TECHNICAL REPORT

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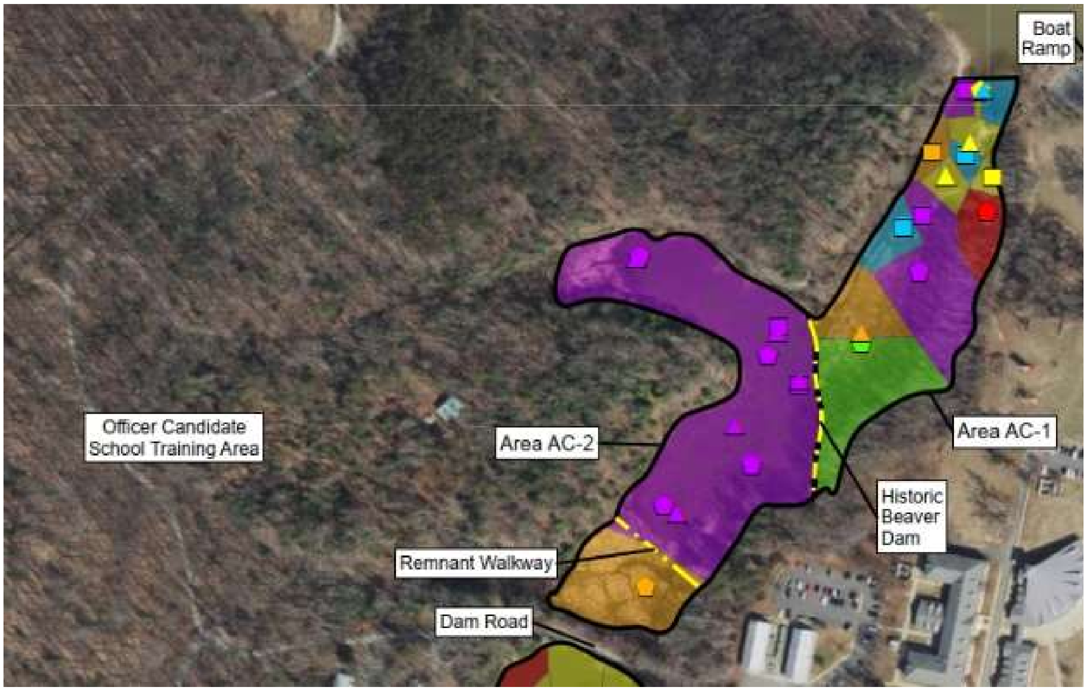
CASE STUDIES USING SURFACE WEIGHTED AVERAGE CONCENTRATION METHODS AT SEDIMENT REMEDIATION SITES



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Surface-Area Weighted Average Concentrations (SWACs) can be used to estimate mean contaminant concentrations over a specified area using contaminant data collected over different temporal and spatial scales. The SWAC method is used to reduce the influence of sampling bias and interpolate contaminant of concern (COC) concentrations in areas with limited sampling locations. SWAC methodologies can also be used to define remedial footprints in the Feasibility Study (FS) and evaluate remedy effectiveness. SWACs are an increasingly common approach for assessing compliance with remediation goals at contaminated sediment sites within the United States.

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ACRONYMS AND ABBREVIATIONS

AOC	area of concern
ARAR	applicable or relevant and appropriate requirement
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
COC	contaminant of concern
DDD	4,4'-dichlorodiphenyl-dichloroethane
DDE	4,4'-dichlorodiphenyl-dichloroethylene
DDT	4,4'-dichlorodiphenyl-trichloroethane
DDx	sum of DDD, DDE, and DDT
DOEE	District of Columbia Department of Energy and Environment
EPA	United States Environmental Protection Agency
EPC	exposure point concentration
FS	Feasibility Study
GIS	geographic information system
JBPHH	Joint Base Pearl Harbor-Hickam
LOAEL	lowest observed adverse effects level
LTM	long-term monitoring
MCBQ	Marine Corps Base Quantico
mg/kg	milligrams per kilogram
NAVFAC	Naval Facilities Engineering Systems Command
NOAEL	no observed adverse effects level
OCS	Officer Candidate School
PAH	polycyclic aromatic hydrocarbon
PCB	polychlorinated biphenyl
PeCDD	1,2,3,7,8-pentachlorodibenzo-p-dioxin
PeCDF	2,3,4,7,8-pentachlorodibenzofuran
PHSS	Portland Harbor Superfund Site
ppb	parts per billion
PRAP	Proposed Remedial Action Plan
PRG	preliminary remediation goal
RAL	remedial action level
RAO	remedial action objective

RI	Remedial Investigation
RM	river mile
ROD	Record of Decision
RPM	Remedial Project Manager
SMA	sediment management area
SWAC	surface weighted average concentration
TCDD	2,3,7,8-tetrachlorodibenzo-p-dioxin
TTNUS	TetraTech NUS
UCL	upper confidence limit
µg/kg	micrograms per kilogram

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1.0 INTRODUCTION

Navy Remedial Project Managers (RPMs) are tasked with the cleanup of contaminated sediment sites to reduce potential risk to ecological and/or human receptors. This report is intended to provide RPMs with background information on the application of a surface weighted average concentration (SWAC) approach to assess the need for remedial action, define remedial footprints, and/or monitor progress in achieving remedial action objectives (RAOs).

A SWAC is defined as a "weighted average of sample data intended to estimate mean contaminant concentration over a specified spatial area" (Kern, 2009 and 2019). The SWAC method is used to reduce the influence of sampling bias and interpolate contaminant of concern (COC) concentrations in areas with limited sampling locations. SWAC methodologies can also be used to define remedial footprints in the Feasibility Study (FS) and evaluate remedy effectiveness. SWACs are an increasingly common approach for assessing compliance with remediation goals at contaminated sediment sites within the United States. They are especially beneficial when targeting COCs that bioaccumulate in the tissues of organisms that migrate within and sometimes outside of an area of interest. SWACs are based on COC concentrations in surface sediment, which represents the biologically active zone where exposure to COCs occurs. A SWAC approach does not address sediment contamination that is buried below the surface layer.

This report describes several SWAC methods (arithmetic averages, weighted polygons and averaging over interpolated values), along with their advantages and limitations to assist RPMs in deciding whether to use SWACs for developing remedial footprints and assessing post-remediation achievement of remedial goals. Several factors inform the selection of the best method to use in SWAC development. These factors can include size and complexity of the site, density of sampling locations, impact of method selection on the decisions to be made, and non-technical considerations such as cost, schedule, and regulator input. Each method has advantages and limitations, and the project team and regulatory agencies should discuss and agree on method selection prior to application. Sometimes it is beneficial to calculate SWACs using multiple methods to determine the most accurate representation of conditions in the project area. Experts in geospatial analysis and statistics should be involved as soon as possible during data analysis so that multiple options can be discussed with the project team. Two case studies from contaminated sediment sites are provided as examples of applying different SWAC methodologies to identify remedial footprints during the FS phase of each project. Although this report focuses on contaminated sediment, the SWAC approach can also be used for contaminated soil sites.

This report is organized as follows:

- Section 2 presents an overview of the SWAC methodology.
- Section 3 presents a case study using weighted polygons to develop SWACs.
- Section 4 presents a case study using interpolation to develop SWACs.
- Section 5 summarizes key points for applying SWACs to sediment sites.
- Section 6 lists references.

2.0 SWAC METHODOLOGY OVERVIEW

There are several ways in which a SWAC approach can be used to compare results to remedial goals, develop remedial footprints, and assess remedy effectiveness. This report discusses the advantages and limitations of the various methods used to develop SWACs and provides example calculations for defining a remedial footprint; it also summarizes several sediment case studies where SWACs were applied.

2.1 Comparing SWACs to Remedial Goals

Preliminary remediation goals (PRGs) are typically developed in the FS and are based on risk-based concentrations such as no observed adverse effects levels (NOAELs), lowest observed adverse effects levels (LOAELs), or site-specific bioaccumulation-based values. In addition, applicable or relevant and appropriate requirements (ARARs) and background concentrations are considered when developing PRGs. COC concentrations in sediment are then compared to these PRGs. These comparisons are made either on a point basis or as SWACs as described below:

- Point concentrations are represented by a particular sampling location and typically characterize a small exposure area. For example, this approach would be appropriate for evaluating exposure point concentrations (EPCs) for benthic organisms with small home ranges.
- SWACs are similar to arithmetic averages of point concentrations, but each individual concentration is weighted in proportion to the area of sediment it represents. SWACs are typically used to target bioaccumulative COCs to account for exposures of animals that move within and sometimes outside the area of interest (Pelletier et al., 2019).

RPMs can use SWACs to address sites with bioaccumulative COCs such as polychlorinated biphenyls (PCBs), DDx,[1] and mercury because remediating localized areas with high COC concentrations can have a large impact on reducing the overall SWAC (and therefore risk) for the project area. Bioaccumulative compounds can be monitored using SWACs, which can be correlated to the fate and transport of contaminants through the food chain (United States Environmental Protection Agency [EPA], 2017a). Conversely, point comparisons to PRGs are usually more suitable for evaluating COCs that are acutely toxic to benthic organisms that are relatively immobile. RPMs should discuss the use of SWACs with regulators in the planning phase of a project because some states or districts may have rules governing the use of SWACs and point-based comparisons.

If the project has a confined area of known contamination and COC concentrations in the surrounding area are below PRGs, then a SWAC is not needed as only a limited area of remediation would be required. For example, if the data reveals a “hot spot” area of contamination that can be remediated with limited removal (e.g., through dredging), then a SWAC would not necessarily be

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[1] Sum of the pesticide 4,4'-dichlorodiphenyl-trichloroethane [DDT] and its degradation products 4,4'-dichlorodiphenyl-dichloroethane [DDD] and 4,4'-dichlorodiphenyl-dichloroethylene [DDE])

warranted. All of these factors should be identified and discussed during planning stages of the FS.

A SWAC approach should be considered when evaluating overall risk from exposure to contaminated sediment through comparison to PRGs. Choosing a SWAC approach could be particularly useful when dealing with mobile receptors. Because mobile receptors such as fish can have large home ranges, they can be exposed to sediment COCs across a large project area. In such cases, comparing SWACs to PRGs allows the project team to determine whether remediation is warranted. For example, no action may be required if the SWAC is below the PRG, even if some of the individual sample results are above the PRG. SWACs can be used in the FS to identify targeted areas for cleanup. SWACs are also of value when analyzing temporal trends in COC concentrations to assess remedy effectiveness over time.

EPCs and SWACs are both used to evaluate risks and hazards at a site. Baseline human health and ecological risk assessments typically use EPCs based on the 95 percent (%) upper confidence limit (UCL) on the mean COC concentration in accordance with Navy and EPA risk assessment guidance. However, a 95% UCL cannot be calculated for a SWAC. SWACs are also used after remediation to assess whether acceptable risk/hazard reduction has been achieved.

2.2 Using a SWAC Approach to Develop a Remedial Footprint

Defining the remedial footprint is a key step during preparation of a FS as part of the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) process. To do this, site data are compared to a single PRG (typically the most protective) or to a range of PRGs. As data are collected throughout the CERCLA process, site characterization may start with sampling based on a random grid with no presumptions of sources, or more likely, a targeted sampling design is used to identify and characterize potential sources or hot spots. Targeted sampling could bias the data set by focusing on hot spots or expected source areas; using a SWAC approach reduces the influence of such sampling bias.

Remedial action typically focuses on the areas with the highest COC concentrations that, when remediated, have the greatest impact in reducing the SWAC and overall risk at a site. Remediating large areas with lower COC concentrations will only lead to marginal reductions in SWACs. One method for developing a remedial footprint to meet PRGs is to establish remedial action levels (RALs), which are chemical-specific, point-based sediment concentrations. A RAL is developed through an iterative process "to determine the maximum concentration, or the 'do-not-exceed' value, that will result in reduction of the SWAC to meet the selected PRGs and achieve all applicable RAOs" (Naval Facilities Engineering Systems Command [NAVFAC], 2018). Multiple RALs are evaluated to determine which RAL, after remediation, will lower the SWAC value below the PRG. RALs are higher than the PRGs and are used to determine where remediation is required to meet the PRGs on an area-averaged basis. Applying the SWAC approach during the FS will help the project team in determining the optimal remedial footprint.

