

Appendix J

Mapping of Contaminant Concentrations in Lower Passaic River Sediments

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ATTACHMENTS

Attachment 1	Support for Geomorphic Groups for Additional Mapped COPCs
Attachment 2	Pooled Data for Resampling of Layer B for Additional COPCs
Attachment 3	Comparison of Mapped Surfaces for Layer A and Resampled Layer B for Additional COPCs

ABBREVIATIONS

1,2,3,4,6,7,8-HPCDF	1,2,3,4,6,7,8-heptachlorodibenzofuran
1,2,3,7,8-PeCDD	1,2,3,7,8-Pentachlorodibenzo-p-dioxin
2,3,4,7,8-PeCDF	2,3,4,7,8-Pentachlorodibenzofuran
2,3,7,8-TCDD	2,3,7,8-tetrachlorodibenzo-p-dioxin
CFT	contaminant fate and transport
cm	centimeter
COPC	chemical of potential concern
CPG	Cooperating Parties Group
CS	conditional simulation
DDD	dichlorodiphenyldichloroethane
DDE	dichlorodiphenyldichloroethylene
DDT	dichlorodiphenyltrichloroethane
FS	Feasibility Study
IC	initial condition
LPRSA	Lower Passaic River Study Area
mg/kg	milligrams per kilogram
NBSA	Newark Bay Study Area
ng/kg	nanograms per kilogram
PCB	polychlorinated biphenyl
QC	quality control
Region 2	U.S. Environmental Protection Agency Region 2
RI	Remedial Investigation
RM	river mile
ROD	Record of Decision
SSS	side scan sonar
SWAC	surface-weighted average concentration
tetra-CB	tetrachlorobiphenyl
TIN	triangulated irregular network
USEPA	U.S. Environmental Protection Agency
WY	water year

1 Introduction

Interpolated surface (0 to 6 inches) and subsurface sediment contamination concentration maps of the 17-mile Lower Passaic River Study Area (LPRSA) and the Newark Bay Study Area (NBSA) are needed to display contemporary contamination patterns, support the development of remedial alternatives, set initial conditions for the modeling evaluation of these alternatives, and assess temporal trends in surface weighted-average concentrations (SWACs). This appendix describes the mapping developed for the following three primary calibration chemicals of potential concern (COPCs) and the six secondary calibration COPCs that are used in the contaminant fate and transport (CFT) modeling:

- 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD)
- Tetrachlorobiphenyl (tetra-CB)
- 1,2,3,4,6,7,8-heptachlorodibenzofuran (1,2,3,4,6,7,8-HPCDF)
- 1,2,3,7,8-Pentachlorodibenzo-p-dioxin (1,2,3,7,8-PeCDD)
- 2,3,4,7,8-Pentachlorodibenzofuran (2,3,4,7,8-PeCDF)
- Polychlorinated biphenyl (PCB)-126
- PCB-167
- Sum of 4,4'-DDx¹
- Mercury

The mapping was developed for two time periods: 1) using contemporary datasets (2005 to 2013); and 2) using historical datasets (1995 to 1999) for LPRSA surface sediments (0 to 6 inches) and subsurface sediments. Three mapping methods were used: 1) a Thiessen polygon interpolation (for all COPCs); 2) a conditional simulation (for contemporary surface 2,3,7,8-TCDD and tetra-CB concentrations between river mile [RM] 0 and RM 14.7); and 3) a resampling approach for the 6- to 18-inch sediments between RM 0 and RM 14.7. The use of conditional simulation for surface sediments is the result of a collaborative discussion with U.S. Environmental Protection Agency (USEPA) Region 2 (Region 2) on the need to factor uncertainty into the estimation of remedial benefit for alternatives considered in the Feasibility Study (FS). Modeled contaminants other than 2,3,7,8-TCDD and tetra-CB are mapped using Thiessen polygons (see Anchor QEA 2016).

¹ Historical data from 1995 to 1999 are available for the sum of 4,4'-DDx but not total DDx. The sum of 4,4'-DDx is defined as the sum of three isomers: 4-4'-DDD, 4-4'-DDE, and 4 4' DDT. To allow the use of the historical data, the sum of 4,4'-DDx is used rather than total DDx (total DDx also includes isomers 2,4'-DDD, 2,4'-DDE, and 2,4'-DDT). A comparison of total DDx and 4,4'-DDx for the post-2005 data is presented in Figure 8 of Appendix I and indicates that 4,4'-DDx is well correlated to total DDx and comprises most of the total DDx.

2 Sediment Datasets and Data Treatment

In the mapping developed herein, data collected between 2005 and 2013 are taken as representative of the contemporary contamination in the LPRSA and are referred to as the “2010 dataset.” Data collected between 1995 and 1999 are taken as representative of historical contamination in the LPRSA and are referred to as the “1995 dataset.” The studies that comprise each of these datasets are listed in Table 2-1.²

Some sampling programs characterize a location using co-located samples, with different contaminants analyzed in the different samples (Table 2-1 identifies these studies). The centroid of the convex hull of these co-located cores was used as the sample location in the mapping, with the exception of core cluster 12A-0427 from the 2012 Supplemental Sampling Program for which the sampling location of the 2,3,7,8-TCDD measurement was used (the reason for this exception is described in Section 3.4).

All available data from the LPRSA, Newark Bay, Hackensack River, Kill van Kull, and Arthur Kill were used—no tributary samples were used.³

2.1 COPC-Specific Data Treatments

In some samples, a total PCB concentration was available, but the tetra-CB homolog was not available. For these samples, tetra-CB concentrations were estimated from total PCB concentrations using a sediment data regression (transmitted to USEPA on April 5, 2017, ahead of the April 6, 2017 USEPA-Cooperating Parties Group (CPG) Modeling Meeting). Equation 1 shows the regression equation.

² The analysis excluded data flagged as “rejected.” Non-detects were set to half of the detection limit, and duplicates were averaged. Data treatments used here differ from Windward and AECOM (2015). Pre-2007 data were used, and treatment of duplicates differed. This mapping is used for modeling, which is exempt from the rules in Windward and AECOM (2015).

³ Available data were used when they met the data treatment requirements described here. For the conditional simulation described in Section 5, only surface sediment LPRSA data between RM 0 and RM 14.7 were used.

Equation 1

$$x = \frac{y - b}{m}$$

where:

x	=	tetra-CB concentration in milligrams per kilogram (mg/kg)
y	=	total PCB concentration in mg/kg
b	=	intercept
m	=	slope

The values for b and m vary depending on the total PCB concentration range and are listed in Table 2-2. The studies for which the equation was applied are listed in Table 2-1.

2.2 Surface Mapping Data Treatment

The surface mapping characterizes the top 6 inches of sediment, which is the surface segment of most datasets listed in Table 2-1. To include data not measured precisely to 6 inches, the data query included single segments measured from the surface to a depth in the range of 5 to 7 inches (0.4167 to 0.59 foot). Length-weighted averages were also calculated to include cores with multiple segments within the upper 6 inches. Cores considered for length-weighted averaging had segments starting within 0 to 6 inches and ending no deeper than 7 inches (0.59 foot), and when combined were required to extend from the surface to a depth in the 5- to 7- inch (0.4167 to 0.59 foot) range.⁴

2.3 Subsurface Mapping Data Treatment

Subsurface mapping was conducted for five layers: B: 6 to 18 inches (0.5 to 1.5 feet), C: 18 to 30 inches (1.5 to 2.5 feet), D: 30 to 42 inches (2.5 to 3.5 feet), E: 42 to 66 inches (3.5 to 5.5 feet), and F: below 66 inches (5.5 feet). These depth intervals were chosen because they corresponded with the most common segmentation scheme in the datasets used. Length-weighted averages were calculated for each layer in instances where a core's segmentation scheme differed from these intervals.⁵ Tables 2-3 through 2-11 list cores with overlapping segments for all nine modeled COPCs.

⁴ Cores where only a small segment of the top 6 inches (0.5 foot) was sampled were excluded from the surface mapping because they may not be representative of the full 6 inches (0.5 foot). If the bottom core segment ended at 5 inches (0.4167 foot), the 0- to 5-inch length-weighted average was used as the surface concentration. If the bottom of the last segment used in surface mapping ended at 7 inches (0.59 foot), a length-weighted average down to 6 inches (0.5 foot) was used as the surface concentration.

⁵ Some core locations contained an additional segment that overlapped a continuous core profile. These overlapping core segments were removed. An example is location 274, which had segments from 0 to 0.5, 0.5 to 0.9, 0.9 to 2.8, 2.8 to 4, and 4 to 5.1 feet. It also had an additional segment from 1.8 to 3.4 feet, which was excluded from this analysis.

Concentrations were assumed to be zero in layers below the deepest core segment for cores that sampled to native material or were judged to have captured the entire chemical inventory. The criteria used to identify these cores is described in Section 1.2 of Appendix I.

