An Independent Evaluation of the PCB Dredging Program On the Upper Hudson and Lower Hudson River

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Executive Summary

In February 2002, the General Electric Company (GE) was ordered by the U.S. Environmental Protection Agency (EPA) to conduct targeted dredging of PCB-contaminated sediment in a 40-mile stretch of the Upper Hudson[1] River between Fort Edward and Waterford, NY. GE performed dredging of the Upper Hudson in two phases, beginning in May 2009 and ending in October 2015. Following completion of dredging operations, the Hudson River Foundation convened an expert panel to evaluate the effectiveness of the dredging program on the Upper and Lower Hudson. Based on water column and fish monitoring data and other information that were available through December 2016, the panel concluded: (i) the dredging program met mass removal targets for PCB-contaminated sediments, (ii) the dredging program was effective in reducing PCB concentrations in fish from Thompson Island Pool, (iii) post-dredging PCB concentrations in fish downstream of Thompson Island Pool showed mixed results, (iv) the reduction in Tri+ PCB[2] loads to the Lower Hudson during the 2016 post-dredging period were in part due to below-average flows in the river, (v) water column, sediment and fish in the Lower Hudson below Albany are showing slow responses to the Upper Hudson dredging program due to the complexities of sediment transport in the Lower Hudson, and (vi) additional years of natural attenuation will be required to reduce PCB concentrations in fish throughout the Upper and Lower Hudson to acceptable levels. Modifications to the post-dredging monitoring program and continued evaluation of the next few years of monitoring data are therefore recommended to assess if natural attenuation will be sufficient in reducing PCB concentrations in fish in a reasonable time frame or if additional remedial actions will be required.

Key findings and recommendations of the panel are provided below:

<u>Dredging Operations</u>

- During the dredging program, GE met mass removal targets of 2.65 million cubic yards of contaminated sediment and 70,000 kg Total PCBs that were specified in EPA's 2002 Record of Decision. In addition, the overall release of PCBs passing the Waterford monitoring station was

[1] The Federal Dam at Troy, NY serves as the designated boundary between the Upper Hudson and Lower Hudson River.

[2] Tri+ PCB represents the sum of the PCB compounds with three or more chlorines on the biphenyl structure.

less than one percent of PCBs that were removed from the Upper Hudson in accordance with EPA's revised 2010 resuspension engineering performance standard.

PCB Responses in the Upper Hudson

- Post-dredging water column and fish monitoring data provide a preliminary indication of decreases in PCB concentrations in Upper Hudson fish following the completion of the dredging program. Decreases are most notable in Thompson Island Pool, where post-dredging PCB concentrations in pumpkinseed (a small pelagic feeder) and small forage fish were three to six times lower than observed pre-dredging levels. Note that this section of the Upper Hudson was the focus of much of the dredging operations.

- Post-dredging fish monitoring data show mixed results for sections of the Upper Hudson downstream of Thompson Island Pool. PCB concentrations in pumpkinseed were reduced by approximately a factor of two, and were closely linked to reductions in Tri+ PCB water column concentrations for low flow conditions (< 13,000 cfs). Little or no reductions however were observed for PCBs in small forage fish. This result is consistent with the linkage between small forage fish and contaminant levels in localized sediments, and the limited amount of dredging that was performed in river sections downstream of Thompson Island Pool.

- Post-dredging water column monitoring data show that Tri+ PCB water column concentrations at Waterford were reduced by approximately a factor of two for low flow conditions (< 13,000 cfs). However, based on limited post-dredging monitoring data, little or no reduction in Tri+ PCB water column concentrations was observed at Waterford for high flow conditions (> 13,000 cfs). This latter finding may indicate that Tri+ PCB water column concentrations during high flows are more likely derived from resuspension of localized sediments and not from sediments further upstream where dredging operations were more extensive.

PCB Responses in the Lower Hudson

- Based on pre-dredging and 2016 post-dredging monitoring data, we estimated a 66 percent reduction in Tri+ PCB loads passing Waterford and entering the Lower Hudson. This large reduction however was in part due to the below-average flows in the Upper Hudson during 2016.

If 2016 flows were more comparable to the 2004-2008 pre-dredging period, the Tri+ PCB loads would have been reduced by 15-35 percent.

- Tri+ PCB water column concentrations at Albany follow trends that are similar to observed Tri+ PCB concentrations at Waterford. This is in contrast to observed Tri+ PCB concentrations 70 miles downstream at Poughkeepsie, which were very variable and not correlated to observed PCB concentrations at Albany. This discrepancy is believed to be related to the complexity of sediment transport in the Lower Hudson.

- Sediment transport processes in the Lower Hudson will dampen PCB responses and greatly extend PCB response times to changes in Upper Hudson PCB loads. Based on previous sediment transport and contaminant transport modeling studies, we expect that it would take a decade or more to see appreciable changes in PCB water column, sediment and fish concentrations at many locations in the Lower Hudson.

Moving Forward

- Post-dredging monitoring plans should be modified to enhance the overall utility of the water column, sediment and fish data and to help determine the effectiveness of the Upper Hudson PCB dredging program within the next few years. Recommendations include: (i) EPA Method 1668 (a high resolution, congener-based method) should be used to improve the accuracy and reproducibility of PCB water column, sediment and fish measurements, (ii) the USGS suspended sediment monitoring at Waterford should be re-instated to support evaluations of PCB loads to the Lower Hudson, (iii) additional high flow samples should be collected at Waterford to support evaluations of PCB loads to the Lower Hudson for high flow conditions, and (iv) PCB concentrations should be monitored in surface sediments and sediment cores from selected locations in the Lower Hudson to improve our understanding of time responses in the tidal freshwater and estuarine portion of the river.

- Continued evaluation of post-dredging monitoring data, re-assessment of PCB mass inventory in sediment and re-evaluation of PCB model projections should be performed. This work should include congener-based analyses and modeling of specific PCB congeners and/or PCB homolog groups to enhance the interpretation of post-dredging data and increase the reliability of model projections. This work will be critical in determining if natural attenuation will be sufficient in reducing PCB concentrations to acceptable levels in a reasonable time frame or if additional remedial action will be required.

Introduction

From the late 1940s to the late 1970s, the General Electric Company (GE) is believed to have discharged one or more million pounds of polychlorinated biphenyls (PCBs) into the Hudson River from its capacitor manufacturing plants in Hudson Falls and Fort Edward, New York. A 200-mile stretch of the Hudson River was subsequently designated by the US Environmental Protection Agency (EPA) as a Superfund Site in September 1984 due to elevated levels of PCBs in water, sediment and fish. This stretch of the river extends for approximately 40 miles from Hudson Falls to Federal Dam at Troy (the designated boundary between the Upper Hudson and Lower Hudson River) and then down to the Battery in New York City (see Figure 1).

An initial Record of Decision (ROD) for the Hudson River was issued by EPA in September 1984 (EPA 1984). In the 1984 ROD, EPA recognized that PCB contamination in the Upper Hudson River sediments was a problem, but selected an interim 'No Action' remedy for the contaminated sediments. This decision was based on monitoring data which showed downward trends in PCB concentrations in fish, sediment and water during the late 1970s/early 1980s. In EPA's view, there was also uncertainty in the reliability and effectiveness of remedial technologies that were available at the time of the 1984 decision.

In 1989, a detailed Reassessment Remedial Investigation/Feasibility Study (RI/FS) of the interim 'No Action' decision for the Upper Hudson River sediments was initiated by EPA. The decade-long reassessment study that followed culminated in the issuance of a new ROD by EPA in February 2002 (EPA 2002). Based on the 2002 ROD, GE was ordered to conduct targeted environmental dredging of PCB-contaminated sediment in a 40-mile stretch of the Upper Hudson River. GE began dredging contaminated sediment from the Upper Hudson in May 2009 and completed the dredging program in October 2015 (GE 2016a). In all, 2.76 million cubic yards (MCYs) of PCB-contaminated sediment were removed from the Upper Hudson.

The Hudson River Foundation (a non-profit organization supporting scientific research integral to the development of sound public policy for the Hudson River and its watershed) convened an expert panel to evaluate the effectiveness of the dredging program. The evaluation was performed using water column and fish monitoring data and other information that was available through December 2016 (i.e., 14 months after the dredging program was complete). Summaries of the EPA 2002 ROD and the Upper

Hudson dredging program are reported below and are followed by the panel's evaluations of the effects of the dredging program on the Upper Hudson and Lower Hudson River.

EPA 2002 Record of Decision

Based on the Reassessment RI/FS, EPA determined that there was "an unacceptable risk to human health and the environment from the consumption of fish from the Hudson River" and that "the unacceptable risk will continue for many decades without active remediation of the PCB-contaminated sediments and control of upstream sources" (EPA 2002). EPA cited the key findings from the geochemical and modeling studies that were conducted as part of the reassessment to support its conclusion for an active remedy of the Upper Hudson sediments. These included:

i. Water column and fish monitoring data showed little decline through the latter part of the 1990s.
ii. Long-term sequestration of PCBs in sediment was not supported by analyses of sediment monitoring and water column data.
iii. Sediment deposition was occurring, on average, in most of the Upper Hudson River, but not at rates or with a consistency sufficient for sequestration of PCB-contaminated sediments.
iv. PCB concentrations in water were currently being driven by PCBs stored in sediments.
v. Mass balance model evaluations and projections indicated that elevated PCB concentrations (and associated human/ecological health risks) were expected to continue for decades without remedial action.

As part of the Reassessment RI/FS, detailed model evaluations were performed to evaluate the effectiveness of five remedial alternatives (EPA 2002). These included the No Action alternative, Monitored Natural Attenuation (MNA) with Upstream Source Control at the GE plant sites, and three active remedies that included Upstream Source Control and targeted dredging and/or capping of contaminated sediment followed by MNA. Details are given in Table 1 for the No Action alternative, MNA, and the three active remedial alternatives: capping (CAP-3/3/Select), dredging removal (REM-3/3/Select) and the more aggressive dredging removal (REM-0/0/3).

For the active remedies, the Upper Hudson was divided into three River Sections (RS): Fort Edward to Thompson Island Dam (RS#1), Thompson Island Dam to Northumberland Dam near Schuylerville (RS#2), and Northumberland Dam to Waterford (RS#3). See Figure 1 insert for the locations. In each river section, target criteria were specified based on PCB mass per unit area (MPA); i.e., the total mass inventory of

PCBs underlying a square meter of surface sediment. MPA targets were expressed in terms of Tri+ PCB (which represents the sum of PCB compounds with three or more chlorines on the biphenyl structure). The decision to use Tri+ PCBs in model evaluations was based on: (i) difficulties encountered in consistently quantifying mono- and di-chlorobiphenyls (CBs) concentrations in the historic datasets (EPA 2000a; Connolly et al. 2000), and (ii) studies showing that Tri+ PCBs provided a very good representation of the total PCB concentrations in fish (EPA 2000a, 2002).

Model projections for the five remedial alternatives were given in the 2002 ROD (EPA 2002) for Tri+ PCB concentrations in fish fillets, for whole-body Tri+ PCB concentrations in largemouth bass, and for Tri+ PCB loads (in kg/yr) passing over the Troy lock and dam. These results were subsequently used in assessing human health risks, ecological risks and potential PCB impacts to the Lower Hudson. Typical model results are presented in Figure 2 for average Tri+ PCB concentrations in fish fillets for a 70-year period with active remedies commencing in 2004. Model results for Tri+ PCB concentrations in fish fillets were compared to interim targets of 0.4 mg/kg-wet weight and 0.2 mg/kg-wet weight, and a Tri+ PCB Remediation Goal of 0.05 mg/kg-wet weight. These values are considered to be protective of individuals consuming one half-pound meal of Upper Hudson fish every two months, one month and every one week, respectively.

As shown in Figure 2, MNA with Upstream Source Control was effective in reducing Tri+ PCB concentrations in fish fillets over the longer time period. Both CAP-3/3/Select and REM-3/10/Select reduced the time to reach the interim targets of 0. 4 mg/kg and 0.2 mg/kg in fish by approximately 11 years. The more aggressive dredging remedy, REM-0/0/3, was not considered to provide an appreciable benefit over REM-3/10/Select. REM-3/10/Select was ultimately selected as the required remedy. Further information on EPA's selection of REM-3/10/Select as the required remedy is given in the 2002 ROD (EPA 2002).

Upper Hudson Dredging Program

The selected remedy for the Upper Hudson, REM-3/10/Select, is summarized in Table 2. As shown in the table, the total area of bottom sediment in RS#1 and RS#2 is approximately 500 acres, with over 3,300 acres of bottom sediment in the longer stretch of RS#3. Target sediment remediation criteria that were specified in the 2002 ROD were subsequently modified to include a MPA of 10 g/m^2 Tri+ PCBs for RS#3

(EPA 2004a). Tri+ PCB concentration criteria for the top 12 inches of sediment were also added (EPA 2004a).

Detailed sediment sampling that was conducted during remedial design phase was used to determine areas targeted for dredging. As shown in Table 2, a large portion of the dredging plan focused on contaminated sediments in Thompson Island Pool (RS#1). Select areas downstream of Thompson Island Dam (RS#2, RS#3) with high levels of PCB contamination were also identified for dredging. In all, 2.65 MCY of contaminated sediment and approximately 70,000 kg of Total PCBs (TPCBs) were slated to be removed from the river bottom.

After dredging and covering with clean backfill, average Tri+ PCB concentration in surficial (0-2 inch) sediments were expected to be reduced substantially for RS#1; smaller reductions in surficial sediment concentrations were expected further downstream (Table 2). In addition, Tri+ PCB concentrations in fish fillets from the Upper Hudson were expected to reach an interim target of 0.4 mg/kg-wet in five years, and 0.2 mg/kg-wet in sixteen years after the completion of dredging program. The PCB Remediation Goal of 0.05 mg/kg-wet was not expected to be met in RS#1 and RS#2 within the 70-year model projection, but was expected to be met in RS#3 43 years after the completion of dredging. Due to the lower initial concentrations of PCBs in the Lower Hudson (compared to RS#3), the Remediation Goal of 0.05 mg/kg-wet was also expected to be attained in 43 years after completion of the dredging program for fish from the majority of the Lower Hudson.

Implementation of the Upper Hudson dredging program was carried out in two phases beginning in 2009. Mechanical dredges with enclosed environmental clamshell buckets were used in both phases to remove PCB-contaminated sediment from the river bottom. Phase 1 was conducted by GE from May – November 2009 following strict Engineering Performance Standards (EPS) (EPA 2004b). Among other conditions, the 2004 EPS included the following:

i. Resuspension: dredging-related releases of Tri+ PCBs should not exceed 200 g/day (based on a 7-day running average Tri+ PCB load at far-field monitoring stations located one mile or more downstream of the dredging area),
ii. Residuals: residual PCB sediment contamination in the dredged areas should be less than 1 mg/kg of Tri+ PCB (prior to placement of one foot of backfill material), and

iii. Productivity: sediment dredging should be scheduled to ensure an overall removal of 2.65 MCY of contaminated sediment over the dredging program.

See EPA (2004b) for further details. During Phase 1, approximately 0.3 MCYs of contaminated sediment and 18,000 kg of TPCBs were removed from approximately 48 acres from a six-mile stretch of the Upper Hudson River near Fort Edward (RS#1).

In 2010, a peer-review panel of scientists was convened by EPA to evaluate the effectiveness of Phase 1 dredging. The peer-review panel concluded that "the 2004 EPS for Resuspension, Residuals and Productivity were not met individually or simultaneously during Phase 1 and cannot be met under Phase 2 without substantive changes" (Bridges et al. 2010). The panel recommended that additional evaluations be performed to better delineate the depth of PCB contamination and that dredged areas be covered with backfill (or capped) in a more-timely fashion to limit downriver releases of PCBs. The 2004 EPS were modified accordingly based on recommendations in Bridges et al. (2010). Changes in the revised EPS for Phase 2 included:

i. Resuspension: dredging-related loss of Tri+ PCBs passing the Waterford monitoring station should not exceed 1.0 percent of the total amount of Tri+ PCBs actually removed from the river bottom during the dredging season, and

ii. Residuals: a maximum of two dredge passes should be employed to limit exposure times of contaminated sediment. In areas with high residual contamination after two dredge passes, sediments should be capped prior to placement of backfill.