To illustrate how a RAL and SWAC for a site are related, it can be useful to look at remedial footprint development for an actual DDx-contaminated site (Battelle et al., 2007). Data collected within the project area boundary were contoured using the NOAEL-based cleanup goal (46 parts per billion [ppb]), the LOAEL-based cleanup goal (240 ppb), and a range of higher concentrations (400, 600, 800, 1000 ppb, as shown in Figure 2-1). The DDx concentration associated with each contour was considered a potential RAL. Predicted post-remediation sitewide average DDx concentrations were then calculated assuming that the sediment inside each contour was remediated (Figure 2-1 and Table 2-1). The predicted post-remediation sitewide average concentrations were then compared to the cleanup goals. This analysis showed that achieving the LOAEL-based cleanup goal would require remediation of 5 acres using a RAL of 800 ppb, whereas achieving the NOAEL-based cleanup goal would require remediation of more than 20 acres. This information was used as the basis for the remedial footprint in the FS.

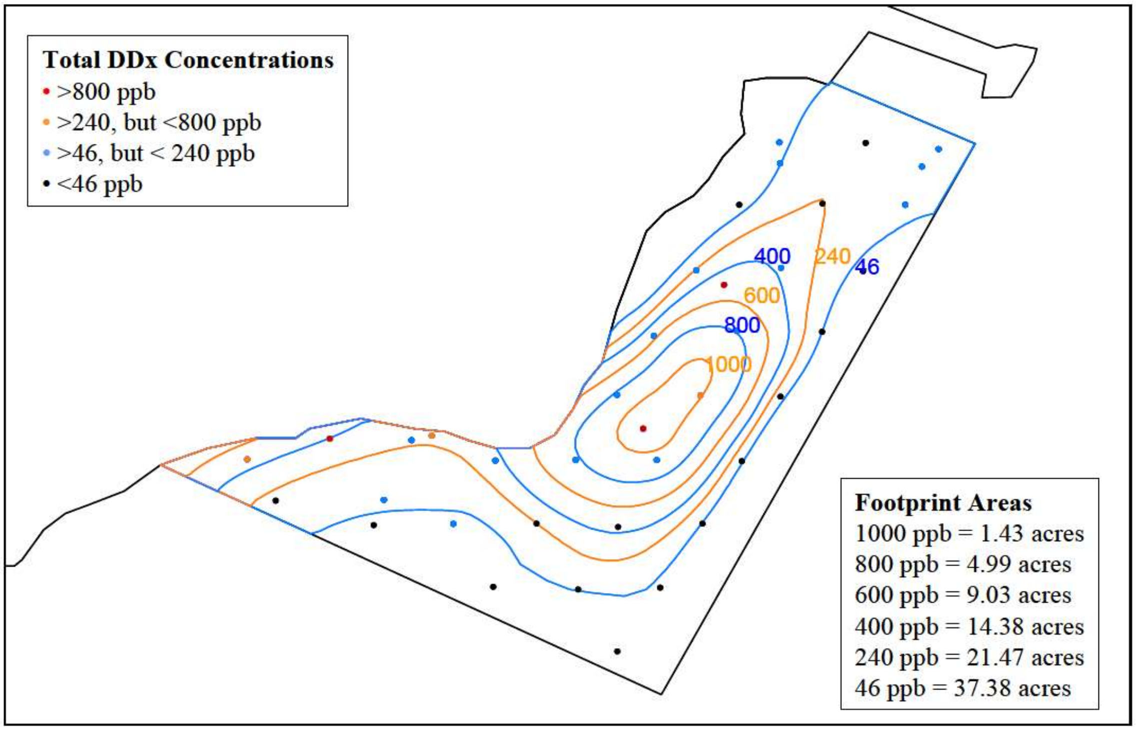


Figure 2-1. Total DDx Contours Based on NOAEL (46 ppb) and LOAEL (240 ppb) Cleanup Goals Note: Additional contours are illustrated to include all sample data.

Table 2-1. Post-Remediation Averages Based on Each Contour Area

DDx Concentration Contour	Size (acres)	Average Inside Contour (Total DDx ppb)	Post-Remediation Sitewide Average (Total DDx ppb)[1]
1000 ppb	1.4	1034	238
800 ppb	5.0	940	182
600 ppb	9.0	833	133
400 ppb	14.4	706	86.7
240 ppb	21.5	576	49.1
46 ppb	37.4	390	9.7
Total Area (black polygon in Figure 2-1)	56.3	265	NA

Notes: ppb = parts per billion. NA is not applicable. [1] Represents the sitewide average concentration if the area within the contour is removed and replaced with clean sediment averaging 9 ppb Total DDx, which is assumed to be the concentration in potential cap material.

2.3 Using a SWAC Approach to Assess Remedy Effectiveness

SWACs can also be used as performance standards to determine whether remediation was sufficient and successful in meeting project objectives and goals (Brunner et al., 2011). The SWAC approach can be used to assess remedy effectiveness by comparing pre- and post-remediation SWAC values to remedial cleanup goals. EPA has applied SWACs at several project sites within the EPA Region 5 Great Lakes area as part of long-term monitoring (LTM) projects and to assess progress in achieving cleanup goals (i.e., Ashtabula River, Ottawa River, Otter Creek, Manistique River). SWACs have been calculated over time at each site to inform the project team of the remedy effectiveness and progress. The repeatability and consistency of the methods allows a project team to assess temporal trends in the data. For example, in the Ashtabula River (EPA, 2017a), SWACs were evaluated two ways: calculating SWACs immediately following dredging and comparing SWACs to LTM goals. Individual surface sediment COC concentrations can inadequately represent the total contaminant exposure to mobile receptors. Therefore, SWAC values are more representative of the surface area where potential receptors are exposed to COCs. SWAC calculations can also support decision making related to removing beneficial use impairments and starting the delisting process as appropriate when the site is restored.

2.4 SWAC Methods

Remedial Investigation (RI) sampling plans typically do not consider future SWAC development because COCs and unacceptable risks have not yet been identified; however, pre-FS sampling plans could include a SWAC-related data quality objective to ensure that sufficient data are available to support the analysis. When planning the analysis, the area over which the SWAC will be calculated must be established. The area over which the SWAC is calculated should be consistent with the size of the home range for the receptor of interest; the boundaries of this area can be based on administrative site boundaries, geographic boundaries, data distribution, or other site-specific conditions.

When developing SWACs, the data are weighted to correct for spatial biases inherent in sampling programs such as those conducted for an RI, an FS, or both. Because these programs typically generate data sets using a mix of sampling designs over several years to fully characterize the nature and extent of contamination, the data should be weighted in proportion to the area of sediment a particular sampling location represents to mitigate the effects of spatially biased sampling designs. In geostatistics, this is referred to as declustering the data (Isaaks and Srivastava, 2005) and is accomplished by applying various SWAC techniques.

SWAC approaches range from simple arithmetic averages where all data points are equally weighted, to averages over the entire area with interpolated data (Kern, 2019). These methods are described in order of increasing complexity below. To choose the appropriate SWAC approach for a particular project, experts in geospatial analysis and statistics should be consulted.

Key considerations include the following when selecting a SWAC method:

- **Size and complexity of the site**: Simple methods that are easy to implement and understand may be sufficient for most sites.
- **Density and distribution of sampling locations**: Methods that do not rely on statistical assumptions tend to work best for larger data sets with higher spatial density.

- **Impact of method selection on the decisions to be made**: If the likely outcome is obvious regardless of the method used, then a simple method may be sufficient. If conclusions regarding the need for remedial action or the extent of a remedial footprint could be sensitive to the SWAC method used, then exploratory data analyses should be considered to support method selection. A SWAC can be calculated using multiple approaches to assess sensitivity to method selection.
- **Nontechnical considerations such as cost, schedule, and regulator input:** Nontechnical factors may also influence the selection of the SWAC method as appropriate.

The following SWAC approaches are described within this report:

- Equally weighted arithmetic average
- Thiessen polygons (weights proportional to polygons of influence)
- Averaging over a map of interpolated values, including the following
    - Inverse distance weighting
    - Natural neighbor
    - Kriging

A streamlined summary of the different SWAC approaches follows this section and includes some of the advantages and limitations of each approach (Table 2-2).

2.4.1 Equally weighted arithmetic average

The equally weighted arithmetic average is the simplest approach to calculate the SWAC. This method can be used when site data are based on a systematic, unbiased sample design (for example, grid-based sampling). In this case, all data points have equal weighting of one, and each sample represents an equal proportion of the total area of concern (AOC). Confidence limits can be calculated to quantify the uncertainty associated with the SWAC.

2.4.2 Thiessen polygons

The Thiessen polygon approach provides a weight to each sampling point based on the area of a polygon drawn around it. These polygonal boundaries define the area that is closest to each point relative to all other points. The boundaries are defined using the perpendicular bisectors of the lines between all points. Thus, the area represented by each data point is weighted depending on the area of each polygon relative to the total project area. If a sampling location is isolated from other locations, then it will generate a Thiessen polygon with a large area and thus have a large influence on the SWAC.

This approach only considers the closest samples around each sample location. In some cases, a project area may be divided into subareas (i.e., stratified) based on the conceptual site model before constructing the Thiessen polygons; for example, separate SWACs may be developed for shallow- and deep-water subareas. The uncertainty associated with a SWAC based on Thiessen polygons is not easily quantified.

The following is an example SWAC calculation based on the Thiessen polygon method as described in the Pearl Harbor Sediment Joint Base Pearl Harbor-Hickam (JBPHH) Record of Decision (ROD) (NAVFAC 2018).

The following equation was used to calculate the SWAC (using the Thiessen polygon method) for each COC:

$$SWAC = \frac{\Sigma A_i C_i}{\Sigma A_i}$$

where:

A_i = surface area of the subarea (Thiessen polygon) associated with sample *i*

C_i = COC concentration reported for sample *i*

The example illustrates the application of the SWAC equation for subareas A, B, C, and D, where subarea A has a concentration of 3 milligrams per kilogram (mg/kg) and a surface area of 10 acres, subarea B has a concentration of 5 mg/kg and an area of 2 acres, subarea C has a concentration of 50 mg/kg and an area of 15 acres, and subarea D has a concentration of 15 mg/kg and an area of 12 acres. The SWAC calculation using Thiessen polygons takes into account the large (15-acre) area with a high COC concentration (50 mg/kg) resulting in a total SWAC of 24.87 mg/kg.

$$\text{SWAC} = \frac{(3\text{ mg/kg} \times 10\text{ ac}) + (5\text{ mg/kg} \times 2\text{ ac}) + (50\text{ mg/kg} \times 15\text{ ac}) + (15\text{ mg/kg} \times 12\text{ ac})}{10\text{ ac} + 2\text{ ac} + 15\text{ ac} + 12\text{ ac}}$$

$$= 24.87\text{ mg/kg}$$

Where ac = acres in the formula. The simple arithmetic average concentration for this example is 18.25 mg/kg ([3 mg/kg + 5 mg/kg + 50 mg/kg + 15 mg/kg]/4).

2.4.3 Averaging over a map of interpolated values

The next three approaches, inverse distance weighting, natural neighbor, and kriging, all involve interpolation to assign COC concentrations to areas where there are no sampling locations. Each method incorporates the data from the known sampling location into a grid-based interpolation in a different way. Additional information about interpolation methods is provided by the Interstate Technology Regulatory Council website titled "*Geospatial Analysis for Optimization at Environmental Sites*" as available at https://gro-1.itrcweb.org/.

Inverse distance weighting

Inverse distance weighting is based on COC concentrations at unsampled points using a search neighborhood defined by a circle with a user-defined radius. The radius is determined based on data inputs such as geography or COC concentrations. The inverse of the distance to each sampling point within the circle is used for assigning weights. All of the sampling locations with the circle contribute to the predicted concentration, but those farther away from the center contribute less than those that are closer to the center. With this method, a SWAC is computed by summing all of the interpolated values on the grid and dividing by the number of grid cells. This method results in a smoothed estimation of COC concentrations across the entire study area but does not consider potential spatial correlation in the data set and does not provide an estimate of the uncertainty in the SWAC.

