FINAL

Appendix J
Interpolation Methods for Delineating Areas with RAL Exceedances

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ABBREVIATIONS

COC	contaminant of concern
LDW	Lower Duwamish Waterway
OC	organic carbon
PCB	polychlorinated biphenyl
PDI	Pre-Design Investigation
RAL	remedial action level
RD	remedial design
TOC	total organic carbon

1 Overview of Data Interpolation Approach

This appendix presents the data interpolation method selection, application, and results used to delineate remedial action level (RAL) exceedance areas in the middle reach of the Lower Duwamish Waterway (LDW), as well as the uncertainty analysis used to assess the level of confidence in the RAL exceedance area boundaries. The same general interpolation methods used in the upper reach of the LDW were used in the middle reach.

Interpolation methods use a local neighborhood of surrounding data points to estimate values (e.g., concentrations, probabilities of exceedance, or other physical or chemical parameters) at all unsampled points in a project area. Interpolation methods are commonly used to support remedial design (RD) and delineate areas requiring remedial action at sediment cleanup sites (e.g., Thornburg et al. 2005; Anchor QEA 2014; Anchor QEA and Tetra Tech 2016; City of Tacoma 2002).

1.1 Design Dataset

This section describes the attributes of the middle reach design dataset as defined in Section 3.1 of main report. Elements described in the following sections include contaminants of concern (COCs) with concentrations exceeding RALs, surface and subsurface sampling depths for which RALs were evaluated, and the appropriate use of organic carbon (OC)-normalized versus dry weight concentrations.

1.1.1 Contaminants of Concern

Polychlorinated biphenyls (PCBs) are the primary COC in the middle reach of the LDW and make up the majority of RAL exceedances. Therefore, PCBs were the primary focus of spatial interpolation, including semivariogram development, indicator kriging, and uncertainty analysis.

COCs other than PCBs were also extensively sampled and analyzed throughout the middle reach and in many cases, other COCs exceeded RALs in the same locations as did PCBs. When other COCs exceeded RALs and PCBs did not, the other COCs were addressed separately from PCBs using a simpler interpolation method—Thiessen polygons—due to their more localized areas of concern. Other COCs that determined local RAL exceedance area boundaries included metals, polycyclic aromatic hydrocarbons, other semivolatile organic compounds (bis[2-ethylhexyl] phthalate, butyl benzyl phthalate, benzoic acid, dibenzofuran, 2,4-dimethylphenol, and chlorobenzenes), and dioxins/furans, depending on the area. For these other COCs, surface and subsurface datasets were used to develop Thiessen polygons, which were then merged into a combined RAL exceedance area boundary encompassing all surface and subsurface exceedances of RALs among other COCs. The interpolation results for all other COCs were then overlain on the PCB interpolation to develop the final combined RAL exceedance area footprints.

1.1.2 Surface and Subsurface PCB Datasets

Interpolations were performed on two sediment depth-defined datasets applicable to RALs: surface sediment, defined as 0 to 10 cm; and subsurface sediment, defined as 0 to 45 cm (intertidal areas), 0 to 60 cm (subtidal areas), and shoaling intervals in the Federal Navigation Channel. The distributions of PCB RAL exceedances (red symbols) and non-exceedances (white symbols) in surface and subsurface sediments are presented on Maps J-1 and J-2, respectively. Histograms of the distributions of the PCB concentrations for surface and subsurface data are presented in Attachment J-1. Ultimately, all datasets were combined to develop an integrated RAL exceedance area boundary circumscribing all surface and subsurface PCB RAL exceedances.

1.1.2.1 Surface Sediment PCB Dataset

Surface sediment PCB data were compared to a PCB RAL of 12 mg/kg OC (expressed on an OC-normalized basis). The results were as follows:

- 317 data points and 24 RAL exceedances (7.6% exceedance frequency) in the surface sediment subtidal PCB dataset
- 225 data points and 93 RAL exceedances (41.3% exceedance frequency) in the surface sediment intertidal PCB dataset.

1.1.2.2 Subsurface Sediment PCB Dataset

The subsurface sediment PCB dataset was divided into separate areas with three different RALs: 12, 65, and 195 mg/kg OC, depending on sediment bed elevation, recovery category area, and whether the data were from shoaling areas in the Federal Navigation Channel. The results were as follows:

- 179 data points and 66 RAL exceedances (36.9% exceedance frequency) in the subsurface PCB dataset in areas with a RAL of 12 mg/kg OC
- 147 data points and 34 RAL exceedances (23.1% exceedance frequency) in the subsurface PCB dataset in areas with a RAL of 65 mg/kg OC[1]
- 94 data points and 1 RAL exceedance (1.1% exceedance frequency) in the subsurface PCB dataset in areas with a RAL of 195 mg/kg OC[2]

1.1.3 Organic Carbon Normalization of PCB Data

Consistent with the LDW Record of Decision (EPA 2014), PCB data were normalized to OC content for comparison to PCB RALs. A small percentage of data (approximately 12%) did not fall within the

[1] Sample counts and exceedance statistics are presented on a location-specific basis. Note that while some shoal areas had multiple sample intervals/results, only the maximum concentration was used to determine whether or not an exceedance was present at a specific shoal location.

[2] The 0- to 60-cm RAL of 195 mg/kg OC PCBs applies to Recovery Category 2/3 subtidal areas with elevations above potential vessel scour depth, which is defined as -24 feet mean lower low water north of the 1st Ave Bridge and above -18 ft mean lower low water south of the bridge (see Record of Decision Table 28 (EPA 2014)).

acceptable total organic carbon (TOC) range for OC normalization;[3] for these data, RAL comparisons were made on a dry weight basis.

Mixed units, such as mixed OC-normalized and dry weight units, can be a confounding factor when interpolations are performed using ordinary kriging of PCB concentrations. However, mixed units are readily accommodated using indicator kriging methods (i.e., kriging of exceedance probability). This is consistent with the approach used in the upper reach of the LDW (Anchor QEA and Windward 2022a).

1.2 Interpolation Method Selection

During RD for the upper reach of the LDW, exploratory spatial data analysis was performed to support selection of a preferred interpolation method (see *Pre-Design Investigation Data Evaluation Report for the Lower Duwamish Waterway Upper Reach*, Appendix K (Anchor QEA and Windward 2022a)). Based on the results of this analysis, indicator kriging was selected as the interpolation method for PCBs, and Thiessen polygons were selected to define the extent of RAL exceedances for other COCs. Given the similarities of waterway processes and contaminants, and for consistency with the RD of the upper reach, these same interpolation methods were applied in the middle reach.

One notable difference between the upper and middle reaches is that different sampling designs were used. The upper reach dataset is a compilation of more targeted and local investigations that occurred over time, whereas a majority of the middle reach dataset was collected on a systematic grid during the Phase I PDI. The use of a grid-based sampling design in the middle reach was selected and implemented to provide a more evenly distributed dataset for interpolation and design.

Indicator kriging provides point-based estimates of the probability of exceeding the PCB RAL. Samples that exceed the RAL are assigned a probability value of 1 (100%), and samples less than the RAL are assigned a probability value of 0 (0%). Indicator kriging can then be used to interpolate the field of samples represented by zeroes and ones. Between sample locations, the indicator is a continuous variable spanning a range of probability values between 0 and 1 (i.e., between 0% and 100%).

Indicator kriging offers a number of advantages over other interpolation methods, such as the following:

- Direct, quantitative estimates of the statistical confidence in RAL exceedance area boundaries
- A nonparametric method that does not require log transformation to control highly skewed concentration data, which is a typical characteristic of PCB data distributions from the LDW and other sediment cleanup sites

[3] The acceptable OC normalization range is TOC ≥ 0.5% and ≤ 3.5% (Ecology 2021).

- Better accommodation of mixed units: specifically, RAL exceedances determined using both OC-normalized and dry weight concentrations[4]
- Successful applications supporting RD and remedial actions on other large sediment sites, particularly the Lower Fox River, Wisconsin (Anchor QEA and Tetra Tech 2016; Thornburg et al. 2005; Wolfe and Kern 2008); Portland Harbor, Oregon (EPA 2022); and the upper reach of the LDW (Anchor QEA and Windward 2022a)

2 PCB Indicator Kriging Input Parameters

Indicator kriging interpolation methods are specified by the following input parameters:

- **Spatial Correlation Structures:** Semivariograms define the spatial correlation structure of PCB indicator data (i.e., the strength and distance over which site-specific, inter-sample correlations occur). Semivariograms are used to assign sample weighting factors during interpolation, such that samples located closer to the estimation point are more strongly correlated to the estimation point and receive greater weighting factors.
- **Search Parameters:** Search parameters define how many neighboring data points are used to calculate the interpolated value of each estimation point and over what distances and directions neighboring data points are included.

2.1 Spatial Correlation Structures and Semivariograms

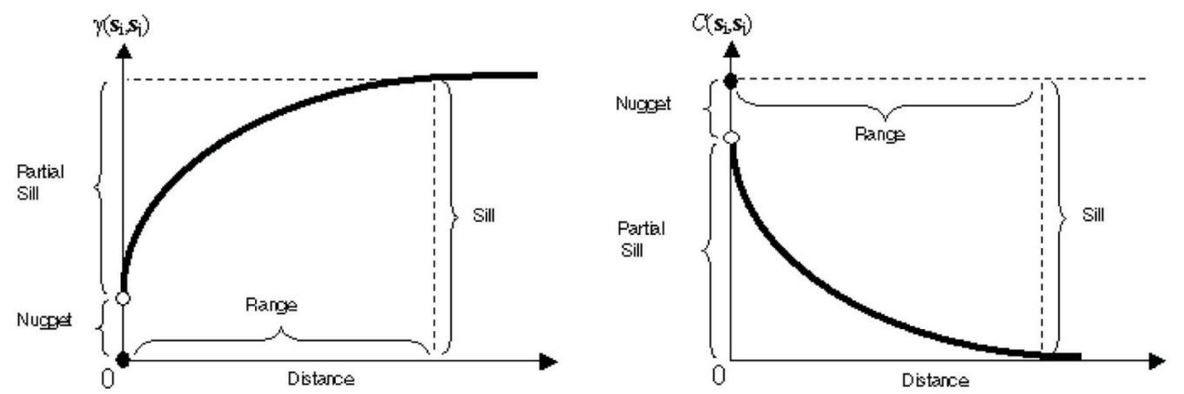
Semivariograms describe the site-specific spatial correlation structures of the data. For indicator kriging, the data are digital indicators (1 and 0) based on exceedance or non-exceedance of PCB RALs. Kriging uses the spatial correlation structures defined by the semivariograms to assign appropriate sample-weighting factors during the interpolation process (Isaaks and Srivastava 1989; Goovaerts 1997).

A typical semivariogram structure—and its complementary function, the covariance structure—are shown in Figure J1-1. Semivariance and covariance functions both measure the strength of statistical correlation with distance. Semivariograms are developed by considering all possible combinations of sample pairs in the dataset and calculating the variance (i.e., squared differences between sample pairs) associated with increasing sample separation distance. Samples that are closer together are expected to be spatially correlated and therefore have lesser variance, or alternatively, greater covariance than samples spaced farther apart.

[4] In the LDW, there is a finite range (from 0.5% to 3.5% TOC) over which PCB data are evaluated on an OC-normalized basis; outside of this range, data are evaluated on a dry weight basis without OC normalization.

Figure J1-1
Typical Semivariogram Structure

Semivariance	*Covariance*



From: Ersi ArcGIS Pro 3.4, 2025.
https://pro.arcgis.com/en/pro-app/latest/help/analysis/geostatistical-analyst/semivariogram-and-covariance-functions.htm

The spatial correlation structure of semivariograms is described by the following three parameters:

- **Nugget:** The nugget is the y-intercept of the semivariogram and represents the inherent sample variance at any given location due to field and laboratory variability and imprecision.
- **Range:** The range is the distance over which samples are spatially correlated. Within the range, the sample variance increases from a minimum value at the nugget to a maximum value at the sill.
- **Sill:** The sill is the variance at the end of the correlation range and represents the background population variance lacking any spatial correlation. The partial sill is the sill minus the nugget.

2.1.1 Site-specific Considerations

The following site-specific factors were considered in developing semivariograms for middle reach datasets:

- **Anisotropy:** Consistent with the upper reach, an anisotropic interpolation was generally applied in the main channel of the LDW middle reach, indicating stronger correlation and continuity of sediment deposits along the channel axis. Anisotropy is a common and expected phenomenon in rivers and engineered waterways (like the LDW) with prevailing flow and tidal current directions. A modest 2-to-1 anisotropy ratio was assumed, as this ratio was commonly observed in upper reach.
- **Directionality:** The middle reach can be divided into two segments with slightly different alignments: a majority of the middle reach (the uppermost 80%) is aligned with an azimuth of

316° (NW), whereas a much smaller portion (the lowest 20%) is aligned with an azimuth of 342° (NNW). Given the relatively small difference in alignments (26° difference), the surface sediment semivariogram was developed along the average channel direction (324°) for the entire middle reach. For the subsurface, a slightly stronger correlative structure was observed in the semivariograms along the direction of the majority of the middle reach (316°). During kriging, interpolations were performed using the segment-specific channel directions as the major correlation axis; the segments were then spliced at the hinge point at river mile (RM) 1.88.

