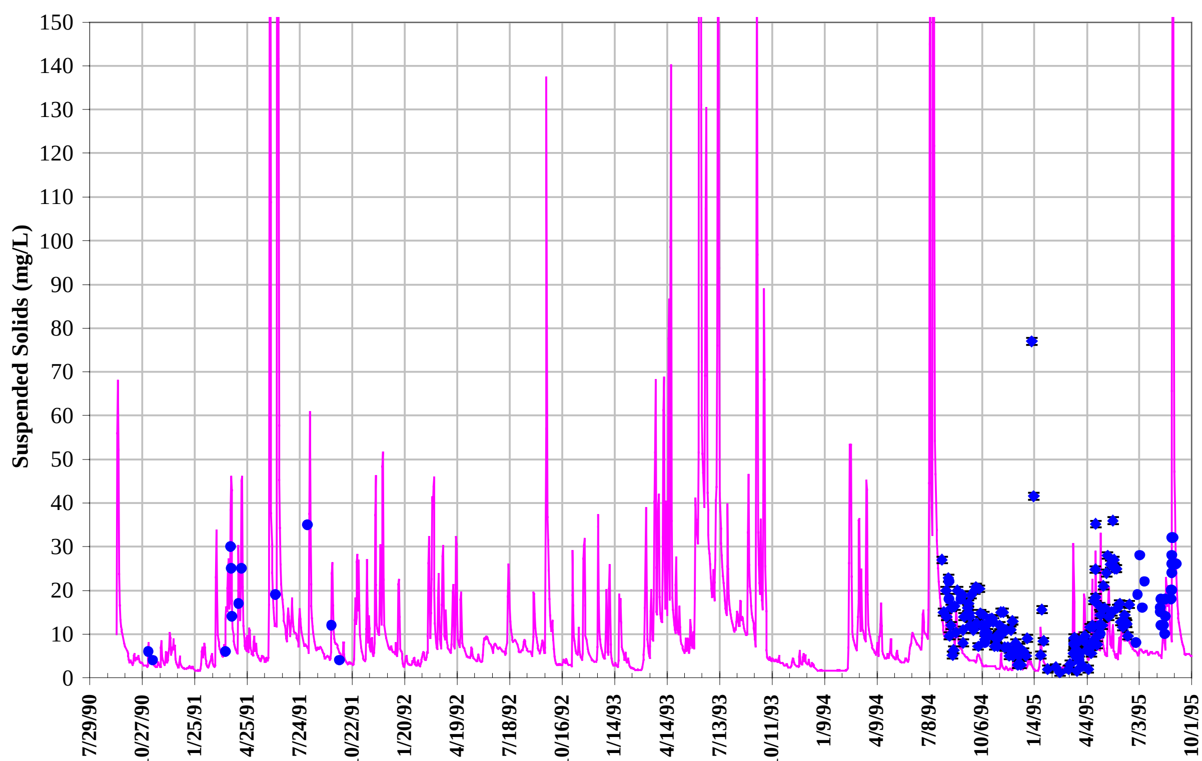


FIGURE 6.2 PREDICTED AND OBSERVED TSS - CEDAR CREEK AT HAMILTON POND (1990-1991)

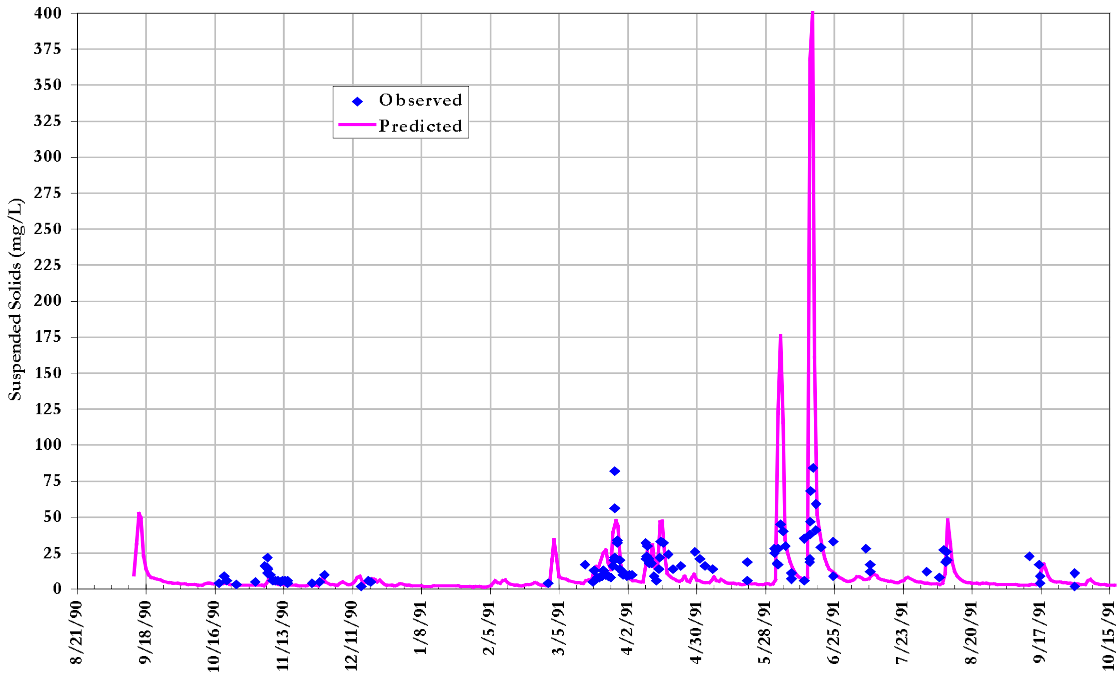


FIGURE 6.3 PREDICTED AND OBSERVED TSS - MILWAUKEE RIVER AT PIONEER ROAD (1993-1995)

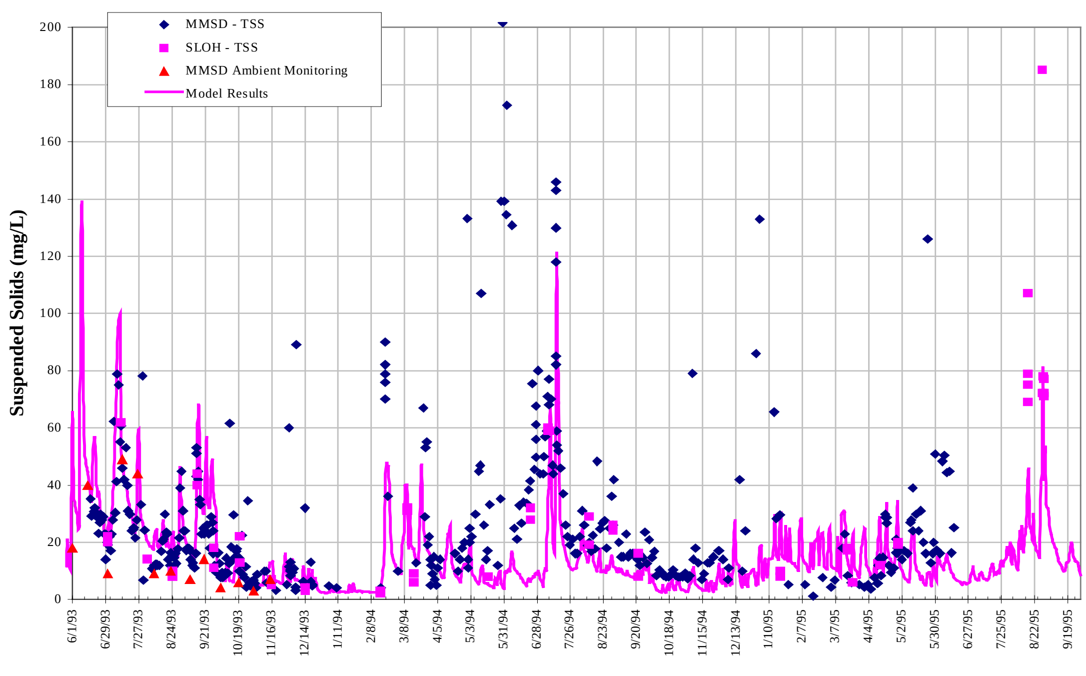
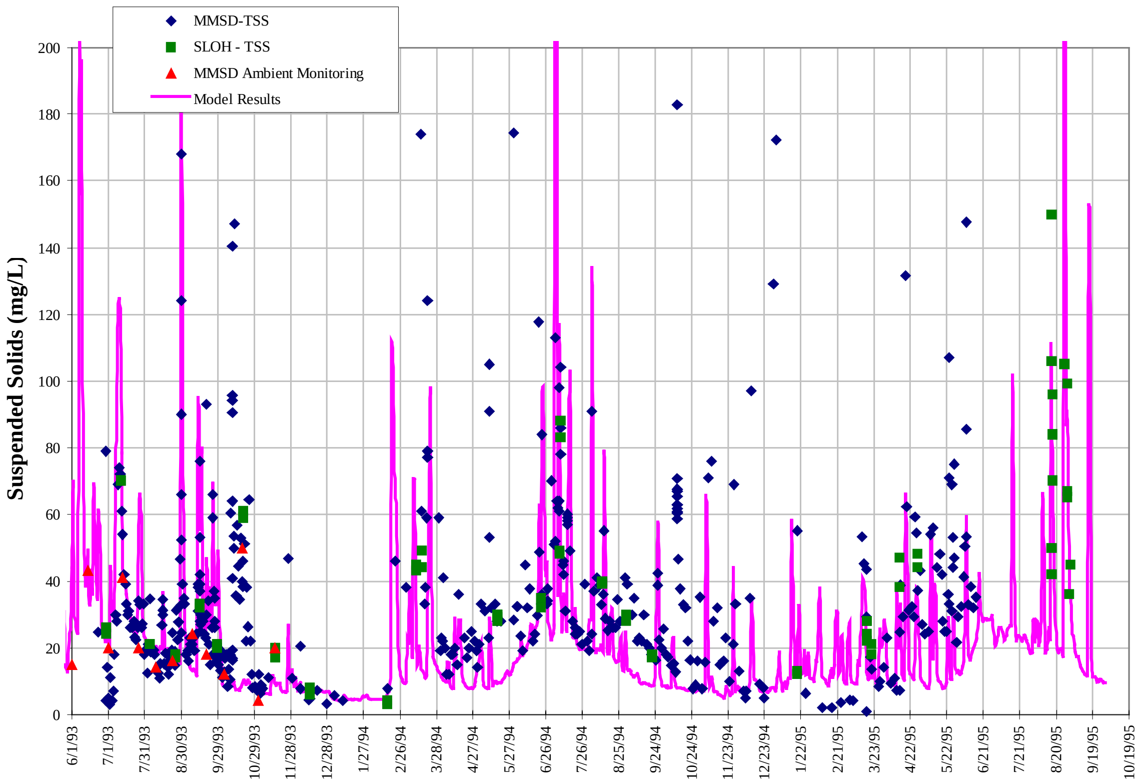


FIGURE 6.4 PREDICTED AND OBSERVED TSS - MILWAUKEE RIVER AT ESTABROOK IMPOUNDMENT (1993-1995)



6.1.2 WATER COLUMN PCB

Figures 6.5-6.9 present comparisons between modeled and observed PCB concentrations for five key locations.