Table 2-2. Summary of SWAC Approaches Including Advantages and Limitations

Method	Description	Advantages	Limitations
Equally Weighted Arithmetic Average	Simple arithmetic average of the COC concentrations for all sampling locations. This simplistic method can be used if the sample data are based on an unbiased sample design. The method assumes the weight of each point = 1 and each sample represents an equal proportion of the total study area.	• Easy to calculate • Can estimate uncertainty	• RI/FS data sets are rarely based solely on unbiased sampling designs
Thiessen Polygons	A polygon is drawn around each sampling data point to represent an area of uniform COC concentration. The area of each Thiessen polygon is then used to weight each measurement relative to the total project area.	• Easy to understand • Uses a polygon network that is easy to construct using a geographic information system (GIS)	• Depending on the data distribution, Thiessen polygons may not be consistent with the conceptual site model • Cannot estimate uncertainty
Inverse Distance Weighting	A circle is drawn around multiple sampling locations (called a "neighborhood") to estimate the COC concentration at unsampled points. The radius of the circle is specified by the user; without any input, points are considered equally in all directions. The distance from the center of the circle to each of the sampling location in the circle is computed, and the inverse of those distances are used as the weights. All of the sampling locations within the circle contribute to the calculation of the interpolated value, but those that are farther away contribute less and those closer to the center contribute more. This method results in predicted concentrations within the AOC and a SWAC is computed by summing all of the interpolated values on the grid and dividing by the number of grid cells.	• Provides a smoothed representation of COC • Easy to understand • Easy to implement in a GIS	• Tend to produce "bull's eye" patterns around high- and low- concentration data points that may not be explained by the conceptual site model • Does not consider spatial correlation in the data set • Cannot estimate uncertainty
Natural Neighbor	This method starts with Thiessen polygons around each sampling location. The model identifies where an interpolated location can be positioned based on the existing data points ("natural neighbors") around it. A new polygon is defined around this interpolated location and the interpolated concentration is a weighted average of the natural neighbors. The SWAC is then calculated as the weighted average of all new polygons.	• Does not require user-specified inputs • Provides a smoothed representation of COC concentrations • Easy to understand • Easy to implement in GIS	• Does not consider spatial correlation in the data set • Cannot estimate uncertainty

Table 2-3. Summary of SWAC Approaches Including Advantages and Limitations (Continued)

Method	Description	• Advantages	• Limitations
Kriging	Kriging is based on a model of spatial correlation within the sample data and relies on a search neighborhood to interpolate concentrations in unsampled areas. It predicts a value at a given point by computing a weighted average based on values in that point's neighborhood. Because kriging predicts the concentration at any given location in the study area, the SWAC is an equally weighted average on all known and predicted concentrations.	• Generates a smooth surface of COC concentrations in a project area • Can predict a large amount of data at unsampled locations to better represent the full surface of the study area • Can estimate uncertainty	• More difficult to understand • Requires specialized knowledge to generate • Requires more data processing time

Natural neighbor approach

The natural neighbor approach starts with Thiessen polygons around each sampling location. Natural neighbors are the locations within the adjacent Thiessen polygons. A new polygon is defined around each interpolated point and its value is estimated using a weighted average of the natural neighbors using associated polygon areas for the weights.

Kriging model approach

Unlike averaging over a map of interpolated results that are directly based on the surrounding sampled observations, the Kriging model offers an alternate interpolation-based approach. Kriging is based on statistical models that include autocorrelation (i.e., the statistical relationships among the sampled observations). Kriging has the capability to generate predictions of surface concentrations that can be used to estimate SWACs and can provide for some measure of the uncertainty of these predictions. This uncertainty prediction is a distinct advantage over other methods, especially in scenarios where sampling is expensive and time-consuming and there is a limit on the number of sampling stations. Kriging models help to explain variation in surface concentrations by assuming that the distance or direction between sample points reflects a spatial correlation.

2.5 Example SWAC Calculations for Developing a Remedial Footprint

This section explains how a remedial footprint can be developed using a SWAC approach based on Thiessen polygons. In this case, sampling locations are spatially biased, with denser spacing closer to shore. COC concentrations at individual sampling locations range from 45 micrograms per kilogram (µg/kg) to 3,500 µg/kg. The PRG for this COC is 250 µg/kg (Figure 2-2).

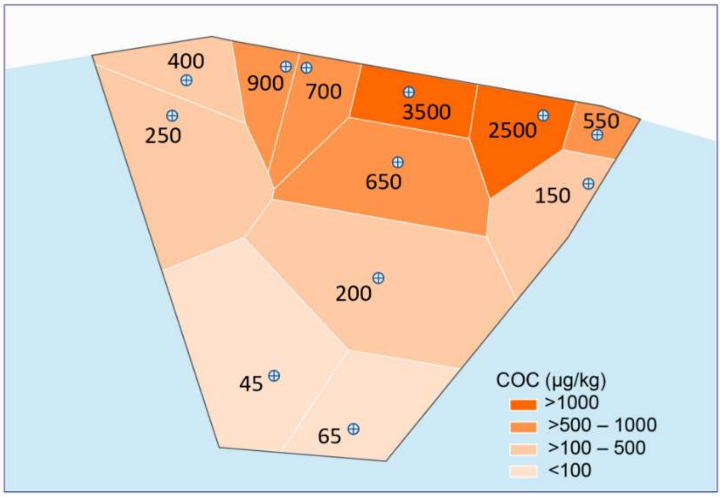
The SWAC is calculated as follows:

- Multiply each sample result by the fractional area of the Thiessen polygon to determine an area-adjusted concentration.
- Sum the area-adjusted concentrations to determine the SWAC.

In this example, the SWAC of 555 µg/kg exceeds the PRG (Figure 2-2, Panel A). To develop the remedial footprint, the polygon with the highest concentration is replaced with an assumed post-remediation concentration (in this case, 0.05 µg/kg). The recalculated SWAC is now 399 µg/kg, which still exceeds the PRG (Figure 2-2, Panel B).

A * B = C

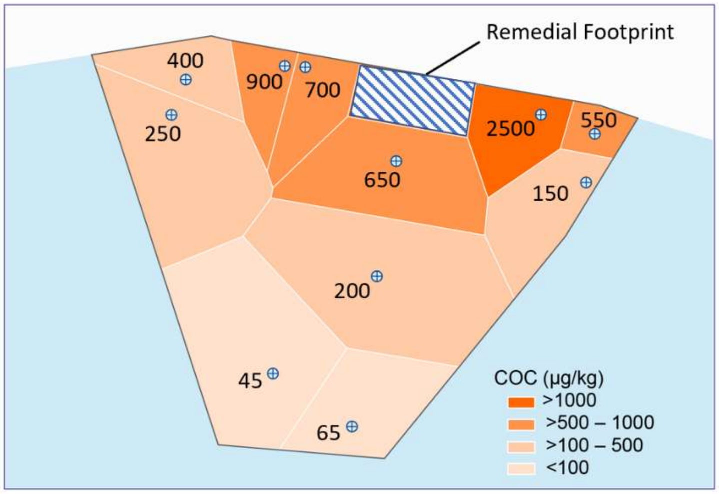
COC (µg/kg)	Percent of Total Area	Area-Adjusted Concentration (µg/kg)
3500	4.5	157
2500	5.6	139
900	3.3	29.9
700	4.4	31.1
650	11.4	73.9
550	2.0	11.0
400	4.5	17.9
250	13.2	33.0
200	19.4	38.8
150	7.8	11.7
65	7.8	5.06
45	16.1	7.26
Total	**100**	**555**



← ***Sum of Area-Adjusted Concentrations***

Panel A

COC (µg/kg)	Percent of Total Area	Area-Adjusted Concentration (µg/kg)
0.05	4.5	0.002
2500	5.6	139
900	3.3	29.9
700	4.4	31.1
650	11.4	73.9
550	2.0	11.0
400	4.5	17.9
250	13.2	33.0
200	19.4	38.8
150	7.8	11.7
65	7.8	5.06
45	16.1	7.26
Total	**100**	**399**



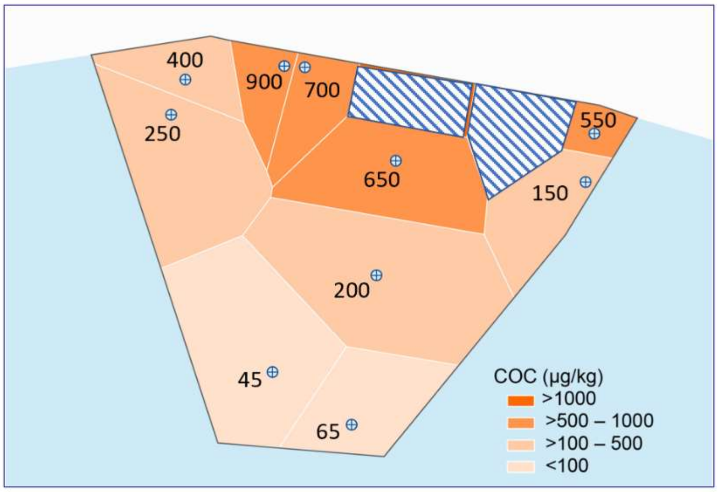
PRG = 250 µg/kg

Panel B

Figure 2-2. Hypothetical Remedial Footprint Developed Using Thiessen Polygons (Panels A and B)

This process is repeated two more times until the SWAC is reduced to 230 µg/kg, a value below the PRG of 250 µg/kg (Figure 2-3, Panels C and D). Although four of the polygons still have COC concentrations exceeding the PRG, the remedial footprint does not need to be expanded because the SWAC is below the PRG. In this example, the RAL is 700 µg/kg because all of the point locations with COC concentrations exceeding 700 µg/kg were included in the remedial footprint.

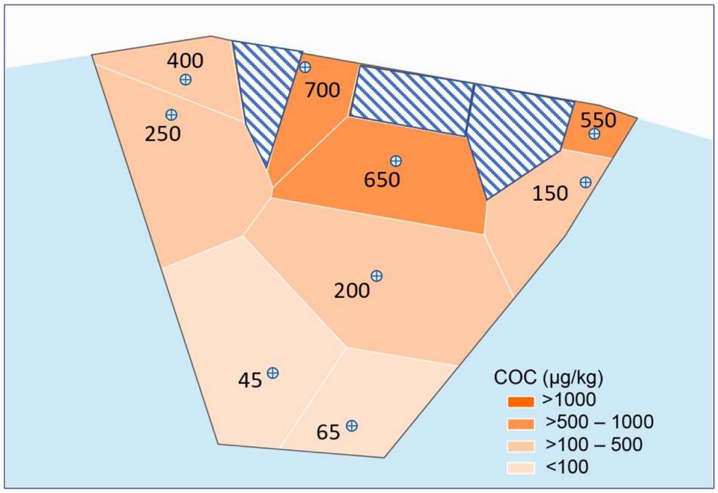
COC (µg/kg)	Percent of Total Area	Area-Adjusted Concentration (µg/kg)
0.05	4.5	0.002
0.05	5.6	0.003
900	3.3	29.9
700	4.4	31.1
650	11.4	73.9
550	2.0	11.0
400	4.5	17.9
250	13.2	33.0
200	19.4	38.8
150	7.8	11.7
65	7.8	5.06
45	16.1	7.26
Total	**100**	**260**



PRG = 250 µg/kg

Panel C

COC (µg/kg)	Percent of Total Area	Area-Adjusted Concentration (µg/kg)
0.05	4.5	0.002
0.05	5.6	0.003
0.05	3.3	0.002
700	4.4	31.1
650	11.4	73.9
550	2.0	11.0
400	4.5	17.9
250	13.2	33.0
200	19.4	38.8
150	7.8	11.7
65	7.8	5.06
45	16.1	7.26
Total	**100**	**230**



RAL = 700 µg/kg

PRG = 250 µg/kg

Panel D

Figure 2-3. Hypothetical Remedial Footprint Developed Using Thiessen Polygons (Panels C and D)

2.6 Sediment Case Studies

SWAC methods have been used to define remedial footprints for evaluation in the FS at Navy and EPA sites across the country (Table 2-3). SWACs are also widely used in risk management to determine whether the RAOs have been achieved. As described in Pelletier et al. (2019), which reviewed RODs and 5-year review reports from 77 contaminated sediment sites in the United States, SWACs are an increasingly common approach for developing remediation goals. SWACs are also increasingly used to evaluate compliance with remedial goals for sites with PCB or mercury contamination (Pelletier et al., 2019). This is because PCBs and mercury are bioaccumulative compounds, and remedies to address them are typically driven by human health or ecological exposures to COCs in fish tissue. Because SWACs are averages of COC concentrations over areas where fish forage, SWAC-based goals are appropriate for remedial actions that are protective of fish and also human and animal receptors that consume fish.