- **Segregation of Off-channel Slips:** Correlations structures for the subsurface subtidal dataset in the main channel were improved by segregating data from the off-channel slips (i.e., Slips 2, 3, and 4, plus the Inlet at RM 2.2W), which were confounding the directional properties of the data. For the surface sediment dataset, only data from the Inlet at RM 2.2W were excluded from the modeling for that reason. For the slips, isotropic (i.e., non-directional) semivariograms were developed for both the surface and subsurface datasets.
- **Segregation of Intertidal and Subtidal Datasets:** Semivariogram structures were improved (i.e., better conformance to correlation models were achieved) by segregating the intertidal subsurface dataset and modeling it separately. The improvements indicated stronger correlations along similar water depths and flow directions (i.e., along slope) and weaker correlations across water depths and flow directions (i.e., downslope, or crossing intertidal to subtidal zones). Intertidal and subtidal areas also have different hydrodynamics, sedimentary processes, and source configurations. Therefore, a separate semivariogram was developed for the intertidal subsurface PCB dataset (i.e., three semivariograms total).

2.1.2 Phase II PCB Semivariograms

Indicator kriging semivariogram correlation plots and semivariogram models are compiled in Attachment J-2; semivariogram model parameters (nugget, range, sill, anisotropy) are summarized in Table J2-1. Spherical semivariogram models provided a reasonable fit to the observed spatial correlation structures. During development of the semivariogram models, a few semivariance observations were available from intertidal data at very close range (i.e., distances of 20 to 40 feet, much less than the subsurface average nearest neighbor spacing of 127 feet) but were considered unreliable due to the increased potential for local biases. These observations were not used to define the correlation structures.

Table J2-1
PCB Indicator Kriging Semivariogram and Search Parameters

Medium	Surface Sediment		Subsurface Sediment		
Zone	**Channel**	**Slips[1]**	**Channel**	**Slips[1]**	**Intertidal**
RAL	**12 mg/kg OC**	**12 mg/kg OC**	**12 mg/kg OC[2]**	**12 mg/kg OC[2]**	**65 mg/kg OC[3]**
Data Attributes					
Dataset	Design Dataset (2025)				
COC	Total PCBs, OC-normalized (mg/kg OC)				
Data count	416	66	174	5	147
Exceedance count	59	6	65	1	34
Exceedance frequency	14.2%	9.1%	37.4%	20%	23.1%
Data count - RAL-30%	50	9	27	1	4
Data count - RAL+30%	11	2	17	0	4
Semivariogram Count	509[1]	542[4]	307	420[4]	158
Semivariogram Parameters					
Model	Spherical	Spherical	Spherical	Spherical	Spherical
Anisotropy	Anisotropic	Isotropic	Anisotropic	Isotropic	Anisotropic
Anisotropy ratio	2 to 1	-	2 to 1	-	2 to 1
Major axis direction	324°	324°	316°	--	316°
Major range	130	110	160	100	95
Minor range	65	-	80	-	47
Nugget	0.022	0.020	0.030	0.010	0.05
Partial sill	0.115	0.115	0.180	0.185	0.110
Full sill	0.137	0.135	0.210	0.195	0.160
Nugget/full sill	16%	15%	14%	5%	31%
Search Parameters					
Search type	Quadrant, 45° Offset				
Search radius	Defined by Semivariogram Correlation Scales				
Minimum/quadrant	2				
Maximum/quadrant	5				

Notes:
1. Includes Slips 2, 3, and 4 and does not include the Inlet at RM 2.3W.
2. RAL=195 mg/kg OC areas are excluded from data counts and exceedance counts for subtidal subsurface; however, data in RAL=195 mg/kg OC areas are included in semivariogram counts and indicator kriging interpolations to provide optimal boundary control for RAL=12 mg/kg OC exceedance areas. RAL=12 mg/kg OC samples in intertidal areas (12 samples) are included in data counts and exceedance counts.
3. RAL=12 mg/kg OC areas (margins of subtidal Recovery Category 1 areas) are excluded from data counts and exceedance counts for intertidal subsurface; intertidal subsurface RAL=12 mg/kg OC areas are interpolated along with their adjacent subtidal subsurface RAL=12 mg/kg OC areas.
4. Isotropic semivariograms were developed using the entire dataset because the scarcity of exceedances in the slips precluded developing a meaningful model based solely on data in those regions.
COC: contaminant of concern
OC: organic carbon

PCB: polychlorinated biphenyl
RAL: remedial action level
RM: river mile

2.1.2.1 Range

In all semivariograms, the spatial correlation ranges exceeded the average nearest neighbor distances (56 feet for surface sediment samples, 82 feet for subsurface samples where RAL = 12 mg/kg OC, and 66 feet for subsurface samples where RAL = 65 mg/kg OC), indicating sufficient data density to support interpolation. The correlation range of subsurface data (100 to 160 feet) was greater than that of surface data (110 to 130 feet). This may have been related to the greater subsurface sediment sampling depth, which represented a longer time interval and longer averaging period compared to those of surface sediment samples, and thus, reduced spatial variability.

2.1.2.2 Nugget

The nugget variance was estimated based on a visual best fit of the semivariogram scatterplots. The nugget variance ranged from 5% to 31% of the sill value.

2.1.2.3 Sill

The sill value is an estimate of the overall population variance of the indicators and ranged from 0.14 to 0.21. In general, higher sill values and population variances are associated with higher frequencies of RAL exceedances, and thus, a larger percentage of ones than of zeroes in the indicator dataset. Specifically, higher sill values (0.19 to 0.21) were observed in the main channel subtidal subsurface dataset and full subsurface dataset used to develop the isotropic model for the slips. Both subsurface datasets had higher PCB exceedance frequencies (37% [main channel subtidal] and 24% [full] exceedance frequencies, respectively) and lower sill values (0.13 to 0.14) than those observed in the surface datasets (full dataset for the isotropic model and main channel dataset): 21% (main channel subtidal surface) and 14% (full surface), respectively.

2.2 Search Parameters

Interpolation search parameters define how many neighboring data points are used to calculate the interpolated value of each estimation point, as well as over what distances and directions neighboring data points are included. In general, increasing the search radius and/or number of data points captured in the search radius tends to result in a smoother interpolated surface and predicted values with less variance. On the other hand, reducing the search radius and/or the number of data points captured in the search radius tends to preserve more detail and local structure in PCB sediment distributions.

For this work, quadrant searches were performed with the search axis oriented along the middle reach channel alignments. Quadrant searches were performed to reduce directional biases potentially caused by variable sampling densities and data clusters. A minimum of two samples and a maximum of five samples from each quadrant were used to perform the interpolations, providing a reasonable balance between prediction stability and local detail preservation. The search radius was set to a value equal to the correlation range. The search algorithm used the closest available samples in each quadrant, up to the maximum of five samples per quadrant, and prioritized samples with the highest weighting factors within the spatial correlation range.

3 Interpolation Results

Indicator kriging and Thiessen polygon interpolations were performed using the Esri ArcGIS program (ArcGIS Desktop 10.8.2 and Geostatistical Analyst 10.8.2 extension, plus the Spatial Analyst 10.8.2 extension for raster analysis and manipulation). The geostatistical surfaces were exported to raster datasets with a raster cell size of 2 feet, an appropriate resolution on which to base RD.

The distributions of PCB RAL exceedances (red symbols) and non-exceedances (white symbols) in surface and subsurface sediments are presented in Map J-1 and Map J-2, respectively. These maps depict the PCB data used for indicator kriging.

The interpolation process included the following steps and products:

1. **Surface Sediment Indicator Kriging (Maps J-3a, J-3b):** Separate applications of indicator kriging were performed on main channel surface sediment and on the full surface sediment dataset for the slips. The full surface sediment design dataset was used for both channel and slip interpolations to provide optimal boundary control; then, the two surface rasters were cropped to their applicable areas and spliced.

2. **Subsurface Sediment Indicator Kriging (Maps J-4a, J-4b):** Separate applications of indicator kriging were performed on intertidal (RAL of 65 mg/kg OC) and subtidal (RAL of 12 mg/kg OC in Recovery Category 1 and shoaling areas) subsurface sediments and on the full subsurface dataset for the slips. The entire subsurface sediment dataset was used for all three interpolations to provide optimal boundary control; then, the three subsurface rasters were cropped to their applicable areas and spliced.

3. **Combination of Surface and Subsurface Indicators (Maps J-5a, J-5b):** Using a GIS raster calculation, the surface and subsurface interpolation layers were combined into a single layer showing the total PCB RAL exceedance footprint of both layers. All interpolation layers used the same grid and were registered to the same origin. ArcGIS selected the highest indicator value in each of the surface and subsurface rasters; these values represented the combined RAL exceedance area for both surface and subsurface datasets.

4. **Thiessen Polygons for Other COCs (Maps J-6a, J-6b, J-7a, J-7b):** These maps show the median (50%) PCB RAL exceedance area boundary derived from indicator kriging overlain with Thiessen polygons for COCs other than PCBs that extend beyond the median PCB boundary. Like PCB interpolations, Thiessen polygons include the combined horizontal extents of contamination for all other COCs in both surface and subsurface intervals. Other COCs that determined local RAL exceedance area boundaries included metals, polycyclic aromatic hydrocarbons, other semivolatile organic compounds (bis[2-ethylhexyl] phthalate, butyl benzyl phthalate, benzoic acid, dibenzofuran, 2,4-dimethylphenol, chlorobenzenes), and dioxins/furans, depending on the area. Maps J-7a and J-7b show the same Thiessen polygon overlays as Maps J-6a and J-6b.

On the PCB indicator kriging maps (Maps J-3a/b, J-4a/b, and J-5a/b), the indicator kriging contours represent the probabilities of exceeding the applicable RALs, expressed in units of percent. The 50% probability contour represents the median or central tendency estimate of the horizontal RAL exceedance boundary. Other contours—including the 20%, 30%, 40%, 50% (median), 60%, 70%, and 80% probabilities of exceedance—are provided for comparison. On the Fox River and Hudson River sediment cleanup sites, the median kriging estimates were used to define the remediation boundaries for RD and were shown to provide a reasonable balance between effectively removing contaminated sediment with concentrations above RALs and excluding sediment with concentrations below RALs (QEA 2007; Wolfe and Kern 2008; Anchor QEA and Tetra Tech 2016). This approach was also used in the upper reach of the LDW.

Maps J-6a/b—which encompass all RAL exceedances associated with PCBs and other COCs in both surface and subsurface sediments—will provide the foundation for RD and the starting point to overlay engineering and constructability considerations. During the RD process, the remediation footprint in many areas will be expanded beyond the median boundary to address engineering and constructability considerations. Thus, a greater level of confidence will be achieved after RD.

4 PCB Uncertainty Analysis

This section presents an overview of the uncertainty analyses that have been conducted to evaluate the indicator kriging results for PCBs. Section 4.1 summarizes the uncertainty evaluation conducted as part of Phase I for the middle reach, and Section 4.2 summarizes the cross-validation analysis conducted for the upper reach. Based on a review of these evaluations, the probability contours were determined to be the best approach for evaluating the uncertainty associated with indicator kriging following the Phase II PDI.

4.1 Phase I Evaluation

The uncertainty of the PCB RAL exceedance area boundary was assessed during Phase I using three independent lines of evidence (see Attachment J-3):

- Indicator kriging probability contours
- Potential analytical uncertainty analysis
- Sensitivity analysis of semivariogram parameters

The second and third lines of evidence were recommended by the U.S. Environmental Protection Agency's statistician.

The indicator probability contours were generally well constrained in both surface and subsurface sediments. In general, the sensitivity analysis showed that the differences in indicator kriging contours were very slight, often imperceptible, and that the kriging algorithm was relatively robust and insensitive to uncertainties in the spatial correlation parameters. The additional data collected for Phase II refined and enhanced the kriging modeling, and did not deviate significantly from the expected results. Therefore, no further sensitivity analysis is warranted.

4.2 Cross-validation Analysis for the Upper Reach

A cross-validation analysis was conducted for the LDW upper reach to evaluate the Phase II indicator kriging results (Anchor QEA and Windward 2022b). Cross-validation provides a measure of prediction error for each sampling location and an overall assessment of method bias, error magnitude, and variance. The objective of this analysis was to assess the uncertainty associated with the RAL exceedance area boundaries. The key conclusions of the cross-validation analysis conducted for the upper reach are as follows:

- **Limitations of cross-validation** – Interpretation of cross-validation results was subject to the limitations of the methodology.
- **Effects of isolated RAL exceedances** – The occurrence of false negative cross-validation predictions was usually indicative of isolated exceedance locations (individual hits) surrounded by non-exceedance locations. False negative error rates were not substantially reduced at lower probability thresholds.
- **False negative errors** – The upper reach evaluation found that every false negative error was within final RAL exceedance area boundaries, meaning that the false negative error rate was effectively zero.
- **Correlations with RAL exceedance frequencies** – The cross-validation reliability metrics were correlated with RAL exceedance frequencies. Higher error rates were generally correlated with higher exceedance frequencies, likely because of the heterogeneity of hits and non-hits in those areas and higher overall indicator variances.

