COMPARING DREDGE RESIDUALS PREDICTION AND PERFORMANCE FOR ESQUIMALT GRAVING DOCK WATERLOT PHASE 1B REMEDIATION

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ABSTRACT

Dredging residuals are a key factor in the success of environmental dredging projects. Predictive tools have been established to estimate the amount of dredging residuals that will be encountered during construction, which are used to inform design decisions such as dredge prism elevations, overdredging specifications, post-dredging sampling plans, and residuals management contingency decision frameworks. Because residuals management has a large effect on both the success of remediation (i.e., contaminant concentrations after dredging) and potential contingency costs, it is important to compare the design predictions with post-construction outcomes to improve the predictive tools.

This paper evaluates dredge residuals performance for the Esquimalt Graving Dock (EGD) Phase 1B remediation, which is a large remediation project conducted by Public Works and Government Services Canada (PWGSC) under the Federal Contaminated Sites Action Plan (FCSAP). The project was completed in March 2014 and implemented an intensive post-dredge subsurface and surface sediment sampling program and an aggressive residuals management contingency program, with contingency redredging conducted over 41% of the area. A total of 144,000 cubic metres (m^3) of contaminated sediment was removed, and more than 74,000 square metres (m^2) of residuals management cover (RMC) was placed following completion of dredging.

This paper describes the project background, the dredge residuals management strategy used in design and construction, and the decision framework for triggering contingency actions. Comparisons of predictions and outcomes for undisturbed dredge residuals (or "missed inventory") are presented by comparing the geostatistical information prior to dredging (kriging and a statistical confidence level approach) to post-construction dredge thicknesses and measurements of undisturbed residuals. Comparisons of predictions and outcomes of generated dredge residuals are presented by comparing mass-balance design prediction calculations with post-construction sample data. The effectiveness and performance of two residuals management approaches—contingency redredging and placement of RMC—are also quantitatively compared. This information can guide more effective use of these predictive tools and residuals management frameworks for future dredging projects.

Keywords: dredge residuals, best management practices, geostatistics, redredging, performance monitoring

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INTRODUCTION

The EGD is located on federal Crown-owned property in Esquimalt Harbour on Vancouver Island, British Columbia, (Figure 1) and is managed by the federal custodian, PWGSC. The EGD facility has been operating for the repair and maintenance of military and civilian vessels since 1927, and it is the largest solid-bottom commercial drydock on the West Coast of the Americas. Sediment contamination is primarily due to legacy contaminants from historical sources, such as metals, polychlorinated biphenyls (PCBs), tributyltin (TBT), and polycyclic aromatic hydrocarbons (PAHs).

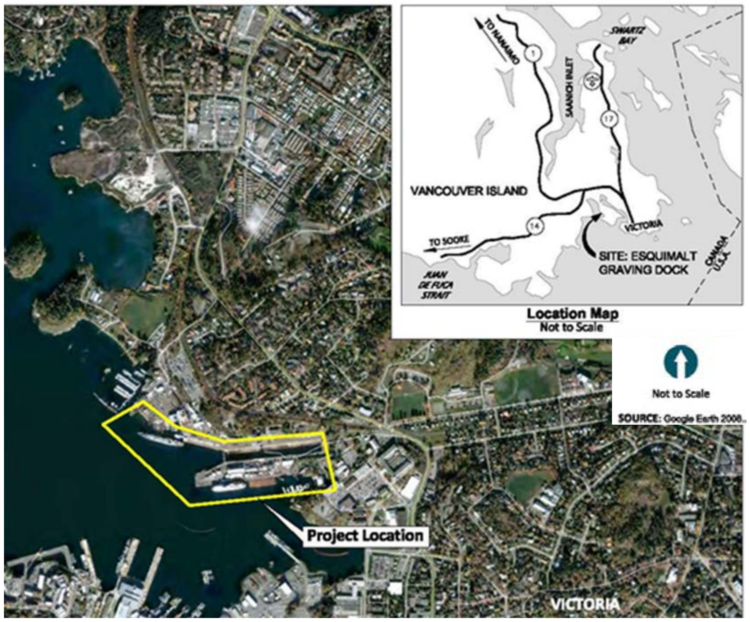

Figure 1. Vicinity map.

In support of FCSAP objectives, as well as a potential governance change of the EGD facility, PWGSC developed a multi-phase remedial action plan for cleaning up contaminated sediments in and adjacent to the EGD Waterlot (Figure 2). Phase 1A was completed in 2013 and included installation of a sheetpile perimeter wall around the existing timber jetty structures to prevent re-contamination of remediated sediments during subsequent phases of the project. Phase 1B was completed in March 2014 and included 144,000 m^3 of remedial dredging and off-site upland disposal of contaminated sediments, placement of approximately 24,000 m^3 of in-water slope armour, and placement of RMC over 74,000 m^2. Phase 1B sought to remove the maximum amount of contaminated sediments that exceeded the most stringent numeric criteria for a given contaminant based on the Canadian Council of Ministers of the Environment (CCME) Probable Effects Level (PEL) or British Columbia Contaminated Sites Regulation (CSR) Sediment Quality Criteria for typical contaminated sites ($SedQC_{tcs}$). These numeric criteria are referred to as numeric remedial action objectives (NRAOs). Phase 2 construction was completed in December 2016 and comprised demolition of the timber-piled South Jetty structures, re-driving of the perimeter sheetpile wall to form a re-suspension barrier, remedial dredging and off-site upland disposal of 37,800 m^3 of contaminated sediments, placement of capping materials, and modifications to the remaining jetty structure. This paper analyzes dredging residuals data associated with the Phase 1B remediation.