FIGURE 6.5 PREDICTED AND OBSERVED PCB - CEDAR CREEK AT RUCK POND (1990-1995)

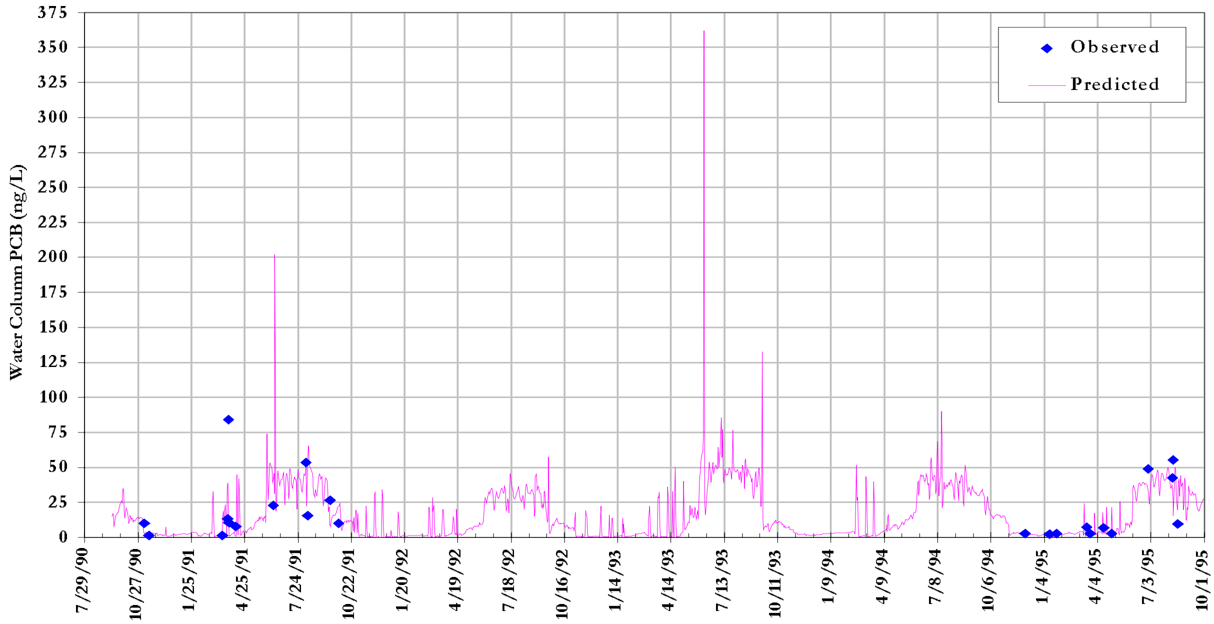


FIGURE 6.6 PREDICTED AND OBSERVED PCB - CEDAR CREEK AT COLUMBIA POND (1990-1995)

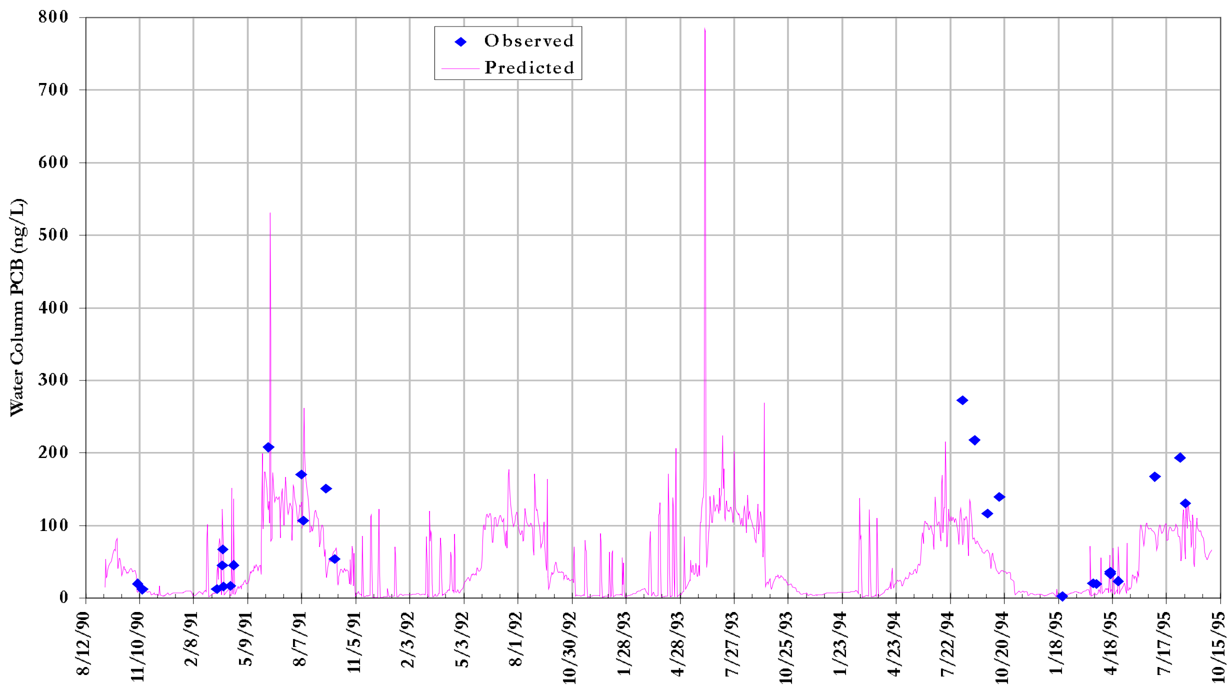


FIGURE 6.7 PREDICTED AND OBSERVED PCB - CEDAR CREEK AT HAMILTON POND (1990-1991)

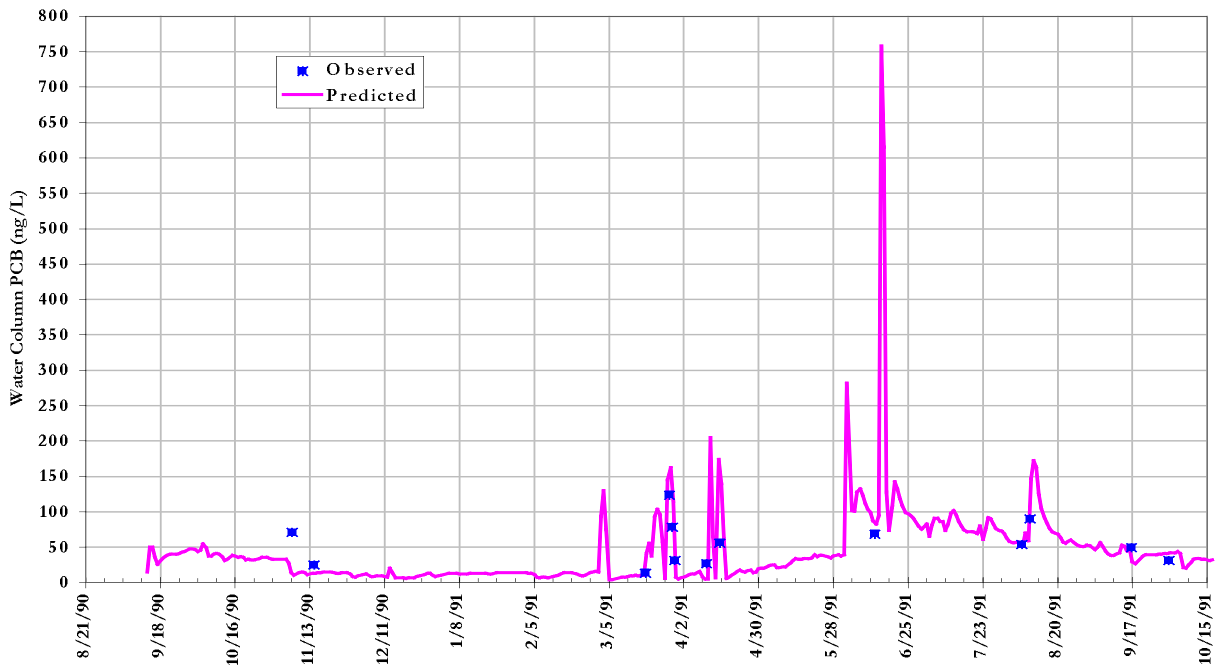


FIGURE 6.8 PREDICTED AND OBSERVED PCB - MILWAUKEE RIVER AT PIONEER ROAD (1993-1995)

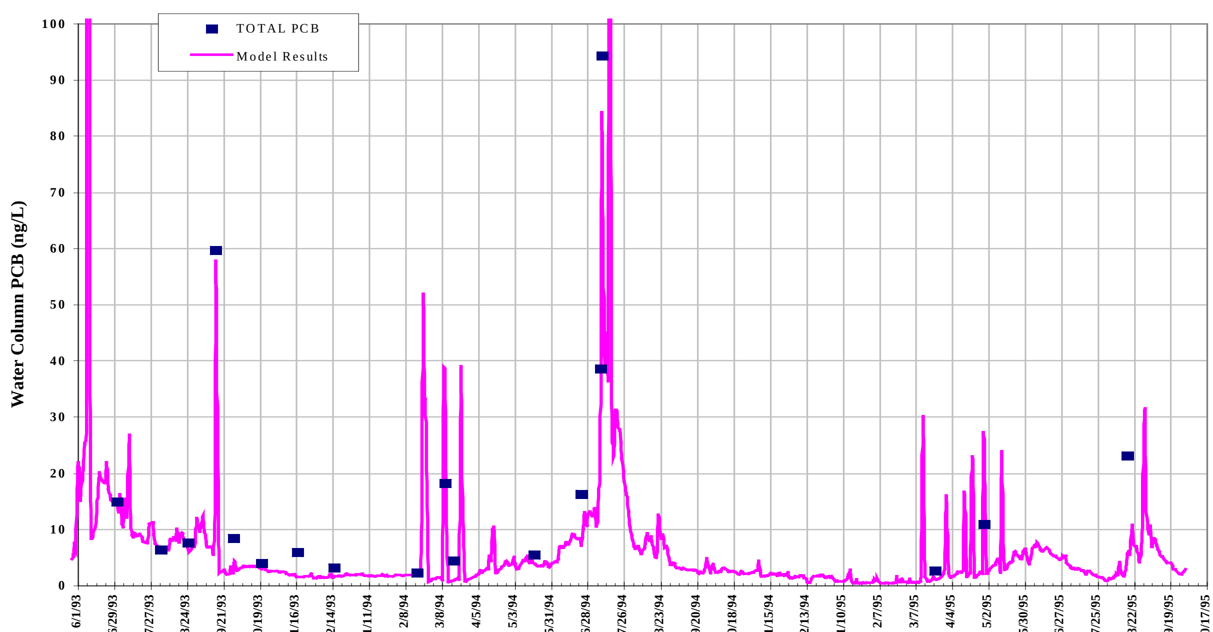
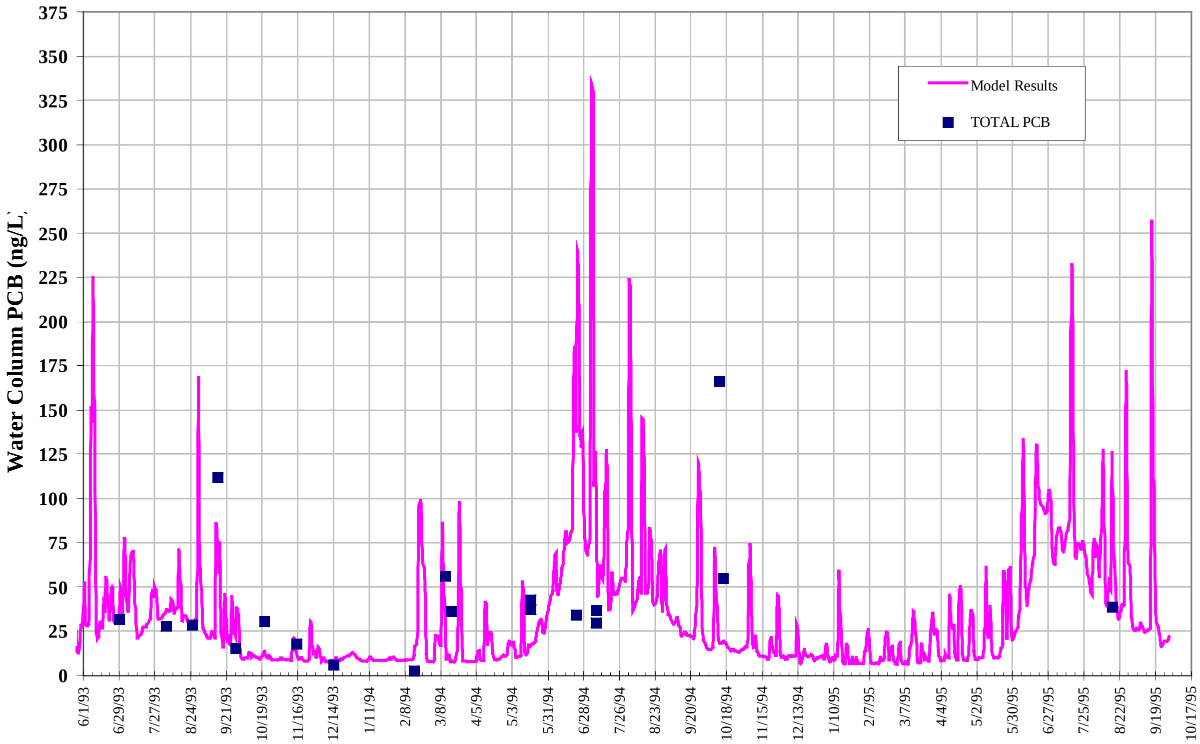