- **Well-defined RAL exceedance area boundaries** – Most of the isolated hits triggering false negative predictions were already well bounded by non-exceedance locations. Thus, this evaluation found that further sampling to bound these areas was unnecessary.
- **Optimized probability threshold** – The cross-validation analysis found that the metrics were reasonably optimized at the 50% indicator probability threshold.

As discussed in the cross-validation memorandum for the upper reach (Anchor QEA and Windward 2022b), the spatial distribution of indicator probability values—which is the direct output of the indicator kriging algorithm—provides the strongest line of evidence for quantifying the uncertainty of the RAL exceedance area boundary. The divergence and widening of indicator probability contours indicates areas of greater boundary uncertainty. Cross-validation provides another line of evidence for assessing boundary uncertainty, albeit a secondary line of evidence given the limitations of the method.

Thus, given the limitations of the cross-validation analysis as well as the fact that the fundamental conditions of the upper reach are the same as those for the middle reach (and are even more tightly controlled due to the gridded sampling design used in the middle reach), no cross-validation analysis of the middle reach interpolation was conducted.

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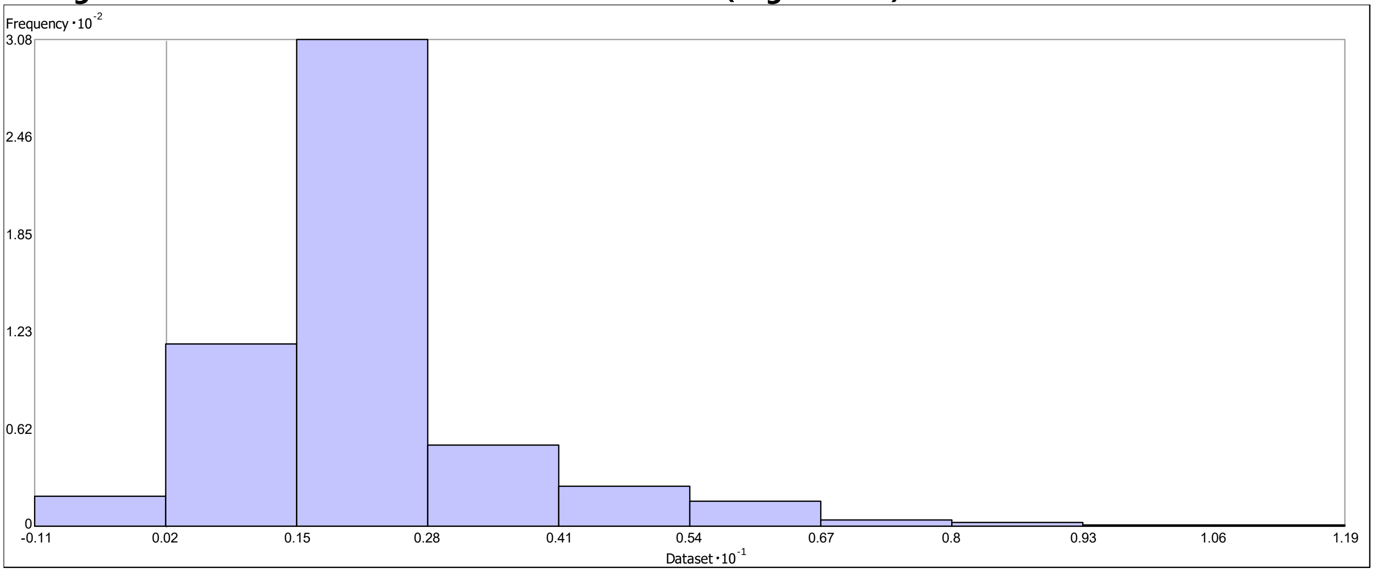
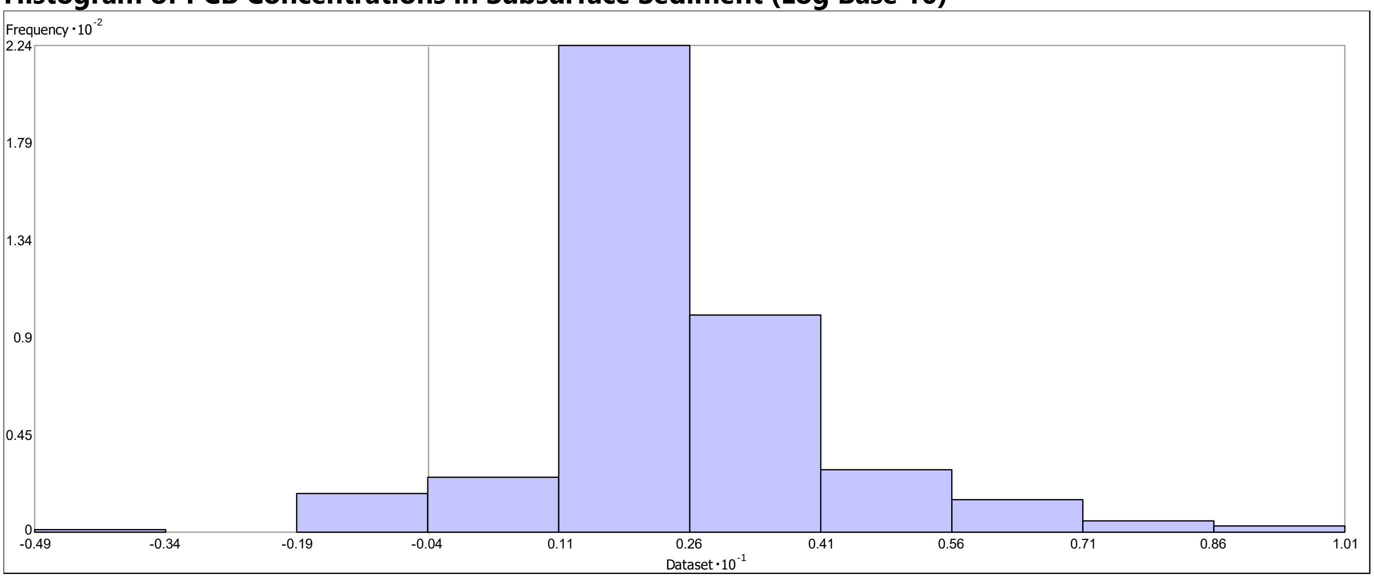
Attachment J-1
PCB Statistical Distributions

Histogram of PCB Concentrations in Surface Sediment (Log Base 10)

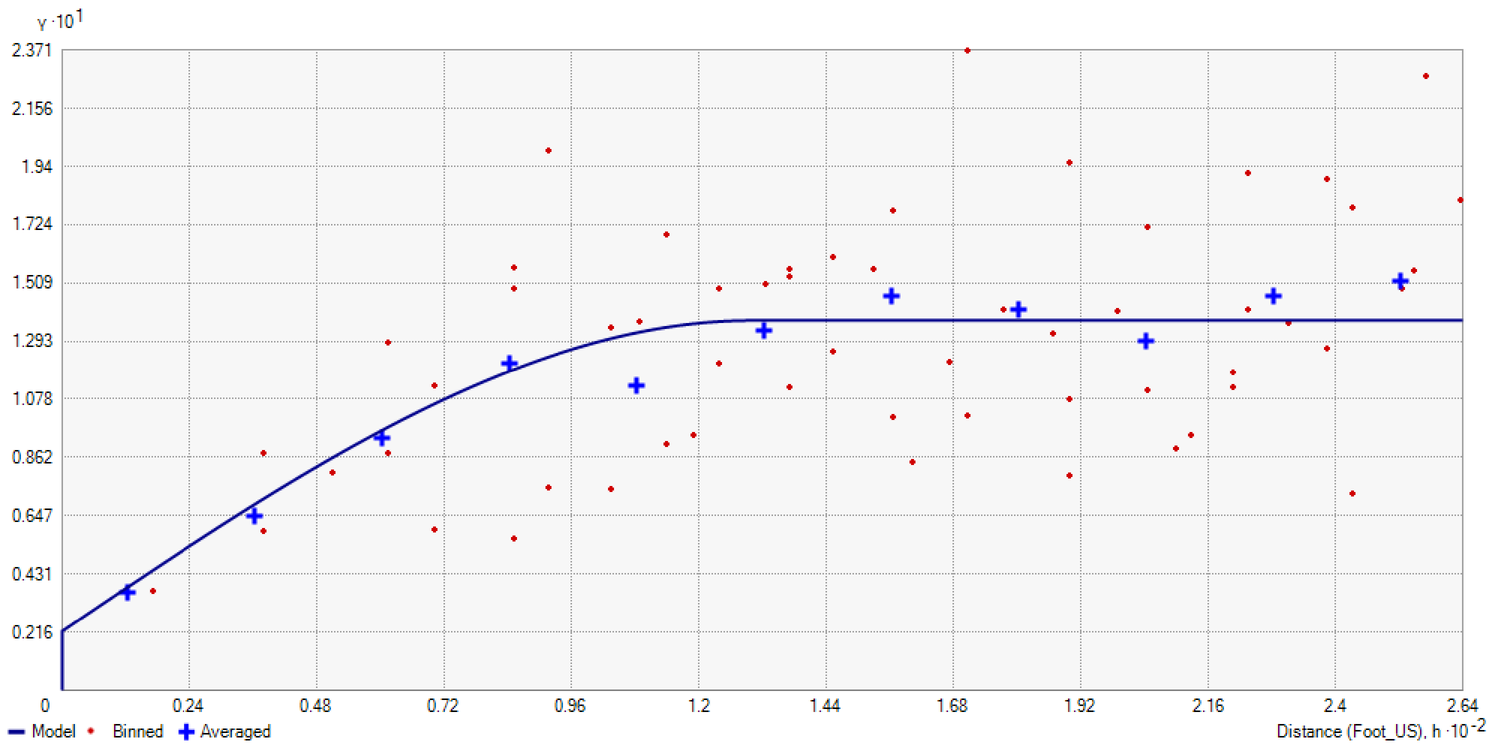


Histogram of PCB Concentrations in Subsurface Sediment (Log Base 10)