Table 2-4. SWAC Methods Used at Navy and EPA Project Sites

Site Name	Reference	SWAC Method
Bremerton Naval Complex OU B Marine	EPA, 2000	Thiessen polygons (called “area weighted average” in ROD)
Portland Harbor Superfund Site	EPA, 2016	Natural neighbor interpolation
Pearl Harbor Sediment	NAVFAC, 2018	Thiessen polygons
Hunters Point Naval Shipyard Parcel F	Navy Base Realignment and Closure, 2018	Thiessen polygons
Washington Navy Yard Operable Unit 2	CH2M Hill, 2021a	Thiessen polygons
Anacostia River Sediment Project	District of Columbia Department of Energy and Environment (DOEE), 2019	Thiessen polygons
Marine Corps Base Quantico (MCBQ) Site 102	CH2M Hill, 2020, 2021a, and 2021b	Thiessen polygons
Apra Harbor Sediment Naval Base Guam	AECOM, 2019	Thiessen polygons
Naval Support Facility Indian Head	CH2M Hill, 2011	Interpolation (method not specified)
Multiple AOCs (Ashtabula River, Ottawa River, Otter Creek, Manistique River) addressed by EPA Region 5 Great Lakes National Program Office	Ashtabula River (EPA, 2017a); other reports in progress	Thiessen polygons

The two case studies that follow (in Sections 3 and 4) explore SWACs that were developed to define remedial footprints at MCBQ Site 102 in Quantico, Virginia and at the Portland Harbor Superfund Site in Portland, Oregon. Both sites feature historical contamination requiring remedial action. Multiple investigations were conducted to characterize these sites and identify the nature and extent of COCs. As part of the FS process, SWACs were calculated to define the remedial footprints to be used as the basis for developing and evaluating remedial alternatives. These two sites were chosen as case studies because they represent two of the most common methods for calculating SWACs.

- MCBQ Site 102, a comparatively small site, calculated SWACs using **Thiessen polygons**. At this site, the data were used to define the remedial footprints for further evaluation in the FS.
- For Portland Harbor, a large and complex site, SWACs were calculated using the **Natural Neighbor** method. A range of RALs were used to define the remedial footprints for evaluation in the FS.

SWAC calculation for these two projects are explored in the following sections and in associated reference documents.

3.0 MARINE CORPS BASE QUANTICO SITE 102

The highlights of the MCBQ Site 102 case study are as follows:

- **Purpose of SWAC evaluation**: Develops remediation target areas for an FS.
- **SWAC area**: Calculates SWACs over three areas separated by geographic boundaries.
- **SWAC method**: Uses Thiessen polygons.
- **Site-specific factors**: The SWAC approach allowed a high-value training area to be excluded from the remedial footprint.

3.1 Site Description

MCBQ is located approximately 35 miles south of Washington, DC, and 75 miles north of Richmond, Virginia. The base is approximately 60,000 acres, with 3 miles of Potomac River shoreline (Figure 3-1). The primary mission of MCBQ is training for general combat; the facility consists of buildings, woodlands, artillery ranges, and other military-use areas (CH2M Hill, 2020).

The Chopawamsic Creek watershed, one of several drainage systems within the MCBQ, is located along the eastern shoreline of the base. The Chopawamsic Creek watershed begins with intermittent streams in the central portion of the facility (west of Interstate 95) and flows generally to the southeast to the Potomac River. The upper portion of Chopawamsic Creek consists of irregularly branched streams, while the lower portion is a tidal estuary that includes a large wetland area. Abraham’s Creek is located in the southeastern portion of the main body of Chopawamsic Creek (Figure 3-1) (TetraTech NUS [TTNUS], 2002).

Abraham’s Creek was designated as Site 102 and consists of three ponds and associated wetlands within its boundary (Figure 3-2). In its northern section, Abraham’s Creek is partially influenced by tidal fluctuations (Area AC-1), while a land bridge (Dam Road) and beaver dam have historically restricted tidal influence in the upstream portions of the creek (Areas AC-2 and AC-3). Site 102 is approximately 16.7 acres; Area AC-1 is approximately 3.7 acres, Area AC-2 is approximately 5.2 acres, and Area AC-3 is approximately 7.8 acres (Battelle et al., 2008). The forested areas around Area AC-3 are part of the exercise areas of the Officer Candidate School (OCS). In the southwest portion of AC-3, an important training area for the OCS is located at the site known as the Quigley.

3.2 Nature and Extent of Contamination

3.2.1 Contaminants of Concern

An RI identified DDx and PCB contamination in Abraham’s Creek sediments (TTNUS, 2007). These COCs were observed throughout the three ponds in both the surface and subsurface sediments. No known sources of these COCs have been identified and there are no known continuing sources of COCs to Abraham’s Creek (Battelle et al., 2008 and 2014).

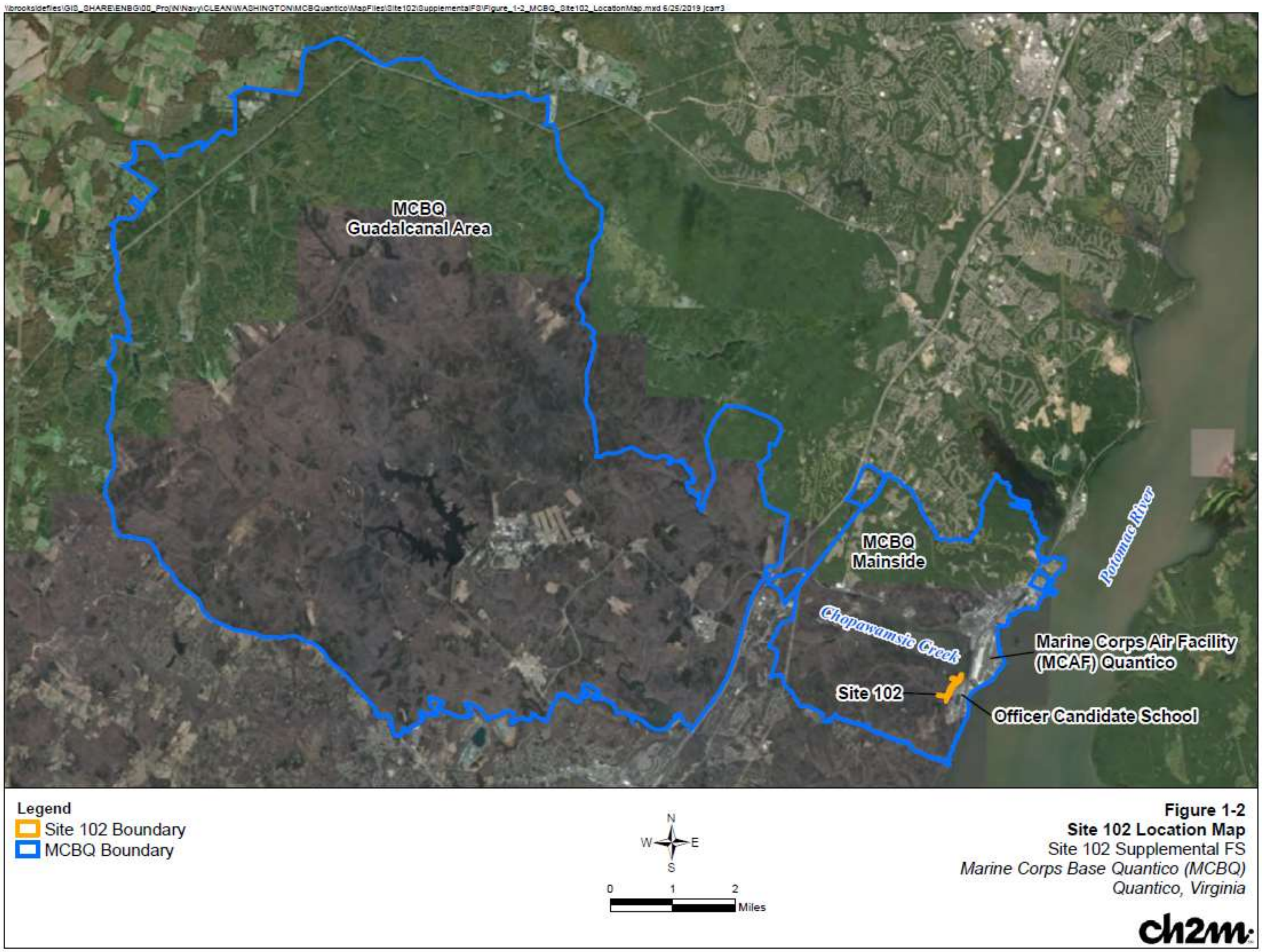


Figure 3-1. Site 102 Location in Southeastern Section of MCBQ (CH2M Hill, 2020)

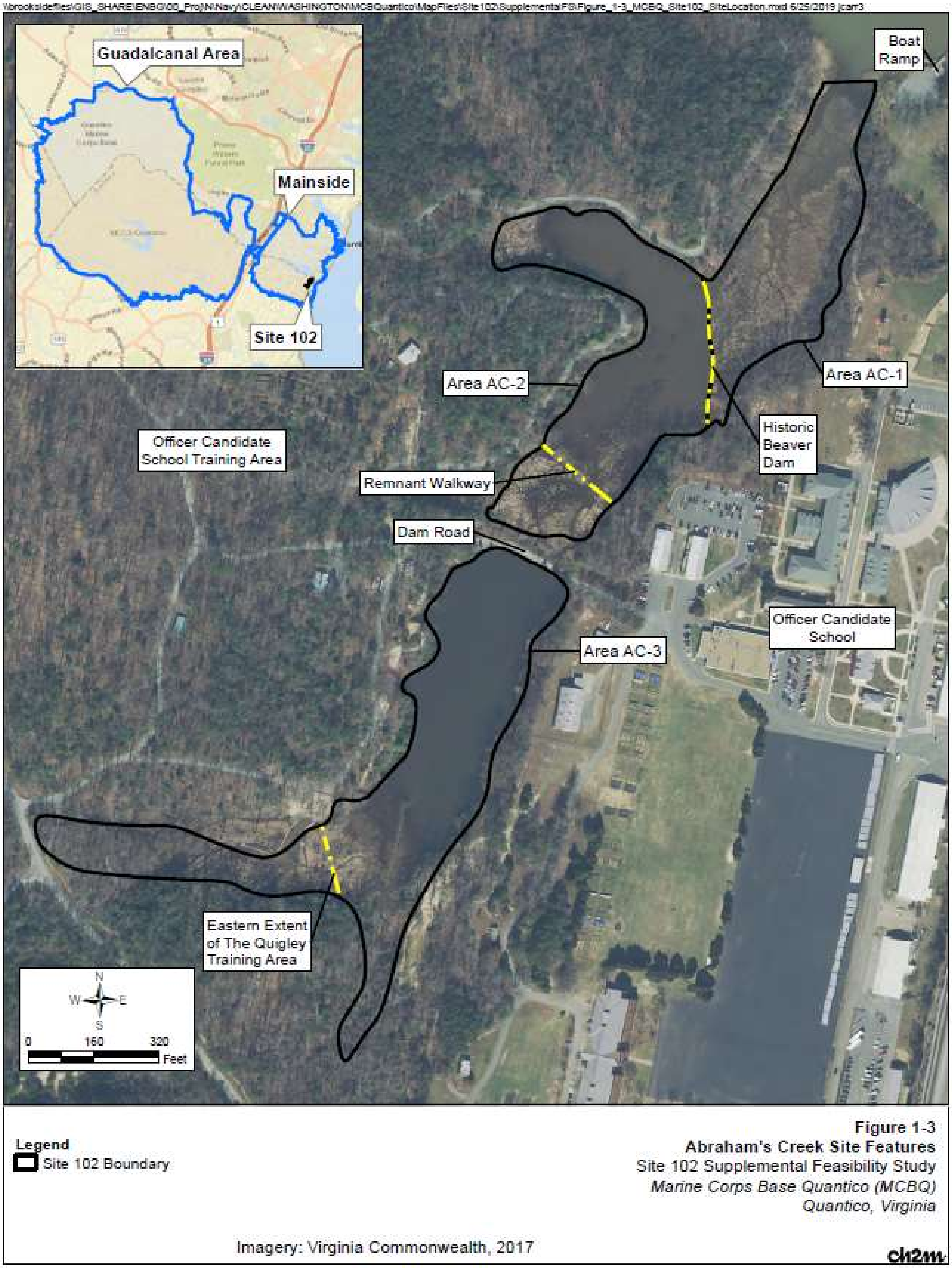


Figure 3-2. Abraham's Creek Subareas and Site Features (CH2M Hill, 2020)

3.2.2 Fate and Transport

There is little to no water movement between the three ponded areas in Abraham's Creek. DDx and PCBs have low solubility in water, a high affinity for organic matter, and are expected to remain bound to sediments with little desorption into the water column (CH2M Hill, 2020). Physical transport of particulate matter (sediment and organic matter) with sorbed DDx and PCBs is unlikely due to the physical constraints in Abraham's Creek (Figure 3-2).