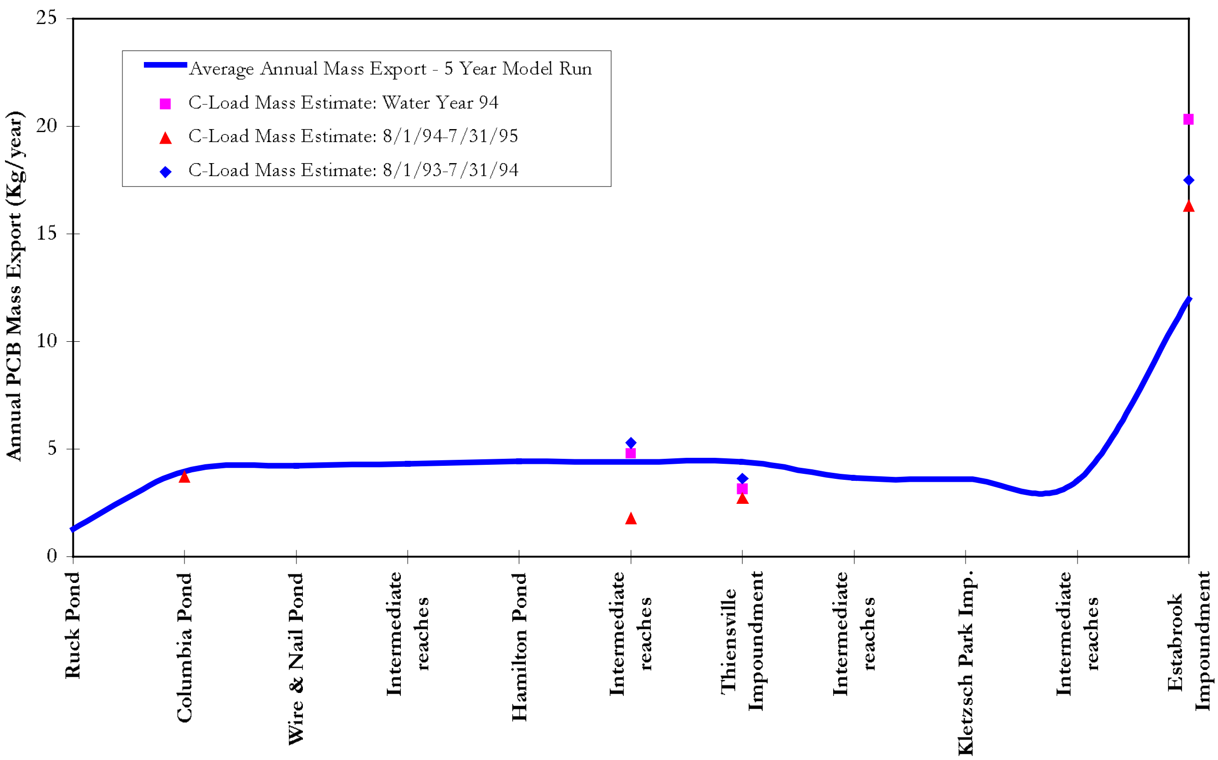
FIGURE 6.9 PREDICTED AND OBSERVED PCB - MILWAUKEE RIVER AT ESTABROOK IMPOUNDMENT (1993-1995)



6.2 RATES OF PCB MASS EXPORT

Another way to judge model performance is to compare the calculated PCB mass export to that output by the model. Figure 6.10 shows this comparison.

FIGURE 6.10 MODELED VERSUS CALCULATED PCB EXPORT



The three sets of points shown above were calculated from the data using the U.S. Geological Survey's "C-Load" program, which uses daily average flow values and interpolated concentration values to produce estimates of annual mass export[4].

As can be seen, the model compares well to the calculated PCB export, except that PCB export from Estabrook Impoundment is underestimated.

6.3 SIMULATED SEDIMENT DEPOSITION

In order to gauge long-term model performance, sediment deposition rates were calculated for the 25-year model simulation. The results show reasonable rates of sediment deposition in the Cedar Creek

[4] Thanks to Jeff Steuer of the U.S. Geological Survey for providing these mass estimates.

system, but show somewhat elevated rates of negative deposition (i.e. scour) as one moves further downstream.

It appears that the background resuspension rates are responsible. The background resuspension rates were varied seasonally in an attempt to fit measured water column PCB results, which generally are up to an order of magnitude higher during the summer than in the winter at the same river flow rates.

The mechanism responsible for this order of magnitude difference is believed linked to the algal productivity of the system. Algal growth during the summer months represents a temporary storage reservoir for PCB within the water column. A study of algal-bound PCB in the Venice Lagoon showed that during summer months, as algae bioconcentrate PCB into their cells, die and settle out, a fine layer of readily resuspendable organic sediments is formed (Pavoni *et al*, 1990). This fine layer of resuspendable material was found to contain PCB at concentrations an order of magnitude higher than sediments sampled during non-growth periods.

In order to simulate the mechanisms outlined above, the background resuspension rates were linked to temperature.

This approach appears to have caused net negative deposition of sediment to occur in a few reaches of the Milwaukee River. The effect of this net negative deposition is that some segments of the lower Milwaukee River exhibit increasing surficial sediment PCB concentrations over time, which serves to over-estimate long-term water column PCB concentrations in the lower reaches (i.e. Estabrook Impoundment).

This is not a problem in the reaches within the Cedar Creek system.

The model may be improved by simulating two solids classes, similar to the work conducted on the Lower Fox River (Wisconsin DNR, 1995). In that work, suspended solids was broken into essentially two solids classes, biotic and abiotic. The biotic fraction of suspended solids exhibited a higher organic carbon content and a negligible settling rate. This adequately represented the increased suspended solids concentrations over the summer period without altering the background resuspension rate significantly.

The model will perform well as a screening-level tool without these improvements, but for more accuracy in long-term simulation of water column and surficial sediment concentrations in the Estabrook Impoundment, an additional biotic solids class is warranted, as well as more work refining loads from Lincoln Creek.

6.4 Discussion of expected model performance

The model described here performs very well when compared to a number of standard benchmarks. Comparisons with time series data and calculated PCB export rates are reasonable, and the probability density functions of field data and simulated water column suspended solids and PCB are comparable..

The model is expected to perform well as a screening-level tool for analyzing river management scenarios. As such, it is expected that the relative impacts of alternate remediation scenarios on PCB mass export rates and trends in long-term water column concentrations may be accurately judged.

In order to accurately project long-term fish tissue concentrations or assess the impact of dam failure, additional modeling and analysis is required.

7. MODEL APPLICATION

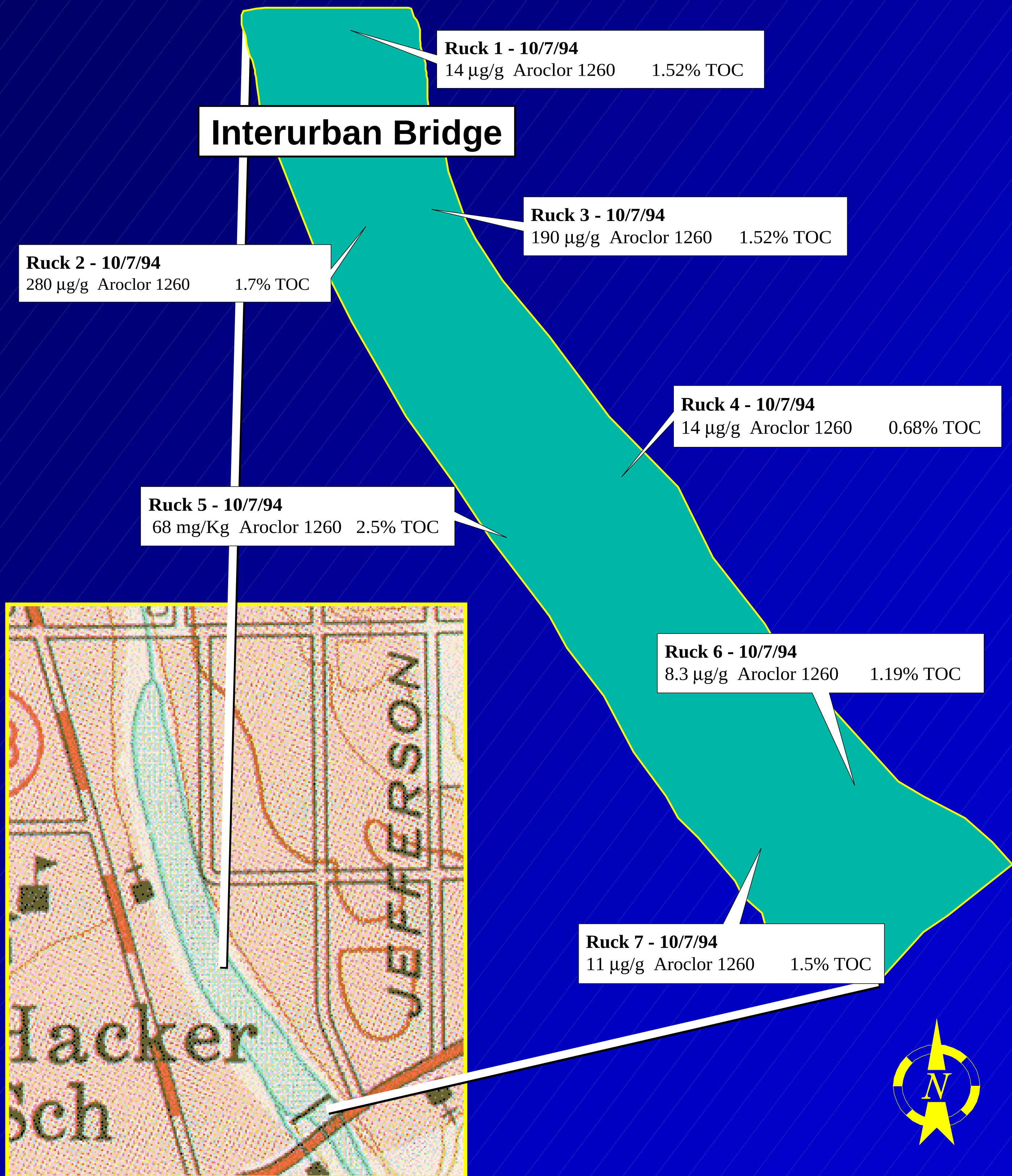
This section describes how the model was applied to various river management scenarios on the Cedar Creek / Milwaukee River system.

7.1 Effectiveness of Ruck Pond Remediation

At 9:00 AM on October 19, 1994, water began to flow over the face of the Ruck Pond Dam for the first time in several months. The entire flow of Cedar Creek had been diverted by responsible party, Mercury Marine, through three large siphon tubes, allowing sediment remediation in Ruck Pond to proceed "in the dry." The remediation reportedly cost over $1,000 per cubic yard, and removed a total of about 7,500 cubic yards of contaminated sediment from the site (Blasland, Bouck and Lee, date unknown). Sediment sampling conducted just prior to refilling of the pond indicated that residual concentrations of PCB remained as high as 280 mg/Kg (see Figure 7.1).

Figure 7.1 Sediment Sample Results

Cedar Creek, Ruck Pond - Following Remediation



The Ruck Pond project has been cited as an example demonstrating the technical limitations associated with removal of contaminated sediments. The Ruck Pond project certainly did show that the removal of PCB-containing sediment, even when pursued under almost ideal conditions, is a difficult process. It is also true that the residual concentrations left behind following remediation were higher than most sediment quality criteria would call for.

However, the fact that high residuals were left behind does not mean that the Ruck Pond Project was flawed, or that dredging or removal should be abandoned as a sediment remediation technique.

The flip side of the Ruck Pond story is that even though relatively high concentrations were left behind, the range of sediment concentrations, the total resident PCB mass, projected future mass transport and projected future average water column PCB concentrations have all been drastically reduced.

7.1.1 MAXIMUM SEDIMENT PCB CONCENTRATION: 99% REDUCTION

The maximum concentration observed in Ruck Pond was reported at 155,200 mg/Kg (Wisconsin DNR, 1992). That level of contamination is best represented in terms of percentages (15%) rather than parts per million.

The maximum concentration observed following Ruck Pond remediation is 280 mg/Kg (see Figure 7.1 above). Split samples taken at the time indicate that this result may has been as high as 300 mg/Kg (Blasland, Bouck and Lee, date unknown).

The maximum observed value is over 99% lower following remediation.

A comparison between pre and post-remediation average sediment concentrations yields similar results: the average sediment PCB concentration following remediation is between 68% and 83% lower than the average calculated prior to remediation, again, depending on which initial average PCB calculation is used (Westenbroek, 1993).

7.1.2 RESIDENT PCB MASS: 96%-98% REDUCTION

The resident PCB mass present in Ruck Pond was reduced by between 96% and 98%, depending on which initial mass estimate is used. Westenbroek (1993) estimated 370 kilograms of PCB present in Ruck Pond prior to remediation. In this study the initial mass was calculated at 743 kilograms, due in part to a revised sediment volume estimate.