Figure 2. Project area and boundaries.

DREDGING RESIDUALS

Undisturbed and Generated Residuals Defined

Dredging residuals refer to the contaminated sediments (at concentrations above an action level) found at the post-dredge surface of the sediment profile, either within or adjacent to the dredging footprint. Residuals are grouped into two categories: 1) undisturbed residuals or “missed inventory”; and 2) generated residuals (Figure 3).

Undisturbed residuals are contaminated sediments that have been uncovered but not removed. The primary causes of undisturbed residuals are: 1) incomplete sediment characterization due to variable dredging depths or elevations that are not captured by sediment core sampling; and 2) incomplete dredging due to technical and logistical limitations.

Generated residuals are contaminated sediments that have been resuspended and deposited during the dredging process. Sediments are inherently mobilized during the dredging process, being resuspended in the water column as the dredging bucket penetrates the sediment surface and as clumps of sediment fall from the equipment as it moves through the water. After dredging, a new surficial sediment layer is formed by the accumulation of disturbed sediments and settling of resuspended sediments. This new layer, comprising sediments targeted for removal, is referred to as the generated residual layer. This is typically a very thin layer comprising a relatively small volume and mass of contaminants in comparison to the volume and mass of the sediments removed during dredging. The generated residual layer has been shown to be a significant factor in accounting for remediation failures (Patmont and Palermo, 2007). The degree of residuals generation is dependent on the conditions of the site (e.g., presence of debris, bedrock, structures, and currents), type of bucket, and operator performance (e.g., speed, overfilling, or over-penetration of the bucket).

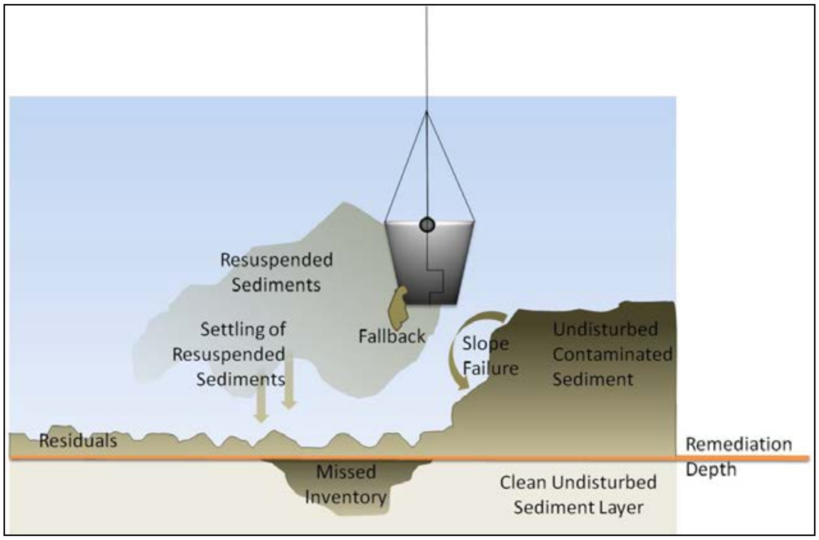

Figure 3. Sediment residuals from mechanical dredging.

The sediment remediation and environmental dredging communities recognized the significance of residuals and created scientific forums to develop guidance manuals. The U.S. Environmental Protection Agency (USEPA) regards post-dredge residuals as a high research priority in its Superfund program (USEPA, 2009). In 2007, USEPA’s Office of Research and Development began a post-dredge residuals study for the remediation of the Ashtabula River in Ohio. The study developed site-specific methods for estimating the volume and contaminant concentration of post-dredge residuals (USEPA, 2008; Technology News and Trends, 2008). The U.S. Army Corps of Engineers (USACE) Engineering and Research Development Center (ERDC) led scientific workgroup meetings and subsequent publications focusing on post-dredge residuals. This scientific workgroup contributed to multiple peer-review publications and scientific conferences and two USACE guidance documents: *The Four Rs of Environmental Dredging: Resuspension, Release, Residual, and Risk* (USACE, 2008a); and *Technical Guidelines for Environmental Dredging of Contaminated Sediments* (USACE, 2008b). In addition to efforts led by USACE, the U.S. National Research Council Committee on Sediment Dredging at Superfund Megasites developed the *Sediment Dredging at Superfund Megasites: Assessing the Effectiveness* report in 2007 (National Research Council, 2007), which focuses particular discussion on assessment and management of post-dredge residuals.

Design Considerations for Undisturbed Residuals

A key consideration during remedial design was undisturbed residuals. The dredge prism identifies the minimum horizontal and vertical extents of required dredging for the contractor. The primary function of the dredge prism is to provide a constructible surface that removes all contaminated sediments above the contaminated neatline surface. The dredge prism design is based on both quantitative evaluation and subjective evaluation based on past dredging experience. One factor that contributes to uncertainty in dredge prism design is the reliance on multiple sediment chemistry datasets with variable levels of precision. Another factor that contributes to dredge prism uncertainty is dredging accuracy and tolerances that limit the ability of a contractor to precisely remove the contaminated sediment from the three-dimensional dredge prism. The dredge prism plan developed for the EGD Phase 1B project is shown in Figure 4.