See EPA (2010a) for further details. Phase 2 was conducted by GE over five dredging seasons (from 2011 to 2015) following the 2010 revised EPS. During this phase, approximately 2.46 MCYs of contaminated sediment and 128,000 kg of TPCBs were removed from approximately 445 acres of river bottom.

A summary of performance results for the Upper Hudson dredging program is given in Table 3. As shown, 2.76 MCY of contaminated sediments were removed from the Upper Hudson during Phase 1 and Phase 2 dredging. In all, 45,680 kg Tri+ PCBs were removed from the river, with 316 kg (or 0.69 percent) of Tri+ PCBs released past the Waterford monitoring station. Comparable measurements for TPCBs show that 146,000 kg TPCBs were removed from the river, indicating that more than two-thirds of the PCBs were present as mono- and di-CBs. The reported monitoring results confirm that GE met mass removal targets of 2.65 MCY of contaminated sediment and 70,000 kg TPCBs that were specified in the 2002 ROD (EPA 2002) and the Productivity EPS (EPA 2004b). In addition, the overall release of PCBs passing Waterford was below the 1 percent of PCBs that were removed from the Upper Hudson in accordance with the revised Resuspension EPS (EPA 2010a). More detailed evaluation of the effects of dredging on PCB responses in the water and fish of the Upper Hudson and Lower Hudson are described below.

PCB Responses in the Upper Hudson

Water Column Monitoring

Water column samples were collected throughout the pre-dredging, dredging and post-dredging periods at five far-field monitoring stations along the Upper Hudson. These included Rogers Island (RM 194.5), Thompson Island (RM 187.5), Schuylerville at Lock 5 (RM 182.3), Stillwater (RM 168.4), and Waterford (RM 156.0). See Figure 1. Far-field water samples were primarily analyzed for whole-water PCB concentrations using the modified Green Bay Peak (mGBP) Method. During periods of dredging, additional water samples were collected and analyzed using an Aroclor PCB analytical method with an accelerated turnaround time. These samples were used to rapidly assess compliance with the resuspension EPS. Further details on water column monitoring are given in EPA (2010b).

Tri+ PCB Water Column Responses at Waterford

Observed Tri+ PCB water column concentrations at Waterford are presented in Figure 3 for 2004 through 2016. To provide a more complete picture of the time record, Tri+ PCB concentrations that were determined using mGBP measurements as well as those estimated from Aroclor measurements are included on the figure. Tri+ PCB concentrations are plotted on a log scale to highlight variations over a wide range of observed concentrations.

As shown on Figure 3, Tri+ PCB water column concentrations were highly variable throughout the entire record, with observed concentrations ranging from approximately 1 to 1,000 ng/L. During the pre-dredging period (2004-2008), variations in the observed concentrations appear to be related to seasonal effects. In particular, the highest observed Tri+ PCB concentrations generally coincide with spring high flow events. During the dredging period (2009-2015), elevated Tri+ PCB concentrations were generally associated with dredging operations, which typically occurred from June through October. Very high Tri+ PCB concentrations were also observed in several of the spring high flow events that followed dredging operations (e.g., spring 2010 and 2011). Finally, Tri+ PCB concentrations were observed to be lower for the 2016 post-dredging year (as compared to the observed concentrations for the pre-dredging period).

To help illustrate differences in the pre-dredging, dredging and post-dredging periods, Tri+ PCB water column concentrations are presented in Figure 4 as monthly geometric mean (with geometric standard deviations) for the pre-dredging, dredging and post-dredging periods. Pre-dredging values show a seasonal pattern with highest Tri+ PCB concentrations occurring in April (coinciding with spring high flows) as well as in June and July. The high Tri+ PCBs in June and July are likely due to enhanced bioturbation during the early part of the summer (Erickson et al. 2005) and to high flows that occurred in late June/early July of 2006. During the dredging period (May through October), Tri+ PCB water column concentrations were generally two to three times higher than the pre-dredging period. Tri+ PCB concentrations for the post-dredging period were generally lower than the pre-dredging results by approximately a factor of two.

At this point, it is important to note that the Upper Hudson experienced below-average flows for most of the 2016 post-dredging year. Because of the potential effects of flow on Tri+ PCB water column concentrations, the Tri+ PCB water column concentrations at Waterford were plotted as a function of river flow (Figure 5A). On the figure, observed concentrations are presented as geometric means (with geometric standard deviations) for selected flow bins. For both the pre-dredging and post-dredging periods, Tri+ PCB concentrations decreased with increasing flows for river flows less than approximately 13,000 cfs (or 1.6 times the long-term mean river flow at Waterford). For river flows greater than 13,000 cfs, Tri+ PCB concentrations increased with increasing flows. This latter result is expected and is associated with increased flow-induced erosion of the streambed and the accompanying increase in suspended sediment loads (and particulate phase PCB transport) during the higher flows. Observed PCB homolog patterns are consistent with this finding. For six water samples collected during 2016 July-August low flows (< 13,000 cfs) (Figure 5B), PCB homolog distributions are dominated by lower chlorinated PCBs (e.g., tri-CBs) suggesting that dissolved phase PCBs are more important. For four water samples collected during 2016 February high flows (> 13,000 cfs) (Figure 5C), PCB homolog distributions are shifted to more chlorinated PCBs indicating of a greater contribution of particulate phase PCBs in the water column.

Based on the data presented in Figure 5A, regression equations were developed for Tri+ PCB concentrations as a function of flow. The regression equations were based on an approach previously used to evaluate suspended sediment loads in the Upper Hudson at Waterford (da Luz et al. in prep). In this approach, separate regression equations were developed for lower flow (non-flood) and higher flow (flood) conditions. See the Supplemental Information for additional details. The resulting regression equations for the non-flood and flood conditions are shown on Figure 5A for both the pre-dredging (solid blue lines) and post-dredging (dashed green lines) periods. As shown, the regression line for post-dredging non-flood period is approximately a factor of two lower than the corresponding regression line for the pre-dredging period. Differences in the regression lines for the pre-dredging and post-dredging periods however showed little or no reduction in Tri+ PCB water column concentrations for flood conditions. This result suggests that Tri+ PCBs in the water column during flood conditions are more likely to be derived from the resuspension of local sediments and not from sediments further upstream where dredging operations were more extensive. However, it is important to note that this finding is currently based on a limited number of high flow observations that were available for the 2016 post-dredging period.

Linking Sediment Concentrations to Water Column Responses

A simplified model was developed as part of a preliminary investigation of the linkage between PCB surface sediment concentrations and water column responses during summer-time low flow conditions. In the model, Tri+ PCBs in the water column are assumed to be primarily comprised of dissolved phase contaminant during low flow periods. A schematic of the simplified model is presented in Figure 6. Briefly, the model represents the Upper Hudson as four consecutive "plug-flow" river reaches. The river reaches correspond to the three River Sections, with the longest River Section (RS#3) divided into RS#3a and RS#3b at Stillwater where the Hoosic River enters the Upper Hudson. Processes considered in the model calculation include flow through the river reaches, PCB diffusion out of (and potentially into) the contaminated sediments, PCB volatilization, and addition of flow from tributaries and surface runoff. For pre-dredging model calculations, average Tri+ PCB concentrations in surface sediments (r_a) for each river reach were based on the Sediment Sampling and Analysis Program (SSAP) that was conducted in 2002-2005 during the remedial design phase (see Table 2). Since post-dredging monitoring data are not yet available for the sediment, post-dredging concentrations of Tri+ PCBs in surface sediments were assigned based on estimates given in EPA (2012) and previously presented in Table 2. An analytical solution of the plug-flow equation was used to calculate Tri+ PCB water column concentrations continuously as a function of distance along each of the four river reaches. Further details of the model and model parameterization are given in the Supplemental Information.

The simplified model was calibrated to the pre-dredging period for a summer-time low flow of 3,500 cfs by adjusting only the PCB diffusive exchange coefficient between the water column and the underlying pore-water (Figure 7A). Calibration results for the pre-dredging period (solid blue line) show a large increase in Tri+ PCB water column concentrations as the water flows through RS#1 (Thompson Island Pool, TIP) and a continued increase in concentration through RS#2 (to Schuylerville). Tri+ PCB concentrations further downstream (RS#3a,b) appear to level off and remain relatively constant with distance. This result could be interpreted as an indication of little or no additional Tri+ PCB inputs from the underlying sediments in RS#3a,b (Schuylerville to Waterford). According to results from the simplified model, a more appropriate explanation would be that additional Tri+ PCB inputs from the downstream sediments are largely being off-set by losses of Tri+ PCBs by volatilization and possibly back-diffusion into sediments. Dilution of Tri+ PCBs by less contaminated tributary and surface runoff flows are also playing a role.

The simplified model was then applied to the post-dredging period by setting the Tri+ PCB concentrations in the surface sediments to estimated values given in EPA (2012) and previously reported in Table 2. Values for all other model coefficients (including the PCB diffusive exchange coefficient) remained the same as in the pre-dredging model calculation. As shown on Figure 7A, the post-dredging model results (green dashed line) show a large decrease in Tri+ PCB water column concentrations at TID (RM 187.5) and at Schuylerville (RM 182.3). Further downstream, model results for Tri+ PCB water column concentrations show an increase between Schuylerville (RM 182.3) and Waterford (RM 156.0). However, the 2016 post-dredging Tri+ PCB concentrations in the water column (green diamonds of Figure 7A) show a different response than the model results. In particular, the observed Tri+ PCB concentrations at TID (RM 187.2) and Schuylerville (RM 182.3) show a smaller decrease in Tri+ PCB water column concentrations than the model calculations for the post-dredging period. Model-calculated Tri+ PCB concentrations however are comparable to the summer-time low flow concentrations at Waterford (RM 156.0).

The discrepancies between the 2016 post-dredging data and the model results at TID (RM 187.5) and Schuylerville (RM 182.3) suggest that the 2016 post-dredging Tri+ PCB concentrations in surface sediments are higher than the EPA (2012) expected concentrations used in the model calculations. Another contributing factor to the higher Tri+ PCB water column concentrations at TID and Schuylerville is that sediments in the dredging zones may need more time to "stabilize" after six years of dredging. For example, the higher Tri+ PCB water column concentrations at TID and Schuylerville may be due to residual effects of dredging disturbances that are continuing to supply localized resuspension of sediments even during summer-time low flow conditions. This would result in higher Tri+ PCB water column concentrations due to the presence of particulate-phase PCBs that were not considered in the simplified model calculations. It could therefore be argued that one year of post-dredging monitoring data is not sufficient to evaluate the full benefits of the dredging program.

Based on uncertainties associated with post-dredging modeling results for TID and Schuylerville, we focused our attention on model results for Waterford to evaluate the effects of flow on Tri+ PCB water column concentrations. Model calculations were limited to non-flood conditions where flows were less than 13,000 cfs. As shown in Figure 7B, model results for both the pre-dredging (solid blue line) and post-dredging (dashed green line) periods show decreases in Tri+ PCB water column concentrations at Waterford with increasing flows. In addition, the post-dredging modeling results are approximately a factor of two lower than the pre-dredging results. These finding are consistent with the non-flood regressions previously presented in Figure 5A.

Although the simplified model evaluations are limited to non-flood conditions, non-flood conditions occurred 76% of the time during the 2004-2008 pre-dredging period and 96% of the time for the 2016 post-dredging period. Tri+ PCB water column concentrations during non-flood conditions are therefore likely to play an important role in determining PCB exposure and responses in pelagic fish populations.

Fish Monitoring

Fish samples were collected annually throughout the pre-dredging, dredging and post-dredging periods at Feeder Dam (representative of reference conditions), and five sampling locations in Thompson Island Pool (TP1-5) in RS#1, Northumberland and Fort Miller Pools (ND1-5) in RS#2, and Stillwater Pool (SW1-5) in RS#3. Fish species included in sampling were: black bass (including largemouth and smallmouth bass); ictalurids (including bullhead and catfish); yellow perch; yearling pumpkinseed; and small forage fish (including spottail shiner, banded killifish, mimic shiner and fall fish). TPCBs in fish samples were measured using a modification of the USEPA Method 8082 Aroclor Sum Method. In addition, a small subset of the fish samples was analyzed using the mGBP Method to verify TPCB quantification from Aroclor measurements. This check was important to ensure that TPCB quantification from Aroclor measurements was not being affected by changes in PCB congener patterns that may have occurred as a result of dredging. Data from the mGBP method was also used to confirm that TPCBs in fish were primarily composed of Tri+ PCBs. Further details on fish monitoring are given in EPA (2010b).

PCB Responses in Upper Hudson Fish

Our evaluation of PCB responses in fish focused on yearling pumpkinseed and small forage fish because they are expected to show the most rapid response to changing PCB exposure conditions. TPCB concentrations in yearling pumpkinseed and small forage fish are presented in Figure 8 as monthly geometric mean (with geometric standard deviations) for the pre-dredging and post-dredging periods. As shown on the figure, post-dredging TPCB concentrations in pumpkinseed and small forage fish were 3-6 times lower than pre-dredging concentrations for the five locations in TIP. These reductions are greater than the observed reduction in Tri+ PCB water column concentrations in TIP. The observed reductions in TIP fish however are in line with reductions in dissolved Tri+ PCB water column concentrations that were calculated based on EPA (2010) projections for post-dredging Tri+ PCB concentrations in surficial sediments (see Figure 7A).

Although pumpkinseed and forage fish showed similar reductions in TIP, their responses were quite different at further downstream locations. For the Northumberland / Fort Miller (RS#2) and Stillwater (RS#3) pools, post-dredging TPCB concentrations for pumpkinseed (Figure 8A) were approximately two times lower than pre-dredging concentrations. In contrast, post-dredging TPCB concentrations for small forage fish (Figure 8B) were reported to be higher than pre-dredging concentrations in two of the four Northumberland / Fort Miller pools (RS#2). In three of the five locations in the Stillwater Pool (RS#3), post-dredging TPCB concentrations in the small forage fish were approximately equal to the pre-dredging values.

Although differences in pumpkinseed and forage fish responses may in part be attributed to the relatively small number of forage fish (i.e., 2-3 fish per sampling location) that were collected at many locations during the 2016 post-dredging monitoring, differences in feeding behavior also play a role. For example, PCB concentrations in pumpkinseed (a pelagic feeder) would be expected to be linked to water column concentrations. A factor of two decrease in TPCB pumpkinseed concentrations at the downstream locations is therefore consistent with the calculated reduction in dissolved Tri+ PCB water column concentrations that was previously presented in Figure 7A. In contrast, TPCB exposure for forage fish is expected to be more closely linked to PCB sediment concentrations within a very localized area. Based on EPA (2012) projected reductions in surface sediments concentrations (see Table 2), smaller reductions in TPCB concentrations for forage fish would therefore seem to be quite reasonable for forage fish in the Northumberland / Fort Miller (RS#2) and Stillwater (RS#3) pools.

Summary of Upper Hudson Finding

Our evaluations of PCB responses in the Upper Hudson River provide a preliminary indication of decreases in PCB exposures in the Upper Hudson following the completion of the dredging program. Decreases are most notable in TIP, as evidenced by observed TPCB reductions in pumpkinseed and small forage fish. Simplified model results that were performed as part of our evaluations are consistent with observed reductions in TIP fish. Observed reductions in Tri+ PCB water column concentrations however show a smaller decline. This discrepancy needs to be investigated further, and as discussed previously, may indicate that the 2016 post-dredging Tri+ PCB concentrations in surface sediments are higher than expected or that localized resuspension of contaminated sediments is occurring in areas where the sediment bed was highly disturbed by dredging activities.

Decreases in PCB concentrations are also noted, but are less pronounced at the downstream locations (e.g., Stillwater, Waterford). This is illustrated by observed reductions of approximately a factor of two in TPCB concentrations for pumpkinseed in the Northumberland / Fort Miller and Stillwater pools, and in Tri+ PCB water column concentrations at Waterford during low flow conditions. Simplified model results for summer-time low-flow conditions are consistent with the observed reductions at the downstream locations. The model results also suggest the less contaminated sediments in RS#3 will continue serve as a net source of PCB to the water column during the post-dredging period.