The PCB mass remaining was estimated by taking the arithmetic average of all post-remediation values and applying that number to a uniform 5 centimeter thickness of sediment spread over the entire 6,240 m^2 bottom of Ruck Pond. This yields a post-remediation PCB mass of 12.6 kilograms.

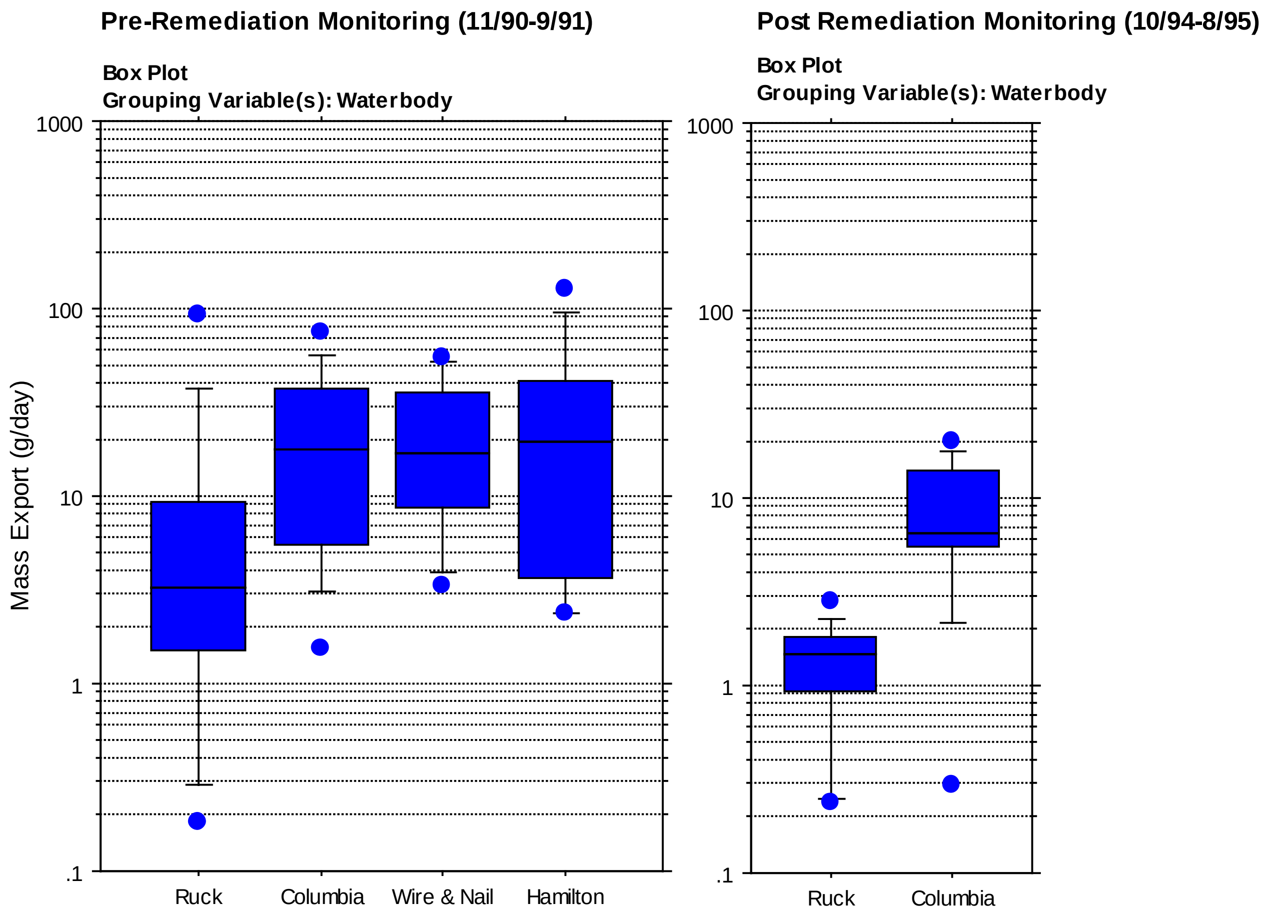
On a mass removal basis this represents an extremely high removal efficiency.

7.1.3 SHORT-TERM PCB MASS TRANSPORT: 40% REDUCTION

Although likely too early to tell, the initial results from post-remediation water column PCB monitoring look promising. The Ruck Pond median concentration is down by 40% following Ruck Pond remediation as compared to data collected in 1990-1991. Columbia Pond mass transport is reduced by a similar factor.

Figure 7.2 shows PCB mass export calculated from 1990-1991 data as compared to the export calculated from 1994-1995 data (post-remediation).

FIGURE 7.2 CALCULATED PCB MASS TRANSPORT: PRE AND POST RUCK POND REMEDIATION



The trend appears to be toward decreasing PCB export following the Ruck remediation. Note, however, that the hydrologic conditions of any particular year may significantly alter the observed levels of PCB and thus the estimate of PCB transport.

The model actually predicts that post-remediation water column PCB concentrations (and thus mass transport) will *increase* for a short period of time (3-5 years), before decreasing sharply, as compared with the no action alternative.

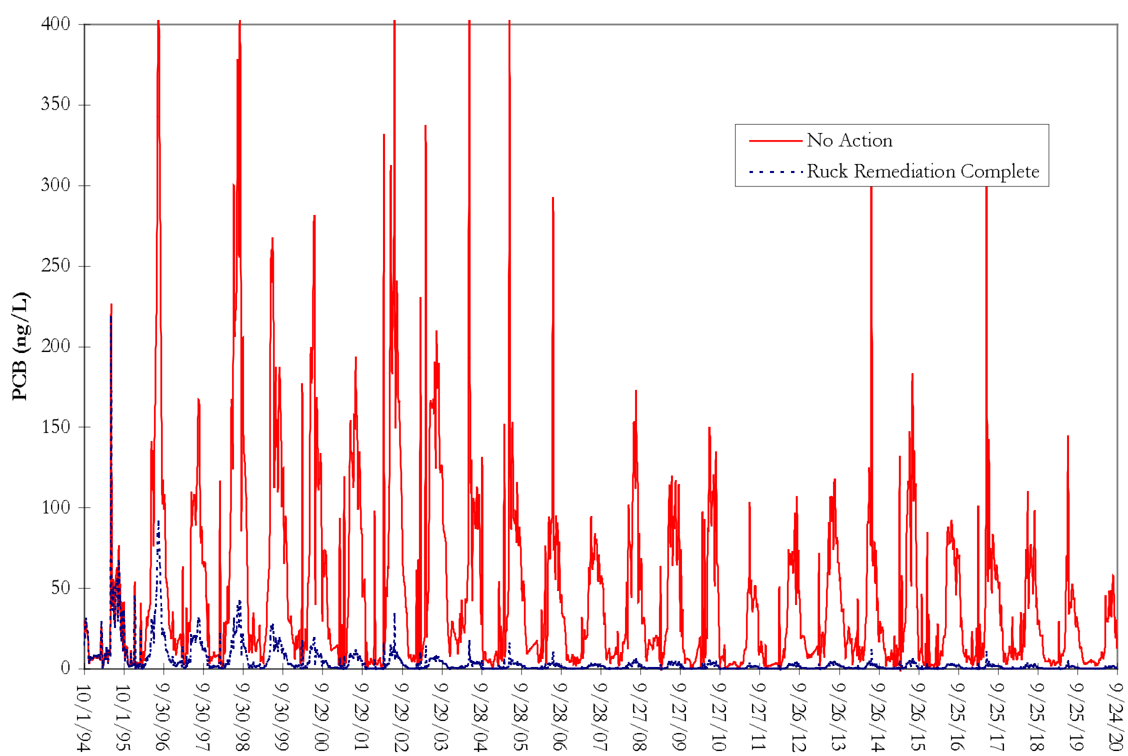
7.1.4 LONG-TERM PCB MASS TRANSPORT: 95% REDUCTION

Model results show that mass removal of PCB from the system is far more important to the long-term success of sediment remediation than is the residual concentration. The difference between action and no action is about 3.8 kilograms per year of PCB transported downstream, which translates into close to 100 kilograms of PCB that will not be transported downstream because of remediation. (See the next section for a graphic depiction of changes in mass transport as related to remediation scenarios).

7.1.5 LONG-TERM AVERAGE WATER COLUMN PCB CONCENTRATIONS: 94% REDUCTION

Along with the reduction in mass transport is the reduction in water column PCB levels. Average water column PCB concentrations are 94% lower following the Ruck Pond remediation as compared to the projected long-term average water column PCB concentration assuming no action.

FIGURE 7.3 PROJECTED RUCK POND WATER COLUMN PCB CONCENTRATIONS - WITH AND WITHOUT REMEDIATION

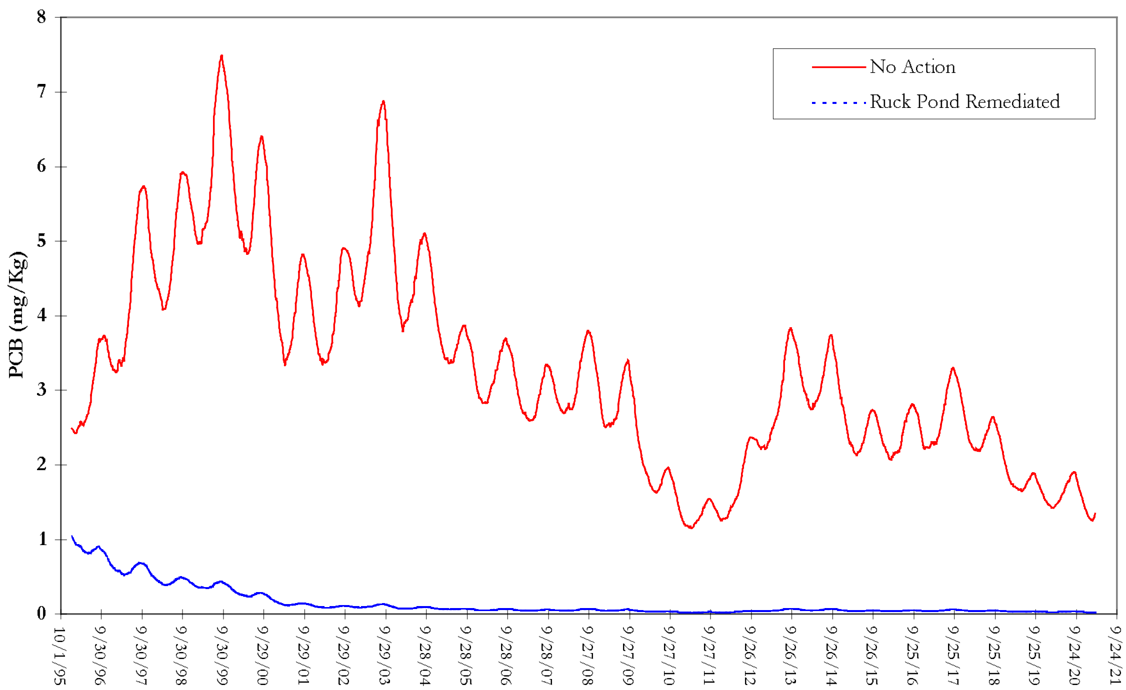


As is demonstrated in figure 7.3 above, even though PCB concentrations of up to 280 mg/Kg were left behind following the remediation of Ruck Pond, the long-term prognosis for the pond is much better following remediation than it would have been if no action had been taken.

Shortly after the turn of the century, water column PCB concentrations should meet the state Wild and Domestic Animal Criteria (3 ng/L) consistently. Realistically, there will still be times when the water column concentration will "spike" to elevated levels, but not to anywhere near the levels that may have been seen with no action taken.

Reduced levels of PCB in the water column will also lead to dramatic reductions in fish tissue PCB concentrations. Figure 7.4 below was produced using a bioaccumulation factor of 135,700 applied to the 90-day running average total PCB concentration in the water column. As such, figure 7.4 presents a rough picture extended to generic forage fish species. It should be noted that the results shown below are a gross simplification of the actual dynamics of PCB uptake and depuration and are not intended to be used in a quantitative manner.

FIGURE 7.4 PROJECTED PCB CONCENTRATIONS IN FORAGE FISH: RUCK POND



The analysis above simply assumes that fish tissue concentrations are directly proportional to average water column concentrations. Even taken on a qualitative level, we see that the difference between action and no action at Ruck Pond has a huge impact on the level of PCB expected in generic Ruck Pond forage fish tissue.