The dredge prism comprises two components: 1) the required dredge prism; and 2) the allowable overdredge. The required dredge prism represents the elevation, grades, and horizontal extent of sediment that a dredging contractor is required to remove. The allowable overdredge is a constant thickness of sediment below the required dredge prism that design engineers typically allow to account for equipment inaccuracies and tolerances. The design of the dredge prism accounts for the fact that it is not possible for any dredge to excavate to an exact surface and that the dredge must remove excess material below the required dredge prism to remove all the required material.

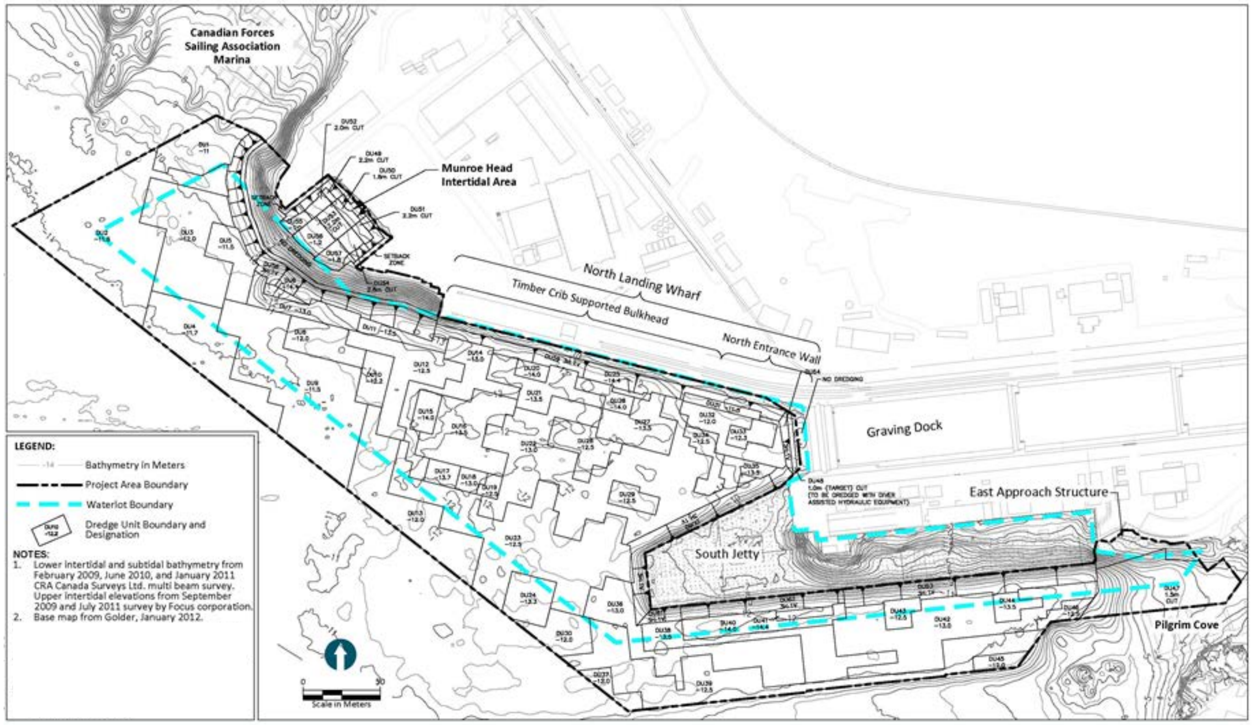

Figure 4. Dredge plan.

To develop the dredge prism for remediation, the neatline surface was identified to specify the minimum required depth of removal for contaminated sediments. The neatline surface is a complex three-dimensional surface that represents the predicted deepest vertical extent of contamination through the project area. The neatline surface was identified through geostatistical interpolation, or kriging. The thickness of contaminated sediment was determined by ordinary kriging the thickness of contaminated sediment at 88 core locations within the 17-hectare remediation area (one core per 1,900 m^2). The thickness of contaminated sediment was then subtracted from the mudline elevation to derive the elevation of the clean sediment surface at the base of the contaminated sediment. The area under the depth of contamination surface was then integrated using GIS-based spatial analysis tools to determine the estimated neatline remediation volume.

The kriging predictions of depth of contamination represent an average estimated value, corresponding to a 50% level of confidence. If the kriging prediction surface is overdredged to a greater depth, there will be greater confidence that all contaminated sediments have been removed. Kriging cross-validation plots were bias-corrected and evaluated for confidence levels, which are associated with removal volumes (Table 1). In practice, it is expected that the neatline surface will be overdredged by at least 0.3 to 1 metres (m) due to the design of a dredge prism that accounts for equipment capabilities, thus providing a higher level of confidence that all contaminated sediments will be removed from the project area. For the EGD Phase 1B project, PWGSC elected to complete remediation using the dredge prism design plus 0.3 m of payable allowable overdredge. This approach provided a 94% confidence level that all contaminated material would be removed, which was determined by PWGSC to meet the goals of the project. The removal of overdredge material was payable, per the Specifications, and significantly increased the confidence level that the removal action would be successful.

Table 1. Summary of removal volumes and contaminant removal confidence level.

Removal Scenario[1,2]	Removal Volume (cubic metres)	Contaminant Removal Confidence Level[3] (%)
Contaminated neatline (no overdredge)	71,250	50%
Contaminated neatline + 0.3-m overdredge	98,444	70%
Contaminated neatline + 0.5-m overdredge	116,573	85%
Dredge prism design (no overdredge)	117,336	90%
Dredge prism design + 0.3-m overdredge	143,785	94%
Dredge prism design + 0.5-m overdredge	162,658	99%

Notes
Shaded: approach selected by PWGSC
1. The contaminated neatline sediment removal volume was developed with geostatistical interpolation kriging methods using core depth of contamination data. The contaminated neatline surface represents the predicted deepest vertical extent of contamination throughout the project area.
2. The dredge prism design was developed to provide a constructible surface that removes all contaminated sediments above the contaminated neatline surface.
3. The confidence level is based on the number of accurate predictions of clean, leave-behind sediment surface based on the bias-corrected kriging cross-validation plot.
m: metre

Further evaluation of these geostatistical predictions is presented below by comparing the design predictions with post-construction outcomes.