2.3.1 Professional Judgement Adjustments

Length-weighted averaging over Layer B was not performed for core 13B-0563-C2 (located at RM 14.4). This core was segmented at 1.1 feet rather than 1.5 feet because of a visual change in sediment type. The 0.5- to 1.1-foot segment had a 2,3,7,8-TCDD concentration of 1.1 nanograms per kilogram (ng/kg) and was composed primarily of fine and medium grain sand. The 1.1- to 2.5-foot segment had a concentration of 2,130 ng/kg and was composed of silt with a hydrocarbon-like odor. Length-weighting of these concentrations would characterize the location as having 853 ng/kg in the 0.5- to 1.5-foot interval, which brings contamination closer to the surface than exists there. This has implications for modeling because the model simulates vertical gradients on 1 centimeter (cm) resolution and the influence of contamination below the top 15 cm (6 inches) on the concentrations in the top 15 cm (6 inches) occurs mostly with the concentrations in the upper portion of the 0.5- to 1.5-foot interval. The model is much less impacted by the choice of concentrations in the lower portion of this interval. For this reason, the concentration of 1.1 ng/kg was used for Layer B and the concentration of 2,130 ng/kg was used for Layer C. Table 2-12 lists core segment concentrations and descriptions from the boring logs (AECOM 2015).

Within the Lower Passaic River, other cores which had Layer B segments with start depths greater than 0.5 and end depths greater than 1.5 feet were examined for potential adjustment (Table 2-13)⁶. However, no further adjustments were made as most of the remaining cores either had concentration differences within an order of magnitude, the segments were mostly within the Layer B interval, or the Layer B concentration at the core location was specified by resampling. Moreover, most of the cores in Table 2-13 are located within the Lower 8.3 Miles (below RI RM 8) of the LPR and consequently they are unlikely to strongly impact model projection results because this reach of the river will be remediated.

2.3.2 Layer F (below 5.5 feet)

Concentrations more than 5.5 feet below the sediment surface are required for simulating contaminant release during dredging beyond 5.5 feet, which is planned in certain navigation channel areas in the Lower 8.3 Miles (below RI RM 8) of the LPR (Record of Decision [ROD]; USEPA 2016). To achieve better spatial coverage for interpolating the deep layers, data collected between 1995 and 2013 were used. The interpolation comprised two types of cores: 1) cores with measured

⁶ High-resolution cores have short segmentation and were not examined here.

concentrations below 5.5 feet and less than 0.5 foot of total gaps in the core profile⁷; and 2) full inventory cores as described in Section 1.2 of Appendix I. Length-weighted-average concentrations were calculated from 5.5 feet down to the dredge depth in the model grid cell or the last measured end depth, whichever was shorter.⁸ Core profiles of full inventory cores beneath which the concentration was assumed to be zero are shown in Appendix I, Figure 4⁹.

⁷ There were five exceptions where high-resolution cores had greater than 0.5 foot of total gaps but had a significant resolution of segments to estimate concentrations: G0000004-7A and G0000005-9A of the USEPA/Malcom Pirnie, Inc. – High-Resolution Sediment Coring Program; and HRC-02H, HRC-03H, and HRC-04H of the 2011 Joint Defense Group – Sediment Sampling Program. Other cores with gaps below 5.5 feet were excluded from this analysis, but none of these excluded cores fell within the model grid cells identified for deep dredging (dredging below 5.5 feet).

⁸ For cores below 5.5 feet that ended before the modeled dredge depth and were not complete cores, the length-weighted-average was calculated down to the last measured depth in the core.

⁹ Layer F was developed for the purpose of mapping contaminant concentrations in areas that undergo dredging below 5.5 feet in the Lower 8.3 Miles. Layer F as described here was not used in the chemical mass inventories presented in Section 6 of the RI; the methodology used in the chemical mass inventories includes mass down to the last measured depth (even if this is deeper than the depth of deep dredging) and is described in Attachment I.

3 Geomorphic Groups

In mapping, the entire 17-mile LPRSA¹⁰ was divided into geomorphic “groups” based on the observation that COPC concentration patterns differed among these groups.¹¹ The groups were used to establish interpolation boundaries directly in the Thiessen polygon mapping approach (Section 4) and in modified form in the conditional simulation mapping approach (due to the geostatistical assumptions of that approach; see Section 5).

Geomorphic groups within the LPR were delineated differently upstream and downstream of RM 7.8 to account for differences in sediment characteristics. Upstream of RM 7.8, there is a mixture of fine and coarse sediments, whereas muddy sediments dominate downstream of RM 7.8 (see Section 4 of the Remedial Investigation [RI] report).

The geomorphic group delineations are shown in Figure 3-1, and the distributions of Passaic River surface sediment 2,3,7,8-TCDD concentrations by group are shown in Figure 3-2. Surface sediment concentrations by group for other modeled COPCs are shown in Attachment 1. The basis for the geomorphic delineations is provided in Sections 3.1, 3.2, and 3.3 for regions below RM 7.8, above RM 7.8, and outside of the LPR, respectively.

3.1 Geomorphic Groups Downstream of RM 7.8

Downstream of RM 7.8, shoals were separated from the channel to reflect the steep contaminant concentration gradients typically observed moving from shoal to channel (see Section 4.1 of the RI report) and the fact that the shoals have—for the most part—not been dredged, whereas the channel has been dredged for navigation at various times (see Section 1 of the RI report). The shoals were separated into *Left Shoal* or *Right Shoal LPR*¹² groups to allow interpolation within a shoal but not across the channel into the opposing shoal. These shoal groups combine the “broad shoals” and “margins” in Region 2’s geomorphic regions (SEI and HQI 2011).

The channel between RM 7.8 and RM 2.3 was subdivided based on historical deposition patterns evident in changes in bathymetry measured in this reach. These patterns were defined using three

¹⁰ NBSA, parts of the Hackensack, and the Kills were also divided into groups using the navigational channel.

¹¹ USEPA conducted evaluations of the grouping approach used here and concluded that this stratification approach had low predictive power (USEPA 2015, 2017). The concept of stratification was retained with the expectation that pre-design investigation data would be used to reevaluate the value of the stratification approach and potentially develop a new mapping procedure.

¹² “Left” and “Right” are used here from the perspective of an observer moving upstream (i.e., the left shoal is the western shoal along most of the LPR).

bathymetric datasets: 1949, 1966, and 2011.¹³ Release of 2,3,7,8-TCDD from the Lister Avenue site started in approximately 1948 (Bopp et al. 1991); thus, the 1949 bathymetry dataset represents the river bathymetry at approximately the time the Lister Avenue site discharge started, and the 1966 bathymetry dataset represents the river bathymetry toward the end of contaminant discharge. (The active release of 2,3,7,8-TCDD from the Lister Avenue site is presumed to have ceased in 1969 based on plant operating history [Bopp et al. 1991]; other point source contaminant loadings are thought to have decreased significantly after the passing of the Clean Water Act in 1972.)

The channel between RM 7.8 and RM 2.3 was divided into the following three groups:

- *No Deposition Since 1949*:¹⁴ Areas deeper in 2011 than 1949 (using 0.4 foot deeper as the break point,¹⁵ reflecting uncertainty in the bathymetry data), indicating that post-1949 sediments that would have contained 2,3,7,8-TCDD released from the Lister Avenue site may be absent
- *Mixed Depositional Since 1966*:¹⁶ Areas that accumulated sediment between 1949 and 1966 but underwent little net change (i.e., less than 6 inches) between 1966 and 2011
- *Highly Depositional Since 1966*:¹⁷ Areas that accumulated 6 inches or more of net sediment between 1966 and 2011

Due to the lack of 1949 bathymetry data above RM 6.8 and below RM 2.3, the channel areas between RM 6.8 and RM 7.8 and between RM 2.3 and RM 2.5 were classified based on 1966 to 2011 bathymetric differencing alone (i.e., there are not any *No Deposition Since 1949* areas in this region).

This delineation of the channel is generally supported by the 2,3,7,8-TCDD concentrations characteristic of each group. Locations in the *No Deposition Since 1949* group tend to have low concentrations (Figure 3-3, left portion of top panel). The highest concentrations tend to be found at locations in the *Mixed Depositional Since 1966* group, presumably reflecting minimal net burial since the time of active 2,3,7,8-TCDD discharges to the river or burial followed by erosion (Figure 3-3, left

¹³ As described in Appendix A, the 1949 bathymetry dataset extends from RM 2.5 to RM 6.8 and consists of post-dredge bathymetry surveys conducted in 1949 (RM 2.5 to RM 5) and 1950 (RM 5 to RM 6.8). The 1966 bathymetry survey extends from RM 2.3 to RM 7.8. Uncertainties related to these datasets are also discussed in Appendix A. The 2011 multi-beam bathymetry survey, which extends from RM 0 to RM 14, was used as an end-year in defining bathymetric groups because it captures the influence of Hurricane Irene. Fifty-two percent of the surface sediment data (including the four highest concentrations) used in the mapping of the channel between RM 2.3 and RM 7.8 are collected post-Hurricane Irene. Bathymetry survey comparisons were done on a 5-foot by 5-foot grid. Assessments of bathymetry differences between 1949 and 1966 or 2011 are limited to RM 2.5 to RM 6.8 in the navigational channel because of the extent of the 1949 survey. Assessments of bathymetry differences between 1966 and 2011 are limited to RM 2.3 to RM 7.8 in the channel because of the extent of the 1966 survey.

¹⁴ This group may include areas that have experienced no deposition since 1949, along with areas where net erosion has exceeded net deposition since 1949.

¹⁵ The cut-off of 0.4 foot of erosion for defining interpolation group boundaries was selected based on the transition in 2,3,7,8-TCDD concentrations observed at approximately this value (Figure 3-3, top panel).

¹⁶ This group may include areas in the river that experience routine erosion and deposition.