In contrast to pumpkinseed results, small forage fish show little or no reductions in observed TPCB concentrations at the downstream locations. This is not an unexpected result based on the direct linkage of forage fish to localized sediments and to the limited dredging of contaminated sediments in RS#3. Further evaluations on the effect of the Upper Hudson dredging program on responses in the Lower Hudson are described below.

PCB Responses in the Lower Hudson

Water Column Monitoring

In addition to monitoring in the Upper Hudson, water column samples were collected at two far-field stations in the Lower Hudson: Albany (RM 140) and Poughkeepsie (RM 77). Fish monitoring was also performed at Albany / Troy, Catskill and Tappan Zee areas. As previously described, water samples were analyzed for whole-water PCB concentrations using the mGBP or an Aroclor PCB analytical method, and fish samples were primarily analyzed using a modification of the USEPA 8082 Aroclor Sum Method. Further details are given in EPA (2010b – SOW Attachment B).

Tri+ PCB Loads to the Lower Hudson

Tri+ PCB loads to the Lower Hudson were calculated for pre-dredging and post-dredging periods using USGS daily flow measurements at Waterford and daily Tri+ PCB concentrations that were calculated as a function of river flow (see regressions in Figure 5A). Results for 2004-2008 pre-dredging and 2016 post-dredging periods are represented by the first and second stacked bars on Figure 9. For these calculations, 13,000 cfs was used in differentiating between low flow and high flow conditions. As shown in Figure 9, the total Tri+ PCB loads passing Waterford during the 2004-2008 pre-dredging period averaged 107.7 kg/yr, with 47 percent of the total load (50.8 kg/yr) occurring during low flow and the remaining 53 percent (57.0 kg/yr) occurring during high flow conditions. For comparison, the total Tri+ PCB loads passing Waterford during the 2016 post-dredging period was estimated to be 37.0 kg/yr, with 78 percent of the total load (28.7 kg/yr) occurring during low flow and only 22 percent (8.3 kg/yr) occurring during high flow conditions.

Based on results in Figure 9, there is a 66 percent reduction in the total Tri+ PCB load for the 2016 post-dredging period (compared to the 2004-2008 pre-dredging period). This is comprised of a 43 percent reduction in the Tri+ PCB load for low flow conditions and an 86 percent reduction in the Tri+ PCB load for high flow conditions. This large reduction in Tri+ PCB loads during high flow conditions is in large part attributed to differences in river flow for the pre-dredging and post-dredging periods. During the 2004-2008 pre-dredging period, river flow at Waterford averaged 10,100 cfs and included an average of 86 days per year with flows in excess of 13,000 cfs. In comparison, the 2016 post-dredging period was characterized by lower flows with an average river flow at Waterford of 6,100 cfs and only 15 days with flows exceeding 13,000 cfs.

To demonstrate the effect of flow on Tri+ PCB load reduction, a hypothetical post-dredging scenario was considered (last stacked bar, Figure 9). In this scenario, the Tri+ PCB load was calculated using the 2004-2008 pre-dredging flow record with the post-dredging regression equations. Comparison of the pre-dredging results with the hypothetical post-dredging scenario shows that total Tri+ PCB loads would have been reduced by only 13 percent if river flows for the post-dredging period were comparable to flows during the pre-dredging period. Tri+ PCB loads for low flow conditions were approximately 27 kg/yr for both the 2016 post-dredging period and hypothetical post-dredging scenario. This indicates that year-to-year variations in river flow will have a small effect on Tri+ PCB loads during low flows. However, Tri+ PCB loads during high flows showed large differences. This result indicates that Tri+ PCB loads during high flow conditions will likely show large year-to-year variations; e.g., from 8.3 kg/yr based on the 2016 flow record to potentially more than 100 kg/yr if the river experiences another year like 2011 with three major high flow events.

Tri+ PCB Water Column Responses in the Lower Hudson

Tri+ PCB water column concentrations at Albany (RM 145) and Poughkeepsie (RM 75) are presented in Figure 10 as monthly geometric means (and geometric standard deviations) for the pre-dredging, dredging and post-dredging periods. Tri+ PCB concentrations at Albany (Figure 10A) follow trends that were previously reported for observed concentrations at Waterford (Figure 4). During the dredging period, Tri+ PCB concentrations at Albany were two to three times higher than the pre-dredging results. Post-dredging Tri+ PCB concentrations at Albany were approximately a factor of two or three times lower than pre-dredging concentrations. Finally, for the pre-dredging, dredging and post-dredging periods, Tri+ PCB concentrations at Albany were a factor of two lower than observed concentrations at Waterford (Figure 4) due to effects of dilution by the Mohawk River.

Observed trends in Tri+ PCB concentrations 70 miles downstream at Poughkeepsie (Figure 10B) were less discernible. Monthly geometric means during the dredging period were typically less than the pre-dredging concentrations. Monthly geometric means for the post-dredging period were also found to be very variable and not correlated to observed Tri+ PCB concentrations at Albany. The reasons for these discrepancies in observed Tri+ PCB water column concentrations at Albany and Poughkeepsie are believed to be related to the complexity of sediment transport in the Lower Hudson as described below.

Dynamic Responses in the Lower Hudson

The Lower Hudson is characterized as an estuary with tidal flows affecting the entire 154-mile stretch from Albany to New York City. In addition, saltwater intrusion (and density-driven flows) typically affect transport patterns in the lower 30-50 miles. About 30-35 percent of the freshwater flow into the Lower Hudson is from the Upper Hudson. Another 25-30 percent is attributable to the Mohawk River which enters the Lower Hudson at the head of tide above Albany. The remainder of the freshwater flow is associated with a number of smaller tributaries (e.g., Catskill Creek, Esopus Creek, the Wallkill River) that enter the Lower Hudson downstream of Albany.

Over a 10-year period (from 2004-2014), approximately 15 million tonnes of suspended sediment was discharged into the tidal freshwater section of the Lower Hudson above Poughkeepsie (Figure 11). A large portion of the suspended sediment load was associated with high flow events (e.g., Tropical Storms Irene and Lee in 2011). Overall, PCB-contaminated sediments from the Upper Hudson account for approximately 35 percent of the incoming suspended sediment load to the Lower Hudson.

In the tidal freshwater section of the Lower Hudson, incoming sediments are continually subject to settling and tidally-induced resuspension. This has two effects on PCB transport: First, suspended sediments (and particulate-phase PCBs) may settle and spend extended periods of time on the river bottom before they are resuspended and transported further downriver. This in effect causes particulate-phase PCBs to be transported through the Lower Hudson more slowly than the river water. Second, only about half of the incoming suspended sediment to the tidal freshwater section of the river is ultimately transported past Poughkeepsie (green dashed line versus blue solid line on Figure 11). This indicates that there is a substantial amount of PCB-contaminated sediments that will be retained in the bottom sediments above Poughkeepsie. Although sediment deposition rates in the tidal freshwater Hudson will show large spatial variations, the average net-accumulation of sediment in the tidal freshwater section of the river is expected to be on the order of 5-10 mm/yr. If we assume that the top 5-10 cm of surficial sediment is relatively well mixed by physical processes and bioturbation, a decade or more would be required to bury recently-deposited sediments below the surficial sediment layer. In addition to tidal effects, trapping of contaminated sediments along the river bottom is further complicated in the downriver section by density-induced (or estuarine) circulation which causes a net movement of bottom waters in the landward direction and enhanced trapping of contaminated sediment.

A more detailed picture of sediment transport in the Lower Hudson is provided by sediment transport modeling results for three moderate high flow events during an 80-day period corresponding to the 2014 spring freshet (Figure 12). Figure 12(a) shows the flow record at Green Island (which includes the flow contributions from both the Upper Hudson and Mohawk Rivers). The tidal signal at the Battery in New York City is also included in the figure. Model results for cross-sectional averaged suspended sediment concentrations from river inputs are presented as a color contour plot in Figure 12(b). In this panel, distance along the Lower Hudson from Albany (Km 250) to the Battery in New York City (Km 0) is plotted on the y-axis and time is plotted along the x-axis. The three gray dashed lines on the figure indicate the travel time of water along the river for the three high flow events. On average, the river water during the high-flow events takes several days to reach Poughkeepsie (Km 125) and 10-20 days to reach the Battery in New York City, and much longer during low-flow periods. In comparison, the incoming sediment mass takes three to ten or more times longer to reach the Battery, depending on the sediment settling velocity. As the incoming suspended sediments are transported downriver, the sediment signal becomes more dispersed and a large portion of the sediment mass is deposited along the river bed (Figure 12(c)). The net deposition of new sediment along the river bed is presented in Figure 12(c) as the total sediment mass (suspended + bed) at the end of the model period (blue line) and as the normalized cumulative mass distribution of new sediment from the Battery to the Troy lock and dam (gray line). During the simulated period, approximately 65 percent of the incoming suspended sediment was deposited above Poughkeepsie and the remaining 35 percent was deposited further downriver.

The effect of sediment dynamics on PCB transport in the Lower Hudson has been examined in previous modeling studies (Farley et al. 1999, 2006). The continuous interaction of the overlying water with sediments (through setting, resuspension, and pore water exchange) and the large capacity of the sediments to sorb PCBs work together to dampen the PCB responses downstream and to greatly extend PCB response times to changes in Upper Hudson PCB loads. This finding was supported by model simulations that were performed as part of the Contamination Assessment Reduction Project (CARP) (HydroQual 2008). Based on these studies, we expect that it would take a decade or more to see appreciable changes in PCB concentrations at many locations in the Lower Hudson.

Summary of Lower Hudson Finding

Our evaluations of PCB responses in the Lower Hudson River show that the 66 percent reduction in Tri+ PCB loads for the post-dredging period was in large part the result of low river flows during 2016. Higher Tri+ PCB loads to the Lower Hudson are therefore likely to occur if the river experiences moderate or high flows over the next few years. Under these conditions, reductions in Tri+ PCB loads to the Lower Hudson are more likely to be in the range of 15-35 percent (compared to the pre-dredging period).

With the exception of very low flow years, Tri+ PCB loads to the Lower Hudson are expected to be dominated by particulate-phase transport of PCBs during high flow. PCB responses will therefore strongly depend on suspended sediment loads and sediment transport processes in the Lower Hudson. Our work in this area indicates that a large portion of the suspended sediment (and particulate-phase PCBs) that is discharged into the Lower Hudson will be deposited along the river bottom. Because of physical and biological processes, the newly-deposited sediment will mix with the top 5-10 cm of bottom sediment. Tri+ PCB concentrations in surficial sediments of the Lower Hudson are therefore expected to reflect an average of the past 5-10 years of incoming PCB loads. Bottom sediments at Poughkeepsie and locations further downriver are therefore expected to show delayed responses to annual changes in Tri+ PCB loads. Since Tri+ PCB concentrations in the overlying water are expected to be largely controlled by tidally-induced resuspension of localized sediments, similar delayed responses are expected for Tri+ PCB water column concentrations.

Moving Forward

Results from our evaluations indicate that the Upper Hudson dredging program has been most effective in reducing PCB exposure levels in TIP, where 53 percent of the river bottom was targeted for dredging. PCB reductions in TIP were most noticeable for pumpkinseed and small forage fish, which showed a factor of three to six decrease from the 2004-2008 pre-dredging period to the 2016 post-dredging period. Smaller reductions (by approximately a factor of two) in the 2016 post-dredging monitoring data were observed further downstream toward Waterford for Tri+ PCB water column concentrations and TPCB concentrations in pumpkinseed. However, little or no reductions were observed for TPCBs in small forage fish at the downstream locations. This latter finding reflects the linkage of TPCB concentrations in forage fish to localized sediment contamination levels and the limited areas that were targeted for dredging between Schuylerville and Waterford. Finally, PCB responses in the Lower Hudson (e.g., at Poughkeepsie) did not exhibit any clear trends, and as described previously, appear to be responding very slowly to changes in PCB inputs from the Upper Hudson.

Based on 2016 post-dredging monitoring, TPCB concentrations in fish throughout the Upper and Lower Hudson remain above interim target levels and remediation goal specified in the ROD (EPA 2002). As described in the ROD (EPA 2002), additional years of MNA will be required to meet TPCB target levels and remediation goals for fish. Post-dredging monitoring is therefore expected to continue into the foreseeable future to determine if MNA will be effective in reducing PCB concentrations to acceptable levels or if additional remedial action will be required. Current monitoring plans for the water column and fish in the Upper Hudson are described in EPA (2010b). Additional information on sediment sampling is provided in GE (2016b). The basic elements of the current monitoring plan include:

- Water Monitoring: Weekly sampling of the water column at four far-field monitoring stations in the Upper Hudson, and monthly collection of water column samples at Albany and Poughkeepsie in the Lower Hudson. Whole water samples are to be analyzed using the mGBP method (with a subset of samples analyzed using EPA Method 1668).
- Sediment Monitoring: Collection of surface sediment samples in the dredged and non-dredged areas of the Upper Hudson every three years. For 2016-2017 sediment survey, 226 samples are being collected and will be analyzed for PCBs (using Aroclor PCB Method GEHR9082) and TOC (using the Lloyd Kahn Method). At this time, there are currently no plans for sampling sediments in the Lower Hudson.
- Fish Monitoring: Annual collections of a variety of fish species at a number of sampling locations in TIP, Northumberland / Fort Miller Pools and Stillwater Pool. Fish samples will also be collected in the Lower Hudson once every two years at Albany, Catskill and Tappan Zee. TPCB concentrations for whole body and fish fillets will be analyzed using a modification of USEPA 8082 Aroclor Sum Method (with a subset of samples analyzed using the mGBP Method).

Although current monitoring plan provide a reasonable framework for assessing the effectiveness of the Upper Hudson PCB dredging program, we recommend the following modifications be incorporated into the plan to enhance the overall utility of the water column, sediment and fish monitoring data. Recommendations for complementary modeling studies are also provided.

Water Monitoring

- EPA Method 1668 (a high resolution, congener-based method) should be used in analyzing PCB water column concentrations in the Upper and Lower Hudson. EPA Method 1668 will provide a more reliable and reproducible measure of TPCB and Tri+ PCB water column concentrations, particularly as PCB concentrations decrease in time. In addition, EPA Method 1668 will provide a more accurate measure of PCB congener concentrations that can be used in supporting congener fingerprinting analyses and more detailed model evaluations. Finally, PCB analyses using EPA Method 1668 will be back compatible with previous PCB analyses for the Lower Hudson that were conducted as part of the Contamination Assessment Reduction Project (CARP).

- Since a large portion of the Tri+ PCB load to the Lower Hudson is likely to be associated with particulate-phase PCB transport, the USGS suspended sediment monitoring should be re-instated at Waterford. This information is critical in efforts to quantify sediment loads and particulate-phase PCB loads to the Lower Hudson.
- To date only a limited number of post-dredging water column samples have been collected at Waterford during high flows. Additional high flow sampling at Waterford is needed to support evaluations of PCB loads to the Lower Hudson during high flows.
- In the Lower Hudson, PCB water column concentrations are likely to be controlled by tidally-induced resuspension of localized sediments. PCB concentrations in whole water samples are therefore expected to vary over the tidal cycle and from one tidal cycle to the next. Water samples for the Lower Hudson stations should be analyzed for dissolved and particulate concentrations to distinguish effects of tidal resuspension of bottom sediment.

Sediment Monitoring

- Analysis of 2016-2017 surface sediment samples should provide a useful "post-dredging" baseline of Tri+ PCB concentrations in surface sediments. However, analysis of the surface sediment samples by EPA Method 1668 would provide more accurate and reliable measure of Tri+ PCB concentrations, especially since PCB congener patterns are likely to change during the post-dredging period. In addition, more accurate PCB congener-based sediment data could be used in congener finger-printing and other model evaluations.
- Sediments will play a major role in determining PCB exposure concentrations and response times for the Lower Hudson. PCB concentrations in sediment should also be monitored in the Lower Hudson. This should include the collection of surface sediments at selected locations in the tidal freshwater and estuarine reaches of the Lower Hudson. Sediment cores should also be collected and used in developing sediment core chronologies at select locations. This information will be critical in documenting time responses in PCB contamination levels in the Lower Hudson.

Fish Monitoring

- A special study that was conducted to evaluate the potential effects of sample preparation on TPCB measurements showed a surprisingly large analytical variation for paired fillet samples. The observed variations in paired samples is attributed to differences in sample preparation and potential inaccuracies in quantifying TPCB concentrations based on Aroclor identification. Efforts should therefore be continued to ensure consistency in fish sample preparations (including fillet preparation). In addition, EPA Method 1668 should be used in place of the less accurate Aroclor Method in analyzing PCB concentrations in Upper and Lower Hudson fish.