Preliminary results from caged fish placed in Ruck Pond before and after remediation show dramatic reductions in PCB bioaccumulation (Jim Amrhein, personal communication).

7.2 EVALUATION OF SEDIMENT MANAGEMENT STRATEGIES

The remediation scenarios described here consider the effect of mass removal on water column PCB concentrations, fish tissue concentrations and PCB mass export to the Milwaukee River system. The scenarios are constructed assuming that a low-tech approach to remediation is chosen, and that a qualitative cleanup objective similar to that used at Ruck Pond is used.

It is further assumed that wet dredging will be acceptable, and that as such a relatively high concentration of PCB will be left behind (5 mg/Kg) in the top 10 cm of material.

The following scenarios were tested as part of this work:

- ***No Action***: Assumes that no remediation takes place, including the Ruck Pond Remediation. Model run begins on 10/1/95.
- ***Ruck***: Assumes that remediation of Ruck Pond was completed on October 1, 1994. Uses measured levels PCB in post-remediation sediments as initial conditions for Ruck Pond. Assumes that remediation reduces PCB mass from approximately 700 Kg to 15 Kg.
- ***Ruck, Columbia***: Same assumptions as above, but includes the assumption that Columbia Pond is remediated on 9/1/98, reducing PCB mass from approximately 540 Kg to 16 Kg.
- ***Ruck, Columbia, Hamilton***: Same as above, but also assumes that Hamilton Pond is remediated on 9/1/98, reducing the PCB mass in that impoundment from approximately 150 Kg to 5 Kg.
- ***Ruck, Columbia, Hamilton, Wire & Nail***: Same as above, but also assumes that the Wire & Nail Pond is remediated on 9/1/98, reducing the PCB mass in that impoundment from approximately 70 Kg to 3 Kg.
- ***Ruck, Columbia, Hamilton, Wire & Nail, Estabrook***: Same as above, but also assumes that the Estabrook Impoundment is remediated on 9/1/98, reducing the PCB mass from approximately 5200 Kg to 60 Kg.

Thiensville Impoundment was not included in any of the scenarios because it represents such a large volume of sediment relative to contaminated sediment volume that it is unlikely that a cost-effective removal technology can be applied to it. Additional model scenarios could be constructed to simulate the effect of other remediation technologies, if desired.

Kletzsch Park Impoundment was initially a concern in this study, but because sediment mapping and sampling showed it to contain very small amounts of soft sediments, it is excluded here from further consideration.

7.2.1 EFFECT OF REMEDIATION ON SURFICIAL SEDIMENT CONCENTRATIONS

The effects of the various remediation scenarios on surficial sediment PCB concentrations are intuitive. Generally, remediation of a particular impoundment produces the following effects:

- a reduction in downstream surficial sediment concentrations proportional to the
  1) distance between two given impoundments and
  2) gradient of average surficial concentrations between two given impoundments;
- a substantial reduction in surficial sediment concentrations in the impoundment being remediated (based on the assumption that 5 mg/Kg will be left behind).

The following three figures demonstrate the points noted above.

FIGURE 7.5 PROJECTED COLUMBIA POND SURFICIAL SEDIMENT CONCENTRATIONS

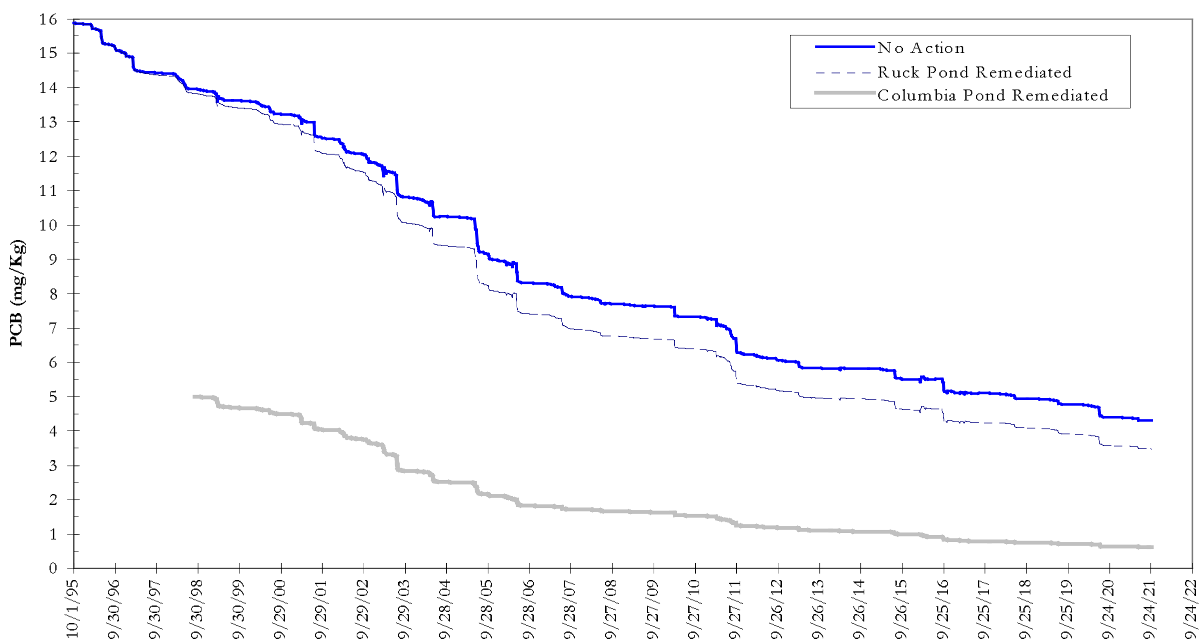


FIGURE 7.6 PROJECTED HAMILTON POND SURFICIAL SEDIMENT CONCENTRATIONS

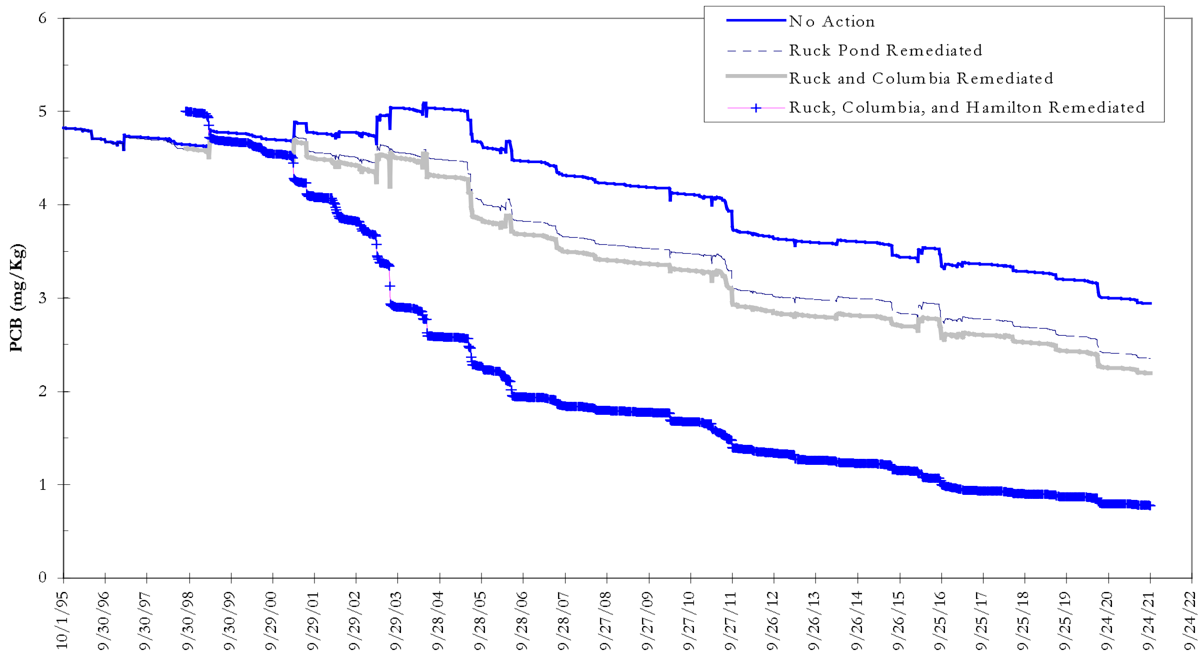


FIGURE 7.7 RELATIVE DECREASE IN SURFICIAL PCB CONCENTRATIONS AT THIENSVILLE IMPOUNDMENT

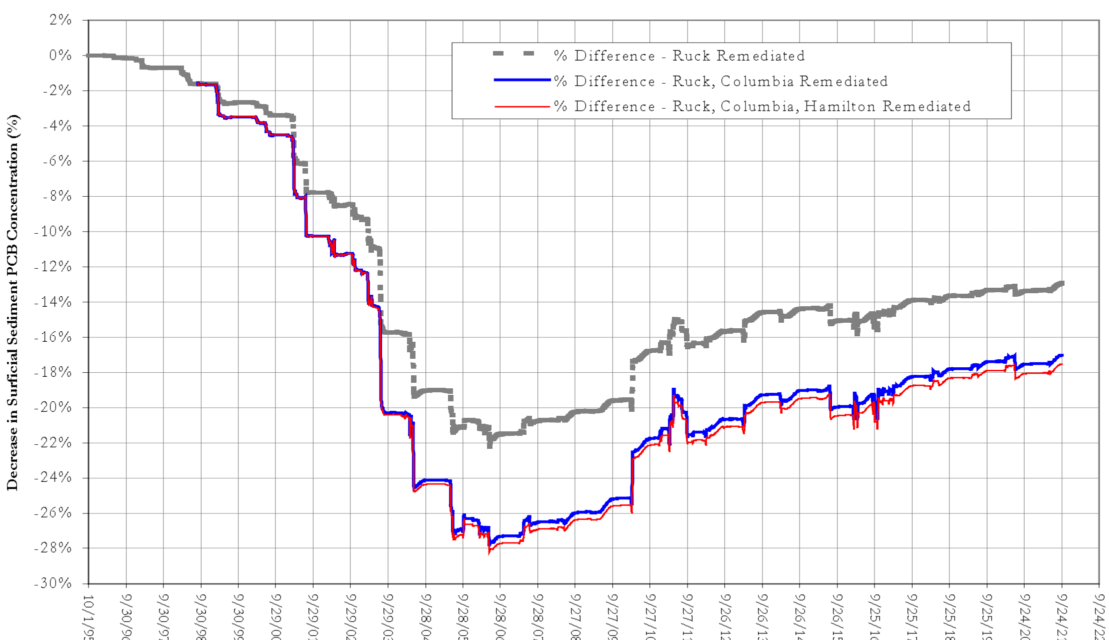


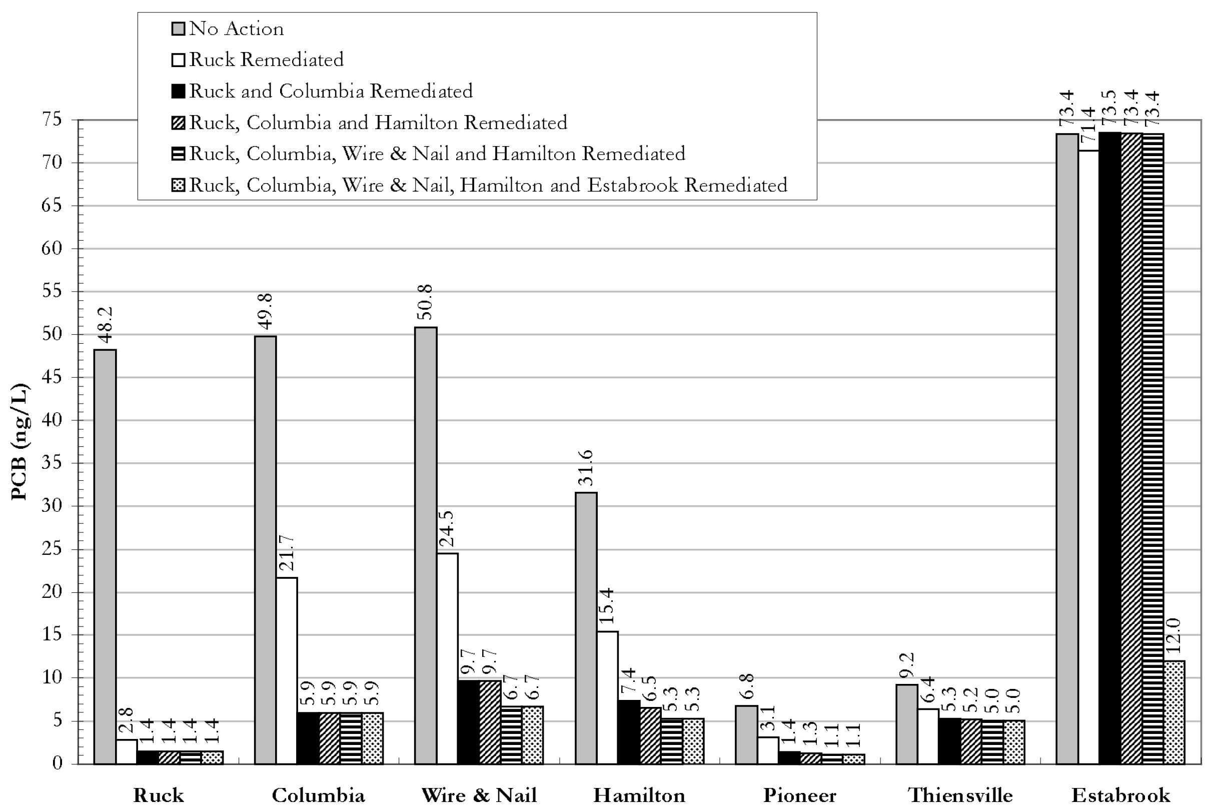
Figure 7.7 above demonstrates that there is a point of diminishing returns with respect to the remediation scenarios. The addition of a Hamilton Pond remediation, while ultimately significant in

Hamilton Pond (see Figure 7.6), does relatively little to drive down long-term surficial sediment concentrations in the Thiensville Impoundment.