¹⁷ This group may include areas that are depositional in the long term but have also experienced erosion that was exceeded by deposition.

portion of bottom panel). Locations in the *Highly Depositional Since 1966* group tend to have intermediate surface sediment contaminant concentrations with relatively low variability (Figure 3-3, right portion of bottom panel), consistent with more recent deposition. These differences among the geomorphic groups are further illustrated by comparing the distribution of 2,3,7,8-TCDD concentrations among them (Figure 3-4).

Parts of the channel where no 1966 bathymetry data were available (14 out of 181 acres in the channel between RM 2.3 to 7.8) were assigned to the *Highly Depositional Since 1966* group (Figure 3-5, hatched areas), except for one area (0.7 acre) that was assigned to the adjoining *Mixed Depositional Since 1966* group (Figure 3-6, hatched area) based on professional judgment. Many of the areas assigned to *Highly Depositional Since 1966* in Figure 3-5 (hatched areas) are near bridges. The four 2,3,7,8-TCDD samples in these areas have concentrations ranging from 150 to 223 ng/kg, which supports their classification as *Highly Depositional Since 1966* (Figure 3-5). Conversely, the area shown in Figure 3-6 has two characteristics consistent with other *Mixed Depositional Since 1966* areas: it is located on an outer bend of the channel and contains an elevated surface sediment 2,3,7,8-TCDD concentration (4,900 ng/kg).

Due to the lack of 1949 and 1966 bathymetry data, the channel downstream of RM 2.3 was classified as a single interpolation group termed *Downstream LPR and Newark Bay Channel*.¹⁸ This region has generally been subject to significant historical infilling, particularly below RM 1.7 where the channel was dredged as recently as 1983 (see Section 1.2 of the main RI report). Consistent with that fact, this region of the LPR has surface sediment 2,3,7,8-TCDD concentration in line with those in the *Highly Depositional Since 1966* areas previously discussed (Figure 3-2, upper panel).

For the other mapped COPCs, Attachment 1 contains comparisons of surface sediment concentration distributions for all geomorphic groups below RM 7.8 (as in the top panel of Figure 3-2 for 2,3,7,8-TCDD) and for channel geomorphic groups between RM 2.6 and RM 6.8 alone (as in Figure 3-4 for 2,3,7,8-TCDD), as well as evaluations of surface concentrations versus bathymetry change (as in Figure 3-3 for 2,3,7,8-TCDD).

The comparison of surface sediment concentrations among geomorphic groups for other COPCs shows both similarities to and differences from the 2,3,7,8-TCDD patterns:

- Similar to 2,3,7,8-TCDD (Figures 3-2 [top panel] and 3-4), for all COPCs, the concentration distributions are visually higher in the *Mixed Depositional Since 1966* channel group than in the *Highly Depositional Since 1966* group (Attachment 1, Figures 1, 3, 4, 6, 7, 9, 10, 12, 13, 15, 16, 18, 19, 21, 22, and 24, albeit with somewhat more overlap in the lower portion of the

¹⁸ On the upper panel of Figure 3-2, this group is labeled *Downstream LPR Channel* because this panel shows only RM 0 to RM 7.8 and excludes Newark Bay.

distributions for PCB-167 and mercury (Attachment 1, Figures 16, 18, 22, and 24). The tendency for *Mixed Depositional Since 1966* to capture the highest channel COPC concentrations is also evident in the cross plots with bathymetric change (Figure 3-3 for 2,3,7,8-TCDD and Attachment 1, Figures 2, 5, 8, 11, 14, 17, 20, and 23 for the other COPCs).

- Similar to 2,3,7,8-TCDD (Figure 3-2 [top panel]), there is substantial overlap between the concentration distributions for the *Downstream LPR Channel* and *Highly Depositional Since 1966* groups for tetra-CB, PCB-126, PCB-167, total 4,4'-DDx, and mercury (Attachment 1, Figures 1, 13, 16, 19, and 22). However, there is comparatively less overlap in these distributions for 1,2,3,4,6,7,8-HpCDF, 1,2,3,7,8-PeCDD, and 2,3,4,7,8-PeCDF (Attachment 1, Figures 4, 7, and 10).
- The relationship between the *No Deposition Since 1949* and the other distributions is variable among COPCs (albeit with a low data count in this group), with tetra-CB (Attachment 1, Figure 1) showing the most similar pattern to 2,3,7,8-TCDD (Figure 3-2 [top panel]). This is also apparent on the cross plots with bathymetric change (Figure 3-3 for 2,3,7,8-TCDD and corresponding figures in Attachment 1 for other COPCs).
- The relationship between the shoal concentration distribution and the channel geomorphic groups varies by contaminant (Figure 3-2 [top panel] for 2,3,7,8-TCDD and corresponding figures in Attachment 1 for other COPCs).

Despite some differences noted above, adjustment of geomorphic groups below RM 7.8 for individual contaminants was not attempted for practical reasons and to avoid COPC-specific interpolation boundaries from causing the mapping to underrepresent the correlation between other contaminants and 2,3,7,8-TCDD (e.g., see Section 4 of the main RI report).

It should also be noted that additional sediment chemistry and physical data have been and will be collected below RM 7.8 as part of the Lower 8.3 Mile remedial design (per the ROD; USEPA 2016). These data will supplement and may in part supersede the RI data, allowing the mapping analysis presented in this appendix to be refined, including the definition of the interpolation groups described above.

3.2 Geomorphic Groups Upstream of RM 7.8

Upstream of RM 7.8, contaminant concentrations correlate with fine sediment content (Figure 3-7). For this reason, fine sediment deposits were delineated as geomorphic groups.

The boundaries of the fine sediment deposits were initially defined as the boundaries of the silt areas identified by the 2005 side scan sonar (SSS) survey and then expanded, as warranted, by probing data and grain size data (see Table 3-1 for the probing and grain size surveys used).

The following rules were applied when expanding boundaries or delineating new silt areas (Figure 3-8)¹⁹:

- Two sediment characteristics were taken as indicative of silt:
 - Probing measurements classified as silt²⁰ at the surface
 - Core data with at least 20% fine sediments²¹ measured at the surface based on the observation that samples with less than 20% fine sediments tend to have lower contaminant concentration (Figure 3-7)
- The boundaries of the silt areas were generally expanded to include a 10-foot radius around probing or grain size measurements meeting the above characteristics. An exception was where a “silt” probing location was adjacent to probing measurements that indicated a mixture of fine and coarser sediment (i.e., “silt and sand” or “gravel and silt or clay”). In this case, the silt boundary was drawn to include the “silt” location and exclude the mixed sediment location with the boundary being drawn halfway between the two locations, rather than 10 feet beyond the “silt” probe.
- Expanded or new silt areas based on probing were accepted only if the “silt” probing was confirmed by at least one sediment sample containing 20% or more fine sediment.
- New silt areas that were not continuous with existing SSS silt deposits were not incorporated into the mapping if they were smaller than 1 acre.

Surface sediment 2,3,7,8-TCDD concentrations within the expanded silt areas are compared to those in other sediment types upstream of RM 7.8 in Figure 3-9. This figure shows that the silt areas contain consistently higher surface concentrations, with the exception of a few samples in areas mapped as “rock and coarse gravel” and “gravel and sand” in the SSS survey. Based on the nature of those samples (e.g., fine sediment content), they likely reflect small pockets of fine sediment within the larger coarse deposits (as discussed in Sections 4.1 and 4.2 of the main RI report).

The majority of the individual silt deposits were separated into subgroups to prevent interpolation between deposits on opposite sides of the channel (these are collectively shown as *Silt* in Figures 3-1c through 3-1g and labeled individually for referencing purposes). A subgroup was split from the RM 10.9 silt deposit to account for the low 2,3,7,8-TCDD concentrations in the coarse

¹⁹ Silt groupings were discussed in interactions with USEPA. Silt groupings will be reassessed for revision pending the collection of additional sediment type data.

²⁰ Probing results indicating “silt and sand” were included in the expanded silt areas if there was other evidence of silt around them (see Figures 3-8c, 3-8d, and 3-8f). There were only four locations with “clay” probing results above RM 7.8. These “clay” probing results were not used to expand the silt areas.

²¹ Fine sediment is here defined as sediment passing through either the 63-micron sieve (#230) or the 75-micron sieve (#200), depending on the method used for grain size.

sediments that exist along the eastern shore (Figure 3-10, hatched area), presumably reflecting shallow water turbulence that prevents long-term accumulation of fine sediment.

The non-silt areas upstream of RM 7.8 were grouped as *Right Shoal LPR*, *Left Shoal*, and *Upstream Channel*.²² These shoals were continuous with the shoals downstream of RM 7.8. The *Upstream Channel* group comprises non-silt regions upstream of RM 7.8 that are not within the shoals.

Distributions of surface sediment concentrations by geomorphic group above RM 7.8 are shown in the bottom panel of Figure 3-2 for 2,3,7,8-TCDD and in Attachment 1 for other COPCs (bottom panel of Figures 1, 4, 7, 10, 13, 16, 19, and 22). Similar to 2,3,7,8-TCDD, concentrations of the other COPCs tend to be somewhat higher in the *Silt* group than in the *Shoal* group (albeit with varying degrees of overlap at the upper and lower tails), and concentrations in both of these groups tend to be notably higher than in the *Upstream Channel* group.

It should be noted that additional sediment chemistry and physical data above RM 7.8 will be collected as part of the Lower 8.3 Mile remedial design (per the ROD; USEPA 2016) and in connection to the remedies currently under consideration upstream of RM 8. These data will supplement and may, in part, supersede the RI data, such that the mapping analysis above RM 7.8 may also be refined in the future.