As stated in the Final Supplemental FS (CH2M Hill, 2020), food-chain model results indicated potential ecological risk for insectivorous birds (common yellowthroat), piscivorous mammals (mink), and piscivorous birds (belted kingfisher and great blue heron) from dietary exposure to sediment-associated DDx in Areas AC-2 and AC-3. No risk from DDx was present to food-chain receptors in Area AC-1. Total PCBs did not pose unacceptable risk to any receptor in any of the three subareas (CH2M Hill, 2020).

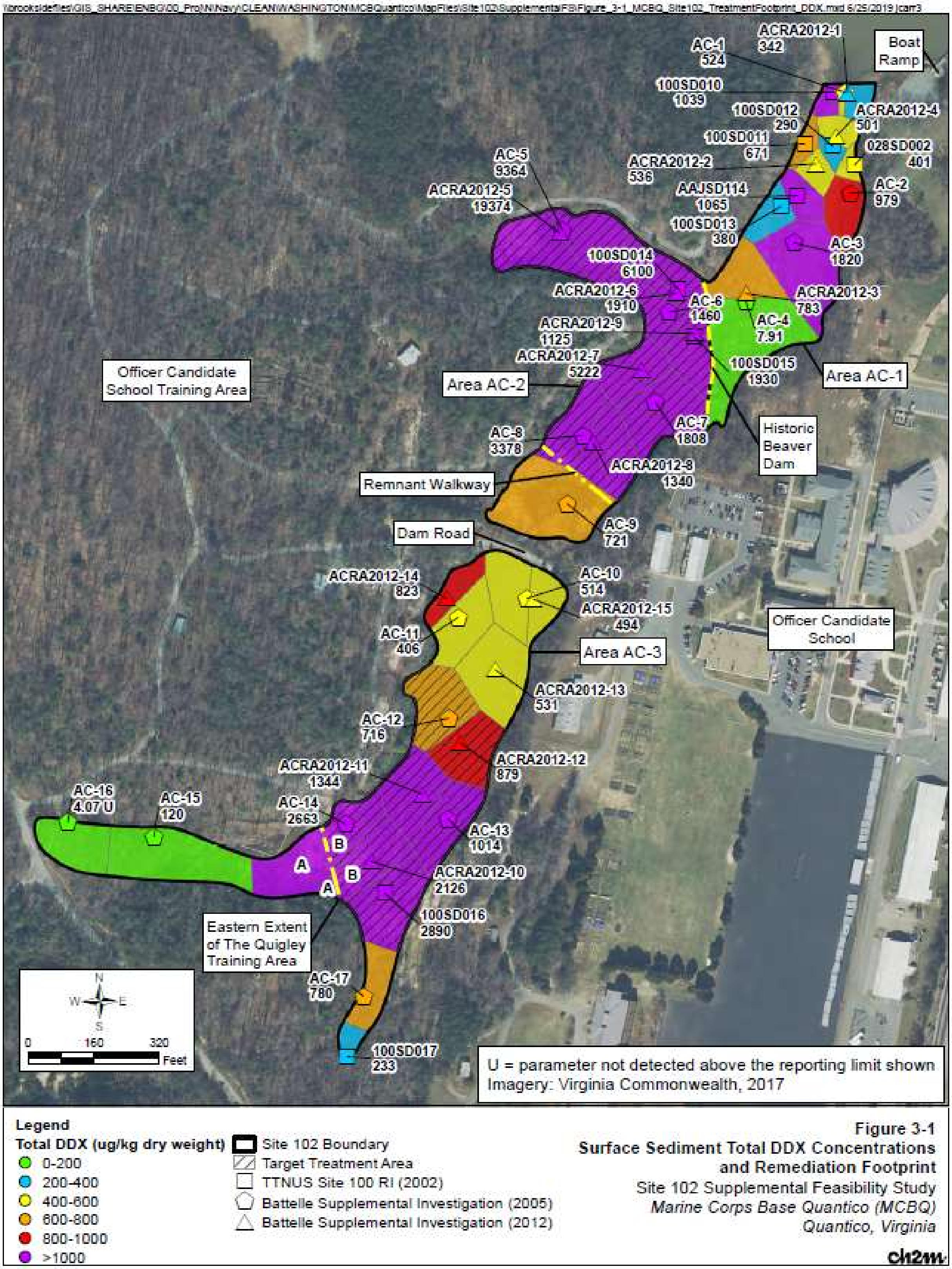
3.3 PRGs and SWACs

To identify the remediation target areas, SWACs were calculated and then compared to project-specific PRGs that were based on risk to four wildlife receptors (three bird species and mink) from uptake of DDx. No risk was identified for wildlife receptors potentially exposed to PCBs because none of the LOAEL-based hazard quotients were greater than 1.0 (CH2M Hill, 2020). SWACs were calculated using the surface sediment concentrations of DDx and PCBs collected during previous investigations. The SWACs were then compared to the most conservative (lowest) PRG for each area. The objective of this comparison was to refine the remediation target areas in each of the Abraham's Creek areas.

Calculating the SWACs for MCBQ involved subdividing each subarea into Thiessen polygons using GIS software to estimate the spatial influence of each sample location. As stated in the FS (CH2M Hill, 2020), this method was employed as follows:

> *The polygon boundaries defined the area that is closest to each sample point relative to all other points… [The boundaries] are mathematically defined by the perpendicular bisectors of the lines equidistant between sample points. The Thiessen polygons for Abraham's Creek were bounded by the current study area and by boundaries and features defining each of the three areas of Abraham's Creek. After creation of the Thiessen polygons, the square footage of each polygon was assigned to each respective sample location for determining a SWAC value.*

Thiessen polygons for each area with representative surface DDx and PCB concentrations are shown on Figure 3-3 and Figure 3-4, respectively. SWACs for both DDx and PCBs were compared to the lowest PRG for each Abraham's Creek area. The PCB SWACs in each of the areas were below the respective PRG, therefore, the remediation target areas were based only on the DDx concentrations.



U = parameter not detected above the reporting limit shown
Imagery: Virginia Commonwealth, 2017

Figure 3-1
Surface Sediment Total DDX Concentrations and Remediation Footprint
Site 102 Supplemental Feasibility Study
Marine Corps Base Quantico (MCBQ)
Quantico, Virginia

Figure 3-3. Surface Sediment Total DDx Concentrations and Remediation Footprint (CH2M Hill, 2020)

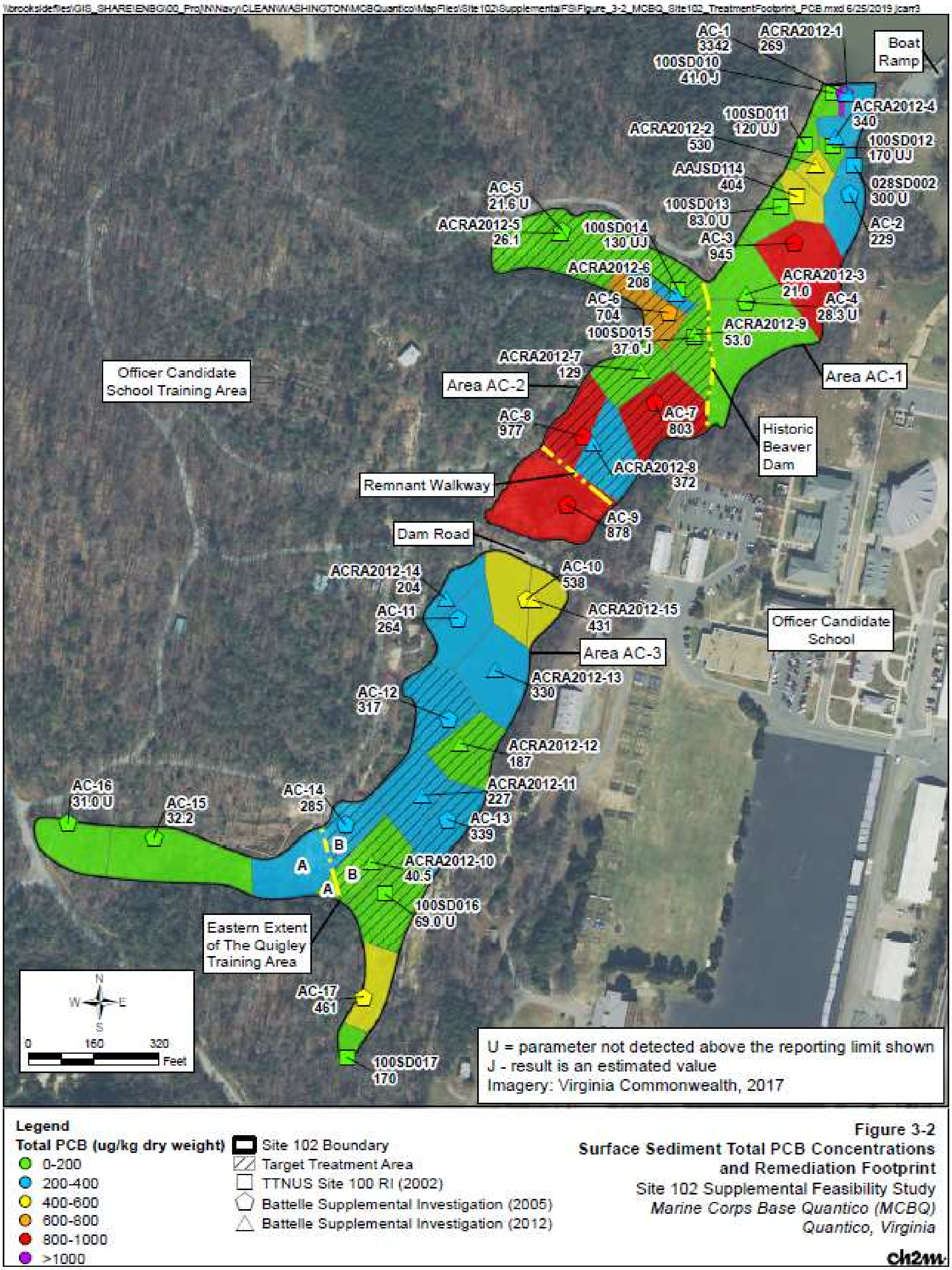


Figure 3-4. Surface Sediment Total PCB Concentrations and Remediation Footprint Based on DDx (CH2M Hill, 2020)

A defined process was followed for determining the remediation target area for each Abraham's Creek subarea. To reduce the SWAC to a level below the PRG, COC concentrations in Thiessen Polygons were systematically replaced with an assumed post-remediation concentration. This replacement step started with the polygon with the highest concentration and continued until the estimated post-remediation SWAC was below the PRG. As stated in the FS (CH2M Hill, 2020), the process used to calculate an estimated post-remedy SWAC involved the following steps:

> *To determine the remediation target area for each Abraham's Creek subarea to bring the area SWAC below the PRG, contiguous Thiessen Polygons with point concentrations above the PRG were systematically removed (starting highest concentration to lowest concentration) from the calculation to simulate a post-remedy SWAC… and substituted with the median detection limit for 4,4'-DDT, -DDD, and -DDE [of 6.1 µg/kg]… multiplied by three to represent a potential sum (18.3 µg/kg).*

As part of pre-design considerations, several constraints to the remedial action were identified. The terrestrial areas surrounding Site 102 are often used for the OCS Training Area and therefore are off limits at certain times of the year. The area called the Quigley is a critically important training area where invasive work should be avoided. As shown in Figures 3-3 and 3-4, during SWAC calculations, the polygons encompassing the Quigley were split into two subareas (AC-14 'A' and 'B'; ACRA2012-10 'A' and 'B'). The evaluation was performed assuming no remediation within the Quigley 'A' subareas to avoid disruption of OCS operations. Only remediation of the polygons outside of the Quigley area ('B' subareas) were considered.