- Intra-species variability in fish populations can result in large variations in TPCB concentrations in fish. Increasing the number of fish samples should therefore be considered to ensure that the fish results provide the required statistical power for evaluating not only the attainment of interim targets and the remediation goal, but also changes or trends in TPCB concentrations in fish over time.

Modeling

Even the most elaborate monitoring program can only provide snapshots of PCB contamination levels in a system as complex as the Hudson. We therefore strongly recommend the following congener fingerprinting analyses and model evaluations.

- Congener fingerprinting analyses of the water, sediment and fish data should be performed to help identify temporal changes in PCB sources (e.g., background, GE plant site, TIP sediments, downriver sediments) during the post-dredging period.
- Simple and complex models should be used to assist in interpreting Tri+ PCB, PCB homolog and/or PCB congener monitoring results for the Upper Hudson. For example, model results should be used in evaluating the relative importance of diffusive exchange in controlling losses of PCBs from surface sediments and to investigate the potential of PCB migration from deeper sediments.
- Model evaluations should be used to help track year-to-year changes in PCB inventory in Upper Hudson sediments and to update projections for PCB concentrations in fish during the post-dredging recovery period.
- Finally, model evaluations should be performed for the Lower Hudson to further our understanding and update projections of PCB time responses in the tidal freshwater and estuarine sections of the river.

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Table 1. Summary of Remedial Alternatives Considered in Model Projections for the 2002 Record of Decision (EPA 2002)

Remedial Alternative	**Description**	**Sediment Remediation Criteria**[(1)]	**Implementation Period**[(2)]
No Action	Relies solely on natural attenuation processes (e.g., burial by cleaner sediments, biodegradation, bioturbation and dilution) to reduce PCB concentrations in sediments and surface water.		
Monitored Natural Attenuation (MNA), with Upstream Source Control[(3)]	Natural attenuation processes with a separate source control action near the GE Hudson Falls plant.		
CAP-3/10/Select[(4)]	Capping (after removal of 1.73 MCY of sediment to allow for cap placement). A layer of fill material would be placed on top of the cap to limit scour.	3 g m^{-2} in RS #1 10 g m^{-2} in RS #2 Select areas in RS #3	6 years followed by MNA
REM-3/10/Select[(4,5)]	Removal of 2.65 MCY of sediment. Dredged areas would be covered by a layer of fill material.	3 g m^{-2} in RS #1 10 g m^{-2} in RS #2 Select areas in RS #3	6 years followed by MNA
REM-0/0/3[(4)]	Removal of 3.82 MCY of sediment. Dredged areas would be covered by a layer of fill material.	0 g m^{-2} in RS #1 0 g m^{-2} in RS #2 3 g m^{-2} in RS #2	8 years followed by MNA

[(1)] Sediment remediation criteria are expressed on a mass per unit area basis; i.e., the total mass inventory of PCBs underlying a square meter of surface sediment.
[(2)] For model projections, the implementation period for the active remediation alternatives was assumed to commence in 2004.
[(3)] For model projections with Upstream Source Control, Tri+ PCB load upstream of Thompson Island Pool is considered to be reduced from 0.16 kg/day to 0.0256 kg/day by January 1, 2005.
[(4)] The three active remedies (CAP-3/10/Select, REM-3/10/Select, REM-0/0/3) all include Upstream Source Control.
[(5)] For REM-3/10/Select model projections, Tri+ PCB releases during dredging were assumed to be equal to 0.13% of the total Tri+ PCBs removed from the river bottom. Tri+ PCB releases during dredging were not considered in model projections for CAP-3/10/Select and REM-0/0/3 based on sensitivity model runs for REM-3/3/Select which showed little or no difference in projected Tri+ PCB concentrations in fish for assumed Tri+ PCB releases of 0, 0.13% and 2.5% of the total Tri+ PCBs removed from the river bottom.

Table 2. Summary of Proposed Remedy for the Upper Hudson (REM-3/10/Select) [1]

	River Sect. #1	River Sect. #2	River Sect. #3	Total
Section length (miles)	6.3	5.1	29.5	40.9
Total Area (acres)	528	463	3,360	4,351
Tri+ PCB sediment remediation criteria (mass per unit area, concentration in top 12 inches) [2]	3 g m^{-2} 10 mg kg^{-1}	10 g m^{-2} 30 mg kg^{-1}	10 g m^{-2} 30 mg kg^{-1}	
Area remediated (acres, percent of total)	282 (53%)	76 (16%)	135 (4%)	493
Volume sediment removed (MCY)	1.56	0.58	0.51	2.65
Total PCB mass removed (kg) [3]	36,000	24,300	9,500	69,800
Average Tri+ PCB surface (0-2 inch) sediment concentration: before / after dredging (mg kg^{-1}) [4]	14.2 / 1.9	11 / 7.1	3.3 / 3.1	
Expected time to reach 0.4 / 0.2 / 0.05 mg kg^{-1} Tri+ PCBs in fish fillets (years after dredging is complete)	5 / 16 / > 70	5 / 16 / > 70	5 / 16 / 43	

(1) Values as reported in the 2002 ROD (EPA 2002) except where noted.

(2) Target sediment remediation criteria, as initially specified in the 2002 ROD, were subsequently modified to include a MPA of 10 g/m^2 Tri+ PCBs for RS#3 and a Tri+ PCB concentration criteria for the top 12 inches of sediment (EPA 2004a). Other factors such as sediment texture, depth and bathymetry were also considered in delineating dredging areas.

(3) PCB mass removals were reported in the 2002 ROD (EPA 2002) in terms of Total PCBs (and not Tri+ PCBs).

(4) Average Tri+ PCB concentrations (before dredging) were based on the Sediment Sampling and Analysis Program (SSAP) that was conducted in 2002-2005 during the remedial design phase. Average Tri+ PCB concentrations (after dredging) were estimated based on expected post-dredging concentrations of 0.25 mg kg^{-1} Tri+ PCBs in surface sediment. See EPA (2012) for details.

Table 3. Performance Summary for the Upper Hudson Dredging Program[1]

	Year	Dredged Season	Dredged Sediment (MCY)	Total PCBs Removed (kg)	Tri+ PCBs Removed (kg)	Tri+ PCBs Released Past Waterford	Tri+ PCBs Released Past Waterford (%)
Phase 1	2009	May 15 – Oct 27	0.296	18,230	5,350	71.3	1.3
	2010						
Phase 2-1	2011	Jun 6 – Nov 8	0.363	27,200	9,070	29.8	0.33
Phase 2-2	2012	May 9 – Nov 16	0.663	33,370	10,080	30.6	0.30
Phase 2-3	2013	Apr 29 – Nov 5	0.628	32,460	9,275	99.3	1.07
Phase 2-4	2014	May 7 – Nov 4	0.583	26,570	8,915	39.8	0.45
Phase 2-5	2015	May 7 – Oct 3	0.230	8.185	2,991	44.7	1.49
Total			2.764	146,000	45,680	316	0.69

[1] Values as reported in GE (2016a).

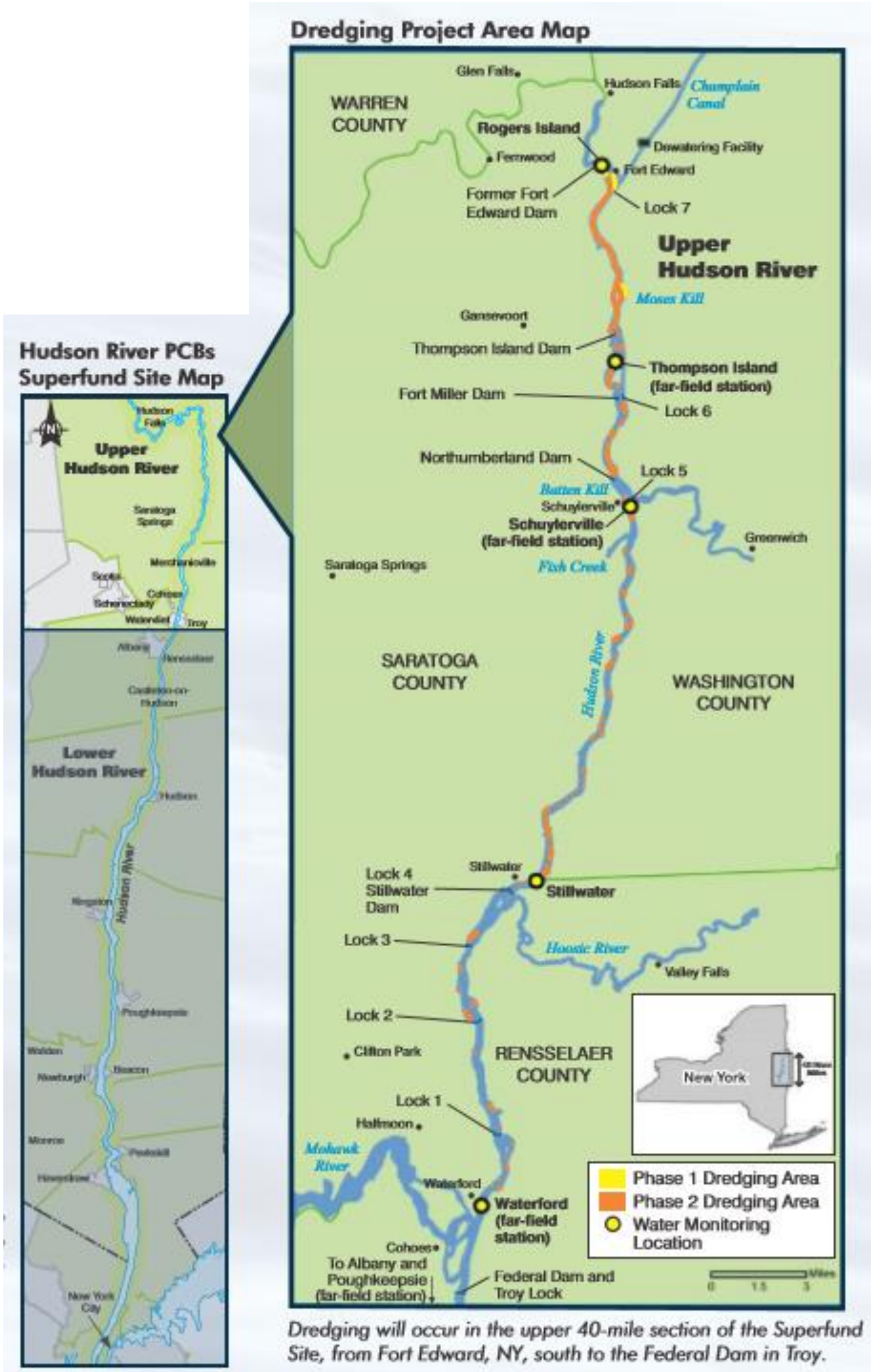


Figure 1. The Hudson River PCB Superfund Site extending from Hudson Falls, NY to the Battery in New York City. The Federal Dam at Troy is the designated boundary between the Upper Hudson and Lower Hudson. From EPA (2011).

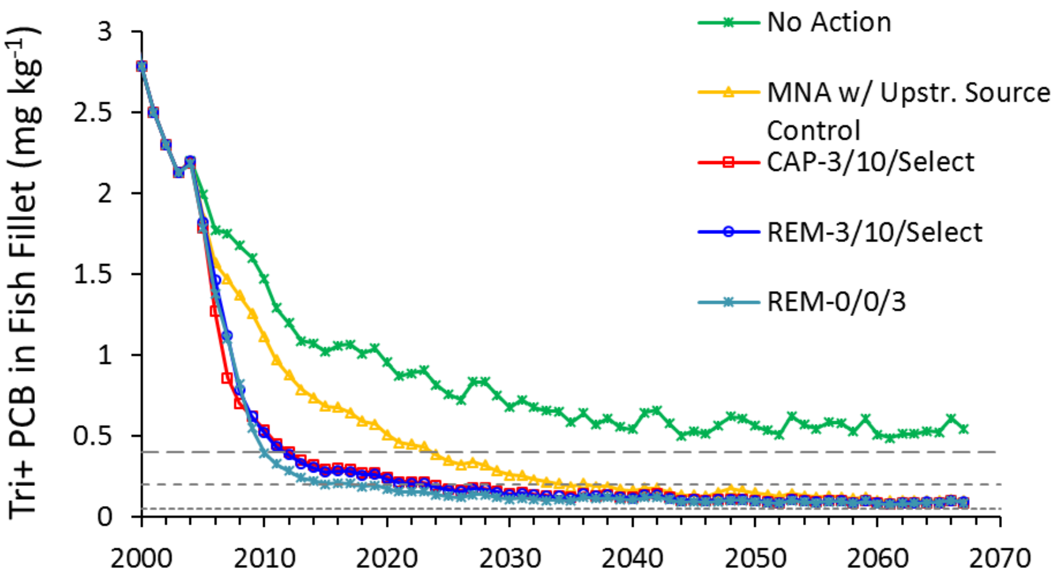


Figure 2. Model projections for Tri+ PCB concentrations in fish fillets from the Upper Hudson. Model results are expressed in terms of a species-weighted diet (36% brown bullhead, 6% carp, 2% eel, 38% bass, 9 % walleye, 9% perch) with river section averages weighted by river section length (15.4% for RS #1, 12.5% for RS #2, 72.1% for RS #3). The three dashed gray lines correspond to the interim targets of 0.4 mg/kg-wet weight and 0.2 mg/kg-wet weight, and Tri+ PCB remediation goal of 0.05 mg/kg-wet weight for protection of human health. Model projection from Table 11-2 (EPA, 2002).

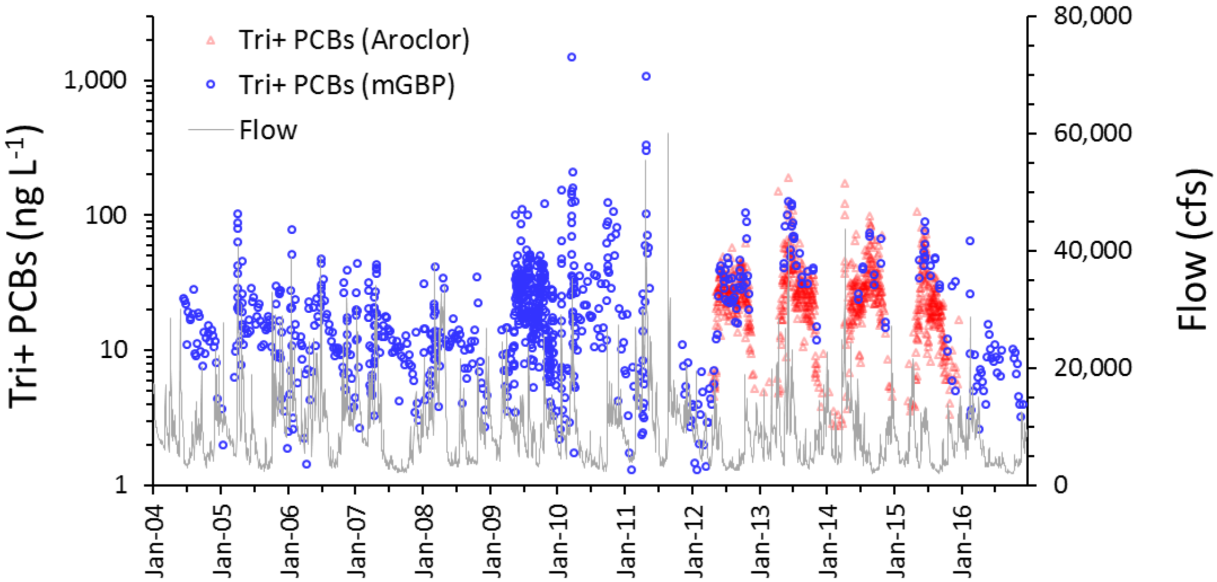


Figure 3. Tri+ PCB whole water concentrations at Waterford for pre-dredging (2004-08), Phase 1 dredging (2009), Phase 1 evaluation (2010), Phase 2 dredging (2011-15) and post-dredging (2016) periods. Tri+ PCBs analyses were determined using a modified Green Bay Peak Congener method (mGBP) with non-detectable peaks set equal to zero or were estimated from PCB Aroclor measurements (Aroclor). Daily flow measurements at Waterford are included for comparative purposes.