3.3 Geomorphic Groups Outside of the Lower Passaic River

The CFT model required sediment concentrations for initial conditions (ICs) within the LPR, Newark Bay, the Hackensack River, Arthur Kill, and Kill van Kull. This section describes the mapping groups used to interpolate sediment concentrations outside the LPR.

Outside the LPR, the navigation channel was used to delineate between channel and shoal for the purpose of mapping; the history of channel dredging and the resulting bathymetric differences justified separating the channel from the less perturbed shoals.

Within Newark Bay, the area within the navigation channel delineation was termed *Downstream LPR and Newark Bay Channel* and was continuous with the channels at the mouth of the LPR and the Kills. Areas not defined by the navigation channel were classified as one of three shoal groupings. The *Left Shoal* grouping follows the western bank of Newark Bay into Arthur Kill and is continuous with the *Left Shoal* grouping of the LPR. The *Hackensack and Newark Bay Right Shoal* grouping lies along the eastern bank starting from within the Hackensack River continuing through Kill van Kull (Figures 3-1n, o, and r). The *Staten Island Shoal and Southern Arthur Kill* grouping lies along the

²² Non-silt shoals from RM 7.8 to RM 14.5 were based on the combination of “broad shoals” and “margins” in Region 2’s geomorphic regions (SEI and HQI 2011). Above the upstream extent of USEPA’s geomorphic region at RM 14.5, two shoal areas were identified based on the 2007 bathymetry (Figure 3-1a).

southern bank of Newark Bay between the confluence of Arthur Kill and Kill van Kull and continues into the Kills (Figures 3-1o and p). The *Staten Island Shoal and Southern Arthur Kill* grouping was also used as the default grouping beyond the navigation channel definition in Arthur Kill (Figures 3-1o and p).

The Hackensack River was delineated into three groups. The navigation channel was used to define the *Hackensack Channel*, and areas not defined by the channel were classified as either *Upper Hackensack and Lower Left Shoal* or *Hackensack and Newark Bay Right Shoal* (continuous with Newark Bay Shoals). Similar to Arthur Kill, the navigation channel definition does not extend to the end of the mapped area. Areas beyond the navigation channel were defaulted into the *Hackensack and Lower Left Shoal* grouping (Figure 3-1r).

Due to a lack of data²³ in the channel area of Kill van Kull, the average concentration of samples in lower Newark Bay within the *Downstream LPR and Newark Bay Channel* grouping was used to estimate the channel concentration in Kill van Kull (Figure 3-11).

3.4 Professional Judgement Adjustments

Two adjustments made on the basis of professional judgment are detailed below.

As noted in Section 2, the location of the 2,3,7,8-TCDD measurement for core cluster 12A-0427 was used in favor of the cluster's centroid location from the 2012 Supplemental Sampling Program. This choice was made because the core cluster consists of samples that straddled two geomorphic groups. As shown in Figure 3-12, the centroid location of the 12A-0427 cluster is located in the *No Deposition Since 1949* group, while the specific core that was analyzed for 2,3,7,8-TCDD falls within the *Mixed Depositional Since 1966* group. Because the concentration of 11,700 ng/kg in this surface sample was more similar to cores in the *Mixed Depositional Since 1966* group, the 2,3,7,8-TCDD sample location was used in favor of the centroid location in this case.

As shown in Figure 3-13, the boundary between *Right Shoal LPR* and *Upstream Channel* at RM 11.75 was moved 5 feet toward the channel. This choice was made so that core LPRT12E is included in the shoal. The 2004²⁴ bathymetry data indicate that this core is at the top of a channel side slope, so its concentration would not be expected to represent the channel. The first inset map in Figure 3-13 shows a 3D view of this location with a five-times vertical exaggeration.

²³ The dataset available at the time of mapping lacked sufficient data in the channel area of Kill van Kull.

²⁴ The 2004 single-beam bathymetry survey is used in Figure 3-13 due to its coverage of this shoal (the roughly 100-foot spaced transects were interpolated onto a 5-foot by 5-foot grid using a triangulated irregular network [TIN]). The 2008 multi-beam survey also shows core LPRT12E at the top of the channel side slope.

3.5 Shallow Sediment Areas

Some parts of the LPR have less than 6 inches of sediment on top of hard bottom that likely contains little contaminant inventory. Such areas were identified by probing and core depth information and termed shallow sediment areas. They were delineated around groups of probing locations and cores that did not reach below 0.5 foot, as well as abandoned locations where cores were attempted but failed because of shallow coarse sediment. These areas were assumed to have no sediment below 0.5 foot and, thus, were assigned a concentration of zero for all subsurface layers. The delineation of shallow sediment areas is shown in Figure 3-14.

The zero subsurface concentrations are constrained to the spatial extent of the shallow sediment areas and are not interpolated beyond this extent.

4 Thiessen Polygon Mapping Approach

A Thiessen polygon delineates an area of influence for a sample location such that any point within the polygon is closer to that sample location than to any other sample location. The concentration throughout the polygon is assumed equal to the measurement at the sample location. This interpolation method is a simple representation of spatial correlation that assumes concentrations are perfectly correlated at the scale of the polygon and change abruptly at the boundary between adjacent polygons. When used to compute SWAC, it amounts to weighting each measured value by a polygon area that depends on the local data density (i.e., concentrations from areas of high density are assigned a smaller weight than concentrations from low-density areas), so the technique is sometimes referred to as de-clustering. Interpolation by Thiessen polygons has the benefit of honoring the distribution of the measured data and has been used at many contaminated sediment sites, including the Grasse and Hudson rivers (New York), Fox River (Wisconsin), and Housatonic River (Massachusetts).

Contaminant concentrations were interpolated using Thiessen polygons, with one exception in Kill van Kull (Figure 3-11).²⁵ Thiessen polygons were created for each geomorphic group described in Section 3 and clipped to the boundaries of the group. The interpolations for each group were combined to generate a continuous map of concentrations. For subsurface groupings, concentrations were set to zero within shallow sediment area polygons.²⁶ Maps of Thiessen polygon concentrations for the 2010 dataset Layers A and B are shown in Appendix O, Attachment 1 Figures 19 through 36.

4.1 Mapping Layer F (below 5.5 feet)

The layer F dataset described in Section 2.3.1 was interpolated using the Thiessen polygon methodology described in Section 4.

4.2 1995 Mapping

Mapped sediment concentrations in 1995 are required to set the ICs for the long-term model calibration period, water year (WY)1996 to WY2013. For increased spatial coverage and data density, data collected between 1995 and 1999 were taken as representative of 1995 (the start of the calibration period). Table 2-1 lists the studies used in the 1995 dataset. Sufficient data from the 1995 dataset were only available between RM 1 and RM 7 and in part of the Newark Bay channel.

²⁵ Due to lack of data and to prevent interpolation from Newark Bay across land into Kill van Kull, Thiessen polygons were not used in the channel area of Kill van Kull. Instead, an average of the data in the black-hatched "averaging area" was used to set the concentration in the magenta-hatched "applied area" as shown in Figure 3-11.

²⁶ The zero concentration in shallow sediment areas is constrained to the spatial extent of the shallow sediment areas and is not interpolated beyond this extent. The zero concentrations below full inventory cores are not interpolated into areas with measured concentrations for that depth interval.

(Appendix O, Attachment 1, Figures 1 through 18 show maps of the 1995 COPC concentrations in Layers A and B.) Elsewhere, the 2010 mapped surface was used to set 1995 ICs, with the exception of Layer A 2,3,7,8-TCDD and tetra-CB for which Thiessen polygons based on the 2010 dataset were used to set 1995 ICs—see Appendix O, Attachment 1, Figures 21 through 36 (a to g and m to q).

5 Conditional Simulation Mapping Approach

From RM 14.7 to the mouth, conditional simulation was used as the basis for mapping surface sediment 2,3,7,8-TCDD and tetra-CB. Conditional simulation provides a way to account for uncertainty in the mapping and in the estimation of remedial benefit for alternatives considered in the FS. An overview of the approach is provided in Section 5.1, and a more detailed discussion of its components is provided in Sections 5.2 to 5.4.

5.1 Overview

Conditional simulation is based on kriging, which is an interpolation method that produces gridded estimates of the parameter of interest and the uncertainty of those estimates (i.e., the prediction error), given the observed data and a variogram function that characterizes spatial correlation. The kriging estimate has the minimum variance among all estimates that are linear functions of the data, providing the best estimate of concentration and its variance at each grid node. The conditional simulation uses the kriging predictions, along with the variogram and the observed data, to create equally probable random realizations of the concentration field. These concentration fields are realistic in the sense that they (on average) reproduce the mean and variance of the observed data and the covariance as defined by the variogram. The measured concentrations at sample locations are also honored, although some deviation may arise from the resolution of the grid and the assumed variance at very small separation distance (termed the nugget of the variogram; see Section 5.3).