The following sections summarize the remediation target areas determined for each area of Abraham's Creek.

3.3.1 Area AC-1

The SWAC for Area AC-1 was below the PRG for both DDx (SWAC of 754 µg/kg compared to a PRG of 798 µg/kg) and PCBs (SWAC of 340 µg/kg compared to a PRG of 3,815 µg/kg). Therefore, no active remediation was necessary within this area. However, monitoring of this area will be included as part of LTM as some historical samples collected within AC-1 were above the PRGs for DDx.

3.3.2 Area AC-2

The SWAC for Area AC-2 was above the PRG for DDx (SWAC of 4,749 µg/kg compared to a PRG of 557 µg/kg) and below the PRG for PCBs (SWAC of 457 µg/kg compared to a PRG of 2,384 µg/kg). Using the SWAC process as described above, remediation of all polygons within AC-2 is required, except the subarea around sampling location AC-9, which is dominated by emergent marsh (Figure 3-3). Using the process stated above for replacing DDx concentrations in polygons with an assumed post-remediation concentration, the estimated post-remediation DDx SWAC (149 µg/kg) was calculated to be below the PRG (557 µg/kg).

3.3.3 Area AC-3

The SWAC for Area AC-3 was above the PRG for DDx (SWAC of 1,100 µg/kg compared to a PRG of 375 µg/kg) and below the PRG for PCBs (SWAC of 230 µg/kg compared to a PRG of 1,621 µg/kg). The southernmost area of AC-3 had the highest concentrations; this is the area known as the Quigley. Two polygons (AC-14 and ACRA2012-10) near the Quigley represent large surface areas. As stated in the FS (CH2M Hill, 2020), the following assumptions were made:

> *… it is assumed two partial polygons that overly the Quigley area (AC-14 and ACRA2012-10) are represented entirely by the elevated concentrations at these sample locations, even though the upgradient concentrations are markedly lower (below the method reporting limit at AC-16 and 120 µg/kg at AC-15).*

The two polygons (AC-14 and ACRA2012-10) were divided and evaluated separately as 'A' and 'B' portions at the line marking the "Eastern Extent of the Quigley Training Area" (Figure 3-3). The new "area-adjusted" SWAC of 1,100 µg/kg was compared to the PRG of 375 µg/kg. The SWAC was significantly influenced by the 2,663 µg/kg concentration at polygon AC-14A (the portion which extends into the Quigley). For example, if the DDx concentrations in the unremediated portion of the polygon were slightly lower (2,600 µg/kg), the post-remedy SWAC would decrease to the PRG (375 µg/kg). Therefore, by splitting this polygon into 'A' and 'B' portions, the SWAC was reduced (379 µg/kg) to near the PRG to be protective of ecological receptor populations and the refined remediation target area was further evaluated in the FS.

3.4 Remedial Alternative Evaluation

The remedial alternatives were evaluated in the FS using the nine criteria as required by CERCLA. In situ treatment with activated carbon was selected as the preferred alternative to reduce bioavailability of DDx and thereby reduce bioaccumulation within the remediation target areas of Site 102. LTM will continue in all three ponds at Site 102 because sediment with DDx concentrations above the PRGs will remain in place. Monitoring will also determine whether bioavailability and bioaccumulation have been reduced, resulting in an overall reduction in ecological risk. The FS concluded that the SWAC approach for establishing the remediation target areas would result "in some sampling locations with sediment above the PRGs that are not treated; however, the alternative would reduce ecological risk to acceptable levels."

3.5 Quantico Case Study Summary

In summary, SWACs were calculated for the FS at MCBQ Site 102 to assist in the development of the remediation target areas. SWACs were calculated using Thiessen polygons and then recalculated after systematically replacing polygons with an assumed post-remedy concentration, starting with the polygon with the highest concentration, until the SWAC was below the PRG. Using the SWAC approach for the FS resulted in the following:

- A remediation target area that achieved acceptable risk reduction without including every location with a COC concentration exceeding a PRG
- A remediation target area that excluded a critically important training area (the Quigley), which had been a major constraint to the remedial action
- No remedial action in Area AC-1.

The SWAC approach was incorporated into the Proposed Remedial Action Plan (PRAP) and ROD for the site.

4.0 PORTLAND HARBOR SUPERFUND SITE

The highlights of the Portland Harbor Superfund Site (PHSS) case study are as follows:

- **Purpose of SWAC evaluation**: Develops a range of remediation target areas for development of remedial alternatives in an FS.
- **SWAC area**: Calculates sitewide SWACs over a 10-mile river reach.
- **SWAC method**: Uses natural neighbor interpolation.
- **Site-specific factors**: Four SWAC methods were evaluated before selecting the natural neighbor approach; remedial alternatives were based on a range of RALs.

4.1 Site Description

The Willamette River originates in Oregon's Cascade Mountain Range and flows approximately 187 miles north to its confluence with the Columbia River. As Oregon's major port and population center, the lower Willamette River, also known as Portland Harbor, sees many uses, including shipping, industrial, fishing, recreational, and others. The lower reach of the Willamette River from river mile (RM) 0 to approximately RM 26.5 is a wide, shallow, slow-moving segment that is tidally influenced. The river segment between RM 3 and RM 10 is the primary depositional area of the lower Willamette River system. The lower reach (from RM 0 to RM 11.7) has been extensively dredged to maintain a 40 foot-deep navigation channel. The PHSS extends from RM 1.9 to RM 11.8 (Figure 4-1) and was evaluated for remedial alternatives in an FS (EPA, 2016). The SWAC method was used during the FS process to define sediment management areas (SMAs) for the PHSS. SMAs are defined as "areas where containment or removal technologies will be considered to immediately reduce risks upon implementation."

Four declustering techniques were considered for estimating SWACs:

1. Thiessen polygons
2. Polygonal declustering
3. Stratified sampling-based methods
4. Natural neighbor interpolation

The process of evaluating each method and deciding on which method to use is described in this case study. The Portland Harbor FS is also a good example of using a SWAC/RAL analysis to develop a range of remedial alternatives.

4.2 Nature and Extent of Contamination

4.2.1 Sources

Contaminants were released to the air, soil, groundwater, surface water, and impervious surfaces during historical industrial operations in the early 1900s until the 1970s. These contaminants migrated to the lower Willamette River via several pathways such as direct discharge, overland transport, groundwater, riverbank erosion, and from the upstream watershed.

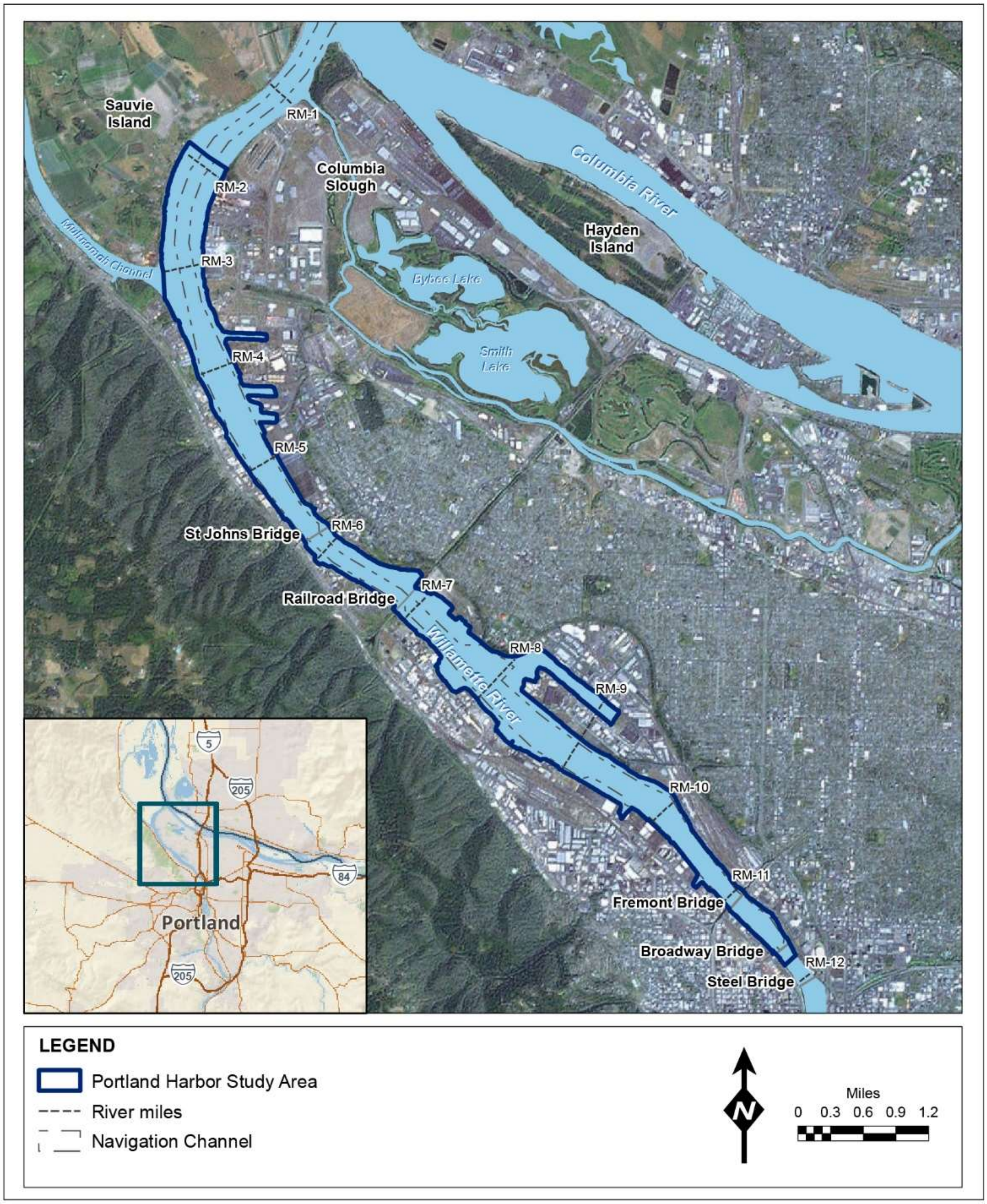


Figure 4-1. Portland Harbor Study Area from RM 1.9 to RM 11.8 (EPA 2016)

A key migration pathway that was investigated was direct discharge through numerous public and private outfalls, including storm drains and combined sewer overflows, located along both shores of the river. Sediments in the Portland Harbor and lower Willamette River were impacted from these historical operations. Surface and subsurface sediment samples were collected from locations that were biased toward areas of known or suspected contamination along the shoreline.