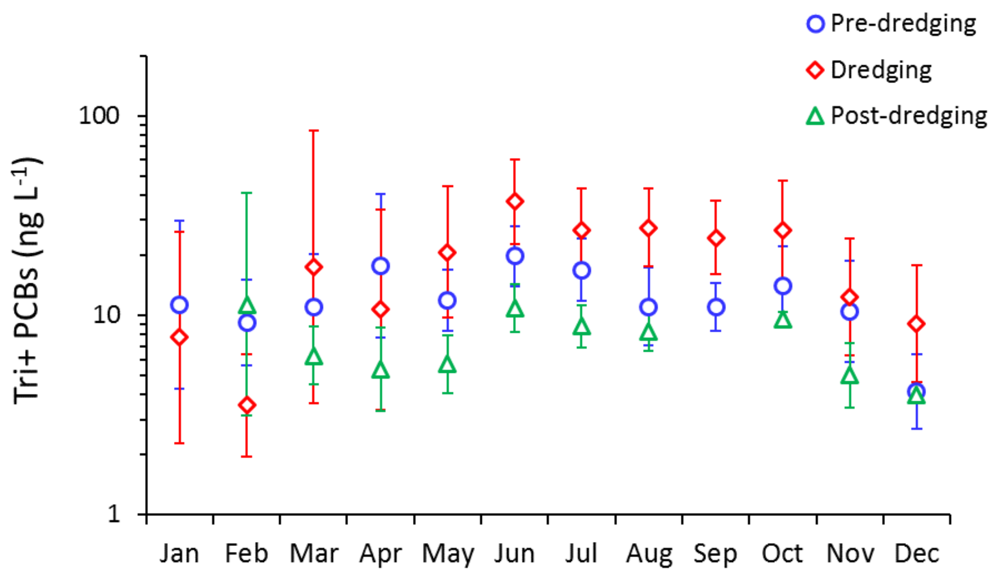


Figure 4. Monthly geometric means (and geometric standard deviations) for Tri+ PCB water column concentrations at Waterford. Whole water concentrations were determined using either the modified Green Bay Peak (mGBP) or an Aroclor PCB analytical methods. Pre-dredging period is based on 2004-2008 measurements; Dredging period is based on 2009-2015 measurements and includes the Phase 1, Phase 1 evaluation and Phase 2 dredging years; Post-dredging period is based on 2016 measurements.

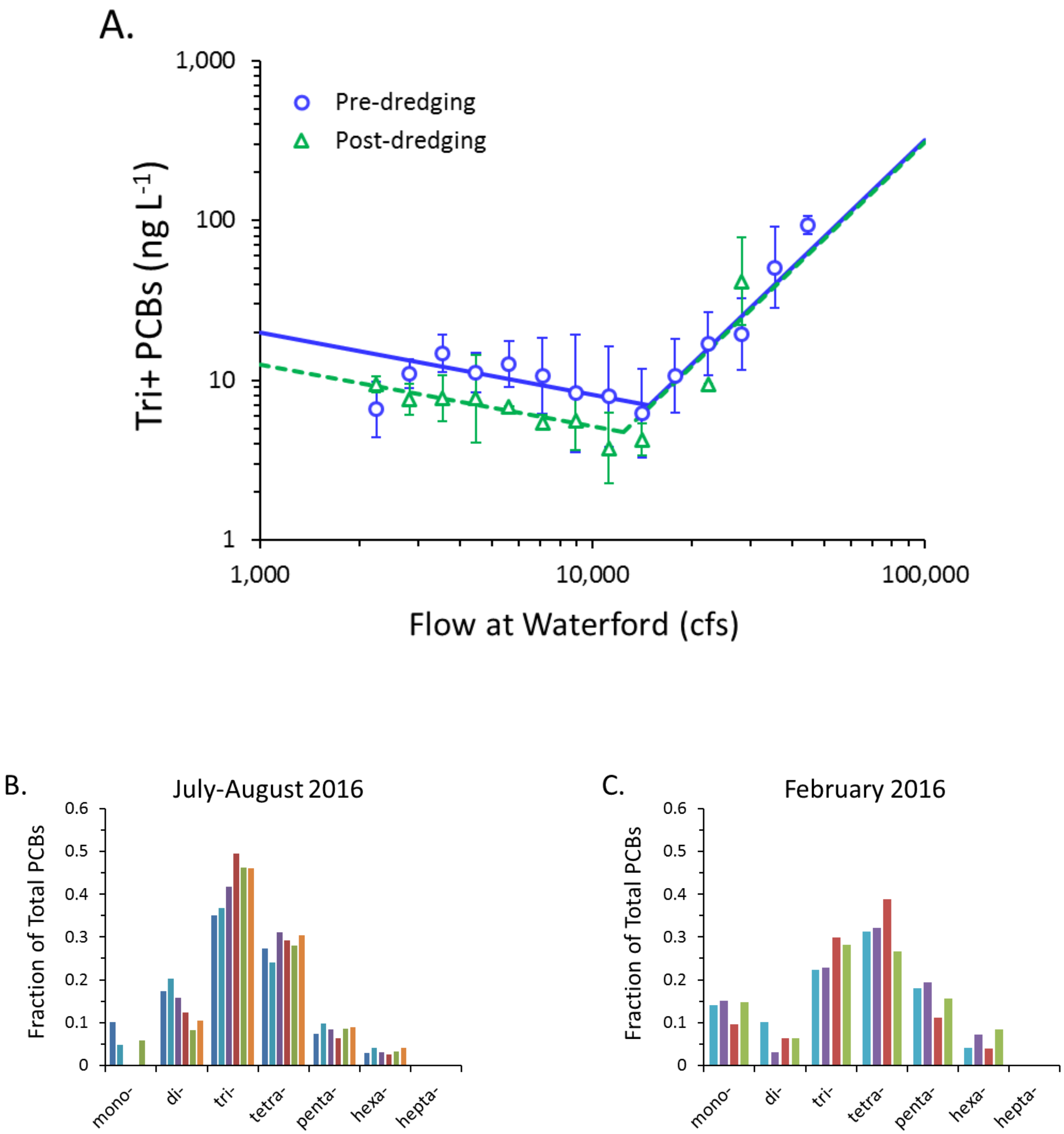


Figure 5. Tri+ PCB water column responses at Waterford. (A) Tri+ PCB concentrations versus flow. Pre-dredging (open blue circles) and post-dredging (open green triangles) are represented as geometric means (with geometric standard deviations) for selected flow bins. The corresponding regression equations are given by the solid blue lines and the dashed green lines for non-flood and flood flow conditions. (B) PCB homolog distributions for six water column samples (color bars) collected during 2016 July-August low flows (< 13,000 cfs). (C) PCB homolog distributions for four water column samples (color bars) collected during 2016 February high flows (> 13,000).

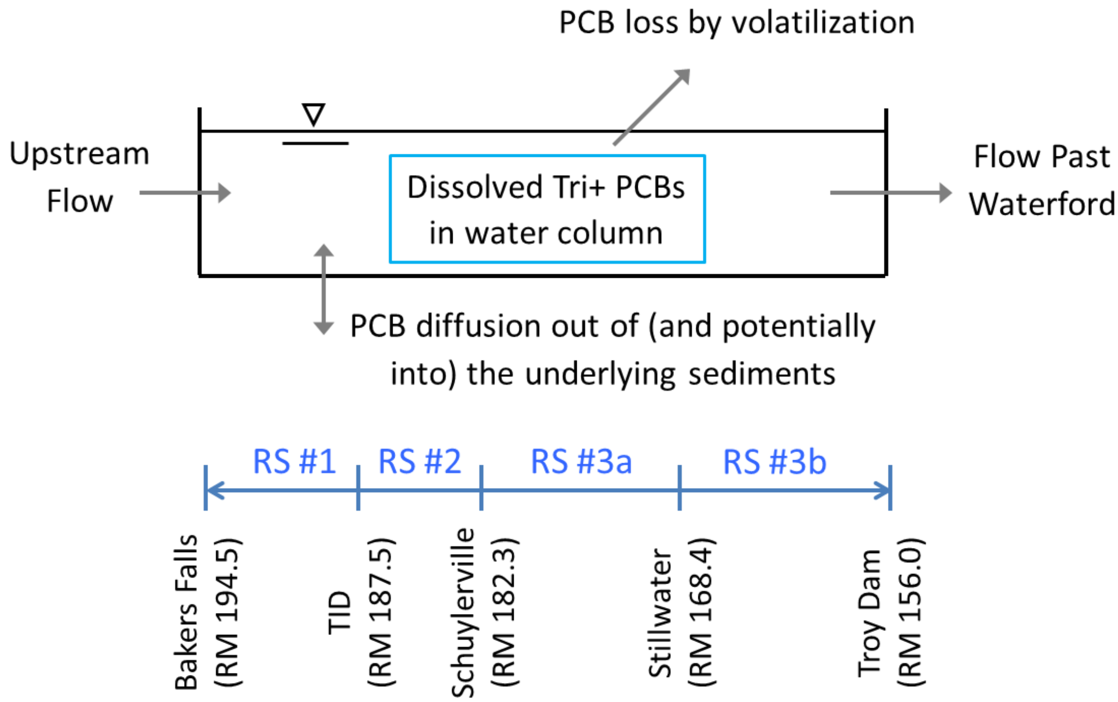


Figure 6. Simplified model for Tri+ PCB transport through the Upper Hudson during summer-time conditions. The model represents the Upper Hudson as four consecutive "plug flow" river reaches and includes the effects of flow, water inflows, PCB diffusion out of (and potentially into) the contaminated sediments, and PCB volatilization.

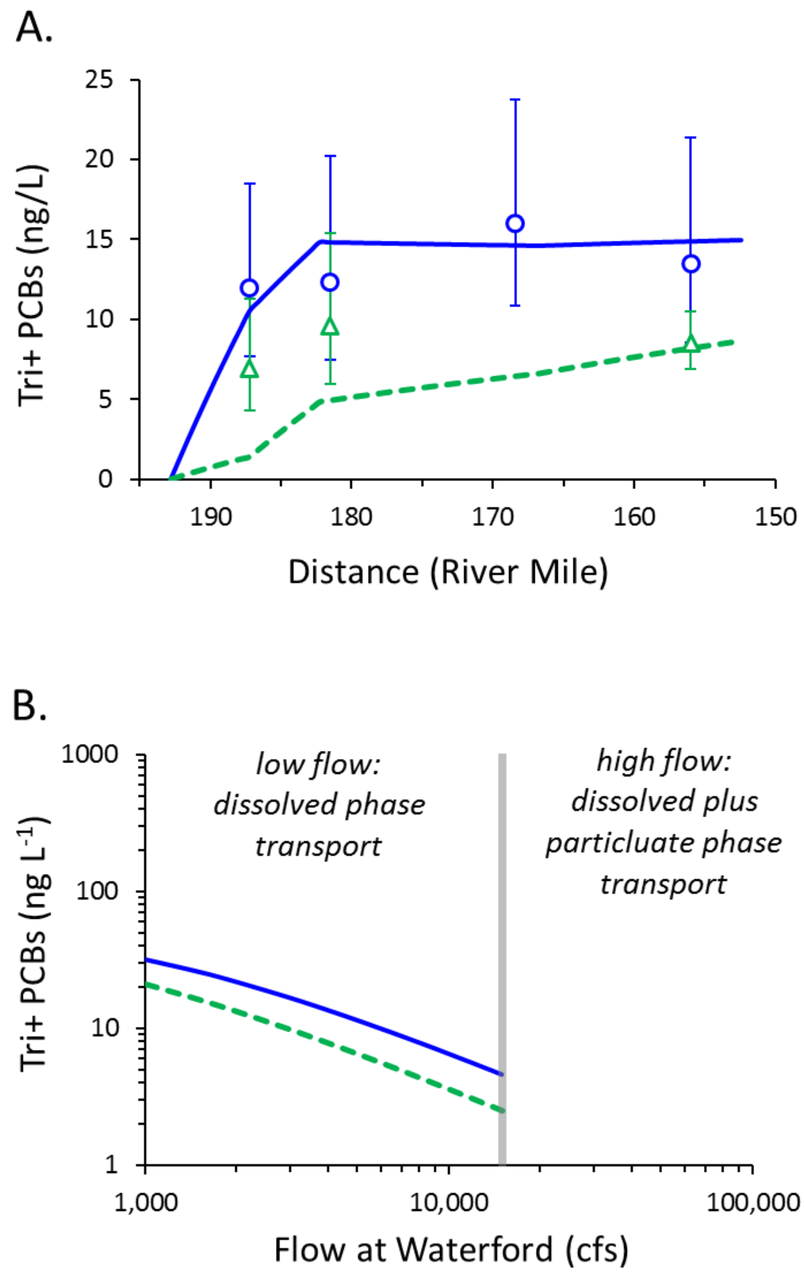


Figure 7. Simplified model results for (A) Tri+ PCB water column concentrations versus River Mile for a summer-time low flow of 3,500 cfs, and (B) Tri+ PCB water column concentrations at Waterford versus flow. Pre-dredging and post-dredging model results are given by the blue solid line and green dashed lines, respectively. For comparison, geometric means (and geometric standard deviations) for Tri+ PCBs for summer-time low flows between 2,500 – 4,500 cfs are included on panel A as blue circles and green triangles for Thompson Island Dam (RM 187.5), Schuylerville (RM 182.3), Stillwater (RM 168.4) and Waterford (RM 156.0).

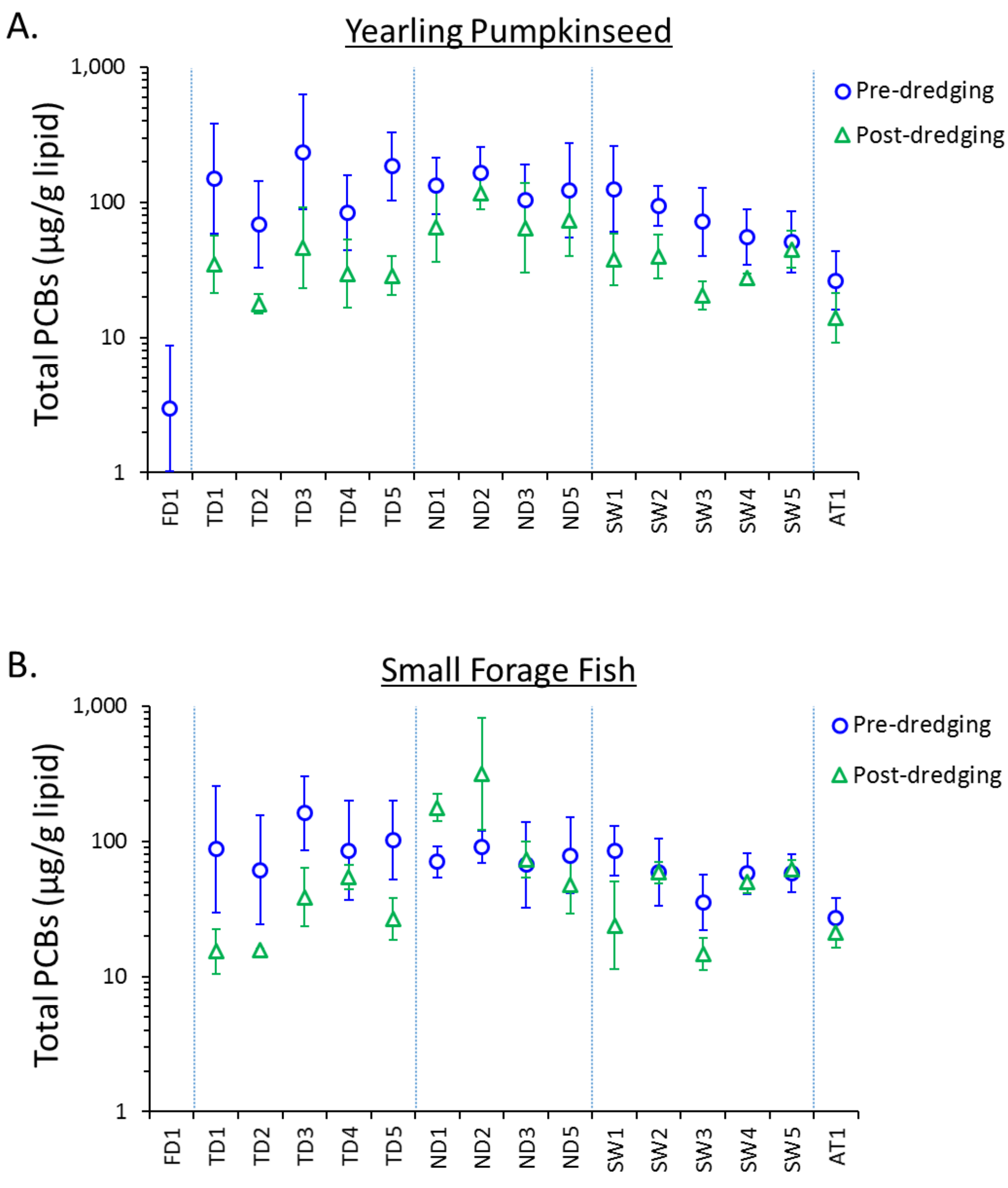


Figure 8. Lipid-normalized PCB concentrations in (A) yearling pumpkinseed and (B) small forage fish for samples pools upstream of the GE plants (FD1), in Thompson Island (TD1-5) in RS#1, Northumberland (ND1-5) in RS#2, Stillwater (SW1-5) in RS#3, and in the Albany Turning Basin (AT1). Observed concentrations are presented as geometric means (and geometric standard deviations) for pre-dredging (2004-2008) and post-dredging (2016) periods. Data provided by Kevin Farrar (NYS DEC).