Kriging methods have been described many times (e.g., Cressie 1993; Chilés and Delfiner 1999; Isaaks and Srivastava 1989; Goovaerts 1997) and multiple variations of the approach exist. The basic simple kriging model used herein may generally be expressed as:

Equation 5-1

$$Z(s) = \mu + W(s) + \varepsilon(s)$$

where:

s	=	a spatial location
$Z(s)$	=	the value to be predicted; in this case, chemical concentration
μ	=	the mean, which is assumed constant over the interpolation domain
$W(s)$	=	the fluctuation, which is assumed to be a stationary Gaussian random field with zero mean and a covariance function defined by the variogram
$\varepsilon(s)$	=	an independent Gaussian random variable with zero mean and variance equal to the nugget of the variogram (τ^2), corresponding to the variance at zero separation distance (e.g., due to measurement error or microscale variance)

The kriging model defined in Equation 5-1 assumes that the field being interpolated is normally distributed²⁷ with stationary (constant) mean and variance, and the conditional simulation used herein is based on the same assumption. In an effort to conform to these assumptions, the concentration data were natural log transformed and divided into spatial groups that were kriged and simulated separately. In particular, the river was divided into areas with similar mean concentration (termed data groups or “mgroups”), and then mgroup data were converted to residuals by subtracting the mgroup mean from the data.²⁸ Mgroups whose residuals have similar variances were aggregated into kriging groups (termed “vgroups”). Kriging and conditional simulation were performed on residual concentrations using a variogram derived on the same basis. The simulation results for each vgroup were combined to generate a continuous map of results via a series of post-processing steps that include re-trending the predicted residuals (i.e., adding back the mgroup mean) and back-transforming the predictions to arithmetic space (by exponentiation).

The kriging and conditional simulations were conducted on a 20-foot by 20-foot grid in a straightened river coordinate system, yielding predictions on grid cell center points. Geostatistical calculations were performed using Ribeiro and Diggle’s (2001) GeoR package for the R environment for programming, graphics, data analysis, and statistical computation (R Core Team 2014).

²⁷ When kriging is applied to a skewed data distribution, the values from the longer tail of the distribution tend to exert disproportionate influence over the interpolator, thereby negatively impacting the accuracy of the interpolator. It is common practice to apply a data transformation to generate a dataset whose marginal frequency distribution is reasonably close to a normal distribution. This step is done prior to variogram development and kriging, and the kriging predictions are then back-transformed.

²⁸ The mean concentration μ in Equation 5-1 is zero when kriging is performed on a residual basis.

Conditional simulation was implemented using GeoR's Bayesian approach (Diggle and Ribeiro 2007), which is part of the `krige.conv` function.²⁹

Details of the major components of the conditional simulation approach are provided in the following sections. Data preparation, including the delineation of kriging groups, is covered in Section 5.2, development of the variogram is covered in Section 5.3, and post-processing results are in Section 5.4.

5.2 Data Preparation and Analysis

5.2.1 *Transformation of the Data*

The surface sediment dataset described in Section 2 was transformed in three ways prior to conducting the interpolation by kriging and conditional simulation.

First, the coordinates of the sample locations were converted to a straightened river coordinate system, which removes the sinuosity of the LPR by defining longitudinal position as distance along the thalweg and lateral position as cross-channel distance from the thalweg (Figure 5-1; based on a combination of the 2004 and 2011 bathymetry surveys). This coordinate transform is commonly implemented to allow the anisotropy of correlation distances of concentration to be represented in the interpolation; concentrations tend to be better correlated in the longitudinal direction than the lateral direction in the LPR (see Section 5.3).

Second, measured contaminant concentrations were converted to natural logarithm space, based on the observation that 2,3,7,8-TCDD and tetra-CB concentrations in the LPR are approximately log-normally distributed.

Third, the natural log concentrations were converted to residual concentrations by subtracting out the mean of the log concentrations within each mgroup (see Section 5.2.2.1).

5.2.2 *Groups for Kriging and Conditional Simulation*

As described in Section 5.1, the conditional simulation approach used herein is based on simple kriging, which assumes a stationary distribution of concentrations (i.e., no trend in mean or variance). Stationarity in the mean concentration was accomplished in an approximate fashion by sub-dividing the geomorphic groups described in Section 3 into data groups with similar means (mgroups). The stationarity of the residual concentration field (i.e., after subtracting out the mgroupp mean) was then

²⁹ It is noted that variogram anisotropy (Section 5.3) was implemented manually in the kriging and conditional simulations via a coordinate transform in the input files rather than directly in the GeoR parameter settings, due to an error that was noted in the GeoR anisotropy inputs.

considered and used to define kriging groups (vgroups) by combining mgroups with similar residual variances. The mgroup and vgroup delineations are described below.

5.2.2.1 Data Groups (mgroups)

In constructing the mgroups, the geomorphic groups (Section 3) were generally split at natural breaks³⁰ or breaks in Region 2's delineation of geomorphic regions (SEI and HQI 2011). The mgroup subdivisions are shown in Figure 5-2 (maps of mgroups) and Figures 5-3 and 5-4 (spatial plots of the mean plus or minus 2 standard errors and variance plus or minus its 95th percentile confidence bounds of natural log transformed 2,3,7,8-TCDD concentrations, and tetra-CB concentrations, respectively). The mgroup delineations are summarized as follows:

- The left shoal geomorphic group was split at RM 11.5 (break in Region 2's geomorphic regions), RM 9 (silt splits shoal), and RM 6 (Region 2 geomorphic break at the Fourth Avenue Bridge). The resulting left shoal mgroups are designated in Figure 5-2 as *Left Shoal RM 11.3-14.4*, *Left Shoal RM 9-11.3*, and *Left Shoal RM 6-9*.
- The right shoal geomorphic group was split at RM 12 (gap in shoal), RM 10.5 (RM 10.9 silt deposit splits shoal), RM 8.5 (silt splits shoal), and RM 6.5 (Region 2 geomorphic break). The resulting right shoal mgroups are designated in Figure 5-2 as *Right Shoal RM 12-14.7*, *Right Shoal RM 11-12*, *Right Shoal RM 8.5-10.5*, *Right Shoal RM 6.5-8.5*, and *Right Shoal RM 0-6.5*.
- The channel upstream of RM 7.8 geomorphic group was split at RM 13.75 (Region 2 geomorphic break at the Gregory Avenue Bridge), RM 13 (Region 2 geomorphic break at the Douglas O. Mead Bridge), RM 12.5 (Region 2 geomorphic break), and RM 9.5 (silt deposit splits channel). The resulting non-silt upstream channel mgroups are designated in Figures 5-2a through 5-2f as *Upstream Channel RM 13.75-14.7*, *Upstream Channel RM 13-13.75*, *Upstream Channel RM 12.5-13*, *Upstream Channel RM 9.5-12.5*, and *Upstream Channel RM 7.8-9.5*.
- The channel geomorphic groups downstream of RM 7.8 were adopted directly as individual mgroups. They are designated in Figures 5-2f through 5-2l as:
 - *No Deposition Since 1949*, also shown in Figures 3-1g through 3-1l
 - *Mixed Depositional Since 1966*, also shown in Figures 3-1g through 3-1l
 - *Highly Depositional Since 1966*, also shown in Figures 3-1g through 3-1l
 - *Downstream LPR and Newark Bay Channel*, also shown in Figures 3-1l through 3-1m
- Delineated silt mgroups include:
 - The silt deposit just upstream of RM 12 (*Silt RM 12* in Figures 5-2b and 3-1c)
 - The RM 10.9 silt deposit (*Silt RM 10.9* in Figures 5-2c and 3-1d)

³⁰ Natural breaks refer to gaps that give rise to separate polygons within a geomorphic group—for instance, multiple individual silt deposits comprise the silt geomorphic group above RM 7.8.

- The nearshore area along the RM 10.9 silt deposit (*Silt RM 10.9 Nearshore* in Figures 5-2c and 3-1d)
- A group of seven silt deposits between RM 10.4 and RM 8.2 (*Silt RM 8-10* in Figures 5-2c through 5-2e; comprises *Silt RM 10 Left*, *Silt RM 9-10*, *Silt RM 9 Left*, and *Silt RM 8-9 Right* in Figures 3-1e through 3-1f)
- The silt deposit just upstream of RM 7.8 (*Silt RM 7.8* in Figure 5-2f and Figure 3-1g)

5.2.2.2 Kriging Groups (vgroups)

To provide a basis for combining mggroups of similar variance for kriging despite differing means, the natural log transformed data were de-trended by subtracting the mean, and the similarity of the residual distributions was evaluated. Adjacent mggroups were generally judged to have similar variance if the 95th percentile confidence limits on the residual variances overlapped significantly³¹ and merged into a kriging group (vgroup). Reducing the number of groups in this manner results in more data per group and yields a better estimate of the variance. It also means fewer instances of the sharp concentration breaks that typically occur at boundaries between interpolation groups.

Kriging vgroups are shown in Figure 5-5 (maps of vgroups) and Figures 5-6 and 5-7 (concentration residuals [upper panel] and the variances plus or minus 95th percentile confidence bounds [lower panel] in relation to river mile). Overall, the 26 mggroups were reduced to 9 vgroups³²:

- Left shoal mggroups *Left Shoal RM 9-11.3* and *Left Shoal RM 6-9* were combined into vgroup *Left Shoal RM 6-11.3*.
- Right shoal mggroups upstream of RM 6.5 were combined into vgroup *Right Shoal RM 6.5-14.7*.
- All silt mggroups were combined into vgroup *Silt*.
- Upstream channel mggroups (non-silt areas above RM 7.8) were combined into vgroup *Upstream Channel*.
- Downstream channel mggroups *No Deposition Since 1949* and *Mixed Depositional Since 1966* were combined into vgroup *No Deposition Since 1949 and Mixed Depositional*. Mggroups *Highly Depositional Since 1966* and *Downstream Channel* were combined into vgroup *Downstream Channel and High Deposition Since 1966*.