Additional sampling was conducted both upstream and downstream of the PHSS for comparison. Generally, concentrations of contaminants were greater in subsurface sediment samples relative to concentrations in surface samples, confirming that historical inputs were greater than current conditions (EPA, 2016). However, in some locations, surface concentrations were greater than subsurface concentrations; this fact indicated more recent releases, disturbance of the bedded sediments, or both. The highest PCB concentrations in surface sediments was mostly in nearshore areas and in slips, outside the navigation channel, and proximal to known or suspected sources (EPA, 2016). Dioxins, furans, DDx and other pesticides, and polycyclic aromatic hydrocarbons (PAHs) concentrations were typically higher in subsurface sediments than in the surface layers, indicating the sources were primarily historical. Limited data exists on the depth of contamination at the PHSS, but core profiles are provided in the FS (EPA, 2016) and were used to evaluate alternatives.

4.2.2 Contaminants of Concern

PHSS COCs were identified based on the following factors:

- The contaminant is a listed hazardous substance or poses unacceptable risks to human health.
- The contaminant poses significant risks to ecological receptors.
- The contaminant exceeds chemical-specific ARARs or other statutory criteria.

The following were identified as focused COCs for PHSS sediment and used to delineate concentration contours for defining remedial footprints:

- PCBs
- Total PAHs
- Dioxins/furans[2]
- DDx

4.2.3 Fate and Transport

The nearshore areas contain the sediments with the elevated contaminant concentrations from both historical and recent sources. Persistent contaminants (particularly PCBs and dioxin/furans) from sediments and surface water bioaccumulate in the food chain and may result in the greatest risks to humans and wildlife that ingest fish and shellfish in the region.

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[2] 1,2,3,7,8-pentachlorodibenzo-p-dioxin (PeCDD); 2,3,4,7,8-pentachlorodibenzofuran (PeCDF); and 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD)

The major processes identified in the Portland Harbor FS (EPA, 2016) that may affect the fate, transport, and redistribution of contaminants include the following:

- Erosion from the sediment bed,
- Deposition to the sediment bed,
- Dissolved flux from the sediment bed (pore water exchange),
- Groundwater advection,
- Degradation (for some of the contaminants),
- Volatilization, and
- Downstream transport of either particulate-bound or dissolved phase contaminants.

The highest sediment contaminant concentrations are generally found in nearshore areas in proximity to likely historical or existing sources, but contaminants were also found in the higher-energy portions of the channel between RM 5 and 7 (EPA, 2016). The FS speculated that contaminants in the channel could reflect past or current dispersal of material away from nearshore source areas. As stated earlier, the subsurface sediments are higher in contaminant concentrations compared to the surface sediments, indicating historical contaminant inputs and improved sediment quality over time. There are a few limited areas of higher surface concentrations, which could reflect more recent releases or disturbances of bedded sediments through natural or anthropogenic processes. A detailed conceptual site model is provided in the Portland Harbor FS (EPA, 2016).

4.3 PRGs, RALs, and SWACs

Unacceptable risks associated from exposure to sediment were primarily associated with the consumption of fish and shellfish. Because fish and shellfish are mobile receptors that can access large areas, the SWAC approach was appropriate for comparison to PRGs, which are numerical representations of the RAOs. Final PRGs for the PHSS were developed based on a site-specific risk assessment, chemical-specific ARARs when available, and background concentrations (EPA, 2016). The risk-based PRGs were compared to the chemical-specific ARARs and the lower of the two values was then compared to background. If both the risk-based PRGs and chemical-specific ARARs were less than the background concentration, then the background concentration was selected as the final PRG (EPA, 2016).

In the Portland Harbor FS, RALs are a range of contaminant-specific sediment concentrations that are less than the sitewide SWACs for a particular contaminant and greater than the PRGs. They are commonly used at sediment sites to develop remedial alternatives and delineate areas exceeding a defined concentration threshold (EPA, 2016). RAL values are not final cleanup levels: however, in the Portland Harbor FS (EPA, 2016) they were used to identify SMAs, which are target areas for active remediation (e.g., dredging or capping). Areas outside the SMAs are targeted for monitored natural recovery. The RAL concentrations were developed by plotting acres remediated (Figure 4-2) against the estimated post-remediation SWAC. The targeted area for active remediation increased as the RAL decreased. An example of this is shown in Figure 4-3 for PCBs, which shows the RAL contours for alternatives evaluated in the Portland Harbor FS (Alternatives B through H) (EPA, 2016).

For the Portland Harbor FS, SWACs were calculated using the natural neighbor algorithm. The process was described as follows in Appendix D to the FS (EPA, 2016):

> *A spatial grid consisting of 10-foot by 10-foot pixels was created, and each pixel was associated with a measured or interpolated concentration. The initial SWAC assumes that no remediation has taken place and establishes the first point on a plot of SWAC-to-sediment area remediated. Then the highest contaminant concentration is removed by drawing a polygon around contiguous regions where the interpolated data exceeded that concentration, replacing that area with the sediment-based PRG and calculating a new SWAC, creating the next point on the curve. This process of sequential truncation, removing the highest remaining sediment concentration and replacing the value with a sediment based PRG, is continued until all sediment concentrations greater than the PRG have been removed and the entire area exceeding the sediment PRGs is remediated. This plot of SWAC-to-area remediated is the RAL curve. Each point on the curve represents a sitewide SWAC and the contaminant concentration that must be removed in order to achieve the associated SWAC.*

The process described above was part of an uncertainty analysis of the predicted post-construction surface sediment COC concentrations (EPA, 2016). Because most RI data are based on a mixture of sampling designs, statistical uncertainties in post-construction SWAC concentrations exist. The nearest neighbor interpolation was identified as a reasonable method to reduce bias in SWAC estimates when these estimates are based on a combination of biased and unbiased sampling designs (Kern, 2009). Appendix I of the Portland Harbor FS provides further evaluation of the uncertainty analysis using the four tested declustering techniques used to understand the sensitivity of the SWAC estimates (Thiessen polygons, polygonal declustering, stratified sampling-based methods, and natural neighbor interpolation). For example, as shown in Table 4-1, estimated SWACs for PCBs based on these four methods ranged from 79 µg/kg to 205 µg/kg, indicating that the effects of biased sampling were substantial. The higher unweighted estimates reflected a tendency to focus sampling on high concentration areas. Therefore, some form of declustering was needed to improve the accuracy of SWAC estimates.

Table 4-1. Declustering Method Sensitivity for PCBs, Portland Harbor

Declustering Method	SWAC Estimates PCBs (µg/kg)
Stratified and Unweighted	205
Stratified on Geographic areas with Thiessen Polygons	135
Stratified on RAL areas with Thiessen Polygons	79
Polygonal Declustering	105
Average Natural Neighbor Map	80

For selected PHSS COCs, a range of seven RALs was selected to bracket the distribution of contamination. In selecting the RALs, several features of the curve were identified (Figure 4-4) and described in Appendix D of the Portland Harbor FS (EPA 2016):

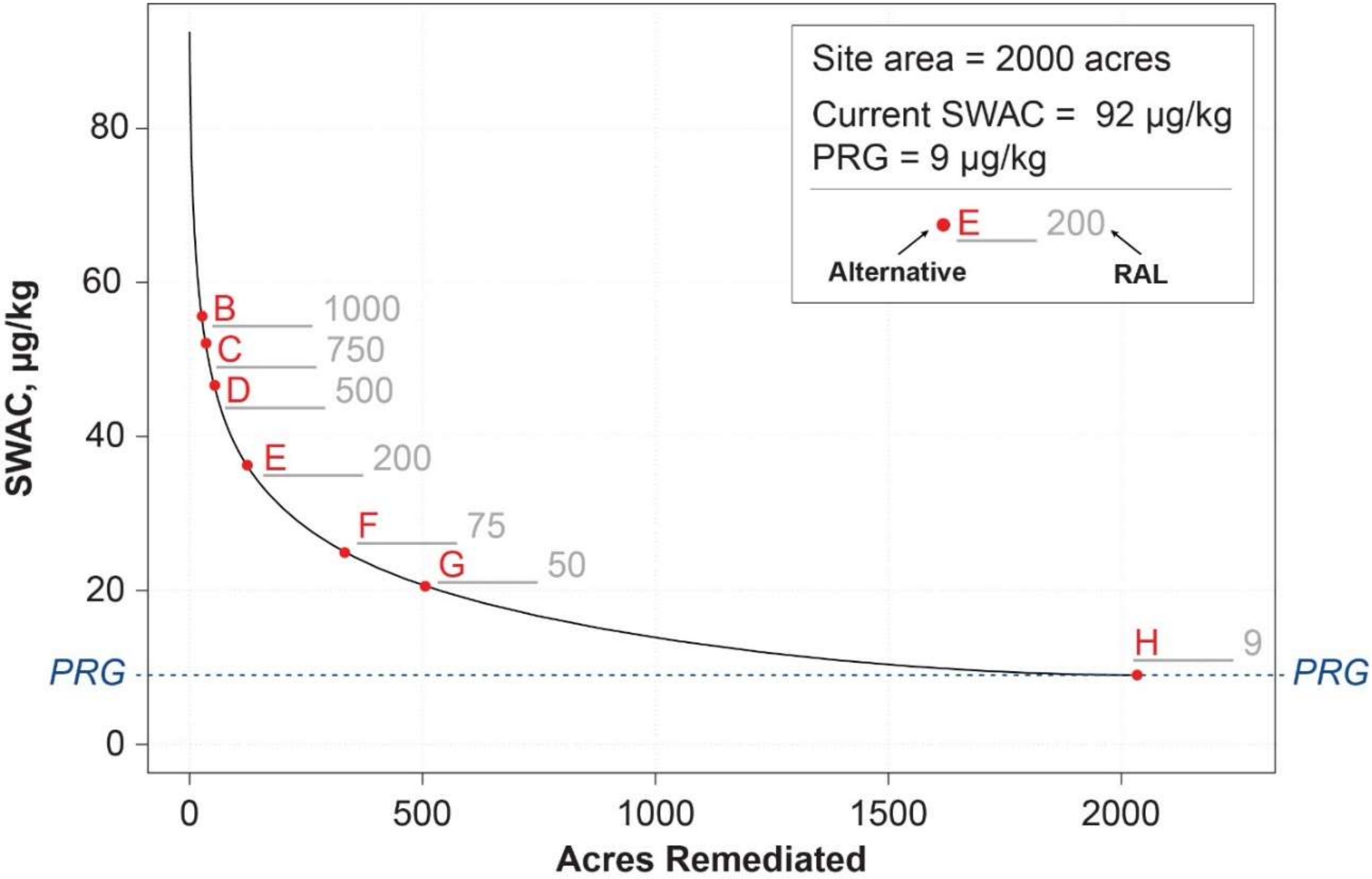
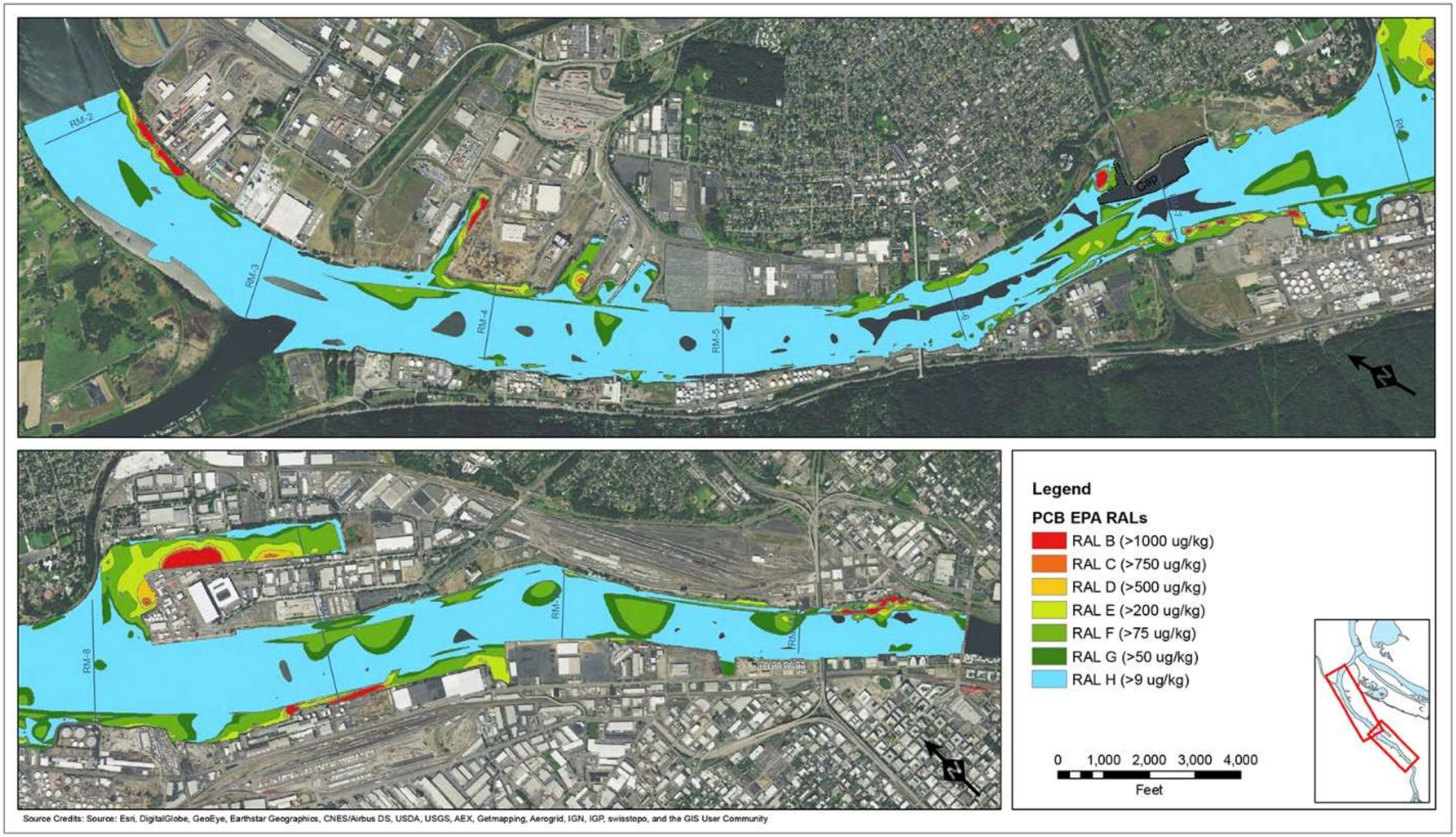