Design Considerations for Generated Residuals

In remedial design, the impact of generated residuals on post-dredging surface sediment was estimated to develop an appropriate residuals management decision framework. The concentration in surface sediment following dredging was predicted using a mass-balance approach, consistent with case study information in Patmont and Palermo (2007), and updated by Desrosiers and Patmont (2009) and Patmont, LaRosa, and Narayanan (2015). These studies examined more than 50 sediment remediation programs with post-dredge residuals data to assess dredging effectiveness and residuals generation estimates. They summarize the factors that impact generation of residuals as follows:

- Contaminant concentrations in residuals approximate the average concentration of contaminants of concern (COCs) in dredged material.
- Generated residuals represent the majority of residuals contaminant mass, while undisturbed residuals contributed a minor amount of contaminant mass.
- Generated residuals range from 1% to 11%, and average 5% of the mass that was present in the last dredge cut.

For the EGD Phase 1B project, the residuals concentrations were estimated based on the mass-weighted average concentration in dredge material in the last dredge cut, and the thickness of generated residuals was estimated assuming a percent loss of 2%, 5%, and 9% of dredged material in the last dredge production cut. The calculation was performed at each sediment core location and averaged over nine Sediment Management Areas (SMAs). These bounding-level estimates are evaluated below by comparing the design predictions with post-construction measurements.

Residuals Management Strategy During Construction

Dredge residuals during Phase 1B dredging were managed with best management practices (BMPs), post-dredging monitoring, and residuals management contingency actions as discussed in the subsections that follow.

Best Management Practices

Several specific BMPs were employed during dredging to reduce the likelihood for sediment re-suspension and recontamination of remediated areas, including construction sequencing, equipment selection, use of a silt curtain, and water quality monitoring.

Zone Sequencing

The contractor was required to sequence the dredging work using Zones to minimize the potential for recontamination, with dredging to be completed in the areas with the highest concentration sediments first (Figure 5). The contractor was required to complete all dredging activities in a Zone before moving to another Zone. Following the completion of dredging activities in a Zone, the Environmental Monitor was responsible for conducting post-dredge confirmation testing to verify that the contamination was removed. Pending the review of confirmation test results, the contractor was directed to dredge additional material from the Zone. After the completion and acceptance of dredging activities in a Zone were approved by PWGSC, the contractor placed slope armour materials, if required. The contractor then moved to dredging activities in the next Zone. RMC placement was to be conducted over the entire project area after the completion of all dredging and armouring activities.

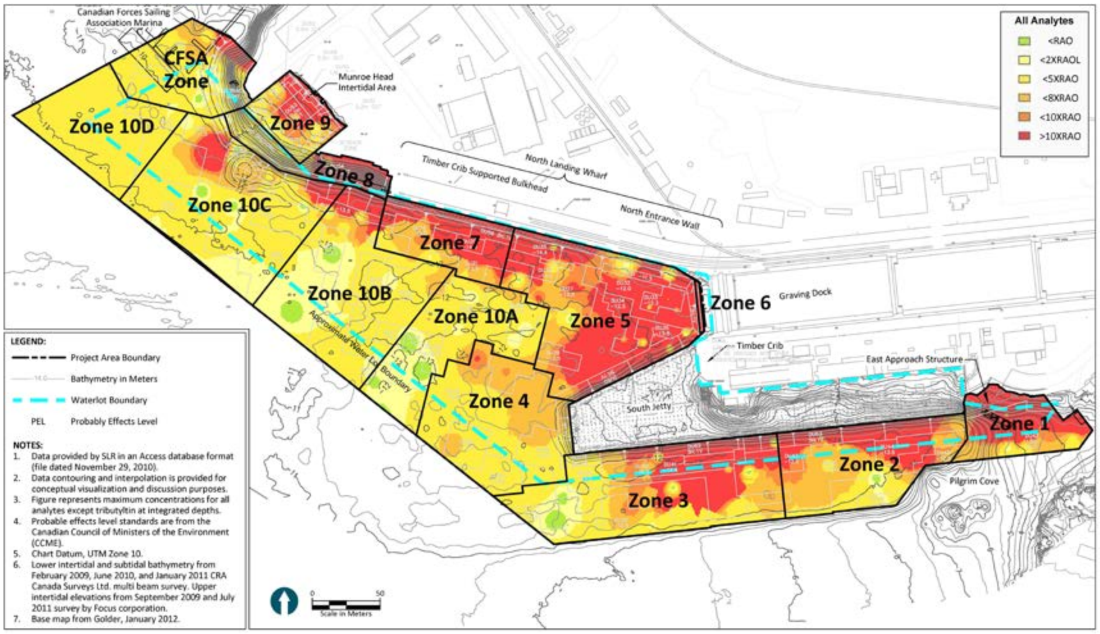

Figure 5. Remediation Zones and disposal characterization.