The distribution of COPC concentration and residual concentration within each vgroup is shown in Figures 5-8 and 5-9 for 2,3,7,8-TCDD and tetra-CB, respectively.

³¹ An F-test of equality of variances was performed on the residuals. P-values are printed above the bottom panel in Figures 5-3 and 5-4.

³² The mggroups *Left Shoal RM 0-6*, *Left Shoal RM 11.3-14.4*, and *Right Shoal RM 0-6.5* were not combined with other mggroups and remain as separate vgroups.

5.3 Variogram Development

Variograms characterize spatial correlation. They describe both the strength and directionality of spatial correlation—in effect, the zone of influence of individual data values on predictions at nearby locations, typically with declining influence of a data point with increasing distance from its location. Variograms take the form of a curve relating semivariance (half the variance) to separation distance, which is fitted to an experimental variogram developed from analyzing the observed data in pairs binned by their separation distance (e.g., Isaaks and Srivastava 1989).

Data in the LPR are generally too sparse to develop a variogram for each vgroup, with the exception of the RM 10.9 silt deposit (Figure 5-10), which contains high-density sediment data collected for remedial design (spaced nominally 90 feet apart). The data within this deposit were used to develop an experimental variogram and fit a variogram model (Section 5.3.1), which was then generalized for application to other parts of the river³³ (Section 5.3.2). Directionality (anisotropy) was incorporated into the variogram based on the observation that surface sediment concentrations within the LPR tend to be more correlated in the along-flow direction than in the cross-flow direction (e.g., Figure 5-11, which suggests sharper gradients laterally than longitudinally).

5.3.1 RM 10.9 Silt Deposit Variogram

The along-flow variograms derived for the RM 10.9 silt deposit dataset for 2,3,7,8-TCDD and tetra-CB are presented in Figures 5-12 and 5-13, where the experimental variogram based on binned data pairs is shown in red (including the number of data pairs per bin) and the fitted Gaussian variogram model is shown in black. Directionality was incorporated by restricting the experimental variogram to data pairs within a search band tolerance of plus or minus 20 degrees around the along-flow axis, and a bin size of 95 feet was used.³⁴ The variogram indicates structure in the along-flow direction, in that there is a five-fold difference between the “nugget” (the y-intercept) and the “sill” (the semivariance at large separation distances)³⁵. Conceptually, the nugget represents variance at near-zero separation distance (e.g., due to measurement error or microscale variance) and the sill reflects the background or global variance. The 2,3,7,8-TCDD variogram in Figure 5-12 indicates a “range” of spatial correlation of 505 feet, which is here defined as the separation distance

³³ The use of contemporary data in other parts of the LPRSA and additional datasets (e.g., historical LPRSA sediment data and Lister Avenue Phase 1/Phase 2 data) in variogram development was explored with Region 2 but ultimately not adopted due to data limitations.

³⁴ Implementation notes: The variogram was developed from the natural log transformed data. The along-flow direction corresponds to the zero azimuth within the straightened river coordinate system; thus, the angle of anisotropy is also zero. Bin size was selected such that most bins would be populated with at least 15 pairs of data; bins with no data are not shown on the variogram. The GeoR package uses the variogram estimator suggested by Hawkins and Cressie (1984), which provides a robust alternative to the classical estimator (see Cressie 1993 for details).

³⁵ For the 2,3,7,8-TCDD variogram (Figure 5-12), the nugget (0.68) is 21% of the sill (3.28, the sum of the nugget and the “partial sill”). For the tetra-CB variogram (Figure 5-13), the nugget (0.34) is 15% of the sill (2.34).

corresponding to a semi-variance equal to the nugget plus 63% of the “partial sill” (defined as the sill minus the nugget)³⁶. Note that definitions of range vary in the literature. The tetra-CB variogram in Figure 5-13 indicates a “range” of spatial correlation of 390 feet.

The variogram in the cross-flow direction is assumed to differ only in the range of spatial correlation (i.e., using the same nugget and sill), and the strength of the anisotropy is expressed by the ratio of the range in the along-flow direction to the range in the cross-flow direction—a quantity termed the anisotropy ratio. The anisotropy ratio was estimated from the 2,3,7,8-TCDD data via rose diagrams (Figure 5-14), which evaluate variogram range along a series of azimuths spanning all directions to characterize anisotropy (see Isaaks and Srivastava 1989). In order to have sufficient data in both the along-flow and cross-flow directions, additional data beyond the RM 10.9 silt deposit were included in constructing the rose diagrams; the expanded dataset is shown in Figure 5-15. The rose diagrams³⁷ in Figure 5-14 suggest an anisotropy ratio between 3 (tolerance of 30 degrees) and 6 (tolerance of 20 degrees).³⁸ A ratio of 5 was selected for the kriging and conditional simulations. Given the high spatial correlation between 2,3,7,8-TCDD and tetra-CB, as discussed in Section 7.1.1.4, the anisotropy was modeled the same for both COPCs. It is noted that an anisotropy ratio of 5 may be an upper bound estimate given that the rose diagram analysis combines data from vgroups that are interpolated separately within the conditional simulation.

5.3.2 Generalization of the RM 10.9 Silt Deposit Variogram to Other Areas

Because there was not enough data to develop a variogram for each of the vgroups, the variogram developed from the RM 10.9 silt deposit dataset was scaled and applied to other vgroups. In particular, the sill and nugget of the RM 10.9 variogram model (Figures 5-12 and 5-13) were scaled to each vgroup based on the local variance relative to that of the RM 10.9 deposit dataset (variance of the natural log transformed data). This approach preserves the shape and range of the RM 10.9 deposit variogram when applying it to other vgroups. This scaling was performed separately for 2,3,7,8-TCDD and tetra-CB. Tables 5-1 and 5-2 list the variogram model parameters used for each vgroup. The anisotropy ratio was set to 5 for all vgroups, in accordance with the RM 10.9 variogram development.

When scaling the variogram, an exception was made for the vgroup encompassing the right shoal below RM 6.5 (*Right Shoal RM 0-6.5*), in that the two lowest 2,3,7,8-TCDD and tetra-CB

³⁶ For 2,3,7,8-TCDD, the range of 505 feet is where the semi-variance is 2.32, corresponding to 63% of the partial sill (2.6) plus the nugget (0.68).

³⁷ The anisotropy ratio corresponds here to the ratio of the major to minor axis lengths of the ellipse fitted to the rose diagram “spokes,” each of which quantifies the range of spatial correlation along a given azimuth using data pairs within the specified directional tolerance (Figure 5-14 evaluates tolerances of 20 and 30 degrees).

³⁸ The anisotropy ratio is lower for the higher tolerance values (here 30 degrees) because data farther from each azimuth are included in the variogram, which dilutes the anisotropy. Lower tolerance values emphasize the directionality of spatial correlation but reduce the number of pairs in the variogram, which can cause the rose diagram to have erratic spokes.

concentrations³⁹ were dropped prior to calculating the variances of 0.8 and 0.7 that were used to scale the variogram for 2,3,7,8-TCDD and tetra-CB, respectively (see Figures 5-8h and 5-9h). This was done to prevent these low outliers from inflating the variance, which allowed the conditional simulation to better reproduce the remainder of the concentration distribution. For tetra-CB, a second exception was made for *No Deposition Since 1949 and Mixed Depositional Since 1966* where the lowest tetra-CB concentration of 0.0031 milligrams per kilogram (mg/kg) (12A-0455) was dropped prior to calculating the variance of 1.9 that was used to scale the variogram (see Figure 5-9b).

5.4 Post-Processing of Results

The kriging and conditional simulation results were re-trended and back-transformed using Equation 5-2.

Equation 5-2

$$C = e^{(Z+\mu)}$$

where:

C	=	2,3,7,8-TCDD concentration in arithmetic space
Z	=	residual concentration in transformed space (output from kriging or conditional simulation)
μ	=	the mean of the natural-log-transformed concentration data in the mgroup

Conditional simulation occasionally predicts unrealistically high or low concentrations (i.e., far outside the range of measured data), which can bias mean concentrations and the estimated benefit achieved by remediation to a particular concentration threshold. To eliminate this, results within each vgroup were capped at two times the maximum measured value within the vgroup and globally at the maximum surface sediment concentration measured in the LPRSA (51,100 ng/kg for 2,3,7,8-TCDD and 10.8 mg/kg for tetra-CB). Likewise, low values within each vgroup were bottomed-out at half the minimum measured value within the vgroup. Tables 5-3 and 5-4 list information relating to capping and bottoming-out for each vgroup for 2,3,7,8-TCDD and tetra-CB, respectively.

³⁹ Sample IDs CLRC-002 (0.05 ng/kg 2,3,7,8-TCDD and 0.0036 mg/kg tetra-CB) and 12A-0421 (0.77 ng/kg 2,3,7,8-TCDD and 0.00026 mg/kg tetra-CB) were dropped. Excluding these samples makes the data distribution closer to log-normal; see Figures 5-8h and 5-9h.