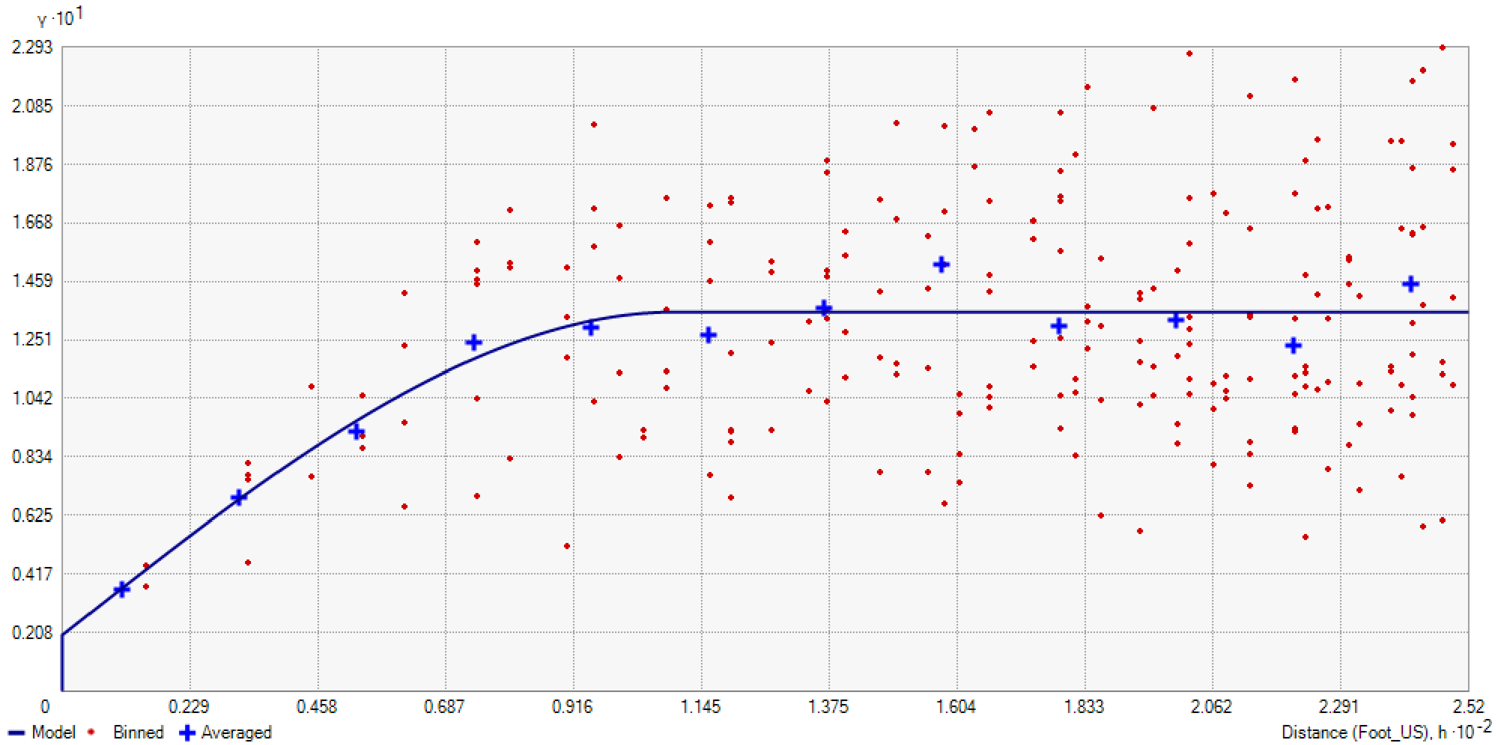
Attachment J-2
PCB Semivariograms

A. Surface Sediment - Anisotropic - RAL=12



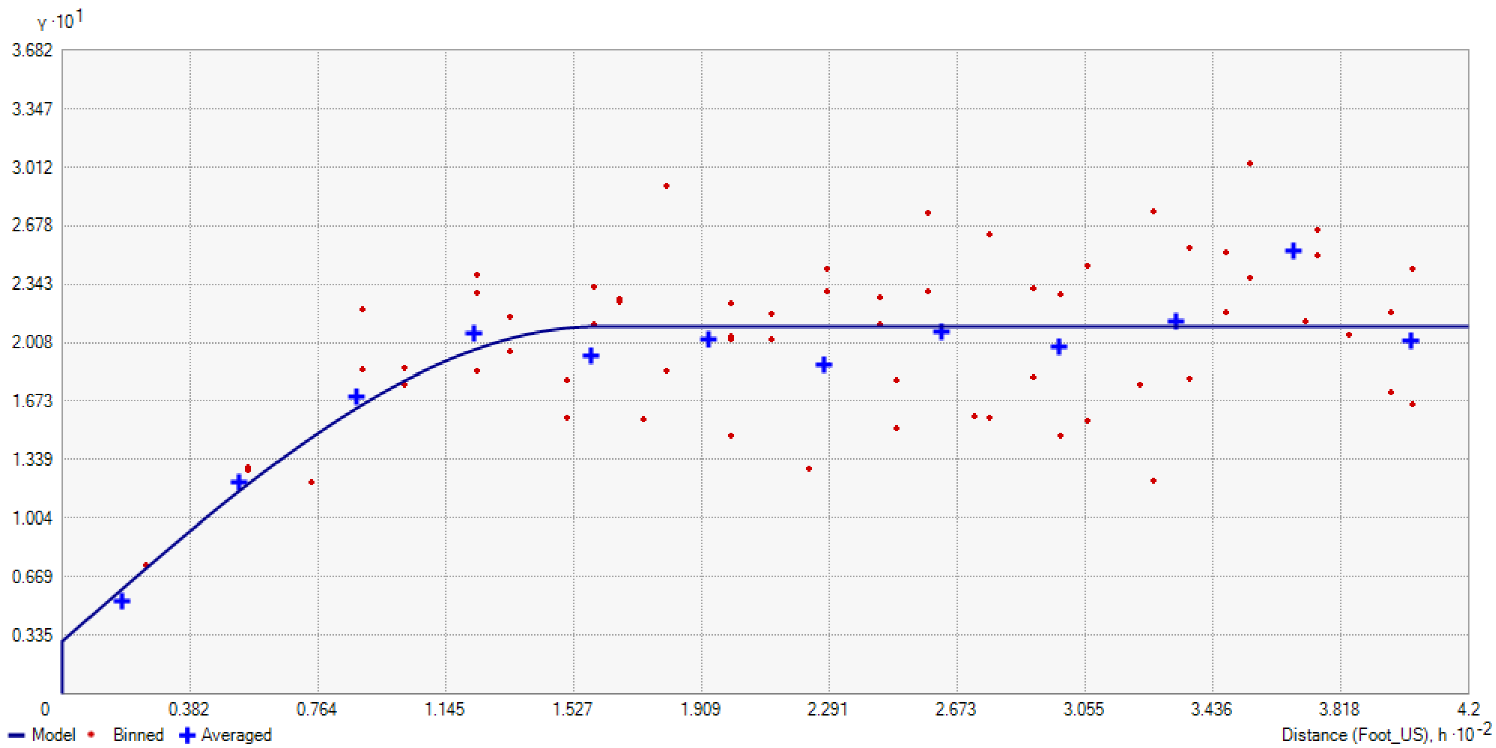
MODEL PARAMETERS	
Number of lags	11
Lag size	24
Nugget	0.022
-Model type	Spherical
Major Range	130
Anisotropy	Yes
Minor Range	65
Direction	324
Partial sill	0.115

B. Surface Sediment – Isotropic - RAL=12



<u>**MODEL PARAMETERS**</u>	
Number of lags	12
Lag size	21
Nugget	0.02
-Model type	Spherical
Major Range	110
Anisotropy	No
Minor Range	
Direction	
Partial sill	0.115

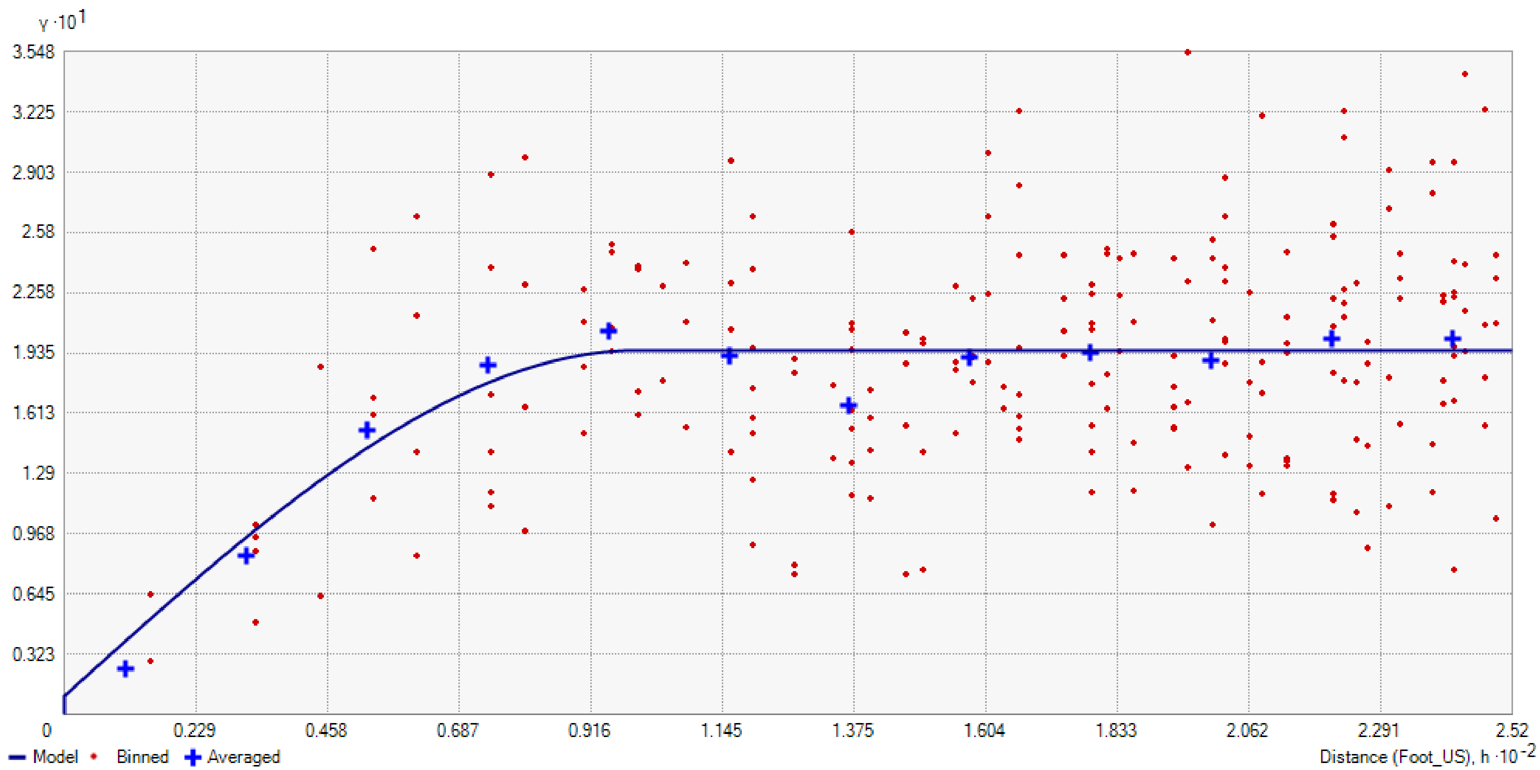
C. Subsurface Sediment - Anisotropic - RAL=12



<u>**MODEL PARAMETERS**</u>

Number of lags	12
Lag size	35
Nugget	0.03
-Model type	Spherical
Major Range	160
Anisotropy	Yes
Minor Range	80
Direction	316
Partial sill	0.18

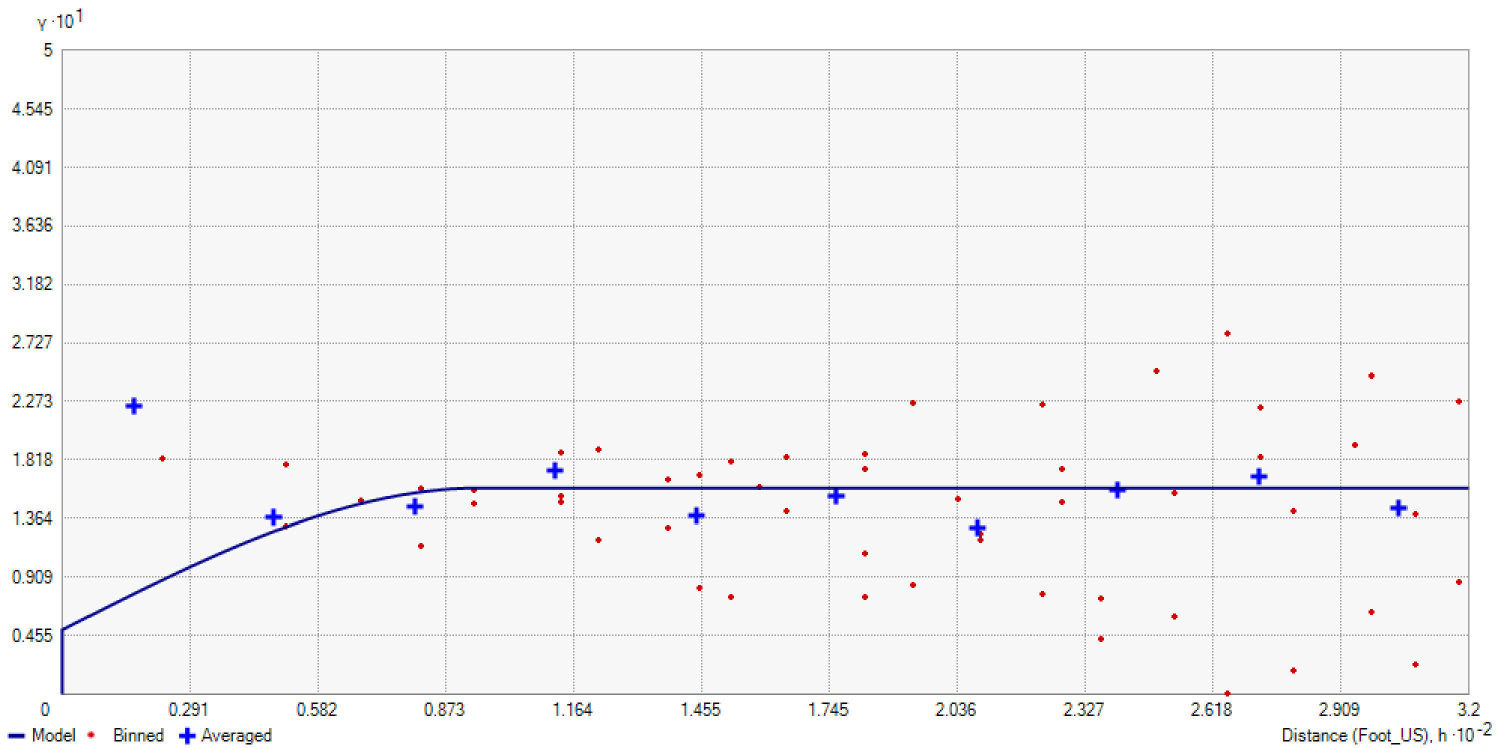
D. Subsurface Sediment - Isotropic - RAL=12



MODEL PARAMETERS

Number of lags	12
Lag size	21
Nugget	0.01
-Model type	Spherical
Major Range	100
Anisotropy	No
Minor Range	
Direction	
Partial sill	0.185

E. Subsurface Sediment - Intertidal - RAL=65



MODEL PARAMETERS

Number of lags	10
Lag size	32
Nugget	0.05
-Model type	Spherical
Major Range	95
Anisotropy	Yes
Minor Range	47
Direction	316
Partial sill	0.11

Attachment J-3
Phase I Interpolation Methods for Delineating Areas with RAL Exceedances

FINAL

Attachment J-3
Phase I Interpolation Methods for Delineating Areas with RAL Exceedances

The evaluation presented in this attachment was conducted after Phase I of the Pre-Design Investigation (PDI) for the middle reach. No updates have been made to this evaluation based on the Phase II PDI. This attachment was originally written as Appendix F to a different document; all in-text callouts and page numbers reflect the original Appendix F designation.