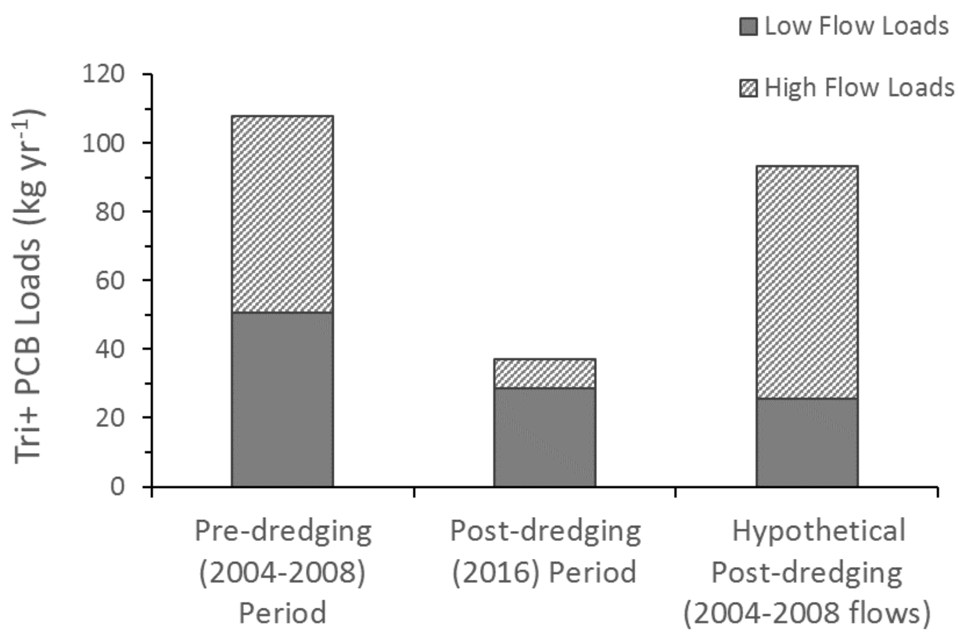
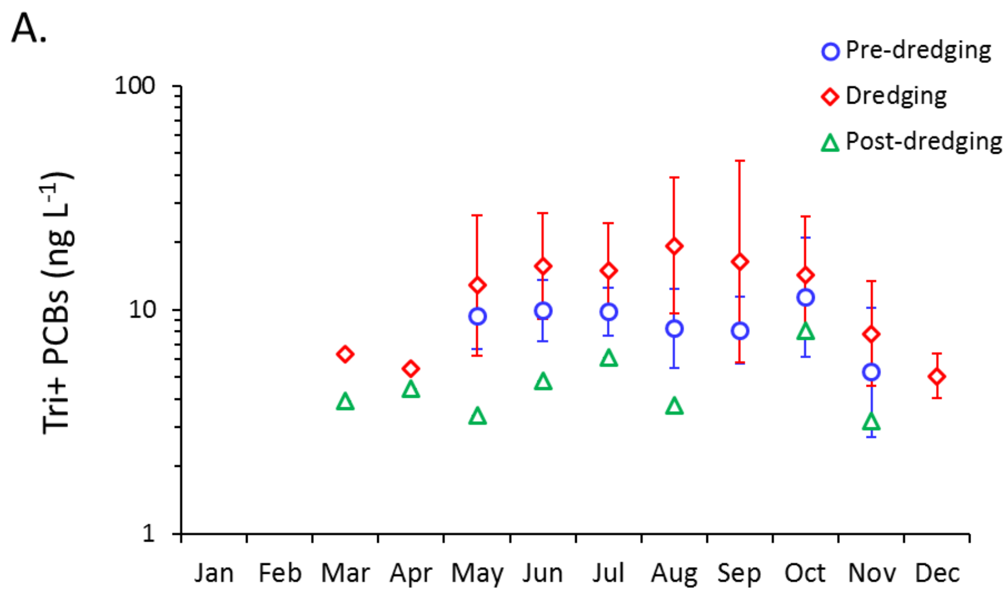


Figure 9. Estimated Tri+ PCB loads to the Lower Hudson for the 2004-2008 pre-dredging period, the 2016 post-dredging period and a hypothetical post-dredging period based on 2004-2008 flow record. Results are presented as stacked bars for low-flow (< 13,000 cfs) and high-flow (> 13,000 cfs) loads.



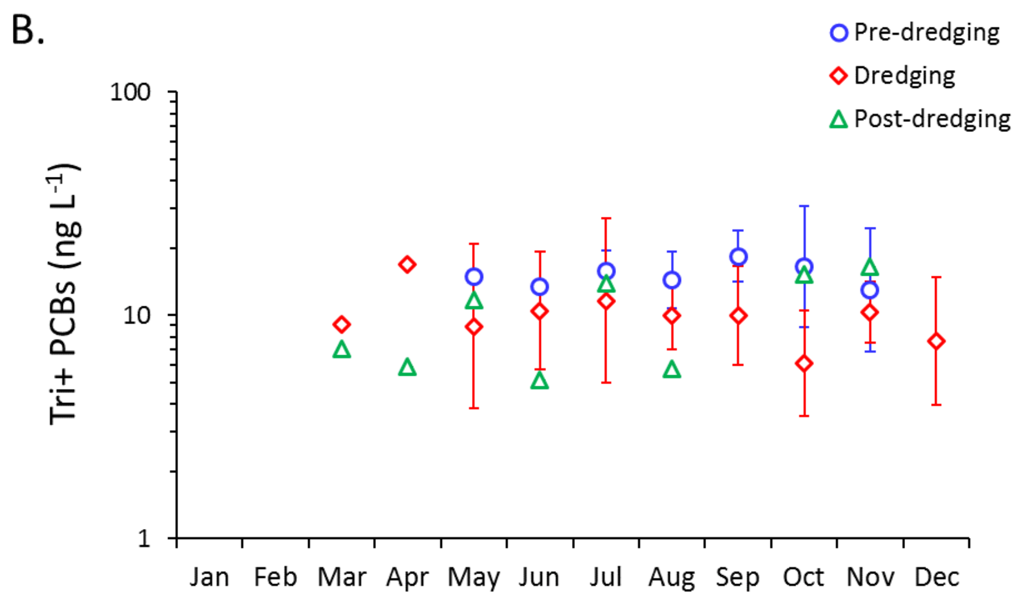


Figure 10. Monthly geometric means (and geometric standard deviations) for Tri+ PCB water column concentrations at (A) Albany (RM 145) and (B) Poughkeepsie (RM 75). Whole water concentrations were determined using either the modified Green Bay Peak (mGBP) or an Aroclor PCB analytical methods. Pre-dredging period is based on 2004-2008 measurements; Dredging period is based on 2009-2015 measurements and includes the Phase 1, Phase 1 evaluation and Phase 2 dredging years; Post-dredging period is based on 2016 measurements.

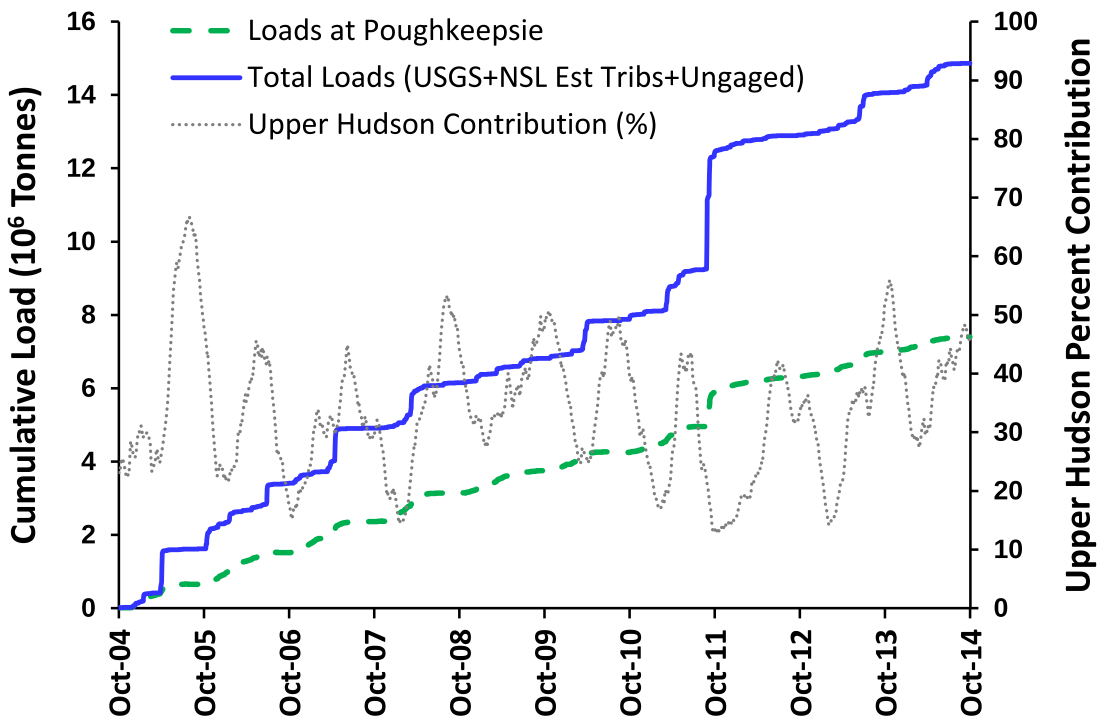


Figure 11. Record of Sediment Loads to the Tidal Freshwater Section of the Hudson River. The solid line represents the cumulative suspended sediment load entering the tidal freshwater Hudson (above Poughkeepsie). The cumulative suspended sediment load was obtained using observed USGS monitoring data, with the modified Normalized Sediment Load (mNSL) function used to fill in missing information for gaged and ungaged portions of the watershed (see da Luz et al. in prep.). The dotted line represents cumulative sediment loads passing Poughkeepsie. Dashed gray line represents the 90-day rolling average of percentage of daily total suspended sediment load attributed to the Upper Hudson. From da Luz et al. (in prep).

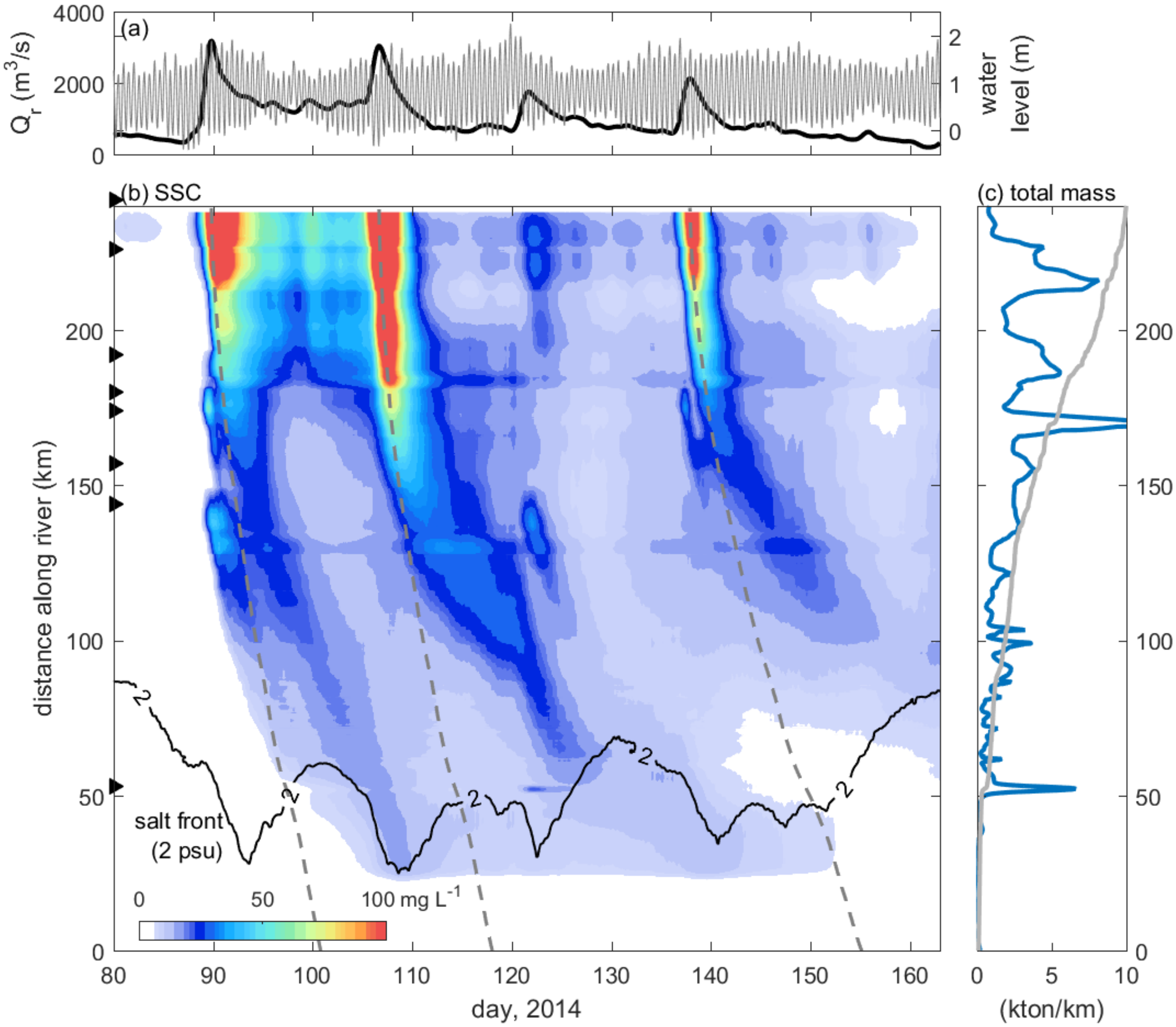


Figure 12. Sediment transport model results for the Lower Hudson from Troy lock and dam (Km 250) to the Battery in New York City (Km 0). (a) River discharge at Green Island with three high flow events during the 80-day simulation period corresponding to day 80 through day 160 in 2014. (b) Cross-sectional averaged suspended sediment concentrations from river inputs as a function of distance along the river and time. Location of tributary inputs are marked with triangles on the y-axis. The rate of water advection associated with the three high flow events is marked by the gray dashed lines. The 2-psu isohaline of bottom salinity is marked in black. (c) Total sediment mass (suspended + bed) at the end of the model period. Gray line is the cumulative mass distribution from the Battery to the Troy lock and dam normalized by the total mass. From Ralston and Geyer (submitted).