6 Resampling of Layer B

6.1 Overview/Rational

Layer B mapping was initially conducted using Thiessen polygons. Overlaying the resultant Layer A and Layer B maps revealed less correlation and greater differences than exist in the underlying data. The problem derives from two sources of incompatibility:

1. The conditional simulation used for 2010 Layer A 2,3,7,8-TCDD and tetra-CB mapping is incompatible with the Thiessen polygon interpolation originally used in Layer B.⁴⁰ Figure 6-1 shows an example of this for 2,3,7,8-TCDD from RM 8 to RM 14.7 in 2010, where the relationship between Layer A and Layer B core concentration data (left panel) was not preserved when Layer A conditional simulation results were paired with the original Layer B interpolation using Thiessen polygons (note the greater density of points away from the one-to-one line).
2. The original Layer A and Layer B Thiessen polygons developed for 1995 and for 2010⁴¹ are mismatched in some areas due to differing data densities. Figure 6-2 shows an example of this for 2,3,7,8-TCDD between RM 0 to RM 7.8 for 1995; the relationship between the Layer A interpolation and the original Layer B interpolation (right panel) was weaker than the relationship between Layer A and Layer B core data (left panel) due to the inclusion of locations where both Layer A and Layer B measurements were not available (see Section 7.1.2 for an example of this issue and its resolution).

To eliminate unrealistic concentration gradients between the layers, a method was developed to select Layer B concentrations based on the Layer A concentrations such that the overall degree of correlation in the data is preserved.

No adjustments were made to deeper layer Thiessen polygon maps because the CFT model is less sensitive to the mapping of these layers than it is to the Layer B mapping. Moreover, the core data indicated that concentrations were less correlated between layers, relative to the Layer A to Layer B correlation.

6.2 Methodology

Layer B values were assigned based on the local Layer A value. To accomplish this, measured Layer A concentrations were segmented into bins. Bin sizes were selected to preserve the overall relationship between measured Layer A and Layer B concentrations while capturing the random variability in Layer B concentrations occurring within relatively narrow ranges of Layer A concentration. The Layer

⁴⁰ This does not apply to the seven other modeled COPCs where Thiessen polygons were used to map Layer A. Also, this only applies to RM 0 to RM 14.7. Outside of this RM range, Thiessen polygons were used for mapping all COPCs.

⁴¹ For the seven modeled COPCs for which conditional simulation was not conducted.

A bins used for each modeled COPC are listed in Table 6-1 and are shown as vertical dashed lines in Figures 6-3 and 6-4 for 2,3,7,8-TCDD and in Attachment 2, Figures 1 through 16 for other COPCs (these figures are described further in the subsections below). For locations with Layer A concentrations within a bin, Layer B concentrations were randomly chosen with replacement from the measured Layer B values within the bin.⁴² Layer B values of zero were removed from the analysis⁴³ and the shallow areas described in Section 3.5 were not resampled because these areas are defined as having a sediment depth of 6 inches or less and are therefore assigned a zero Layer B concentration.

The resampling depended on the method used to map Layer A. For Layer A conditional simulation mapping, Layer B concentrations were assigned at every point on the conditional simulation map. For Layer A Thiessen polygon mapping, Layer B concentrations were assigned only at Layer A sampling locations where a measured Layer B concentration was lacking in the data (largely where grab samples were collected). This resulted in a map comprised of paired Thiessen polygons for the two layers (i.e., equally sized polygons containing either measured concentrations in both Layer A and Layer B or a Layer B concentration assigned based on a measured Layer A concentration).

Implementation details for the 2010 conditional simulation mapping and the 2010 and 1995 thiessen polygon mapping are described in Section 6.2.1 through 6.2.2. Table 6-2 summarizes the datasets and the interpolated layer A surfaces used in the resampling.

6.2.1 Conditional Simulation Resampling (2010 Only)

The largest mismatch between the Layer A mapping and the original Layer B Thiessen polygon mapping occurred where the conditional simulation was used to represent Layer A (Figure 6-1).

Resampling was done separately for RM 0 to RM 7.8, silt areas between RM 7.8 to RM 14.7, and non-silt areas between RM 7.8 to RM 14.7.⁴⁴ The split at RM 7.8 was chosen to be consistent with how the conditional simulation mapping was conducted. Above RM 7.8, Layer A-Layer B relationships for silt and non-silt regions were established using the 2010 data (Figures 6-3a and 6-3b for 2,3,7,8-TCDD and Figures 1a and 1b of Attachment 2 for tetra-CB). Below RM 7.8, 1995 and 2010 data were pooled to form a larger resampling dataset because of the similarity in the Layer A-Layer B relationship in the two individual datasets (blue and green points in Figure 6-3c for

⁴² There were some cases of no available paired Layer A and Layer B data in the smallest or largest concentration bins. In these cases, the next smallest or largest bin was used to resample the data (i.e., bins were merged during resampling in these cases).

⁴³ There were zeros in layer B data due to the assumption of zero concentrations below the last measured segment for complete cores (see Appendix I). These zeros were excluded from the pool of data for resampling because they are not likely to be representative of other areas of the river outside of the specific locations where they were collected. Zeros are not shown on the cross-plots, but the number of zeros is indicated in the notes.

⁴⁴ Layer B was not resampled above RM 14.7 because less data are available here and the Layer B mapping is of lesser importance to the CFT model in this region because it is treated as non-erodible hard-bottom in the sediment transport model.

2,3,7,8-TCDD and Figure 1c of Attachment 2 for tetra-CB). Layer B values were assigned based on the local Layer A value using the methodology described above (i.e., randomly selected from the measured Layer B values within the relevant Layer A concentration bin) applied on the 20-by-20-foot kriging grid. Results of the resampling are discussed Section 7.1.2.

6.2.2 Thiessen Polygon Resampling

For cases where the Layer A mapping and the original Layer B mapping were both based on Thiessen polygons, the disconnect between the interpolated Layer A and Layer B concentrations was limited to locations that did not have measured concentrations for both Layer A and Layer B (as seen in Figure 6-2 and described in Section 6.1). Thus, the Thiessen polygon resampling was applied only at these locations, i.e., a Layer B concentration was assigned to the Layer A sampling location and a new Layer B polygon was drawn around this point. Outside of these areas, the original Layer B Thiessen polygon mapped concentrations were maintained (i.e., those based on measured Layer B concentrations).

6.2.2.1 2010 Thiessen Polygon Resampling

For the 2010 Layer B Thiessen polygon mappings (i.e., all COPCs except 2,3,7,8-TCDD and tetra-CB), resampling was applied as needed to the Layer A 2010 mapped surfaces described in Section 4. The resampling was performed separately for RM 0 to RM 7.8, silt areas between RM 7.8 to RM 14.7, and non-silt areas between RM 7.8 to RM 14.7 using the datasets shown in Attachment 2, Figures 2 through 8. For Thiessen polygons that overlapped the RM 7.8 boundary, the resampled Layer B concentrations from the 0 to 7.8 RM data pool were used.

6.2.2.2 1995 Thiessen Polygon Resampling

For the 1995 Layer B Thiessen polygon mappings (all COPCs), resampling of Layer B was applied as needed to the Layer A 1995 mapped surfaces described in Section 4.2, and was conducted separately within RM 1 to RM 7 and outside this RM extent.

RM 1 to RM 7 is the only region where there are 1995 data available for Layer B resampling. Within this region, the 1995 data were supplemented with 2010 data in order to have sufficient data counts in each of the Layer A concentration bins, as shown in Figure 6-4 for 2,3,7,8-TCDD and Figures 9 through 16 of Attachment 2 for the other COPCs.

Outside of RM 1-7, the datasets used for resampling are the same as for 2010 (Section 6.2.1 for 2,3,7,8-TCDD and tetra-CB and Section 6.2.2.1 for other COPCs).

7 Results of the Mapping in the LPR

The mapped concentrations resulting from the methods described above are shown in Figures 7-1 (2,3,7,8-TCDD) and 7-2 (tetra-CB) (two example conditional simulations). Maps for Layer A and Layer B for all COPCs are shown in Appendix O, Attachment 1, Figures 1 through 36 (see Attachment 1, Table 1 for a list of maps used in CFT model ICs).⁴⁵

7.1 Quality Control

Quality control (QC) checks were performed on the mapping results to verify that the approaches were behaving as expected, particularly for the results of the conditional simulation (Section 7.1.1) and Layer B resampling (Section 7.2.2) because they are derived from the more complicated approaches.

7.1.1 Quality Control for Conditional Simulation Mapping

A representative subset of the QC checks conducted is presented in the following subsections to illustrate the performance of the conditional simulation implementation.

7.1.1.1 Recovery of the Input Concentration Distributions

The output from the simulations should approximately honor the distribution of the input data. This is checked in Figures 7-3 and 7-4 on a full river basis (Figures 7-3a and 7-4a) and vgroup basis (Figures 7-3b through 7-3j and 7-4b through 7-4j) for the two sample conditional simulations illustrated in Figures 7-1 and 7-2. The Thiessen polygon approach was for the purposes of this QC check sampled on the 20-foot-grid used in the conditional simulations to approximate de-clustered data (red markers) and appropriately area-weight the data for the full river comparison.

Exact agreement is not expected for the following reasons:

- The data are not perfectly log-normally distributed.
- There are cases where Thiessen polygons draw from data outside the vgroup (e.g., for *Left Shoal RM 11.3-14.4* in Figure 7-3f, the 0.12 ng/kg concentration in the Thiessen results [red points] is based on a sample upstream of the vgroup and is therefore not included in the conditional simulation for this vgroup [blue and green points]).
- The variance of the Thiessen-predicted distributions may slightly differ from the variance of raw data used to generate the conditional simulation results.

⁴⁵Note that the COPC maps developed for areas downstream of RM 8 were used solely for initializing the CFT model. For the FS, simulated scenarios will assume the ROD remedy for the Lower 8.3 Miles (below RI RM 8).

Regardless, the agreement in Figures 7-3 and 7-4 is judged to be reasonable, and it is therefore concluded that the conditional simulations are adequately recovering the concentration distributions of the data.