Equipment Selection

Equipment used to implement the remedial design was evaluated based on the ability to achieve the remedial objectives and site conditions to ensure the selected dredging method was feasible for remediating specific portions of the project area. The evaluation identified mechanical dredging equipment as the primary dredging method, with limited use of hydraulic dredging equipment for a small portion of the dredge area adjacent to the graving dock sill. Mechanical dredging effectively removes consolidated sediment, debris, and other materials such as piling and riprap, and its relatively compact operational footprint reduces potential impacts to existing site operations (compared to hydraulic dredging equipment). The contractor elected to use a cable-supported conventional clamshell dredge for the majority of the project area, but also used a smaller environmental bucket for the last dredging pass to achieve target elevations.

Environmental buckets were required by PWGSC to be available in the event of elevated turbidity or suspended solids during dredging operations. These buckets helped minimize the loss of sediment out of the bucket when used properly; however, minimizing sediment loss out of the bucket does not necessarily equate to a reduction of suspended sediments or lower turbidity in all site conditions (Wang et al., 2002). In order to increase the efficiency of the buckets, debris was removed when encountered at the time of dredging.

Silt Curtain

Silt curtains create a physical barrier around dredge equipment to limit the spread of suspended sediment that is generated during dredging operations. Silt curtains can be an effective tool to minimize or reduce potential water quality impacts during dredging. However, if silt curtains are set up improperly, not maintained, or applied to inappropriate conditions, they may have limited or negligible effectiveness in reducing water quality impacts. Silt curtains are advantageous and, when used properly, they can protect against the spread of suspended sediment in the portion of the water column to which they extend down. Consistent with the Fisheries Act authorization that required a minimum 5-m length silt curtain, the contractor elected to use a fixed frame to support a 6-m length silt curtain around the mechanical dredging operation. Full-length silt curtains were not required or considered feasible because of the tidal water level changes and water depth, which was deeper than -12 m Chart Datum in most areas.

Intensive Water Quality Monitoring

A Water Quality Monitoring Plan was implemented during dredging and placement activities. This monitoring assessed the turbidity, total suspended solids (TSS), and contaminant concentrations generated by the in-water work activities, especially during dredging. Compliance monitoring was conducted at monitoring locations 25 to 100 m from the work activity. Turbidity thresholds were developed based on a TSS/turbidity relationship established prior to construction to avoid impacts to aquatic life. Turbidity measurements above compliance standards resulted in modifications to the work activity, such as checking the silt curtain, slowing the dredge cycle, or changing the bucket. Laboratory analysis was conducted to confirm the previously established TSS/turbidity relationship, and to confirm that chemical concentrations were not above compliance standards.

Residuals Management Contingency Action Framework

The selection of a residuals management approach depends on the nature and extent of residuals, as well as an engineering/operational assessment of site conditions related to potential management actions. The two post-dredge residuals management approaches were a cleanup dredge pass (redredging) and placement of RMC (i.e., a thin layer of clean sand).

Redredging was used following production dredging for the following purposes: 1) removal of undisturbed residuals (e.g., missed inventory); or 2) removal of high-concentration, post-dredge generated residuals. Though cleanup passes support the removal of high-concentration residual layers, they have not been very effective at achieving very low residual concentrations. Thus, cleanup passes for dredging residuals were reserved for areas with a significant residuals layer thickness or concentration.

The placement of a residuals management layer of clean material has provided more certainty in achieving residuals performance standards (Desrosiers and Patmont, 2009). RMC was used to target areas with sufficiently thin and low concentrations of residuals. Project area sediments are subject to regular mixing as a result of propeller wash (propwash) and, to a lesser extent, tidal circulation. Thus, a clean cover layer was anticipated to temporarily isolate and eventually mix with the underlying residuals to enhance the recovery process. The RMC layer was placed throughout the entire project area.

The residuals management approach is summarized below in three stages and is illustrated in Figures 6 and 7:

- **Stage 1: Production Dredging –** Conducted to a minimum design depth as prescribed in the final design. BMPs were used to reduce the residuals, as described above.
- **Stage 2: Confirmational Testing, Contingency Redredging** – Sampling conducted to determine if contaminant concentrations present above objectives in surface sediment (top 10 centimetres [cm]) or subsurface sediment (top 50 cm or deeper) would require redredging and/or RMC. High concentrations at depth (i.e., undisturbed residuals) and very high concentrations in surface sediment were targeted for redredging.
- **Stage 3: Residuals Management Cover –** Placement of a thin layer of RMC sand to enhance the natural recovery process after dredging is complete.