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ABBREVIATIONS

COC	contaminant of concern
LDW	Lower Duwamish Waterway
OC	organic carbon
PCB	polychlorinated biphenyl
PDI	Pre-Design Investigation
RAL	remedial action level
RD	remedial design
TOC	total organic carbon

1 Overview of Data Interpolation Approach

This appendix presents the data interpolation method selection, application, and results used to delineate remedial action level (RAL) exceedance areas in the middle reach of the Lower Duwamish Waterway (LDW), as well as the uncertainty analysis used to assess the level of confidence in the RAL exceedance area boundaries. The same general interpolation methods used in the upper reach of the LDW were used in the middle reach.

Interpolation methods use a local neighborhood of surrounding data points to estimate values (e.g., concentrations, probabilities of exceedance, or other physical or chemical parameters) at all unsampled points in a project area. Interpolation methods are commonly used to support remedial design (RD) and delineate areas requiring remedial action at sediment cleanup sites (e.g., Thornburg et al. 2005; Anchor QEA 2014; Anchor QEA and Tetra Tech 2016; City of Tacoma 2002).

1.1 Phase I Dataset

This section describes the attributes of the middle reach design dataset, including contaminants of concern (COCs) with concentrations exceeding RALs, surface and subsurface sampling depths over which RALs are evaluated, and the appropriate use of carbon-normalized versus dry weight concentrations.

1.1.1 Contaminants of Concern

Polychlorinated biphenyls (PCBs) are the primary COC in the middle reach and make up the majority of RAL exceedances. Therefore, PCBs were the primary focus of spatial interpolation, including semivariogram development, indicator kriging, and uncertainty analysis.

Analysis of other COCs—which were also extensively sampled and analyzed throughout the middle reach as part of the Pre-Design Investigation (PDI)—resulted in some localized areas with RAL exceedances where PCBs did not exceed RALs. These other COCs were addressed separately from PCBs using a simpler interpolation method—Thiessen polygons—due to their more localized areas of concern. Other COCs that determined local RAL exceedance area boundaries included metals, polycyclic aromatic hydrocarbons, other semivolatile organic compounds (bis[2-ethylhexyl] phthalate, butyl benzyl phthalate, benzoic acid, dibenzofuran, 2,4-dimethylphenol, phenol, and chlorobenzenes), and dioxins/furans, depending on the area. For these other COCs, surface and subsurface datasets were used to develop Thiessen polygons, which were then merged into a combined RAL exceedance area boundary encompassing all surface and subsurface exceedances of other COCs. The interpolation results for all COCs were then overlain on the PCB interpolation to develop the final combined RAL exceedance area footprints.

1.1.2 Surface and Subsurface PCB Datasets

Interpolations were performed on two sediment depth-defined datasets applicable to RALs: surface sediment, defined as 0 to 10 cm; and subsurface sediment, defined as 0 to 45 cm (intertidal areas), 0 to 60 cm (subtidal areas), and shoaling intervals in the Federal Navigation Channel. The distributions of PCB RAL exceedances (red symbols) and non-exceedances (white symbols) in surface and subsurface sediments are presented in Map F-1 and Map F-2, respectively (Attachment F-1). Ultimately, all of these datasets were combined to develop an integrated RAL exceedance area boundary circumscribing all surface and subsurface PCB RAL exceedances.

1.1.2.1 Surface Sediment PCB Dataset

Surface sediment PCB data were compared to a PCB RAL of 12 mg/kg organic carbon (OC) (expressed on an OC-normalized basis). The results were as follows:

- 287 data points and 18 RAL exceedances (6.3% exceedance frequency) in the surface sediment subtidal PCB dataset
- 160 data points and 46 RAL exceedances (28.8% exceedance frequency) in the surface sediment intertidal PCB dataset.

1.1.2.2 Subsurface Sediment PCB Dataset

The subsurface sediment PCB dataset was divided into separate areas with three different RALs: 12, 65, and 195 mg/kg OC, depending on sediment bed elevation, recovery category area, and whether the data were from shoaling areas in the Federal Navigation Channel. The results were as follows:

- 129 data points and 49 RAL exceedances (38% exceedance frequency) in the subsurface PCB dataset in areas with a RAL of 12 mg/kg OC
- 66 data points and 5 RAL exceedances (7.6% exceedance frequency) in the subsurface PCB dataset in areas with a RAL of 65 mg/kg OC[1]
- No exceedances in areas with a RAL of 195 mg/kg OC[2]

1.1.3 Organic Carbon Normalization of PCB Data

Consistent with the LDW Record of Decision (EPA 2014), the PCB data were normalized to OC content for comparison to PCB RALs. A small percentage (approximately 14%) of data did not fall

[1] Sample counts and exceedance statistics are presented on a location-specific basis. Note that while some shoal areas had multiple sample intervals/results, only the maximum concentration was used to determine whether or not an exceedance was present at each particular shoal location.

[2] The 0- to 60-cm RAL of 195 mg/kg OC PCBs applies to Recovery Category 2/3 subtidal areas with elevations above potential vessel scour depth, which is defined as -24 feet mean lower low water north of the 1st Ave Bridge and above -18 ft mean lower low water south of the bridge (see Record of Decision Table 28 (EPA 2014)).

within the acceptable total organic carbon (TOC) range for OC normalization;[3] for these data, RAL comparisons were made on a dry weight basis.

Mixed units, such as mixed OC-normalized and dry weight units, can be a confounding factor when interpolations are performed using ordinary kriging of PCB concentrations. However, mixed units are readily accommodated using indicator kriging methods (i.e., kriging of exceedance probability). This is consistent with the approach used in the upper reach of the LDW (Anchor QEA and Windward 2022).

1.2 Interpolation Method Selection

During RD for the upper reach of the LDW, exploratory spatial data analysis was performed to support selection of a preferred interpolation method (see *Pre-Design Investigation Data Evaluation Report for the Lower Duwamish Waterway Upper Reach*, Appendix K (Anchor QEA and Windward 2022)). Based on the results of this analysis, indicator kriging was selected as the interpolation method for PCBs, and Thiessen polygons were selected to define the extent of RAL exceedances for other COCs. Given the similarities of waterway processes and contaminants, and for consistency with the RD of the upper reach, these same interpolation methods were applied in the middle reach.

One notable difference between the upper and middle reaches is that different sampling designs were used. The upper reach dataset is a compilation of more targeted and local investigations that occurred over time, whereas a majority of the middle reach dataset was collected on a systematic grid during the Phase I PDI. The use of a grid-based sampling design in the middle reach was selected and implemented to provide a more evenly distributed dataset for interpolation and design.

Indicator kriging provides point-based estimates of the probability of exceeding the PCB RAL. Samples that exceed the RAL are assigned a probability value of 1 (100%), and samples less than the RAL are assigned a probability value of 0 (0%). Indicator kriging then interpolates the field of samples represented by zeroes and ones. Between sample locations, the indicator is a continuous variable spanning a range of probability values between 0 and 1 (i.e., between 0% and 100%).

Indicator kriging offers a number of advantages over other interpolation methods, such as the following:

- Direct, quantitative estimates of the statistical confidence of RAL exceedance area boundaries
- A nonparametric method that does not require log transformation to control highly skewed concentration data, which is a typical characteristic of PCB data distributions in the LDW and other sediment cleanup sites

[3] The acceptable OC normalization range is TOC ≥ 0.5% and ≤ 3.5% (Ecology 2021).

- Better accommodation of mixed units: specifically, RAL exceedances determined using both OC-normalized and dry weight concentrations[4]
- Successful applications in supporting RD and remedial action on other large sediment sites, particularly the Lower Fox River, Wisconsin (Anchor QEA and Tetra Tech 2016; Thornburg et al. 2005; Wolfe and Kern 2008); Portland Harbor, Oregon (EPA 2022); and the upper reach of the LDW (Anchor QEA and Windward 2022)

2 PCB Indicator Kriging Input Parameters

Indicator kriging interpolation methods are specified by the following input parameters:

- **Spatial Correlation Structures:** Semivariograms define the spatial correlation structure of the PCB indicator data (i.e., the strength and distance over which site-specific, inter-sample correlations occur). Semivariograms are used to assign sample weighting factors during interpolation, such that samples located closer to the estimation point are more strongly correlated to the estimation point and receive greater weighting factors.
- **Search Parameters:** Search parameters define how many neighboring data points are used to calculate the interpolated value of each estimation point and over what distances and directions neighboring data points are included.

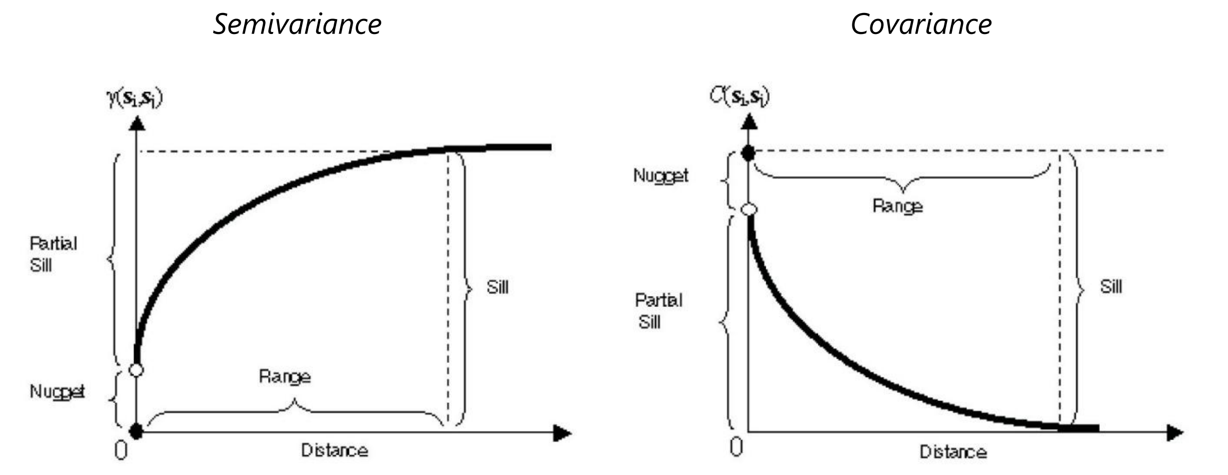
2.1 Spatial Correlation Structures and Semivariograms

Semivariograms describe the site-specific spatial correlation structures of the data. For indicator kriging, the data are digital indicators (1 and 0) based on exceedance or non-exceedance of PCB RALs. Kriging uses the spatial correlation structures defined by the semivariograms to assign appropriate sample-weighting factors during the interpolation process (Isaaks and Srivastava 1989; Goovaerts 1997).

A typical semivariogram structure—and its complementary function, the covariance structure—are shown in Figure F1-1. Semivariance and covariance functions both measure the strength of statistical correlation with distance. Semivariograms are developed by considering all possible combinations of sample pairs in the dataset and calculating the variance (i.e., squared differences between sample pairs) associated with increasing sample separation distance. Samples that are closer together are expected to be spatially correlated and therefore have a lesser variance, or alternatively, a greater covariance, than samples spaced farther apart.

[4] In the LDW, there is a finite range (from 0.5% to 3.5% TOC) over which PCB data are evaluated on an OC-normalized basis; outside of this range, data are evaluated on a dry weight basis without OC normalization.

Figure F1-1
Typical Semivariogram Structure



From: ESRI ArcGIS Pro 2.9, 2022.
https://pro.arcgis.com/en/pro-app/latest/help/analysis/geostatistical-analyst/semivariogram-and-covariance-functions.htm

The spatial correlation structure of semivariograms is described by the following three parameters:

- **Nugget:** The nugget is the y-intercept of the semivariogram and represents the inherent sample variance at any given location due to field and laboratory variability and imprecision.
- **Range:** The range is the distance over which samples are spatially correlated. Within the range, the sample variance increases from a minimum value at the nugget to a maximum value at the sill.
- **Sill:** The sill is the variance at the end of the correlation range that represents the background population variance lacking any spatial correlation. The partial sill is the sill minus the nugget.