Figure 4-2. PCBs Sitewide RAL Curve, Portland Harbor FS (EPA, 2016)



Source Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

Figure 4-3. PCB RAL Contours for Alternatives B through H, Portland Harbor FS (EPA, 2016)

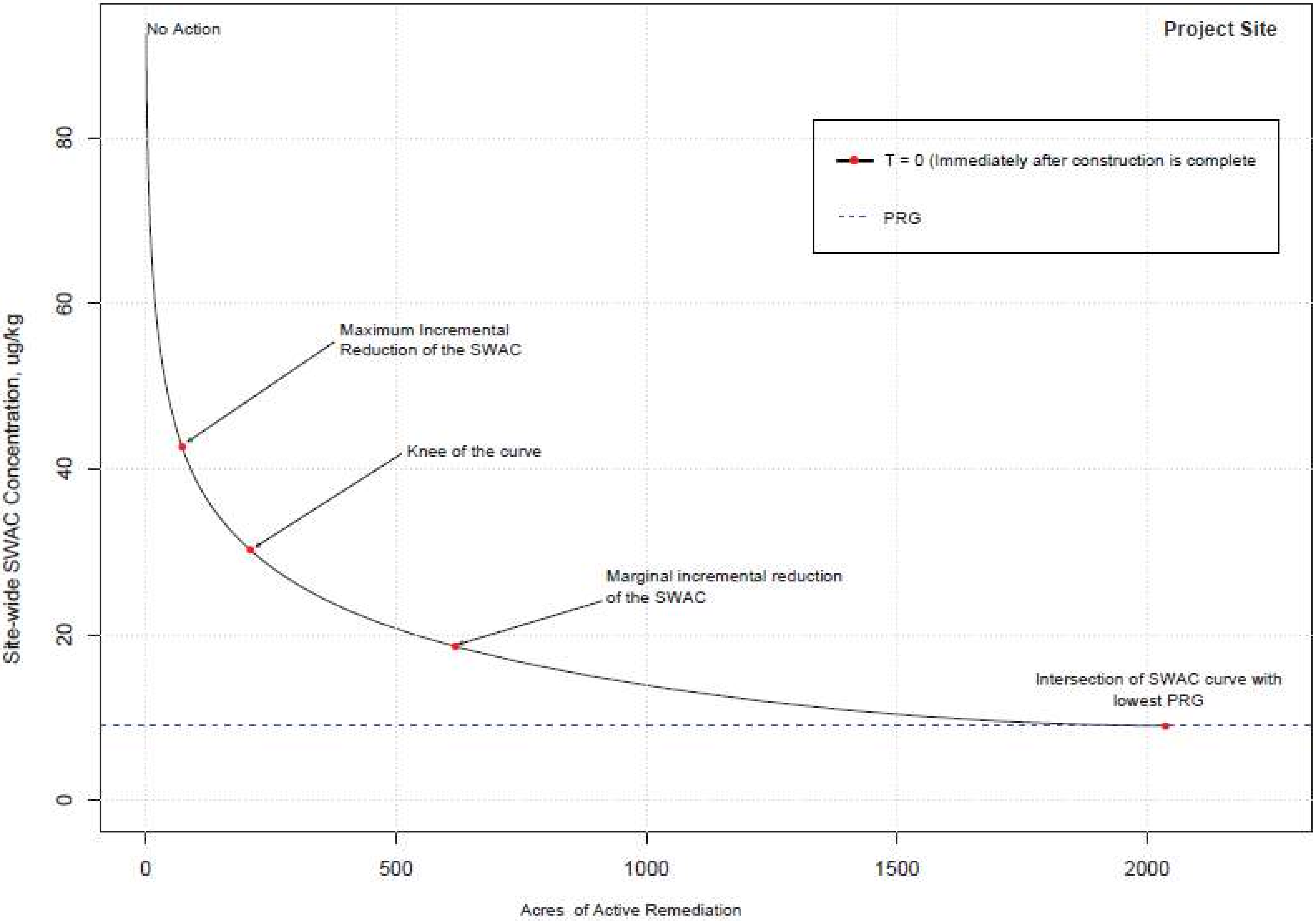


Figure 4-4. Example of Comparison of Sitewide SWAC to Potential RALs and Acres Remediated (EPA, 2016)

- **The maximum incremental reduction of the SWAC**: This is the point on the curve where further reductions in SWAC concentrations result in minimal increase in acres to be capped or dredged.
- **The marginal incremental reduction of the SWAC**: This is the point on the curve where further increases in acres capped or dredged do not result in discernable reductions in SWAC concentrations.
- **The intersection point**: Where the SWAC curve meets the lowest PRG.
- **The knee of the curve**: The inflection point where the reductions in the SWAC value begin to level off with incremental increases in acres capped or dredged.

The higher SWAC concentrations were associated with a steeper slope of the line (Figure 4-4). As stated earlier, a key benefit of the SWAC approach is that removing the area with highest concentrations results in the greatest SWAC reduction and the greatest impact in reducing overall risk. The curve intersects the PRG when all areas exceeding the PRG have been removed. For the PHSS, this process was used for PCB and PAH concentrations. For DDx, because the highest concentrations were localized, RALs were developed based on the distribution within the localized area and then applied to a RAL curve on a sitewide basis. Due to the focused nature of the sampling and the lack of data density for dioxins/furans, RAL curves and values were developed based on areas with greater data density. The RAL values for dioxins/furans were then applied to a RAL curve on a sitewide basis.

4.4 Remedial Alternative Evaluation

In the Portland Harbor FS, the evaluation of remedial alternatives focused on the sediment RAOs, although impacts to surface water, groundwater, and the riverbank were also evaluated relative to actions taken on the sediment. The effectiveness of each remedial alternative was evaluated by comparing the estimated post-remedy SWAC for each alternative to the PRGs to assess the degree to which each alternative would reduce sediment contaminant concentrations at the completion of construction, which was directly related to risk reduction. Alternatives with lower RALs showed greater risk reduction at the completion of construction but had greater impacts to the community and the environment due to the increased size of SMAs and increased construction duration. SWACs were computed differently between the Portland Harbor FS and the ROD (EPA, 2017b). In the FS, the sitewide SWAC values were based on the 95% UCL of the mean, and the mean was calculated as the average SWACs of 27 subareas delineated in the statistical analysis presented in Appendix I of the FS (EPA, 2016). In the ROD (EPA, 2017b), the SWACs were based on the arithmetic average of concentrations for each pixel of the natural neighbor interpolation over the entire PHSS. The EPA made this change to the SWAC calculation in response to public comments regarding how the SWACs were calculated. These comments indicated that the basis for the SWAC calculations was not transparent and appeared to be inconsistent with other assumptions presented in the FS. Therefore, the updated method provided in the ROD was based on an approach that was easier to reproduce and more consistent with other FS elements.

4.5 Portland Harbor Case Study Summary

Because biased sampling was used to characterize Portland Harbor, it was necessary to spatially weight the data to reduce bias in the estimated SWACs. An evaluation was conducted as part of the FS to identify the optimal method for declustering the data and natural neighbor interpolation was selected for developing SWACs. SWAC/RAL curves were developed for focused COCs, and remedial alternatives were developed in the FS based on a range of RALs. The RAL-based alternatives represented a range of areas targeted for active remediation (i.e., dredging, capping, or both) versus monitored natural recovery. Estimated post-remedy SWACs were calculated and compared to cleanup levels to assess relative risk reduction at the completion of construction

5.0 SUMMARY

The strength of using a SWAC approach is that areas of elevated COC concentrations can be targeted for remediation in a smaller footprint, while decreasing the risk associated with the entire project area. SWACs also reduce the influence of sampling bias when calculating average COC concentrations over a project area. In addition, a SWAC approach provides flexibility in developing remedial footprints; for example, remediation in sensitive habitats or operational areas may be avoided as long as the post-remediation SWAC for the site is below the PRG.

A SWAC approach may not be warranted at a site where the project area has a confined or limited area of known contaminants and COC concentrations in the surrounding area are below the PRG. One potential challenge with using a SWAC approach is the perception that using an average concentration may overlook “hot spots” with high COC concentrations. In addition, SWACs only address surface sediment contamination; management of subsurface contamination may also need to be considered, as appropriate. An RPM should work with the regulators and other stakeholders to weigh the advantages and limitations of the SWAC approach.

Several different methods can be used to calculate SWACs based on site size and complexity, density and distribution of data, and nontechnical considerations such as cost, schedule, and regulator input. Project teams should consider calculating SWACs several ways to determine whether the results are sensitive to the method used. The advantages and limitations of SWAC methods are described to assist RPMs in method selection.

The two case studies described in this report highlight two different SWAC approaches, Thiessen polygons and interpolation using the natural neighbor method, and provide details on how these approaches addressed project goals. The conclusions of the MCB Quantico Site 102 project using Thiessen polygons highlighted how targeted remediation of elevated areas would reduce the overall risk without affecting critically important training areas. The natural neighbor interpolation approach used at the Portland Harbor Superfund Site was selected as the most suitable for project objectives. SWAC/RAL relationships were used at the site to develop a range of remedial alternatives representing various degrees of risk reduction after remedy construction.

SWACs can also be used to determine remedy effectiveness. When remediation ends, SWACs can be calculated to verify whether remediation was successful by determining whether cleanup levels were met. Post-remedy SWACs can be compared to pre-remedy SWACs to determine the degree of risk reduction. As described in the Ashtabula River project (EPA, 2017a), SWACs were developed as a goal immediately following dredging and in the long term. Several other projects for EPA Region 5 (Ottawa River, Otter Creek, Manistique River) are employing different SWAC approaches as part of their LTM for determining remedy effectiveness.

RPMs can consider the use of SWACs as an optimized approach to support data analysis and remedial decision-making at contaminated sediment sites.

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