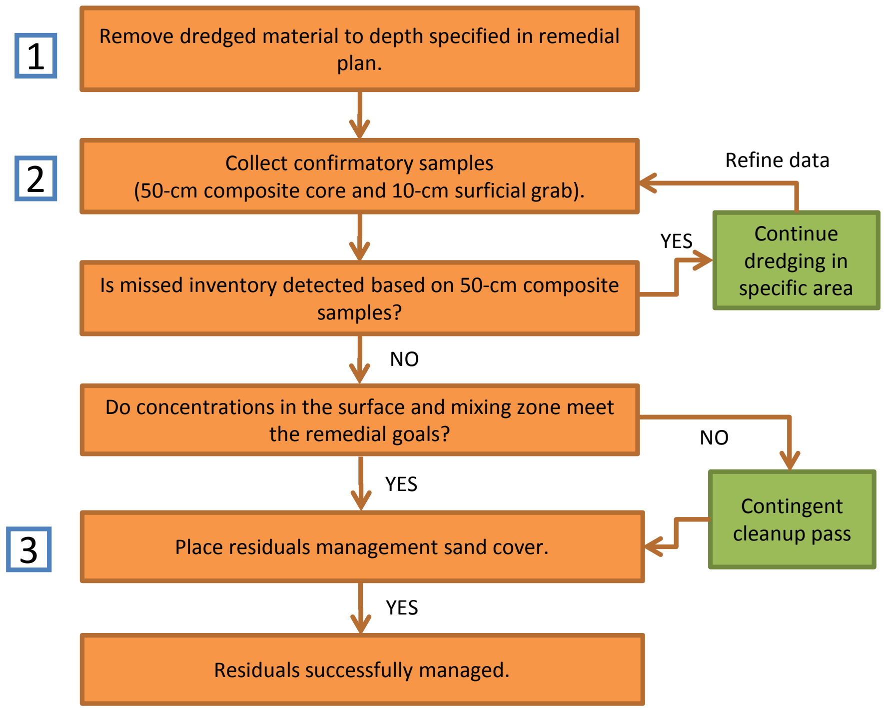

Figure 6. Residuals management decision framework.

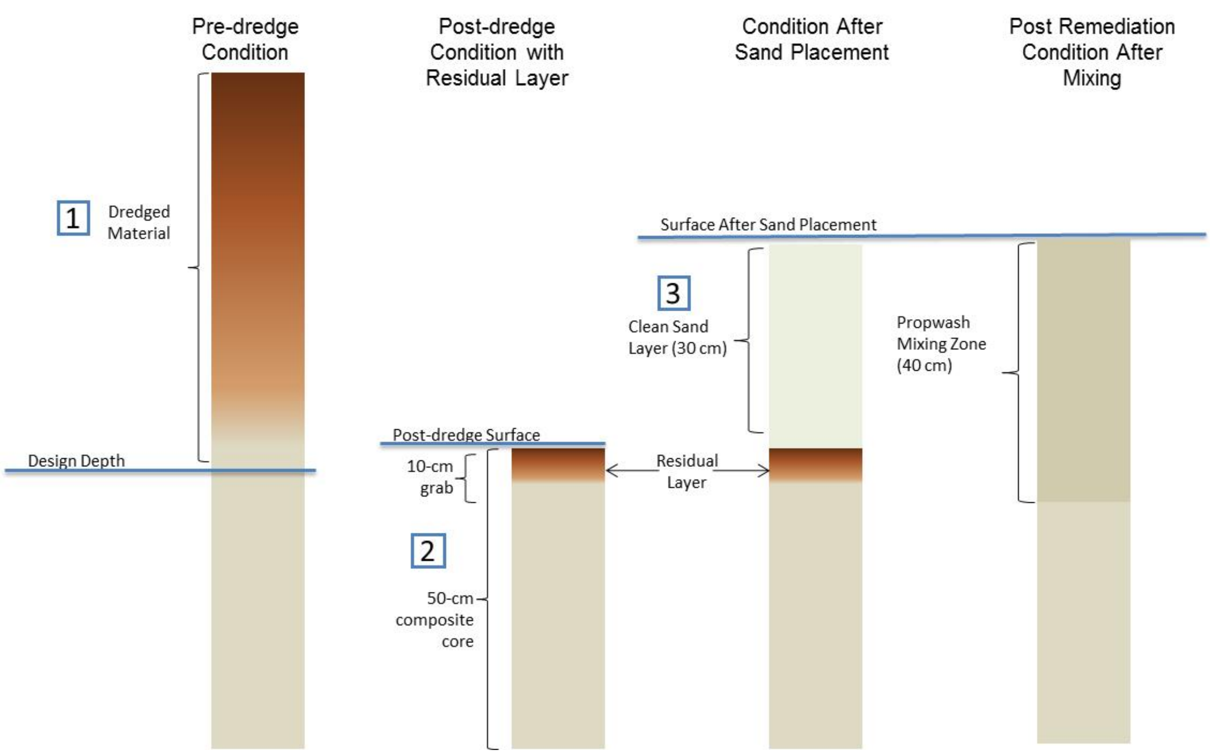

Figure 7. Conceptual cross-section of surficial sediments during remediation to illustrate decision framework for residuals management.

Based on the intensive post-dredge sampling program, contingency redredging was conducted over 41% of the dredge area, and RMC was subsequently placed over 100% of the dredge area (Figure 8). The following sections compare the pre-construction predictions for undisturbed and generated residuals with field measurements from the post-dredge sampling.