7.2.2 EFFECTS OF REMEDIATION ON WATER COLUMN PCB CONCENTRATIONS

The long-term average water column concentrations projected for the various remediation scenarios are shown in Figure 7.8 below.

FIGURE 7.8 PROJECTED LONG-TERM AVERAGE PCB CONCENTRATIONS IN THE MILWAUKEE RIVER SYSTEM



As can be seen, remediation of Columbia Pond is projected to significantly reduce the long-term average water column PCB concentrations in the system, with reductions clearly visible all the way downstream to the Thiensville Impoundment. Remediation scenarios that include the Wire & Nail Pond and the Hamilton Pond produce much smaller changes, and those changes do not extend as far downstream.

Thus, remediation of Wire & Nail and Hamilton Ponds will produce significant reductions in the long-term average within the Cedar Creek system, but will not significantly affect the long-term average water column PCB concentration in the Milwaukee River system.

7.2.3 EFFECTS OF REMEDIATION ON FISH TISSUE PCB CONCENTRATIONS

Since the projected fish tissue concentrations are based on a simple bioaccumulation factor for a general forage fish, the charts included in this section mirror the results of water column projections. The initial (no action) projected fish tissue concentrations fall within the range of observed fish tissue concentrations (see the appendix for fish tissue results).

FIGURE 7.9 PROJECTED PCB CONCENTRATIONS IN FORAGE FISH: HAMILTON POND

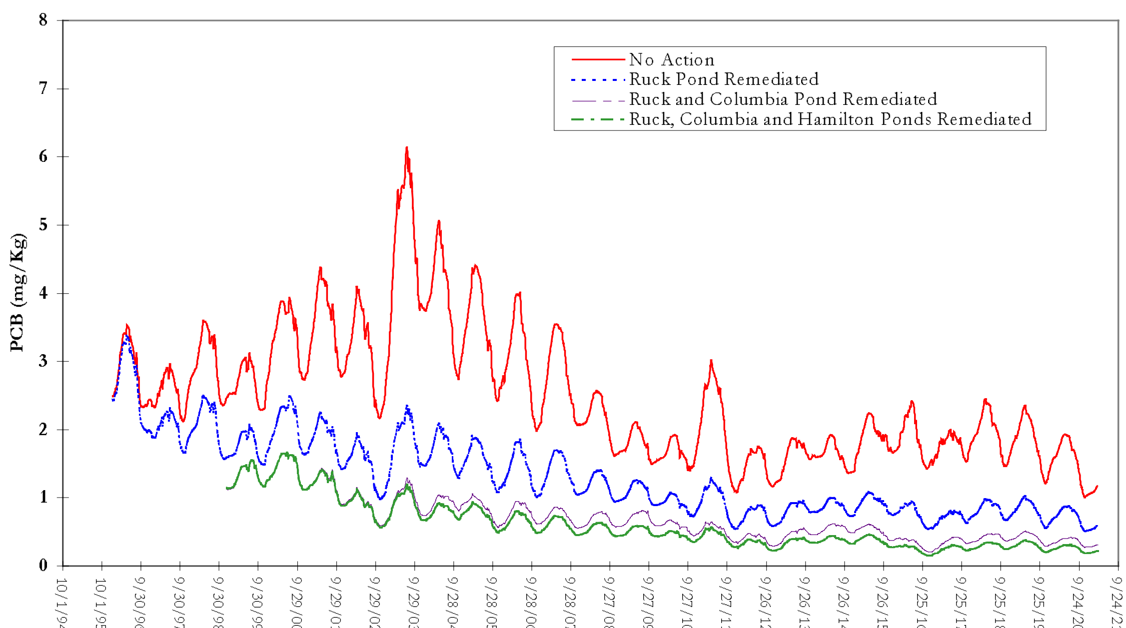


Figure 7.9 presents a fish tissue projection for Hamilton Pond for the various remediation scenarios. The projection shows that pursuing additional remediation in the Cedar Creek system may be expected to yield lower fish tissue values sooner than the no action case.

Figure 7.10 presents a fish tissue projection for the Thiensville Impoundment on the Milwaukee River.

FIGURE 7.10 PROJECTED PCB CONCENTRATIONS IN FORAGE FISH: THIENSVILLE IMPOUNDMENT

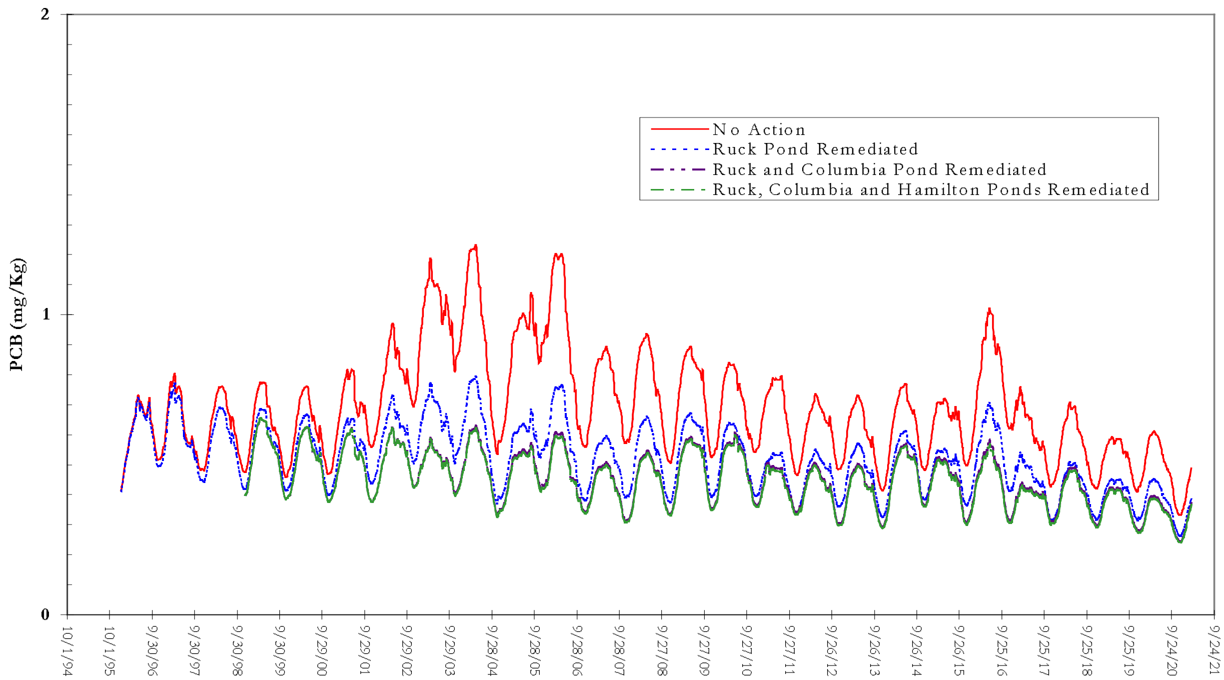
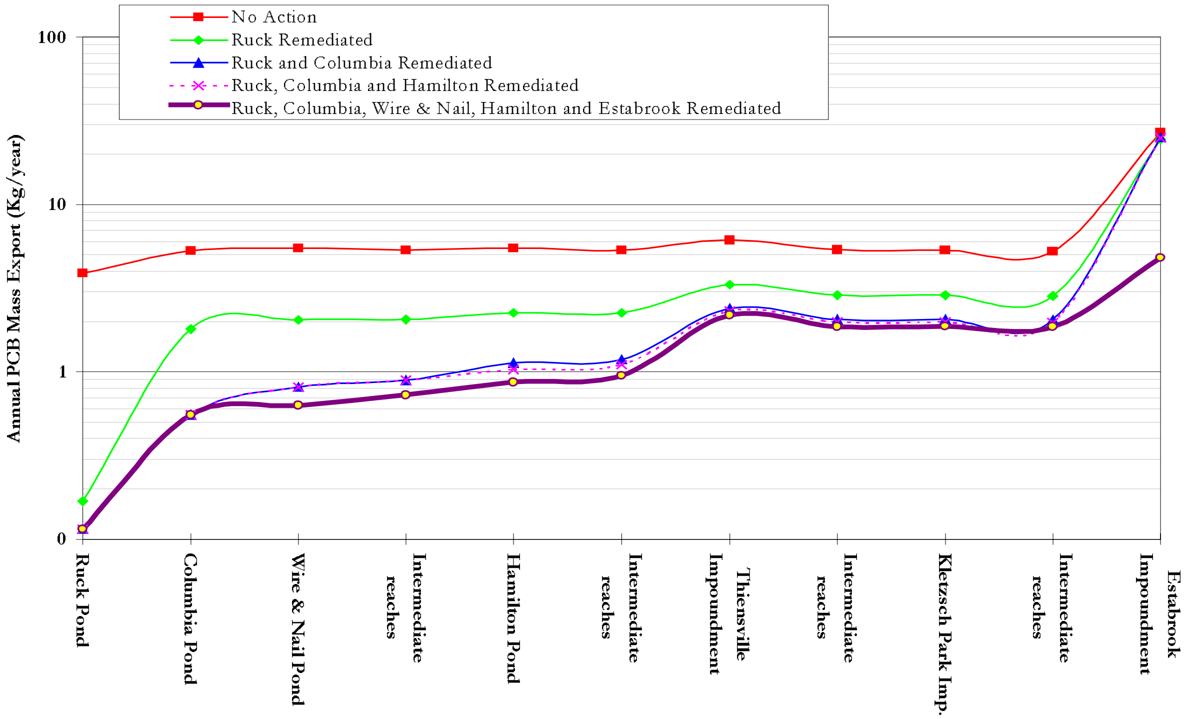


Figure 7.10 shows significant improvement due to remediation of Ruck and Columbia Ponds, with diminishing impact due to remediation of Hamilton Pond.

7.2.4 EFFECTS OF REMEDIATION ON PCB MASS EXPORT

Remediation of certain impoundments in Cedar Creek and the Milwaukee River will significantly reduce the PCB mass exported downstream. Figure 7.11 shows the long-term effect of the remediation scenarios on PCB mass export. All charts in this section are based on the 25-year model runs.

FIGURE 7.11 EFFECTS OF REMEDIATION SCENARIOS ON LONG-TERM PCB EXPORT



As can be seen, remediation of Ruck and Columbia Ponds on Cedar Creek produces the most significant decrease in PCB mass export. Another significant reduction may be had if the Estabrook Impoundment is also remediated.

Figure 7.12 presents another way of looking at the mass export estimates. Instead of creating a cumulative record, as is shown in Figure 7.11, the individual mass contributions are tallied. Also, the mass export calculations assume that Ruck Pond is remediated as of 10/1/94. None of the other impoundments is assumed to be remediated.

The figure can be viewed as a Pareto chart: the biggest contributor of mass exported in the system is by far Columbia Pond, with the Wire and Nail Pond falling well below in second place.