An Independent Evaluation of the PCB Dredging Program on the Upper Hudson and Lower Hudson River

Supplemental Information

1. Development of Regression Equations for Tri+ PCB Water Column Concentrations at Waterford as a Function of River Flow
2. Estimation of Tri+ PCB Loads Passing Waterford and Entering the Lower Hudson
3. A Simplified Mass Balance Model to Investigate the Linkage between Sediment Concentrations and Water Column Responses during Summer-time, Low-flow Conditions

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1. Development of Regression Equations for Tri+ PCB Water Column Concentrations at Waterford as a Function of River Flow

Methods

Tri+ PCB concentrations at Waterford were evaluated as a function of river flow using approaches that have previously been applied in examining the effects of flow of suspended sediment load (Ralston and Geyer 2009; da Luz et al. in prep.). In these approaches, suspended sediment loads (in kg/day) are related to river flow using separate log-log regression equations for low flow (non-flood) and high flow (flood) conditions. A similar approach is used here in relating suspended sediment concentration (in mg/L), and subsequently, Tri+ PCB water column concentrations (in ng/L) to river flow.

For suspended sediment, regression equations were developed using paired observations of daily-averaged suspended sediment concentrations and river flow that were collected at Waterford for the 2004-2008 pre-dredging period by the New York U.S. Geologic Survey (NY-USGS) [see Wall et al. (2008) for details]. The paired observations were fit using separate regressions lines for non-flood and flood conditions:

Non-flood conditions: $$\log C = \log a_1 + b_1 \log Q \quad \text{(Eq. S-1)}$$

Flood conditions: $$\log C = \log a_2 + b_2 \log Q \quad \text{(Eq. S-2)}$$

where log a and b represent the intercept and slope of the regression lines. Determination of the delineation for the non-flood and flood conditions (i.e., the break point, BP), log a_1, b_1 and b_2 values was accomplished by minimizing the sum of the squares about the regression lines for the non-flood and flood conditions using Solver in Microsoft Excel. In fitting the regression equations, the intercept of the regression equation for the flood condition (log a_2) was fixed and was set at:

$$\log a_2 = \log a_1 + (b_1 - b_2) \cdot \log BP \quad \text{(Eq. S-3)}$$

to ensure that the regression equation for flood conditions matched the regression equation for non-flood conditions at the break point. Variations of the suspended sediment concentrations about the regression lines were assumed to be normally distributed (in log space) and were quantified by the standard deviation of the residuals of the log suspended sediment concentrations ($S_{\log C}$) across the entire range of flows.

For Tri+ PCB water column concentrations, regression equations were developed using paired observations for Tri+ PCB water column concentrations at Waterford and USGS daily flows. The paired observations were again fit to the regression equations (Eqs. S-1 and S-2). The method followed the approach described above for suspended sediment with one exception. Since Tri+ PCB water column concentrations are expected to be dominated by particulate phase PCBs for the high flow (flood) conditions, the slope of the regression for flood conditions (b_2) was fixed and set equal the b_2 value that was determined for the suspended sediment – flow regression. Because of the large number of observations (particularly for suspended sediment concentrations), suspended sediment concentrations and Tri+ PCB concentrations were binned according to ranges of river flow for graphical presentations.

Results

Regressions for suspended sediment – flow regressions during non-flood and flood conditions are presented graphically in Figure S-1A. The corresponding regression coefficients are given in Table S-1. As shown in Figure S-1A, the suspended sediment concentrations increase slightly as a function of flow up to 10,400 cfs. At higher flows, there is a more substantial increase in suspended sediment concentrations with flow. This finding is consistent with previously reported for the Upper Hudson and for many other rivers, and is attributed to increased erosion of the bottom sediment during periods of high flow (Ralston and Geyer 2009; da Luz et al. in prep.)

Similar results for the Tri+ PCB – flow regressions are presented graphically in Figure S-1B for both 2004-2008 pre-dredging period and the 2016 post-dredging period. See Table S-1 for the corresponding regression coefficients. As shown in Figure S-1B, Tri+ PCB concentrations decrease as a function of flow up to approximately 13,000-15,000 cfs. These results do not align with the suspended sediment – flow regression and suggest that Tri+ PCB water column concentrations are associated with dissolved (and not particulate) phase PCBs. Tri+ PCB water column concentrations also appear to be primarily associated with dissolved phase PCB up to 13,000-15,000 cfs. At higher flows, Tri+ PCB concentrations increase with increasing flows with a slope that is consistent with the suspended sediment – flow regression for flood conditions (b_2 = 2.2). This result indicates that Tri+ PCB water column concentrations are primarily associated with particulate phase PCBs for the higher flows.

A comparison of Tri+ PCB – flow regressions for the 2004-2008 pre-dredging and 2016 post-dredging periods (Figure S-1B) shows that the regression line for post-dredging non-flood period is approximately a factor of two lower than the corresponding regression line for the pre-dredging period. Differences in the regression lines for the flood conditions however show little or no change for the pre-dredging and post-dredging periods. This latter finding is currently considered tentative because of the limited number of high flow observations that were available for the 2016 post-dredging period.

2. Estimation of Tri+ PCB Loads Passing Waterford and Entering the Lower Hudson

Method

Tri+ PCB loads to the Lower Hudson were calculated for pre-dredging and post-dredging periods using USGS daily flow measurements at Waterford and daily Tri+ PCB concentrations that were calculated as a function of river flow (see previous section). In this approach, daily estimates of log C were determined for non-flood and flood conditions using regression equations (Eqs. S-1 and S-2), previously-determined regression coefficients (Table S-1) and daily flow at Waterford (USGS Gaging Station 01335770). Since the regression equations were developed in log space, the computed log C value corresponds to the median or 50th percentile value of the probability distribution of the daily Tri+ PCB water column concentration. Median concentrations were therefore converted into arithmetic means as:

$$C = 10^{\left(\log C + \frac{2.303}{2} S^2_{\log C}\right)} \qquad \text{(Eq. S4)}$$

where the value of 2.303 corresponds to the natural log of 10. The daily Tri+ PCB load passing Waterford was then calculated by multiply the daily flow at Waterford (Q) times the estimated Tri+ PCB water column concentration (C). Finally, the annual Tri+ PCB load passing Waterford was determined by summing the daily Tri+ PCB loads.

Results

Annual Tri+ PCB loads passing Waterford and entering the Lower Hudson are presented in Table S-2 for 2004-2008 pre-dredging period and the 2016 post-dredging periods. For these calculations, 13,000 cfs was used in differentiating between low flow and high flow conditions. The total Tri+ PCB loads passing Waterford during the 2004-2008 pre-dredging period averaged 107.7 kg/yr, with 47 percent of the total load (50.8 kg/yr) occurring during low flow and the remaining 53 percent (57.0 kg/yr) occurring during high flow conditions. For comparison, the total Tri+ PCB loads passing Waterford during the 2016 post-dredging period was estimated to be 37.0 kg/yr, with 78 percent of the total load (28.7 kg/yr) occurring during low flow and only 22 percent (8.3 kg/yr) occurring during high flow conditions.

During the 2004-2008 pre-dredging period, river flow at Waterford averaged 10,100 cfs and included an average of 86 days per year with flows in excess of 13,000 cfs. In comparison, the 2016 post-dredging period was characterized by lower flows with an average river flow at Waterford of 6,100 cfs and only 15 days with flows exceeding 13,000 cfs. Because of the importance of flow on the Tri+ PCB load, a hypothetical post-dredging scenario was considered using the 2004-2008 pre-dredging flow record with the post-dredging regression equations (Table S-2). Comparison of the pre-dredging results with the hypothetical post-dredging scenario shows that total Tri+ PCB loads would have been reduced by only 13 percent if river flows for the post-dredging period were comparable to flows during the pre-dredging period. Tri+ PCB loads for low flow conditions were approximately 27 kg/yr for both the 2016 post-dredging period and hypothetical post-dredging scenario. This indicates that year-to-year variations in river flow will have a small effect on Tri+ PCB loads during low flows. However, Tri+ PCB loads during high flows showed large differences. This result indicates that Tri+ PCB loads during high flow conditions will likely show large year-to-year variations; e.g., from 8.3 kg/yr based on the 2016 flow record to potentially more than 100 kg/yr if the river experiences another year like 2011 with three major high flow events.

3. A Simplified Mass Balance Model to Investigate the Linkage between Sediment Concentrations and Water Column Responses during Summer-time, Low-flow Conditions

Model Description

A simplified model was developed as part of a preliminary investigation of the linkage between PCB surface sediment concentrations and water column responses during summer-time low flow conditions. In the model, Tri+ PCBs in the water column are assumed to be primarily comprised of dissolved phase contaminant during low flow periods. A schematic of the simplified model is presented in Figure S-2. As shown, the model represents the Upper Hudson as four consecutive "plug-flow" river reaches. The river reaches correspond to the three River Sections, with the longest River Section (RS#3) divided into RS#3a and RS#3b at Stillwater where the Hoosic River enters the Upper Hudson. Processes considered in the model calculation include flow through the river reaches, PCB diffusion out of (and potentially into) the contaminated sediments, PCB volatilization, and addition of flow from tributaries and surface runoff.

The plug-flow, mass balance equation that was applied to each river reach is given as:

$$\frac{dC}{dt^*} = \frac{k_f'}{h}\left[C_{pw} - C\right] - \frac{k_v'}{h} C \qquad \text{(Eq. S-5)}$$

where the term on the left-hand side represents the change in the Tri+ PCB water column concentration as the river water flows downstream, the first term on the right-hand side represents the net gain of Tri+ PCB from diffusion out of (and potentially into) the contaminated sediments, and the last term on the right-hand side represents the loss of Tri+ PCB by volatilization as the water flows downstream. Specific notation is given as: C = Tri+ PCB water column concentration (in ng/L); t* = travel time (in days) which is equal to the distance downriver (x) divided by the river velocity (U); k_f' = diffusive exchange coefficient between the pore-water and the overlying water (in m/day); h = average depth of the river (m); C_{pw} = Tri+ PCB concentration in the underlying pore-water (in ng/L); and k_v' = the volatilization rate coefficient in m/day). For our calculations, the Tri+ PCB pore-water concentrations for each river reach (C_{pw}) were calculated based on equilibrium partitioning:

$$C_{pw} = \frac{r_a}{K_D} \qquad \text{(Eq. S-6)}$$

where r_a is the Tri+ PCB concentration in the surface sediments (in mg/kg); and K_D is the equilibrium partition coefficient (in L/kg).

The analytical solution for the plug-flow, mass balance equation (Eq. S-5) is given as:

$$C = \frac{k_f' C_{pw}}{\left(k_f' + k_v'\right)} \cdot \left[1 - e^{-\left(\frac{k_f' + k_v'}{h}\right)\cdot t^*}\right] + C_o \cdot e^{-\left(\frac{k_f' + k_v'}{h}\right)\cdot t^*} \qquad \text{(Eq. S-7)}$$

where C_o represents the Tri+ PCB concentration at the beginning of the river reach. For the first river reach, C_o is set equal to the Tri+ PCB concentration Bakers Falls (RM 194.5). For subsequent river reaches, Co is determined from a mass balance calculation at the beginning of the reach:

$$Q_u \cdot C_u + Q_t \cdot C_t = Q \cdot C_o \qquad \text{(Eq. S-8)}$$

where Q_u and C_u represent the river flow and Tri+ PCB water column concentration at the end of the previous reach; Q_t and C_t represent the river flow and Tri+ PCB water column concentration associated with tributary inflows; and Q represents the river flow for the river reach.

Methods

Model parameters and coefficients for the four river reaches are given in Table S-3 for a summer-time, low-flow of 3,500 cfs (99.1 m^3/sec) at Waterford. Channel geometry (length, width, depth) and drainage area were obtained from information in EPA (2000a). Flow (Q) was considered to be constant through each river reach and was scaled according to the total drainage area. For simplicity, tributary and surface runoff flows were assumed to enter the river at the beginning of each reach. This assumption is expected to have a minor effect on the model calculations because the major tributaries to the Upper Hudson, Batten Kill and the Hoosic River, enter at the beginning of river reaches RS#3a and RS#3b. Based on the river geometry and flow rate, the average velocity in each river reach was calculated by dividing the flow (Q) by the average depth (h) and average width (b), and the travel time (t*) through each river reach was calculated by dividing the length of the river reach by the average velocity (U).

For pre-dredging model calculations, average Tri+ PCB concentrations in surface (0-2 inch) sediments (r_a) for each river reach were based on the Sediment Sampling and Analysis Program (SSAP) that was conducted in 2002-2005 during the remedial design phase. See EPA (2012) for details. Tri+ PCB pore-water concentrations were calculated from the Tri+ PCB surface sediment concentrations using the equilibrium partitioning relationship in Eq. S-6. For these calculations, the K_D value was estimated from $K_D = f_{oc} \times K_{oc}$ where f_{oc} (the fraction organic carbon in surface sediments) was taken as 0.03 and K_{oc} (the organic carbon – water partition coefficient) was were taken 10^6 L/kg. The volatilization rate coefficient (k_v') was calculated based on two-film theory. For this calculation, the transfer through liquid-side of the interface was assumed to control volatilization, and the transfer rate coefficient for the liquid-side of the interface was estimated using the O'Connor-Dobbins formula. Based on these assumptions, k_v' was computed as:

$$k_v' = \sqrt{D_w \frac{U}{h}} \qquad \text{(Eq. S9)}$$

where D_w is the molecular diffusivity of PCBs in water and was taken as 5×10^{-6} cm^2 sec^{-1}. The final model coefficient, the diffusive exchange coefficient between pore-water and the overlying water (k_f'), was adjusted to match the calculated Tri+ PCB water column concentrations to Tri+ PCB water column concentrations during summer-time low flows (corresponding to 3,000 – 4,000 cfs at Waterford).

Comparable model calculations were performed for post-dredging conditions by modified only the Tri+ PCB concentrations in the surface sediment. All other model parameters and coefficients (including the calcibrated k_f' value) remained unchanged. Since post-dredging monitoring data are not yet available for the sediment, post-dredging concentrations of Tri+ PCBs in surface sediments were assigned based on estimates given in EPA (2012).

Finally, model calculations were performed over a wider range of summer-time low flows at Waterford (i.e., 1,000 to 13,000 cfs). Particulate-phase PCBs were expected to control Tri+ PCB water column concentrations for flows greater than 13,000 cfs at the Waterford monitoring station. For the higher flows, the simplified model (which is based on dissolved-phase transport of Tri+ PCBs) would no longer apply.

Pre-dredging Model Calibration

The simplified model was calibrated to the observed Tri+ PCB water column concentrations for the pre-dredging period by adjusting the PCB diffusive exchange coefficient between the water column and the underlying pore-water (k_f') to 0.05 cm/day. For the model calibration, a flow at Waterford of 3,500 cfs was considered to be representative of summer-time low-flow at Waterford. Comparison of the calibrated model (blue solid line) with observed Tri+ PCB water column concentrations at TID, Schuylerville, Stillwater and Waterford (blue open circles) is shown in Figure S-3A. The observed concentrations are represented as geometric means (with geometric standard deviations) based on 2004-2008 summer-time Tri+ PCB measurements that were taken on days with river flows of 3,000 – 4,000 cfs at the USGS Waterford monitoring station. The calibrated k_f' value of 0.05 cm/day was found to be comparable to values previously reported in modeling studies of the Upper Hudson (Connolly et al. 2000; Erickson et al. 2005).

Post-dredging Model Projection

The simplified model was used as part of a preliminary investigation investigating the potential effects of dredging on Tri+ PCB water column concentrations during a summer-time low-flow of 3,500 cfs at Waterford. As shown by the green dashed line in Figure S-3A, post-dredging model results show a large decrease in Tri+ PCB water column concentrations (compared to the pre-dredging modeling results). Observed Tri+ PCB water column concentrations for the 2016 post-dredging period are shown by the green triangles in Figure S-3A. The observed concentrations are again as geometric means (with geometric standard deviations) summer-time Tri+ PCB measurements that were taken on days with river flows of 3,000 – 4,000 cfs at the USGS Waterford monitoring station. As shown, the model projection is aligned to the observed Tri+ PCB concentrations at Waterford (RM156.0). Model projections however are lower than the observed Tri+ PCB water column concentration at TID (RM 187.5) and Schuylerville (RM 182.3).