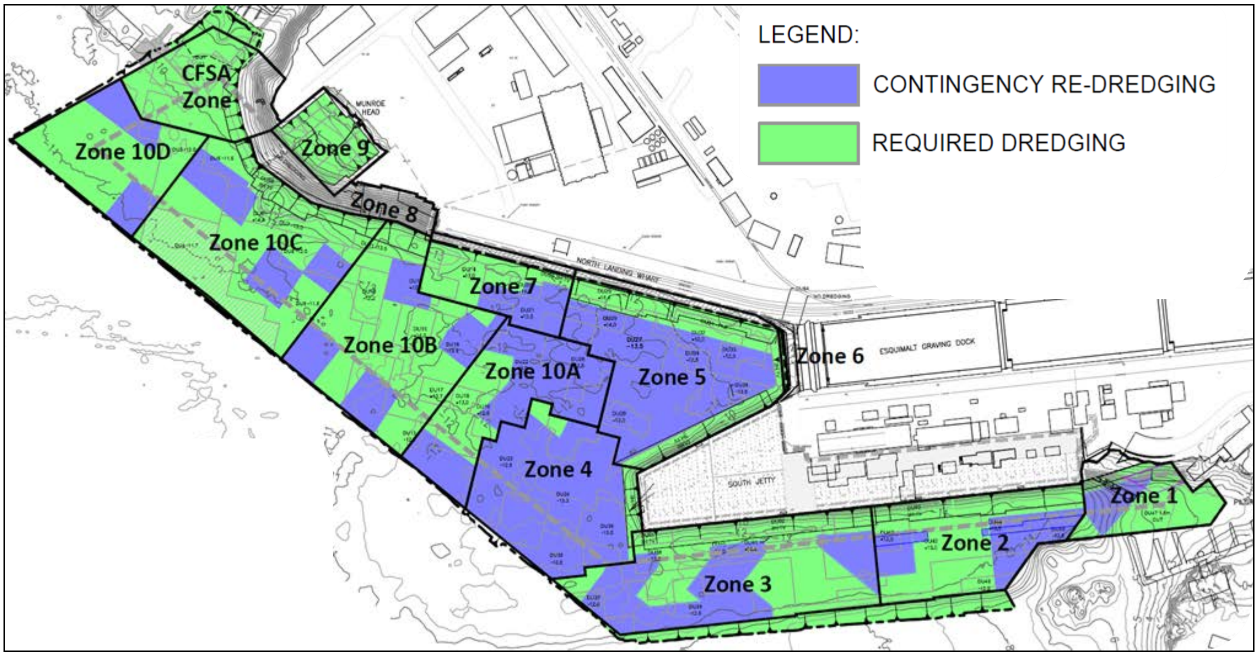

Figure 8. Required and contingency dredging areas.

UNDISTURBED RESIDUALS PERFORMANCE

As discussed above, undisturbed residuals were evaluated in design by the geostatistical techniques of kriging and confidence level assessment. The dredging design and payable overdredge specification were selected to increase the contaminant confidence interval to 94% (dredge prism design + 0.3-m overdredge); however, the percent of redredging determined by post-production dredging was 41% of the dredging area. Approximately 75% of the redredge area was due to missed inventory (31% of the dredging area), and 25% was due to generated residuals (10% of the dredging area). Several potential trends were explored to identify potential causes for the high percentage of missed inventory; however, no specific trends were identified. Rather, the percentage of missed inventory is attributed to the heterogeneity in subsurface sediment conditions, such as undulations in historical dredging elevations that could result in variation in dredge depths over short distances. The number of post-dredge sediment cores was collected on a 25-m grid, or one core per 625 m^2, which was higher than the density of design sediment cores (one core per 1,900 m^2). Some of the trends that were explored included the following:

- **Areas with deeper contamination.** The potential exists for the kriging process to underestimate the dredge depth in areas with the deepest deposits of contaminated sediment. However, the analysis demonstrated that areas with deeper design dredge depths were not more likely to have missed inventory.
- **Areas with higher contaminant concentrations.** The potential exists for areas with higher maximum concentrations of contaminants to be more likely to underestimate the depth of contamination. However, areas with greater concentrations of contaminants were not more likely to require redredging.
- **Areas further from design cores.** The potential exists for areas farther from design cores to be more likely to underestimate depth of contamination due to reliance on interpolation. However, no trend was found between required redredging and the distance from the nearest design core.
- **Bathymetric elevation.** The potential exists for deeper or shallower areas of the site to be more or less likely to underestimate depth of contamination. However, no trend was found between required redredging and the bathymetric elevation.

- **COC driver.** The potential exists for a specific COC to have been under-characterized, and therefore contribute disproportionately to redredging. However, all the key COCs at the site (metals, PCBs, and PAHs) triggered missed inventory redredging roughly proportionally to their occurrences at the site.

GENERATED RESIDUALS PERFORMANCE

As previously discussed, generated residuals were predicted using a bounding level analysis during design. The analysis estimated the concentration in surface sediment following production dredging and after RMC cover and placement. The following sections compare the post-dredging predicted concentrations (from design) to the actual concentrations measured following dredging to evaluate the accuracy of the predictive residuals modeling.

Comparison of Predicted and Measured Surface Sediment Concentrations Following Dredging

Table 2 and Figure 9 present the predictions performed during design with the measured post-construction concentrations for eight chemicals of interest to assess the residuals estimates. The predicted concentration in surface sediment was calculated with the mass-balance approach described above. The calculation was performed at each sediment core location over nine SMAs and spatially-weighted averaged over the entire site. The calculation was performed for three percent losses: 2%, 5%, and 9%.

Surface sediment concentrations presented in Table 2 were measured after completion of all dredging. The measured concentration was then compared to the predicted concentrations, and the corresponding percent loss for the measured calculation was estimated based on a linear interpolation between each data point for the predicted concentrations.

An alternative method was also used to calculate percent loss, in which the contaminants are used as a tracer for residuals. The post-dredging surface sediment sample was assumed to be comprised of generated residuals, with a higher concentration, and undisturbed sediment below the dredge elevation, with lower concentrations. A generated residuals concentration was estimated using the volume-weighted average approach described above, and an undisturbed sediment concentration was estimated based on the average of core samples collected below the dredge elevation (thought to represent native material). The residuals thickness was estimated based on the measured surface sediment concentration, the sample thickness, and the concentrations of the two layers. Then, the residuals thickness was compared to the total dredge volume to calculate a percent loss for the whole dredging volume. This is representative of the final percent loss for the entire dredging project, including production passes and redredging.