2.1.1 Site-specific Considerations

The following site-specific factors were considered in the development of semivariograms for middle reach datasets:

Anisotropy: Consistent with the upper reach, an anisotropic interpolation was generally applied in the main channel of the LDW middle reach, indicating stronger correlation and continuity of sediment deposits along the channel axis. Anisotropy is a common and expected phenomenon in rivers and engineered waterways (like the LDW) with prevailing flow and tidal current directions. A modest 2-to-1 anisotropy ratio was assumed, as this ratio was commonly observed in upper reach. The one exception was the intertidal subsurface dataset, which did not show evidence of anisotropy; intertidal subsurface data were therefore modeled using an isotropic (i.e. non-directional) correlation structure.

- **Directionality:** The middle reach can be divided into two segments with slightly different alignments: a majority of the middle reach (the upper 80%) is aligned with an azimuth of 316° (NW), whereas a much smaller portion (the lowest 20%) is aligned with an azimuth of 342° (NNW). Given the relatively small difference in alignments (26° difference), semivariograms were developed along the average channel direction (324°) for the entire middle reach. During kriging, interpolations were performed using the segment-specific channel directions as the major correlation axis; the segments were then spliced at the hinge point at river mile (RM) 1.88.
- **Segregation of Off-channel Slips:** Correlations structures in the main channel were improved by segregating data from the off-channel slips (i.e., Slips 2, 3, and 4), which were confounding the directional properties of the data. In the slips, an isotropic (i.e., non-directional) correlation structure was assumed using a correlation range averaged between the major and minor correlation ranges from the anisotropic model in the main channel.
- **Segregation of Intertidal and Subtidal Datasets:** Semivariogram structures were improved (i.e., longer ranges and better conformance to correlation models were achieved) by segregating intertidal and subtidal datasets. The improvement indicated stronger correlations along similar water depths and flow directions (i.e., along slope) and weaker correlations across water depths and flow directions (i.e., downslope, or crossing intertidal to subtidal zones). Intertidal and subtidal areas also have different hydrodynamics, sedimentary processes, and source configurations. Therefore, semivariograms were separately developed for intertidal and subtidal PCB datasets in both surface and subsurface sediments (i.e., four semivariograms total).

2.1.2 Phase I PCB Semivariograms

Indicator kriging semivariogram correlation plots and semivariogram models are compiled in Attachment F-2. Semivariogram model parameters (nugget, range, sill, anisotropy) are summarized in Table F2-1. Spherical and exponential semivariogram models provided a reasonable fit to the observed spatial correlation structures. During the development of the semivariogram models, a few semivariance observations were available from pre-PDI data at very close range (i.e., distances of 40 to 80 feet, much less than the sample grid spacing of 200 feet) but were considered unreliable due to the small numbers of supporting sample pairs, as well as increased potential for local biases. These observations were not used to define the correlation structures.

Table F2-1
PCB Indicator Kriging Semivariogram and Search Parameters

Medium	Surface Sediment		Subsurface Sediment	
Zone	**Subtidal**	**Intertidal**	**Subtidal**	**Intertidal**
RAL	**12 mg/kg OC**	**12 mg/kg OC**	**12 mg/kg OC[1]**	**65 mg/kg OC[2]**
Data Attributes				
Dataset	Preliminary Phase I			
COC	Total PCBs, OC-normalized (mg/kg OC)			
Data count	287	160	129	66
Exceedance count	18	47	49	5
Exceedance frequency	6.3%	28.1%	38%	7.5%
Data count - RAL-30%	36	12	17	2
Data count - RAL+30%	8	4	13	0
Semivariogram Count[3]	243	136	183	72
Semivariogram Parameters				
Model	Spherical	Spherical	Exponential	Spherical
Anisotropy	Anisotropic	Anisotropic	Anisotropic	Isotropic
Anisotropy ratio	2 to 1	2 to 1	2 to 1	--
Major axis direction	324°	324°	324°	--
Major range	225	254	800	700
Minor range	112	127	400	--
Nugget	0.010	0.040	0.035	0.020
Partial sill	0.063	0.135	0.230	0.120
Full sill	0.073	0.175	0.265	0.140
Nugget/full sill	14%	23%	13%	14%
Search Parameters				
Search type	Quadrant, 45° Offset			
Search radius	Defined by Semivariogram Correlation Scales			
Minimum/quadrant	2			
Maximum/quadrant	5			

Notes:
1. RAL=195 mg/kg OC areas are excluded from data counts and exceedance counts for subtidal subsurface; however, data in RAL=195 mg/kg OC areas are included in semivariogram counts and indicator kriging interpolations to provide optimal boundary control for RAL=12 mg/kg OC exceedance areas. RAL=12 mg/kg OC samples in intertidal areas (6 samples) are included in data counts and exceedance counts.
2. RAL=12 mg/kg OC areas (margins of subtidal Recovery Category 1 areas) are excluded from data counts and exceedance counts for intertidal subsurface; intertidal subsurface RAL=12 mg/kg OC areas are interpolated along with their adjacent subtidal subsurface RAL=12 mg/kg OC areas.
3. Excludes side channels: Slip 2, Slip 3, Slip 4, and interior portion of the inlet at RM 2.2W.
COC: contaminant of concern
OC: organic carbon
PCB: polychlorinated biphenyl

RAL: remedial action level
RM: river mile

2.1.2.1 Range

In all semivariograms, the spatial correlation ranges exceeded the sample grid spacing (100 feet × 200 feet), indicating sufficient data density to support interpolation. The correlation range of subsurface data (700 feet to 800 feet) was longer than that of surface data (225 feet to 254 feet). This may have been related to the greater subsurface sediment sampling depth, which represented a longer time interval and longer averaging period compared to those of surface sediment samples, and thus, reduced spatial variability. A sensitivity analysis showing the effects of varying range values on the resultant indicator probability contours is presented in Section 4.3.

2.1.2.2 Nugget

The nugget variance was estimated based on a visual best fit of the semivariogram scatterplots. The nugget variance ranged from 13% to 23% of the sill value. A sensitivity analysis showing the effects of varying nugget values on the resultant indicator probability contours is presented in Section 4.3.

2.1.2.3 Sill

The sill value is an estimate of the overall population variance of the indicators. The sill value ranged from 0.07 to 0.27. In general, higher sill values and population variances are associated with higher frequencies of RAL exceedances, and thus, a larger percentage of ones than of zeroes in the indicator dataset. Specifically, higher sill values (0.18 to 0.27) were observed in the intertidal surface and subtidal subsurface datasets, both of which had higher PCB exceedance frequencies (26% and 24% exceedance frequencies, respectively), and lower sill values (0.07 to 0.14) were observed in the subtidal surface and intertidal subsurface datasets, both of which had lower PCB exceedance frequencies (7% and 10% exceedance frequencies, respectively).

2.2 Search Parameters

Interpolation search parameters define how many neighboring data points are used to calculate the interpolated value of each estimation point, as well as over what distances and directions neighboring data points are included. In general, increasing the search radius and/or the number of data points captured in the search radius tends to result in a smoother interpolated surface and predicted values with less variance. On the other hand, reducing the search radius and/or the number of data points captured in the search radius tends to preserve more detail and local structure in PCB sediment distributions.

For this work, quadrant searches were performed with the search axis oriented along the middle reach channel alignments. Quadrant searches were performed to reduce directional biases potentially caused by variable sampling densities and data clusters. A minimum of two samples and a maximum of five samples from each quadrant were used to perform the interpolations, providing a reasonable balance between prediction stability and local detail preservation. The search radius was set to a value equal to the correlation range. The search algorithm used the closest available samples in each quadrant, up to the maximum of five samples per quadrant, and prioritized samples with the highest weighting factors within the spatial correlation range.

3 Interpolation Results

Indicator kriging and Thiessen polygon interpolations were performed using the Esri ArcGIS program (ArcGIS Desktop 10.8.1 and Geostatistical Analyst 10.8.1 extension, plus the Spatial Analyst 10.8.1 extension for raster analysis and manipulation). The geostatistical surfaces were exported to raster datasets with a raster cell size of 2 feet, an appropriate resolution on which to base RD.

The distributions of PCB RAL exceedances (red symbols) and non-exceedances (white symbols) in surface and subsurface sediments are presented in Map F-1 and Map F-2, respectively. These maps contain the raw data for PCB indicator kriging.

The interpolation process included the following steps and products:

1. **Surface Sediment Indicator Kriging (Maps F-3a, F-3b):** Separate applications of indicator kriging were performed on intertidal and subtidal surface sediments. The entire surface sediment dataset was used for both intertidal and subtidal interpolations to provide optimal boundary control; then, the two surface rasters were cropped to their applicable areas and spliced.

2. **Subsurface Sediment Indicator Kriging (Maps F-4a, F-4b):** Separate applications of indicator kriging were performed on intertidal (RAL of 65 mg/kg OC) and subtidal (RAL of 12 mg/kg OC in Recovery Category 1 and shoaling areas) subsurface sediments. The entire subsurface sediment dataset was used for both intertidal and subtidal interpolations to provide optimal boundary control; then, the two subsurface rasters were cropped to their applicable areas and spliced.

3. **Combination of Surface and Subsurface Indicators (Maps F-5a, F-5b):** Using a GIS raster calculation, the surface and subsurface interpolation layers were combined into a single layer showing the total PCB RAL exceedance footprint of both layers. All interpolation layers used the same grid and were registered to the same origin. ArcGIS selected the highest indicator value in each of the surface and subsurface rasters; these values represented the combined RAL exceedance area for both surface and subsurface datasets.

4. **Thiessen Polygons for Other COCs (Maps F-6a, F-6b, F-7a, F-7b):** These maps show the median (50%) PCB RAL exceedance area boundary derived from indicator kriging overlain with Thiessen polygons for COCs other than PCBs that extend beyond the median PCB boundary. Like the PCB interpolations, Thiessen polygons include the combined horizontal extents of contamination for all other COCs in both surface and subsurface intervals. Other COCs that determined local RAL exceedance area boundaries included metals, polycyclic aromatic hydrocarbons, other semivolatile organic compounds (bis[2-ethylhexyl] phthalate, butyl benzyl phthalate, benzoic acid, dibenzofuran, 2,4-dimethylphenol, phenol, chlorobenzenes), and dioxins/furans, depending on the area. Maps F-7a and F-7b show the same Thiessen polygon overlays as Maps F-6a and F-6b, but without polygons for phenol-only exceedances. Based on the transient and ephemeral nature of phenol in sediments, the potential for natural sources, and previously collected sediment time series data for the LDW, phenol is not expected to be persistent in the aquatic environment or in sediment. The persistence of the Phase I phenol exceedances will be further investigated as part of the Phase II PDI, as described in the PDI QAPP Addendum for Phase II (Anchor QEA and Windward 2023). Pending the results of this investigation, Thiessen polygons for phenol are shown separately from RAL exceedance areas (Map 3-3) and are not included in the numbered RAL exceedance areas for remedial technology assignment discussed in Section 3.4.2. Additional investigation of phenol contamination is planned, as described in the PDI QAPP Addendum for Phase II.

On the PCB indicator kriging maps (Maps F-3a/b, F-4a/b, and F-5a/b), the indicator kriging contours represent the probabilities of exceeding the applicable RALs, expressed in units of percent. The 50% probability contour represents the median or central tendency estimate of the horizontal RAL exceedance boundary. Other contours—including the 20%, 30%, 40%, 50% (median), 60%, 70%, and 80% probabilities of exceedance—are provided for comparison. On the Fox River and Hudson River sediment cleanup sites, the median kriging estimates were used to define the remediation boundaries for RD and were shown to provide a reasonable balance between effectively removing contaminated sediment with concentrations above RALs and excluding sediment with concentrations below RALs (QEA 2007; Wolfe and Kern 2008; Anchor QEA and Tetra Tech 2016). This approach was also used in the upper reach of the LDW.

Maps F-6a and F-6b, which encompass all RAL exceedances associated with PCBs and other COCs in both surface and subsurface sediments, will provide the foundation for RD and will be the starting point to overlay engineering and constructability considerations. During the RD process, the remediation footprint in many areas will be expanded beyond the median boundary to address engineering and constructability considerations. Thus, a greater level of confidence will be achieved after RD.

4 PCB Uncertainty Analysis

The uncertainty of the PCB RAL exceedance area boundary was assessed using three independent lines of evidence:

- Indicator kriging probability contours
- Potential analytical uncertainty analysis
- Sensitivity analysis of semivariogram parameters

The second and third lines of evidence were recommended by the U.S. Environmental Protection Agency's statistician. The uncertainty of RAL exceedance area boundaries defined by Thiessen polygons for COCs other than PCBs in small, localized areas will be evaluated on a location-specific basis using best professional judgement during RD, in consideration of the magnitude of the exceedance.

4.1 Indicator Kriging Probability Contours

Indicator kriging probability contours are a primary line of evidence for assessing the uncertainty of the PCB RAL exceedance area boundary. Compared to other interpolation methods, indicator kriging has the distinct advantage of providing direct output data that are quantitative and probabilistic. In addition, the probability contours can be used throughout RD to continually assess confidence in the proposed remedy.