FIGURE 7.12 NET CONTRIBUTION OF CEDAR CREEK SEDIMENTS TO LONG-TERM PCB EXPORT

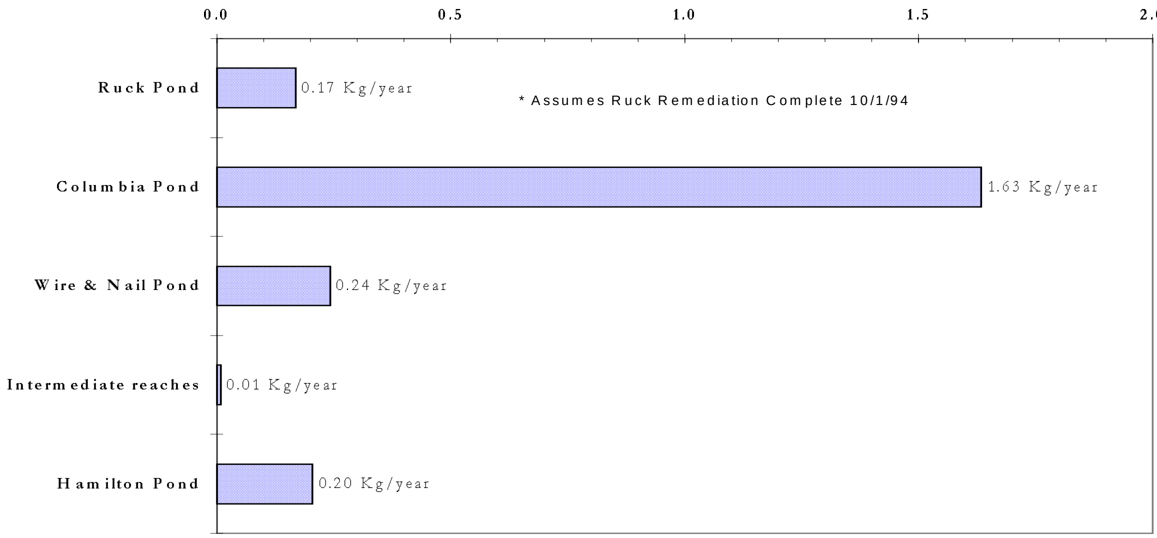


Figure 7.13 is essentially the same as Figure 7.12, except that the Milwaukee River impoundments are added in.

FIGURE 7.13 NET CONTRIBUTION OF ALL SEDIMENTS TO LONG-TERM PCB EXPORT

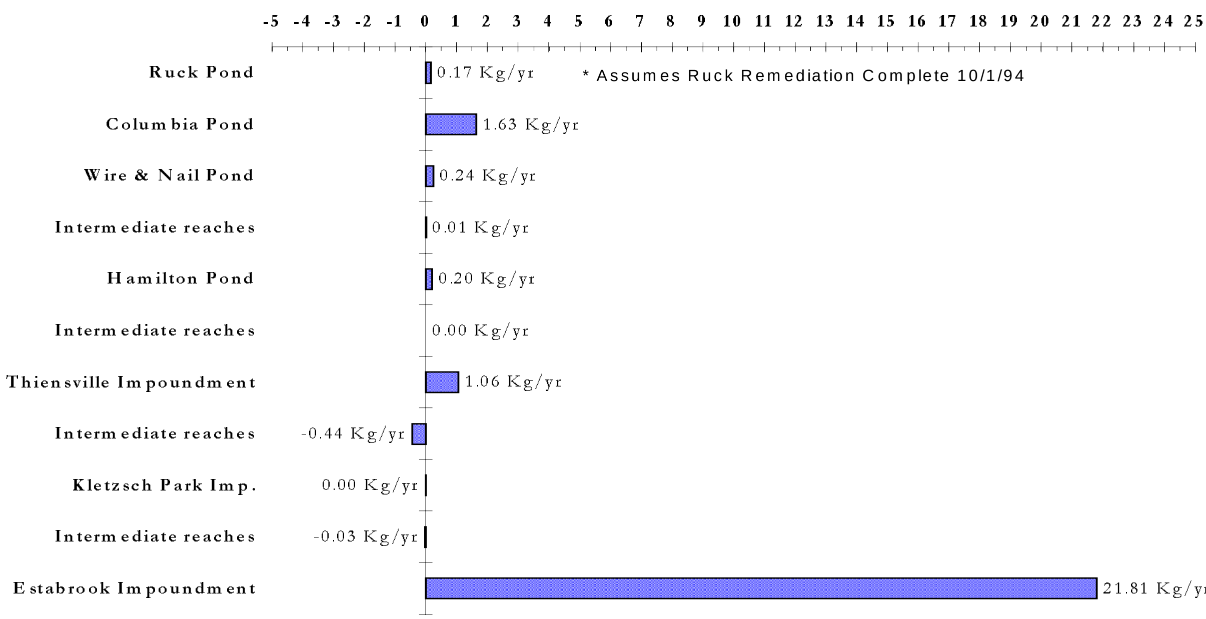
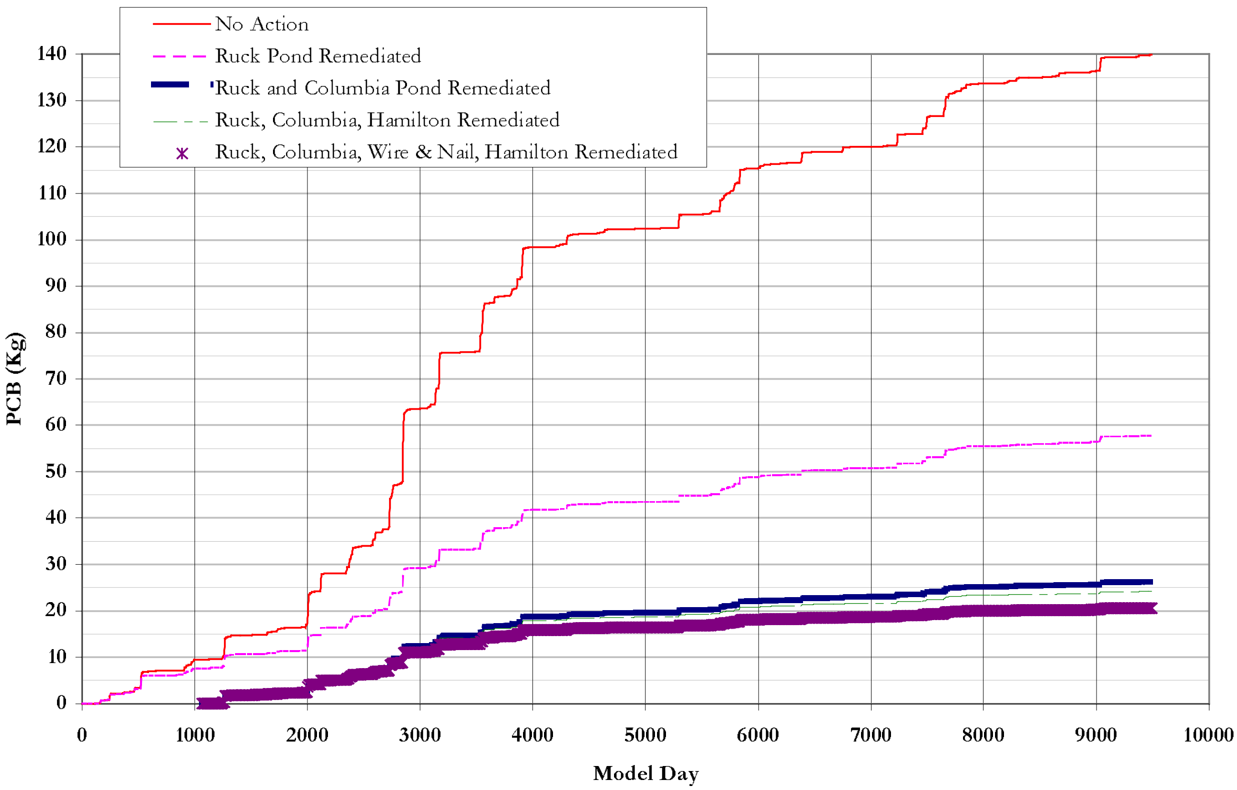


Figure 7.14 shows the integrated PCB mass export over the 25-year simulation. Without the remediation at Ruck Pond, a substantial mass of PCB would have ended up in the Milwaukee River. The Ruck Pond remediation significantly reduced the cumulative mass export of PCB.

FIGURE 7.14 CUMULATIVE PROJECTED PCB EXPORT TO THE MILWAUKEE RIVER FROM CEDAR CREEK



Remediation of Columbia Pond would keep another 20 or 30 kilograms of PCB out of the Milwaukee River. Remediation beyond that point, however, has a somewhat more limited effect on PCB mass export.

8. ACKNOWLEDGEMENTS

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- Wisconsin Department of Natural Resources, Environmental Repair Program
- Milwaukee Metropolitan Sewerage District
- United States Geological Survey, Merit Proposal Program

In addition to financial support, the individuals from the aforementioned agencies contributed countless hours to the collection, data analysis and modeling efforts. The author gratefully acknowledges their contributions.

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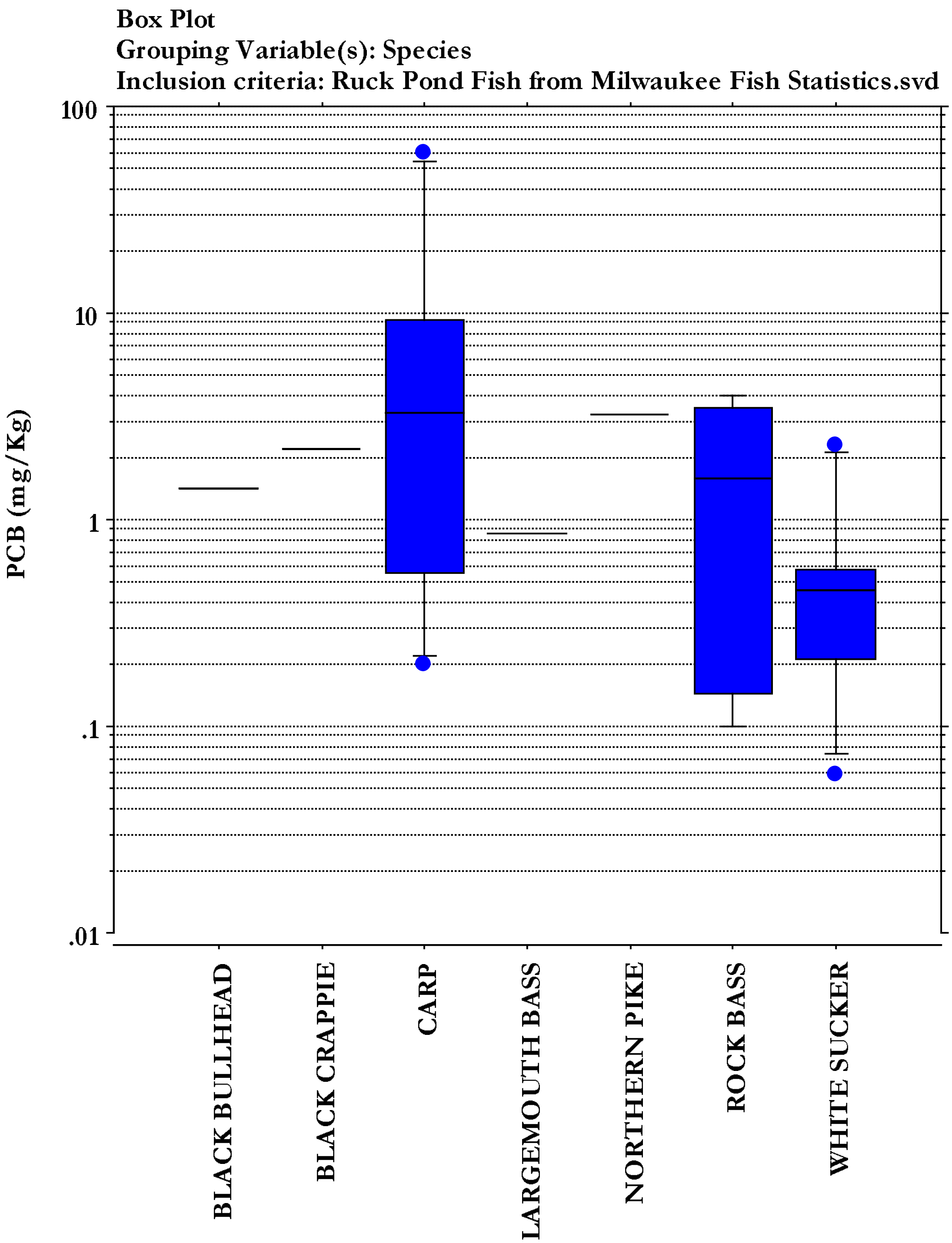
10. APPENDICES