Discrepancies between the simplified model results and the 2016 post-dredging data at TID (RM 187.5) and Schuylerville (RM 182.3) suggest that the 2016 post-dredging Tri+ PCB concentrations in surface sediments are higher than the EPA (2012) estimated concentrations that were used in the model calculations. However, another plausible explanation is that sediments in the dredging zones need time to "stabilize" after six years of dredging. For example, the higher Tri+ PCB water column concentrations at TID and Schuylerville may be due to residual effects of dredging disturbances that are continuing to cause supply localized resuspension of sediments even during summer-time low flow conditions. This would result in higher Tri+ PCB water column concentrations due to the presence of particulate-phase PCBs that were not considered in the simplified model calculations. It could therefore be argued that one year of post-dredging monitoring data may is not sufficient to evaluate the full benefits of the dredging program.

Effect of River Flow on Tri+ PCB Water Column Response

The simplified model was used to examine the effects of river flow on Tri+ PCB water column concentrations for summer-time low-flow conditions (i.e., < 13,000 cfs). As presented in Figure S-3B, model results for both pre-dredging and post-dredging periods show decreases in Tri+ PCB water column concentrations at Waterford with increasing flows. In addition, the post-dredging modeling results are approximately a factor of two lower than the pre-dredging results. These findings are consistent with the non-flood regressions previously presented in Figure S-1 and suggest that Tri+ PCB water column concentrations are controlled by Tri+ PCB diffusion from the underlying sediments during low-flow conditions.

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Table S-1. Regression Coefficients for Suspended Sediment and Tri+ PCB Water Column Concentrations[a]

	Suspended Sediment Concentrations (mg/L)	Tri+ PCB Water Column Concentrations (ng/L)	
	2004-2008 Pre-dredging Period	2004-2008 Pre-dredging Period	2016 Post-dredging Period
$\log a_1$	-1.66	2.44	2.42
b_1	0.59	-0.38	-0.43
BP	10,050	15,450	12,400
$\log a_2$[b]	-8.14	-8.38	-8.35
b_2	2.2	2.2[c]	2.2[c]
$S_{\log C}$	0.30	0.24	0.18

[a] Regression coefficients ($\log a_1$, b1, BP, b_2) were determined for the log-log relationships for non-flood and flood conditions (Eqs. S-1 and S-2).

[b] $\log a_2$ values were calculated using Eq. S-3 to ensure that the regression equation for flood conditions matches the regression equation for non-flood conditions.

[c] For the Tri+ PCB regressions, the slope for flood conditions (b_2) was fixed and set equal to the b_2 value that was determined for the suspended sediment – flow regression.

Table S-2. Estimated Annual Tri+ PCB Loads Passing Waterford and Entering the Lower Hudson.

Calendar Year	Average Annual Flow (cfs)	Number of days with high flows[a]	Annual Tri+ PCB Loads (kg yr^{-1})		
			Non-flood	Flood	Total
Pre-dredging Period(b)					
2004	8,822	50	56.3	18.8	75.2
2005	10,055	83	50.1	63.1	113.1
2006	11,801	112	56.2	61.7	117.9
2007	8,743	71	45.9	49.1	95.1
2008	11,185	114	45.4	92.0	137.4
Average	10,121	86.0	50.8	57.0	107.7
Post-dredging Period[c]					
2016	6,105	15	28.7	8.3	37.0
Hypothetical Post-dredging Period[d]					
2004	8,822	50	30.8	25.0	55.8
2005	10,055	83	26.0	73.3	99.3
2006	11,801	112	24.5	77.7	102.3
2007	8,743	71	24.1	57.9	82.0
2008	11,185	114	23.1	104.1	127.2
Average	10,121	86.0	25.7	67.6	93.3

[a] Number of days with flows exceeding 13,000 cfs at Waterford.

[b] Tri+ PCB loads for the pre-dredging period are based on regression coefficients for the pre-dredging period (see Table S-1) and the 2004-2008 flows at the USGS Waterford monitoring station.

[c] Tri+ PCB loads for the post-dredging period are based on regression coefficients for the post-dredging period (see Table S-1) and the 2016 flows at the USGS Waterford monitoring station.

[d] Tri+ PCB loads for the hypothetical post-dredging period are based on regression coefficients for the post-dredging period (see Table S-1) and the 2004-2008 flows at the USGS Waterford monitoring station.

Table S-3. Model Parameters and Coefficients for Summer-time, Low-flow Model Calculations[a]

		RS#1	RS#2	RS#3a	RS#3b
Length	km	9.03	8.19	24.49	23.01
Drainage Area	mi^2	2,971	2,971	4,455	4,573
Average Width	m	304.9	226.6	207.0	299.6
Average Depth (h)	m	2.36	2.90	3.79	3.80
Flow (Q)[b]	m^3/sec	64.4	64.4	96.5	99.1
Average Velocity (U)[c]	m/sec	0.09	0.10	0.12	0.09
Travel Time (t*)	days	1.17	0.97	2.30	3.06
Diffusive Exch. Coef. (k_f')	m/day	0.05	0.05	0.05	0.05
Volatilization Rate Coef. (k_v')	m/day	0.38	0.36	0.35	0.29
Partition Coef. (K_D)	L/kg	3×10^4	3×10^4	3×10^4	3×10^4
Pre-dredging Tri+ PCB Concentrations in Surface Sediments					
Tri+ PCBs Surf. Sediment (r_a)	mg/kg	14.2	11.0	3.3	3.3
Tri+ PCBs Pore-water (C_{pw})	ng/L	473	367	110	110
Post-dredging Tri+ PCB Concentrations in Surface Sediments					
Tri+ PCBs Surf. Sediment (r_a)	mg/kg	1.9	7.1	3.1	3.1
Tri+ PCBs Pore-water (C_{pw})	ng/L	63	237	103	103

[a] See text for explanations of how model parameters and coefficients were obtained for the four river sections.

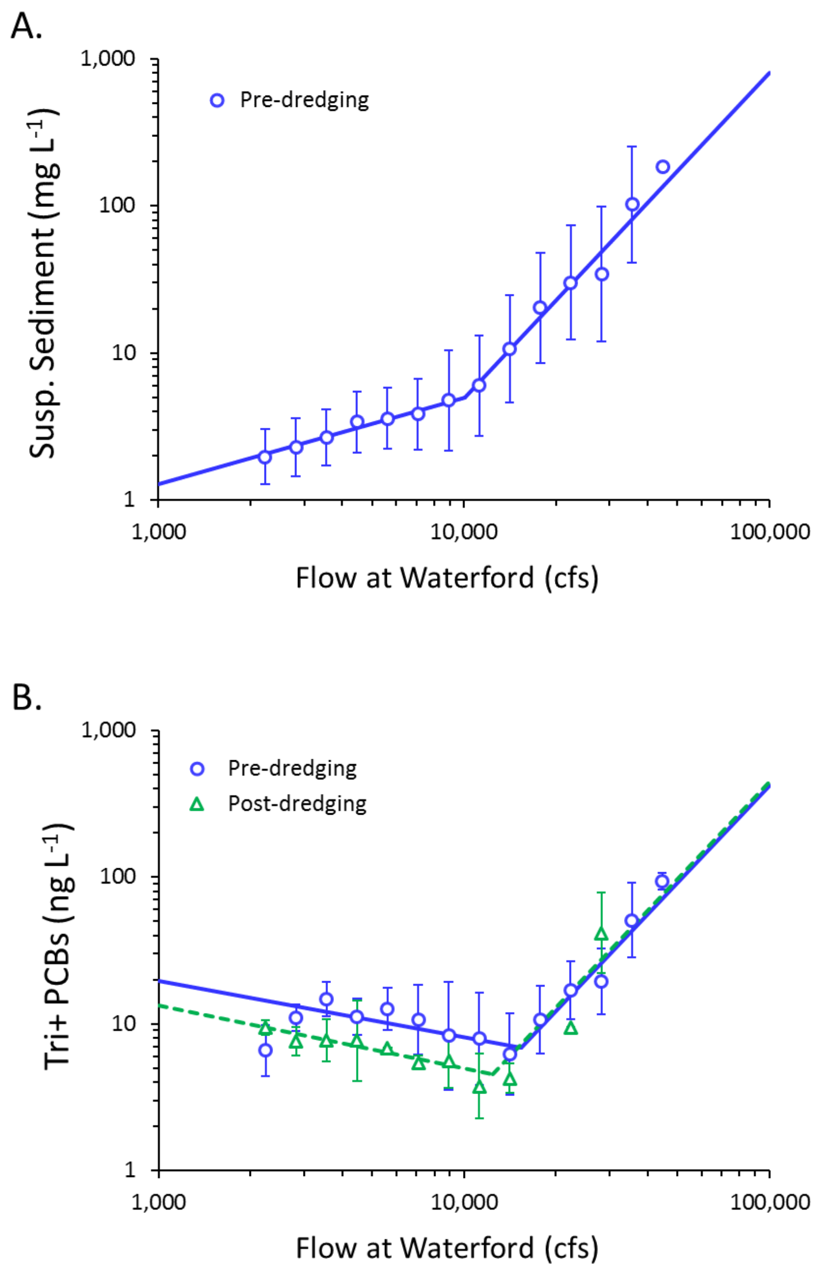

Figure S-1. Suspended sediment and Tri+ PCB water column responses at Waterford. (A) Suspended sediment concentrations versus river flow, and (B) Tri+ PCB concentrations versus river flow. Observed 2004-2008 pre-dredging (open blue circles) and 2016 post-dredging (open green triangles) concentrations are represented as geometric means (with geometric standard deviations) for selected flow bins. The corresponding regression equations are given by the solid blue lines and the dashed green lines for non-flood and flood flow conditions.

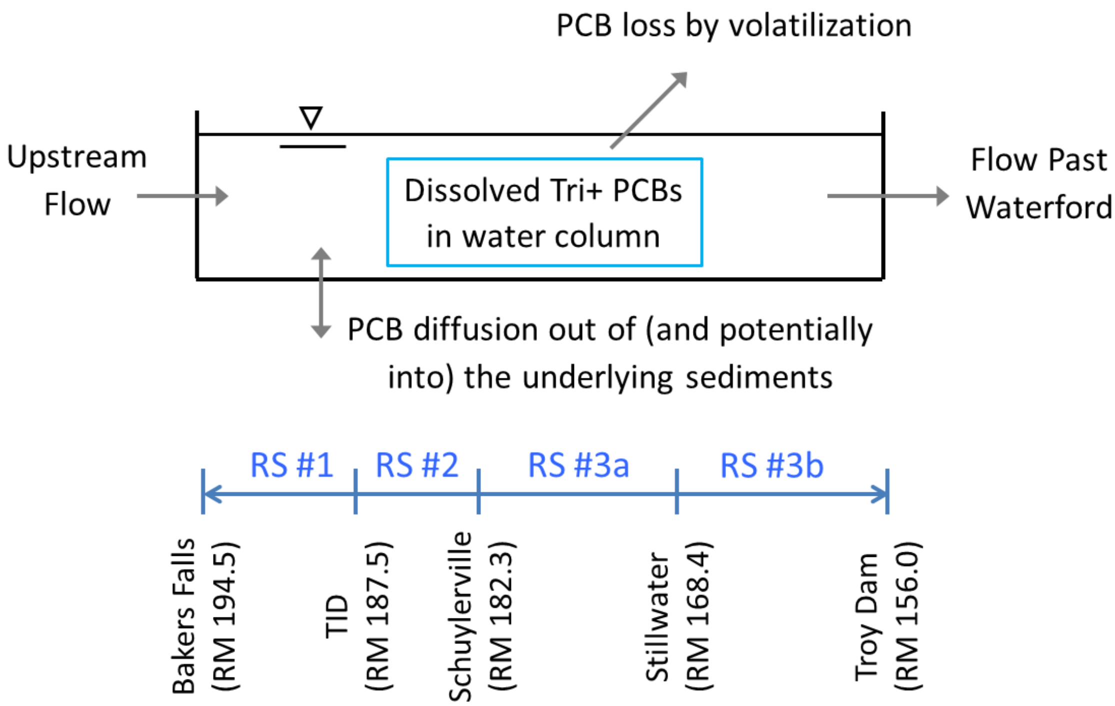

Figure S-2. Simplified model for Tri+ PCB transport through the Upper Hudson during summer-time conditions. The model represents the Upper Hudson as four consecutive "plug flow" river reaches and includes the effects of flow, water inflows, PCB diffusion out of (and potentially into) the contaminated sediments, and PCB volatilization.

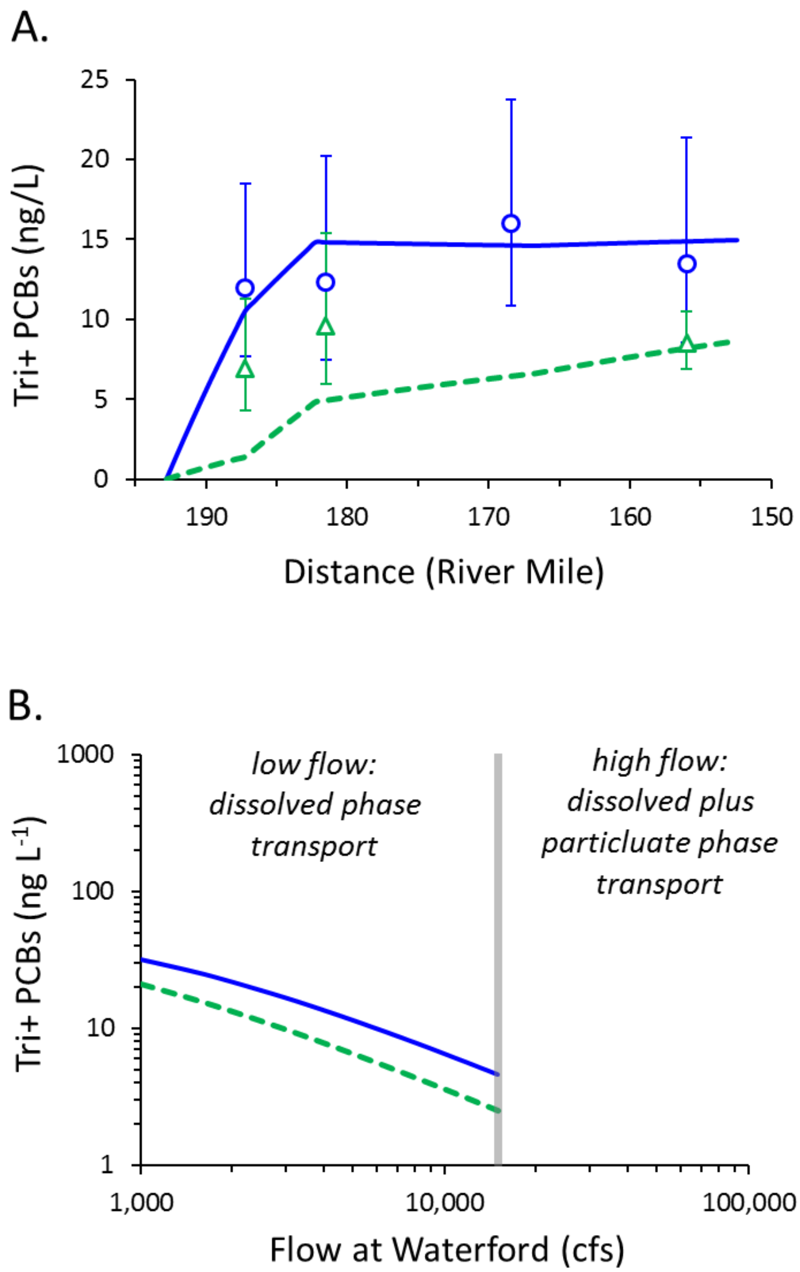

Figure S-3. Simplified model results for (A) Tri+ PCB water column concentrations versus River Mile for a summer-time low flow of 3,500 cfs, and (B) Tri+ PCB water column concentrations at Waterford versus flow. Pre-dredging and post-dredging model results are given by the blue solid line and green dashed lines, respectively. For comparison, geometric means (and geometric standard deviations) for Tri+ PCBs for summer-time low flows between 2,500 – 4,500 cfs are included on panel A as blue circles and green triangles for Thompson Island Dam (RM 187.5), Schuylerville (RM 182.3), Stillwater (RM 168.4) and Waterford (RM 156.0).