The boundary corresponding to the 50% probability of exceedance is assumed to be the initial basis for RD. During RD, the remediation footprint will generally be expanded beyond the RAL exceedance boundary as a result of the following:

- Simplifying the curved and irregular RAL exceedance area boundaries to more rectilinear but fully encompassing boundaries to provide a more constructible design
- In dredging areas, extending the side slopes of the dredge prism beyond the minimum required dredge boundary to maintain side slope stability

Locations with greater uncertainty will be addressed by collecting additional PDI data to further reduce boundary uncertainties, or by designing to a more conservative cleanup footprint. For these reasons, a greater level of confidence will generally be achieved during RD.

Where indicator probability contours are more tightly compressed, there is less uncertainty in the location of the RAL exceedance boundary; where probability contours diverge, there is more uncertainty in the RAL exceedance boundary location. For example, some broadening of the indicator probability contours is evident in subtidal subsurface sediments between RM 2.5 and RM 2.8, especially in the lowest (20% to 30%) probability range (Map F-4b). Otherwise, the indicator probability contours are generally well constrained in both surface and subsurface sediments. The use of a systematic, gridded sampling design in the middle reach, with sample spacings that are smaller than the spatial correlation ranges of surface and subsurface sediments, helps to constrain the indicator probability contours.

Areas of greater uncertainty in critical remediation areas will be addressed by collecting Phase II PDI samples or by designing remedial action area boundaries to encompass such areas. As described in the Phase II quality assurance project plan addendum (Anchor QEA and Windward 2023), certain Phase II sampling locations have been placed to reduce the uncertainty of the RAL exceedance area boundaries, and to provide increased confidence in remediation boundaries.

4.2 Assessment of Potential Analytical Uncertainty

An assessment of potential interpolation errors that may be caused by laboratory analytical uncertainty is discussed in this section. Phase I field replicate results for PCBs had an average relative percent difference of +/-30%, reflecting both analytical variance and heterogeneity within homogenized samples. Therefore, PCB concentrations that are within 30% of the applicable RAL have the potential to be misclassified as an exceedance (i.e., false positive) or non-exceedance (i.e., false negative). False negative errors are a potential concern in terms of missed contaminant inventory, and false positive errors are a potential concern in terms of remediation inefficiency.

Maps F-8, F-9a, and F-9b show exceedances and non-exceedances of a RAL of 12 mg/kg OC in surface sediments, a RAL of 12 mg/kg OC in subsurface sediments, and a RAL of 65 mg/kg OC in subsurface sediments, respectively. Samples with “close call” concentrations (i.e., concentrations within 30% of the applicable RAL) are also highlighted, including samples within the range of 8.4 to 15.6 mg/kg OC in 12 mg/kg OC RAL areas (Maps F-8 and F-9a), and samples within the range of 45.5 to 84.5 mg/kg OC in 65 mg/kg OC RAL areas (Map F-9b). Sample counts of close-call concentrations (+/-30% of RAL) are presented in Table F2-1.

4.2.1 Surface Sediments, RAL of 12 mg/kg OC (Map F-8)

Approximately 13% (60 out of 447 samples) of the surface sediment dataset, including combined subtidal and intertidal data, includes close-call samples within +/-30% of the RAL (Table F2-1). A large majority of those samples (48 out of 60 samples) are below but near the RAL. However, in nearly all instances, the close-call samples below the RAL (green symbols) are corroborated by neighboring samples well below the RAL (blue symbols) and well outside the range of typical laboratory error, indicating little risk of false negative misclassification. On the other hand, many of the close-call samples above the RAL (orange symbols) are isolated occurrences surrounded by samples well below the RAL (blue symbols), indicating a potential for false positive misclassification. Such a misclassification would tend to make remediation boundaries conservatively large.

4.2.2 Subsurface Subtidal Sediments, RAL of 12 mg/kg OC (Map F-9a)

Approximately 23% (30 out of 129 samples) of the subtidal subsurface dataset includes close-call samples within +/-30% of the RAL (Table F2-1). Most of the close-call samples above the RAL (orange symbols) are associated with neighboring samples well above the RAL (red symbols), and similarly, most of the close-call samples below the RAL (green symbols) are associated with neighboring samples well below the RAL (blue symbols), indicating a relatively low risk of false positive or false negative misclassification errors. One notable exception is the subtidal subsurface area between RM 2.5 and RM 2.8, where close-call samples near but below the RAL (green symbols) are bounded by one or more neighboring samples well above the RAL (red symbols). Additional samples will be collected in this area and analyzed in the Phase II PDI.

4.2.3 Subsurface Intertidal Sediments, RAL=65 mg/kg OC (Map F-9b)

Approximately 3% (2 out of 66 samples) of the subsurface intertidal dataset includes close-call samples within +/-30% of the RAL (Table F2-1) and both samples are below the RAL. These two samples are bounded upstream and downstream by samples well below the RAL, indicating a low risk of false negative misclassification errors.

4.3 Sensitivity Analysis of Semivariogram Parameters

Sensitivity analyses were performed to evaluate uncertainty in the parameterization of the semivariograms used to assign weighting factors during indicator kriging, and to assess the effects of semivariogram uncertainty on the resultant kriging probability contours.

4.3.1 Uncertainty of Semivariogram Parameter Values

The semivariogram model parameters compiled in Table F2-1 were derived by manual fitting of the spatially averaged semivariance estimates at different separation distances. Spherical and exponential semivariogram models with relatively steep near-field functions were selected to place greater emphasis on the closest neighbors. Relatively small nugget values and long range values were selected within the constraints of the empirical semivariance estimates, because such values tend to result in conservatively large exceedance areas within the 50% probability boundary.

The manually fitted semivariogram model parameters in Table F2-1 were compared to model parameters estimated using the automated, least-squares regression algorithm in the ArcGIS Geostatistical Analysist package. Two types of regressions were performed: In the first, all semivariogram parameters (nugget, sill, and range) were estimated using least-squares analysis; in the second, a nugget value was assigned and the sill and range values were estimated using least-squares analysis. The second type of regression was necessary to control some of the semivariance observations at very close range (i.e., distances of 40 to 80 feet, much less than the sample grid spacing of 100 to 200 feet); these observations were considered less reliable due to the small numbers of supporting sample pairs (see Section 2.1.2).

A comparison of manually fitted estimates of semivariogram model parameters with regression-based estimates is presented in Table F4-1.

Table F4-1
Semivariogram Model Parameters Derived using Least-squares Regression

Medium	Surface Sediment		Subsurface Sediment	
Zone	**Subtidal**	**Intertidal**	**Subtidal**	**Intertidal**
RAL	**12 mg/kg OC**	**12 mg/kg OC**	**12 mg/kg OC**	**65 mg/kg OC**
Common Attributes				
Model	Spherical	Spherical	Exponential	Spherical
Anisotropy	Anisotropic	Anisotropic	Anisotropic	Isotropic
Manually Fitted Parameters				
Major range	225	254	800	700
Nugget	0.010	0.040	0.035	0.020
Full sill	0.073	0.175	0.265	0.140
Regression Fitted Parameters				
Major range	202	840	1,200	840
Nugget	0.000	0.117	0.162	0.071
Full sill	0.069	0.199	0.244	0.135
Regression Fitted Range and Sill (Fixed Nugget)				
Major range	210	274	516	662
Nugget	0.010	0.060	0.070	0.040
Full sill	0.069	0.177	0.239	0.136

Notes:
OC: organic carbon
RAL: remedial action level

In the first type of regression, in which all semivariogram parameters are fitted automatically, the presence of less reliable, close-range semivariance estimates tends to inflate nugget values. The second type of regression, in which nugget values are fixed, helps control the disproportionate influence of these less reliable values. In the second type of regression, the sill values are well corroborated (i.e. regression-based sill values are within 10% of manually fitted sill values) and the nugget and range values are within a factor of two of the manually fitted values.

A primary objective of semivariogram model parameterization is to control nugget values to minimize misclassification errors. A low nugget value is supported in the middle reach of the LDW because among 23 pairs of field duplicate samples, 22 generated the same indicator value (i.e., 0 and 0, or 1 and 1) and only 1 generated a contradictory indicator value (i.e., 0 and 1). The collection of Phase II data should help improve the semivariance estimates at close range and further reduce the uncertainty of nugget values.

4.3.2 Effect of Semivariogram Uncertainty on Indicator Kriging Results

The sensitivities of the nugget and range values were assessed by varying the parameter ranges by plus or minus a factor of two relative to the base-case parameter values shown in Table F2-1 (i.e. 50% and 200% of the base-case values). The differences between manually fitted and regression-fitted semivariogram parameters, as discussed in Section 4.3.1, are consistent with a factor of two sensitivity range. The results of the sensitivity analyses for surface sediments and subsurface sediments are presented over a representative portion of the middle reach (RM 1.7 to RM 2.4) in Maps F-10a/b and Maps F-11a/b, respectively.

In general, the sensitivity maps show that the differences in indicator kriging contours are very slight, often imperceptible, and that the kriging algorithm is relatively robust and insensitive to uncertainties in the spatial correlation parameters. The one notable exception is the 50% range scenario in surface sediment (Map F-10b, left frame). In that scenario, the reduced range drops below the sample grid spacing, such that strings of connected exceedances start to break up into individual fragments. However, in the base-case scenario, which is used to support 30% RD, the range is higher than the grid spacing and there is much better connectivity between exceedances. In subsurface sediments, the ranges are substantially higher, such that reducing the range by 50% has negligible effect on the indicator probability contours (compare Map F-10b and Map F-11b). In all cases, no exceedances were excluded (i.e., missed) from the 50% probability boundary within the sensitivity ranges of the semivariogram parameters.

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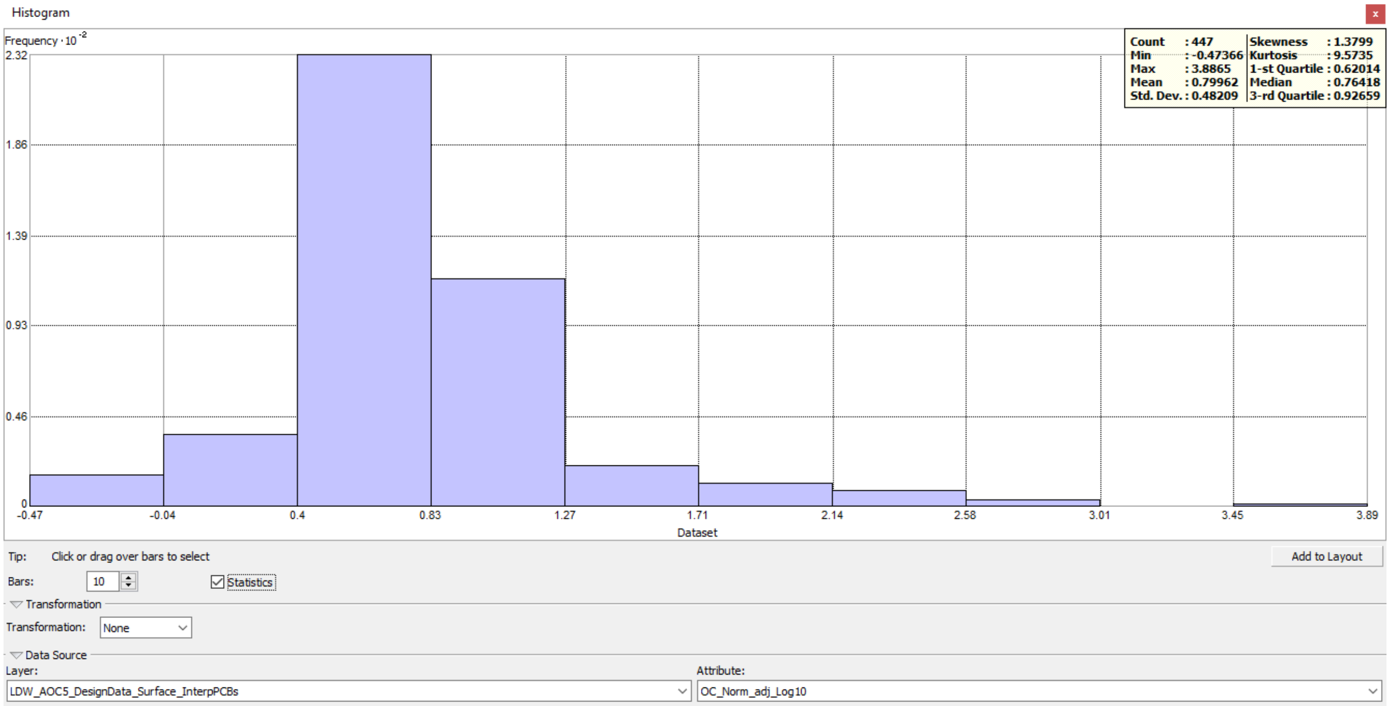
FINAL