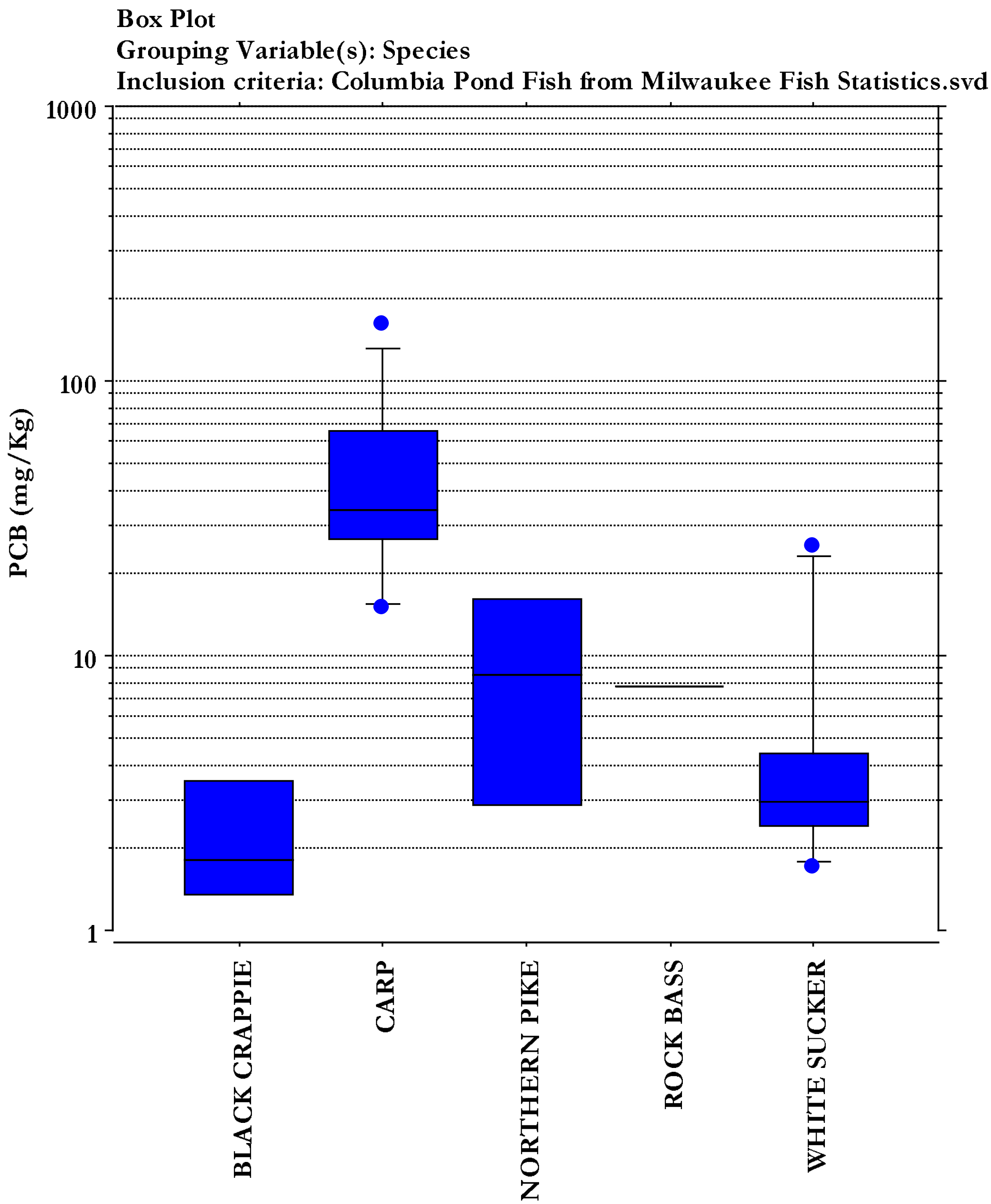
10.1 Appendix A. - Milwaukee River PCB Mass Balance Field Sampling Plan

10.2 APPENDIX B. - PCB CONGENER DATA FOR SEDIMENT CORES

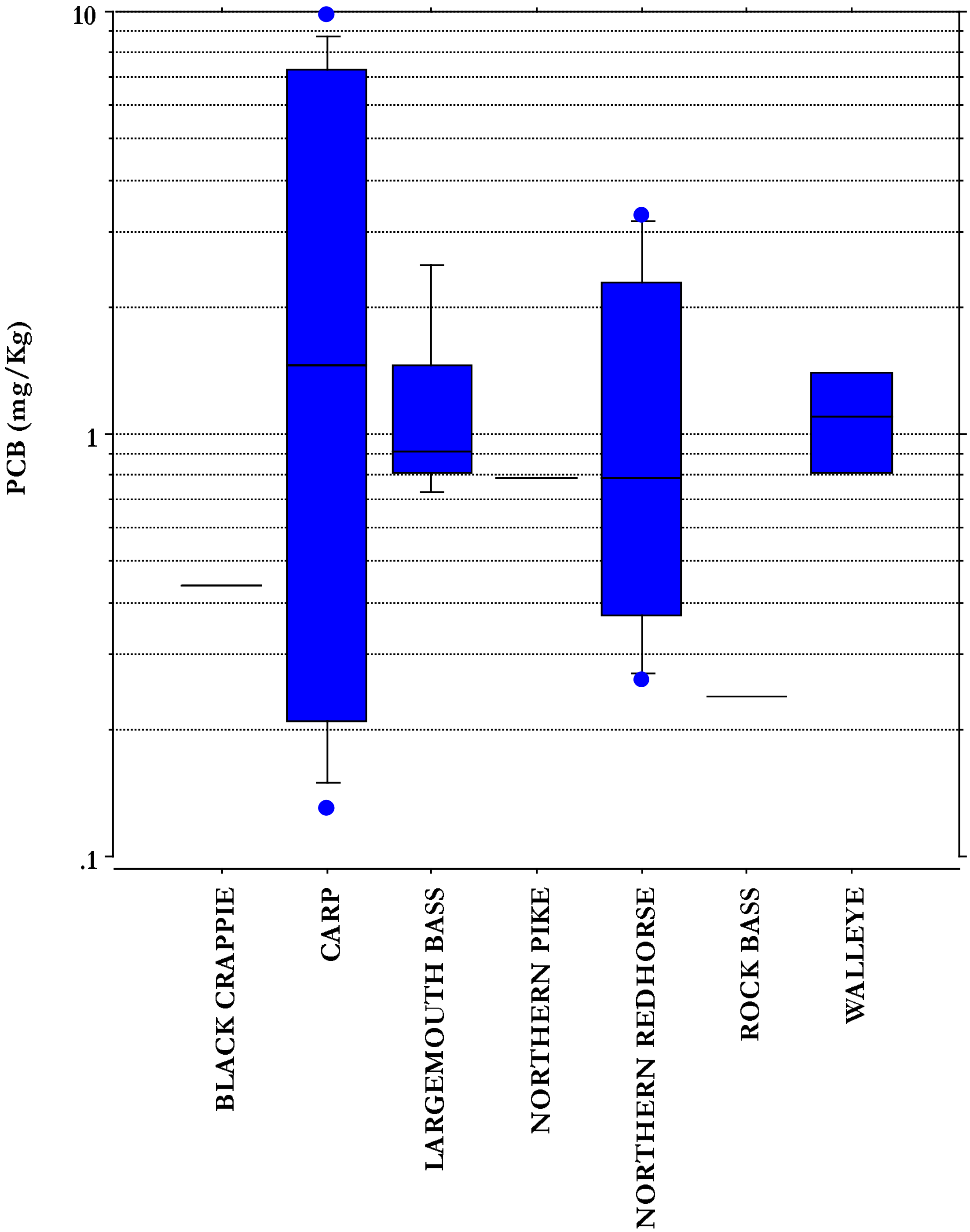
10.3 APPENDIX C. - FISH TISSUE DATA FOR SELECTED SITES BY SPECIES



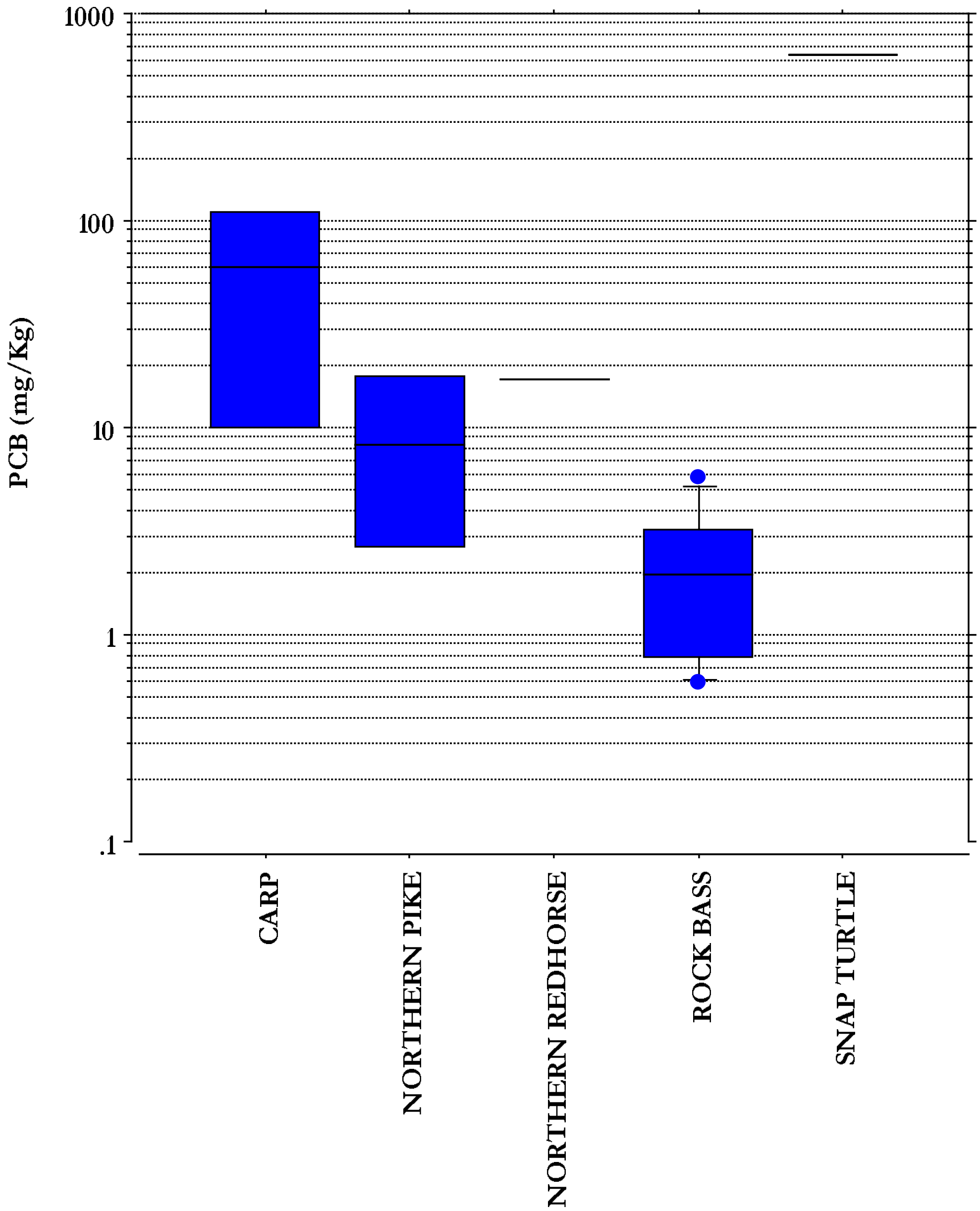
Box Plot
Grouping Variable(s): Species
Inclusion criteria: Ruck Pond Fish from Milwaukee Fish Statistics.svd
100
10
1
.1
.01
PCB (mg/Kg)
BLACK BULLHEAD
BLACK CRAPPIE
CARP
LARGEMOUTH BASS
NORTHERN PIKE
ROCK BASS
WHITE SUCKER


Box Plot
Grouping Variable(s): Species
Inclusion criteria: Columbia Pond Fish from Milwaukee Fish Statistics.svd
1000
100
10
1
PCB (mg/Kg)
BLACK CRAPPIE
CARP
NORTHERN PIKE
ROCK BASS
WHITE SUCKER

Box Plot
Grouping Variable(s): Species
Inclusion criteria: Thiensville Fish from Milwaukee Fish Statistics.svd



Box Plot
Grouping Variable(s): Species
Inclusion criteria: Downstream of Hamilton Pond from Milwaukee Fish Statistics.svd



10.4 Appendix D. - Milwaukee River PAH Data