7.1.1.2 Recovery of the Input Variograms

The output from the simulations should, on average, honor the variograms from which they were constructed. A variogram (azimuth zero, tolerance 5 degrees) was developed from the conditional simulation output separately for each vgroup and for each conditional simulation. The 100 variograms were then aggregated into a single variogram for each vgroup (Figures 7-5 and 7-6, blue dots) and compared to the input variogram (black lines). The conditional simulation results generally indicate good recovery of the model variogram, particularly at small separation distances. Some deviation is exhibited at larger separation distances, which is attributed to factors such as the shape of the interpolation groups and the normality of the input dataset (i.e., the de-trended residual concentrations). The largest deviation for 2,3,7,8-TCDD is observed for the *Right Shoal RM 0-6.5* vgroup, where the aggregate variogram is generally higher than the variogram model. In this instance, the comparison is likely influenced by the fact that the input variogram was scaled with a variance calculated by excluding the two lowest points from the distribution (blue dashed line; as discussed in Section 5.3, the two data points cause the input distribution for this vgroup to depart from log normality and they were excluded from the variance calculation to avoid inflating the variance). Because the conditional simulations include these two data points, it is not surprising that the aggregate variogram derived from the simulations predicts a higher population variance (higher sill) than the input variogram. For tetra-CB, the largest deviation in Figure 7-6 is observed for *No Deposition Since 1949 and Mixed Depositional Since 1966*. For this vgroup, the input tetra-CB variogram was scaled with a variance that excluded the lowest data point.⁴⁶ Because the conditional simulations include this data point, it is not surprising that the aggregate variogram derived from the simulations predicts a higher population variance (higher sill) than the input variogram.

7.1.1.3 Recovery of the Observed Concentrations Near Sample Locations

Predicted concentrations compared reasonably well to the input data on a residuals basis (Figures 7-7 and 7-8) and after back-transformation (Figures 7-9 and 7-10) and do not indicate a bias. It is noted that the concentrations are not expected to fall exactly on the one-to-one line because concentrations are predicted on a 20-foot by 20-foot rectangular grid that is not perfectly aligned with the sample locations, and the interpolations are based on a variogram with a non-zero nugget (Figures 5-12 and 5-13).

⁴⁶ This low data point (which caused the input distribution to deviate from log normality) was excluded to avoid inflating the variance.

7.1.1.4 Recovery of the Correlation Between 2,3,7,8-TCDD and Tetra-CB Data

Surface sediment 2,3,7,8-TCDD and tetra-CB concentrations are correlated (Figure 7-11, right panel). It was important to preserve this correlation in the conditional simulation used for model initial conditions. Using the same random seed for both the 2,3,7,8-TCDD and tetra-CB conditional simulations resulted in correlated simulations (Figure 7-11, left panel).

7.1.2 Quality Control for Layer B Resampling

A representative subset of the QC checks conducted is presented below to illustrate the performance of the Layer B resampling.

The resampled Layer B surface was compared to the mapped Layer A surface in cross-plots and box-plots to verify that the resampled layer approximately honored the relationship between the Layer A and Layer B in the measured data. Cross-plots comparing resampled Layer B to Layer A for 2,3,7,8-TCDD are shown in Figures 7-12 through 7-14. Table 7-1 lists the appropriate data versus data plots and Layer A mapped surface versus resampled Layer B plots for comparison across all COPCs. The box plots on the right panels are qualitatively consistent between the mapped surfaces and the measured data, indicating that the mean, median, and outliers of the resampled data are generally representative⁴⁷ of the relationship between the Layer A and Layer B measured data.⁴⁸

Maps of Layer B concentrations in Appendix O, Attachment 1, Figures 10 through 18 and 28 through 36 allow for a visual comparison with maps of Layer A concentrations in Appendix O, Attachment 1, Figures 1 through 9 and 19 through 27. The relationship between Layer A and Layer B is particularly evident for the conditional simulation (within Appendix O, Attachment 1, compare Figure 19 with Figure 28 for 2,3,7,8-TCDD and Figure 20 with Figure 29 for tetra-CB). In these two sets of maps, the Layer B mapped surface has more noise than the Layer A surface, but they have similar patterns such that high values on the Layer A map are generally also elevated on the Layer B map, and the same correspondence applies to low values between the maps.

Figure 7-15 compares the 1995 Layer A Thiessens (left panel), with the old layer B Thiessens (middle panel) and the resampled layer B (right panel). In this map, resampled areas on the right panel occur in areas where there was a mismatch between the polygons based on point data in Layer A (left panel) and Layer B (middle panel). For example, Figure 7-15t shows areas with more 2,3,7,8-TCDD

⁴⁷ In some cases, a divergence between the box plots of the resampling data and the mapping results may be caused by a low number of resampled points in the mapping. For example, in Figure 10 of Attachment 3 there are no resampled points in the 100 to 300 ng/kg bin and thus the statistics of the resampling dataset (Figure 10 of Attachment 2) are not reproduced in the mapping for this bin.

⁴⁸ Note that the number of instances of zero concentrations (reported in the figure notes) differs between the cross-plots of Layer A versus Layer B concentrations in the data and the corresponding plots for the mapped concentrations. Whereas both plots reflect the number of complete cores (where a concentration of zero is assumed below the last measured segment; see Appendix I), the cross-plots of mapping results also have zero Layer B concentration within shallow sediment areas (see Section 3.5).

data points in Layer A (left panel) than Layer B (middle panel), which are addressed by resampling Layer B (right panel).

7.2 Combining Results from Different Interpolation Methods

For the 2,3,7,8-TCDD and tetra-CB mapping of the surface sediment concentrations in the 2010 dataset, conditional simulation (CS) 37 was used as a base simulation based on USEPA-CPG interactions from the May 1, 2017 mapping meeting and subsequent interactions. This simulation is shown in the right panel of Figures 7-1 and 7-2. CS 37 was used to represent concentrations between RM 0 and RM 14.7. Outside the extent of the conditional simulation, the 2010 Thiessen polygon mapping shown in Appendix O, Attachment 1, Figures 19 and 21 was used to represent surface sediment concentrations.

For subsurface mapping of all COPCs, Layer B concentrations, as described in Section 6, were used to represent concentrations between RM 0 and RM 14.7. Outside RM 0 to RM 14.7, the Thiessen polygon Layer B mapping was used to represent surface sediment concentrations. Appendix O, Attachment 1, Figures 28 through 36 show the combination of these two mappings.

8 References

- AECOM, 2015. *Low Resolution Coring Supplemental Sampling Program Addendum Second Supplemental Sampling Program Characterization Summary*. Draft. Lower Passaic River Study Area RI/FS. November 2015.
- Anchor QEA (Anchor QEA, LLC), 2016. Memorandum to: Dr. Robert Law and Willard Potter, de maximis, inc. Regarding: Proposed COPCs to be Calibrated in the Lower Passaic River/Newark Bay Contaminant Fate and Transport Model. December 8, 2016.
- Bopp, R.F., M.L. Gross, H. Tong, H.J. Simpson, S.J. Monson, B.L. Deck, and F.C. Moser, 1991. "A major incident of dioxin contamination: sediments of New Jersey estuaries." *Environmental Science and Technology* 25(5):951–956.
- Chilés, J.P. and P. Delfiner, 1999. *Geostatistics Modeling Spatial Uncertainty*. New York: John Wiley & Sons.
- Cressie, N., 1993. *Statistics for Spatial Data*. New York: John Wiley & Sons.
- Diggle, P.J. and P.J. Ribeiro, Jr., 2007. *Model-Based Geostatistics*. New York: Springer Science+Business Media, LLC.
- Goovaerts, P., 1997. *Geostatistics for Natural Resources Evaluation*. New York: Oxford University Press.
- Hawkins, D.M. and N.A.C. Cressie, 1984. "Robust kriging – a proposal." *Journal of the International Association for Mathematical Geology* 16:3–18.
- Isaaks, E.H. and R.M. Srivastava, 1989. *An Introduction to Applied Geostatistics*. New York: Oxford University Press.
- Ribeiro, P.J., Jr., and P.J. Diggle, 2001. "geoR: A Package for Geostatistical Analysis." *R-NEWS* 1(2):51–18.
- R Core Team, 2014. *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. Vienna, Austria. Available at: <http://www.R-project.org/>.
- SEI and HQI (Sea Engineering, Inc. and HydroQual, Inc.), 2011. *Lower Passaic River: System Understanding of Sediment Transport*. May 2011.
- USEPA (U.S. Environmental Protection Agency), 2015. *Lower Passaic River Study Area Remedial Investigation and Feasibility Study EPA Review of the Cooperating Parties Group Approach to Mapping Contaminants of Potential Concern*.
- USEPA, 2016. *Record of Decision. Lower 8.3 Miles of the Lower Passaic River. Part of the Diamond Alkali Superfund Site. Essex and Judson Counties, New Jersey*. March 2016.

USEPA, 2017. *EPA Comments – June 30, 2017 Draft Lower Passaic River Study Area Remedial Investigation/Feasibility Study Remedial Investigation Report, Appendix J Dated February 2017.*

Windward and AECOM (Windward Environmental, LLC, and AECOM, Inc.), 2015. *Data Usability and Data Evaluation Plan for the Lower Passaic River Study Area Risk Assessments.* Final. Prepared for Cooperating Parties Group, Newark, NJ. Lower Passaic River Restoration Project.