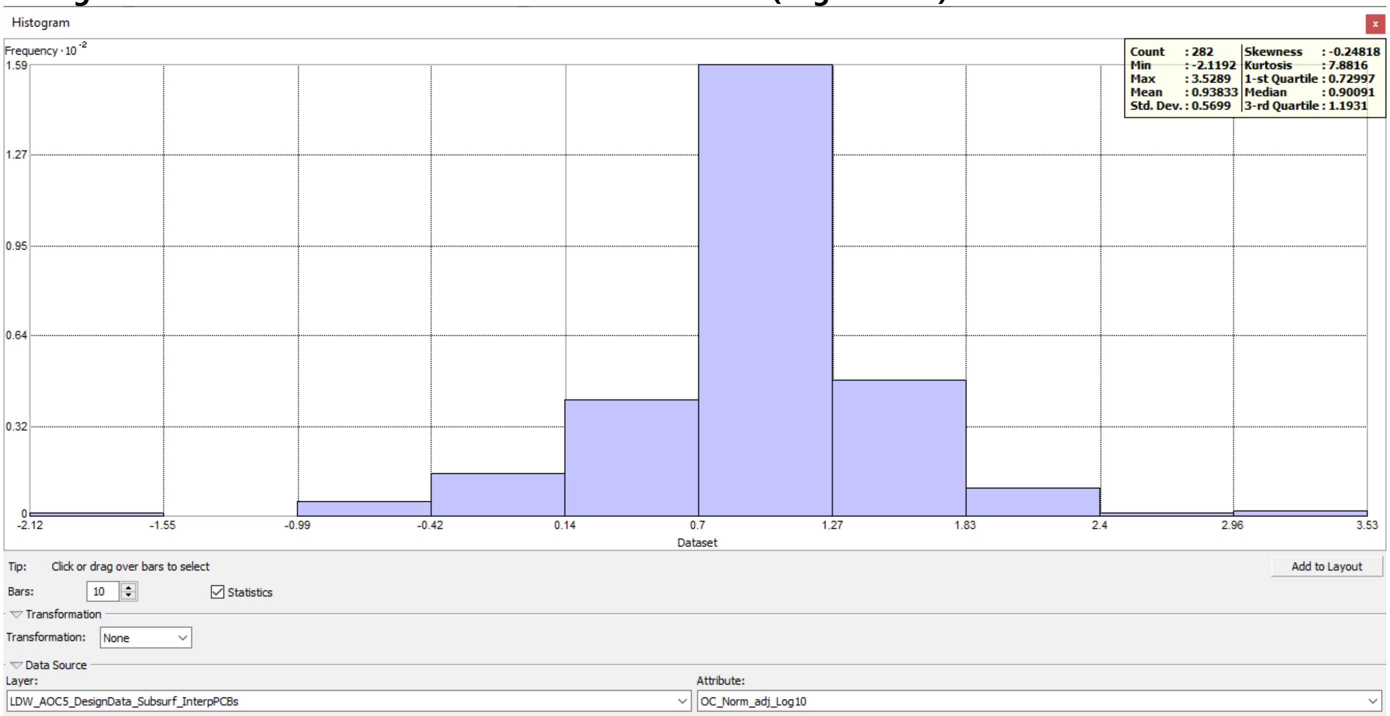
Attachment F-1

PCB Statistical Distributions

Histogram of PCB Concentrations in Surface Sediment (Log Base 10)

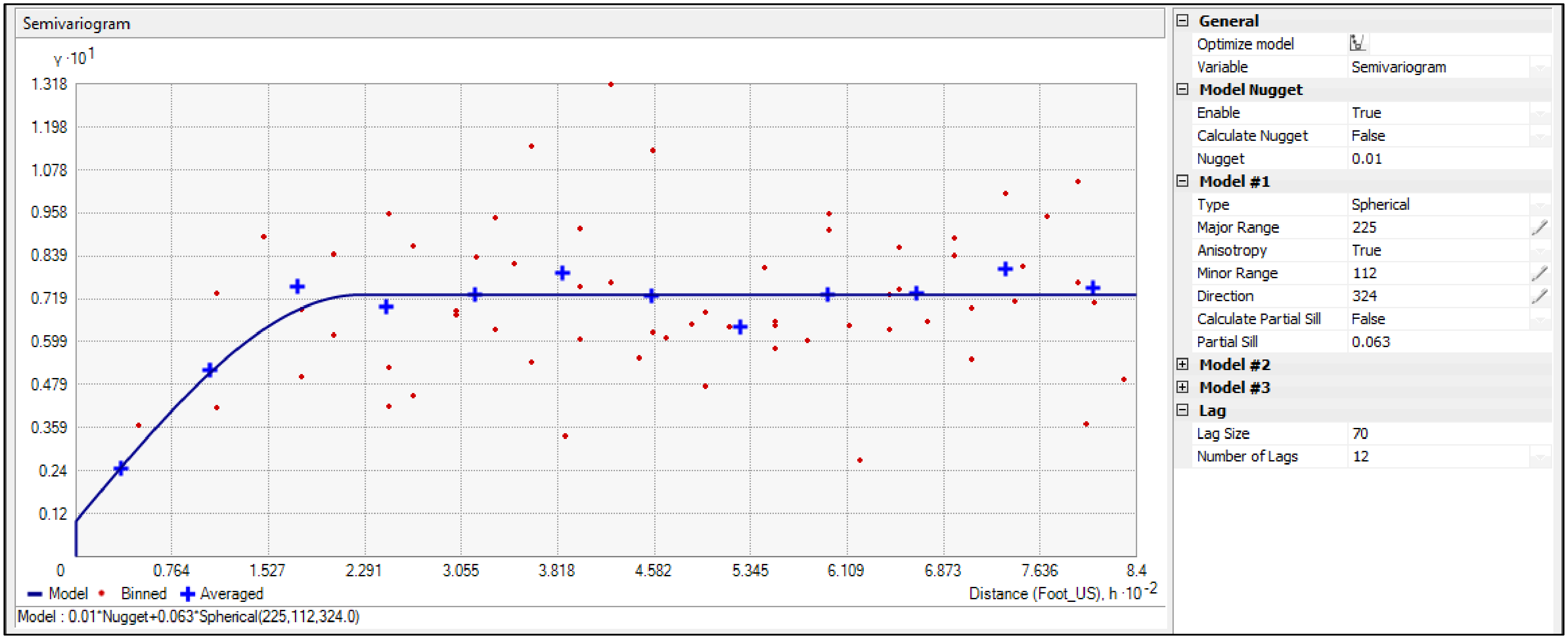


Histogram of PCB Concentrations in Subsurface Sediment (Log Base 10)

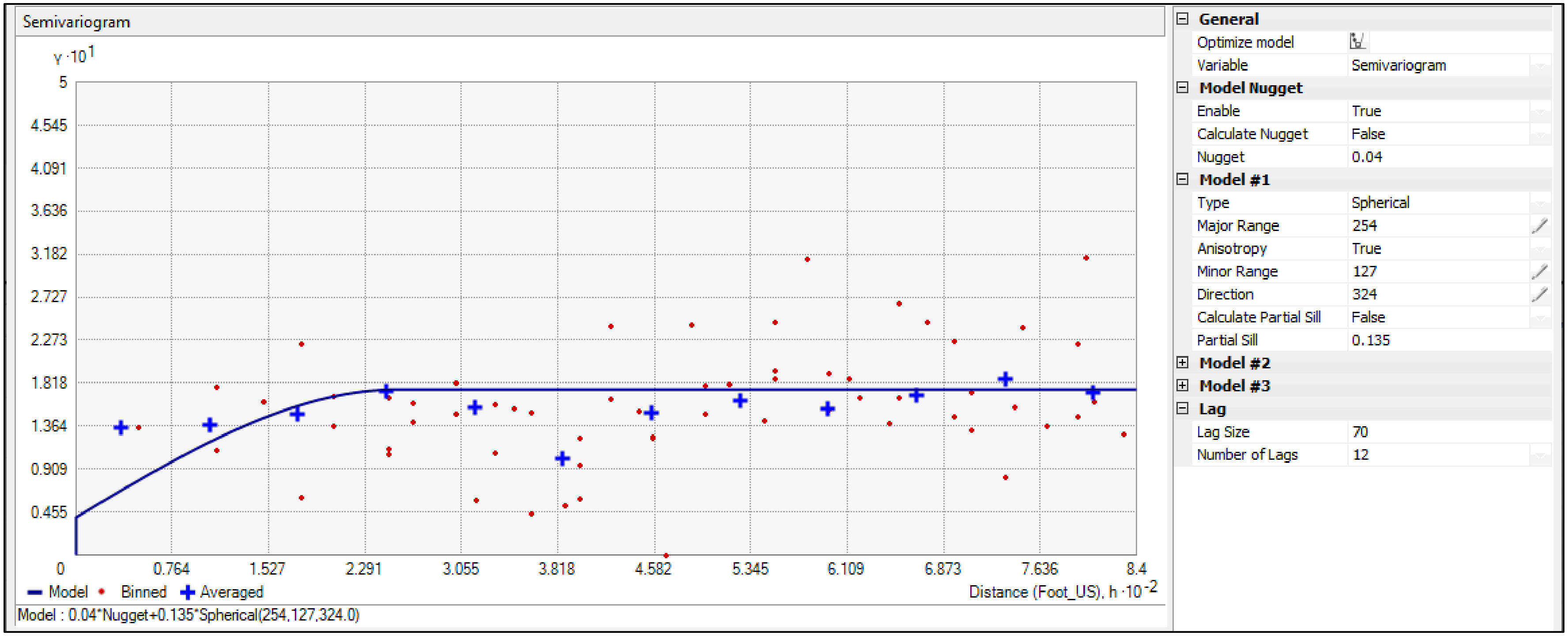


Attachment F-2
PCB Semivariograms

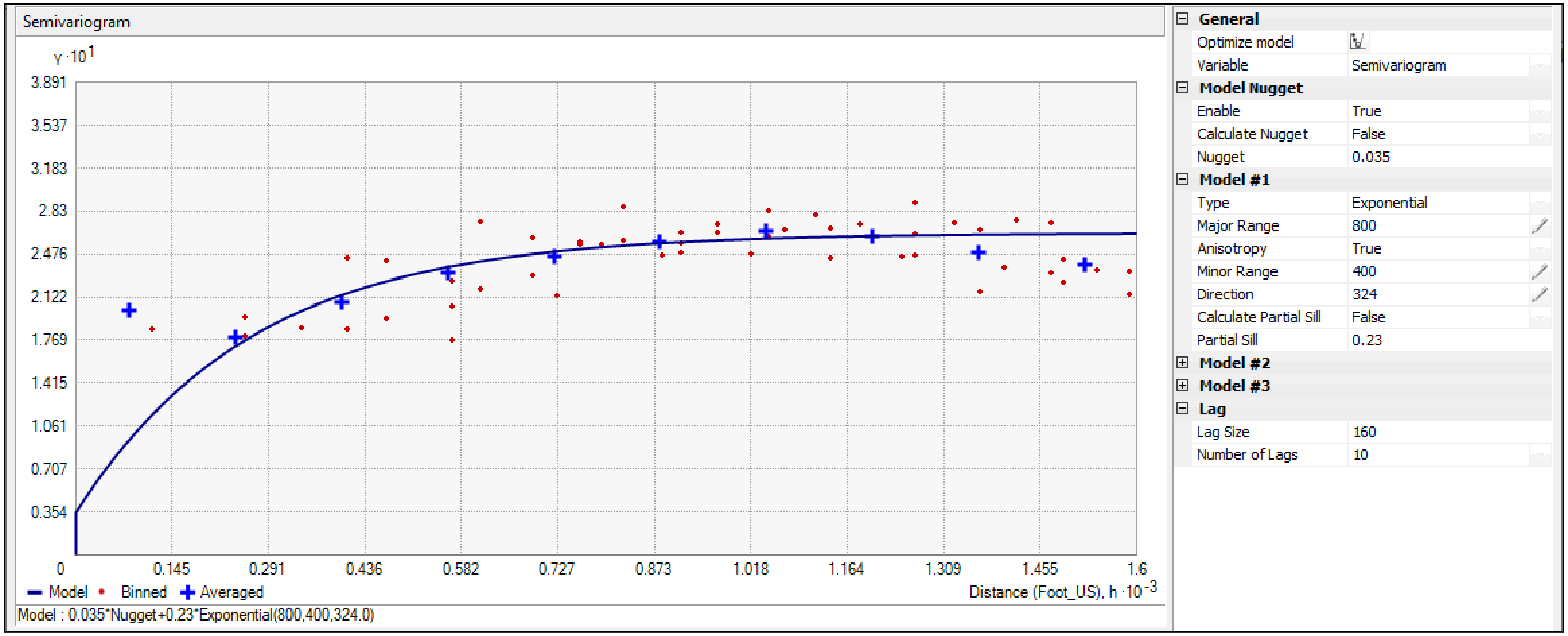
A. Surface Sediment - Subtidal - RAL=12



B. Surface Sediment - Intertidal - RAL=12



C. Subsurface Sediment - Subtidal - RAL=12



D. Subsurface Sediment - Intertidal - RAL=65