Table 2. Comparison of predicted and measured surface sediment concentrations following dredging.*

Item[1]	**tPAH**	**tPCB**	**As**	**Cd**	**Cu**	**Pb**	**Hg**	**Zn**	**Average**
NRAO:	*20*	*0.189*	*41.6*	*4.2*	*108*	*112*	*0.7*	*271*	
Predicted[2]									
2% Loss for Each Dredge Cut	0.61	0.16	8.9	0.9	35	46	0.5	57	
5% Loss for Each Dredge Cut	1.57	0.29	16.2	1.4	65	68	1.0	111	--
9% Loss for Each Dredge Cut	2.61	0.35	22.4	1.6	84	86	1.2	151	
Measured[3,4]									
Average Concentration	3.25	0.29	15.2	1.4	87	55	1.0	136	--
Representative Percent Loss (Linear Interpolation of Predicted Results Between Data Points)	11.5%	4.9%	4.6%	5.6%	9.7%	3.2%	6.1%	7.5%	6.6%
Alternative Percent Loss Calculation Using Contaminant Concentration as a Tracer									
Percent Loss for all Dredging	6.7%	4.0%	3.9%	4.4%	5.4%	3.3%	4.2%	4.8%	4.6%

Notes:
* Units are milligrams per kilogram dry weight unless otherwise noted.
1. Tributyltin (TBT) and dioxins/furans were not included in the analysis because of smaller sample datasets (both chemicals) and the high number of non-detect samples (TBT).
2. Predicted concentrations are based on the spatially-weighted average concentration based on results for 94 to 148 cores (depending on the analyte).
3. Measured concentrations are based on the median of 148 surface sediment samples.
4. Measured concentrations are concentrations following production dredging and contingency redredging.

As: arsenic; Cd: cadmium; Cu: copper; Hg: mercury; NRAO: numeric remedial action objective; Pb: lead; tPAH: total polycyclic aromatic hydrocarbons; tPCB: total polychlorinated biphenyls; Zn: zinc

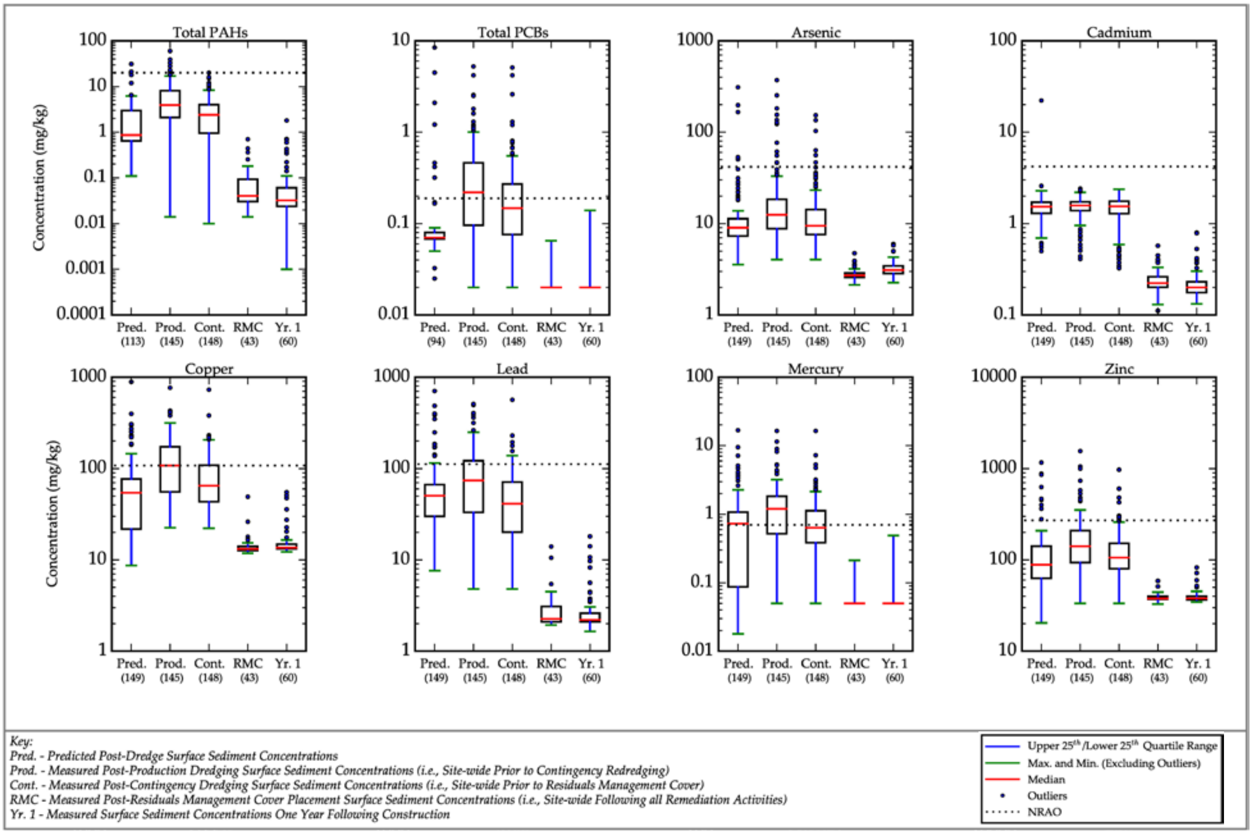

Figure 9. Predicted and actual post-remediation concentrations.

Concentrations for seven of eight chemicals fall within the range of the bounding predictions. The concentrations ranged from 3.2% to 11.5% and averaged 6.6% loss for all eight chemicals, which is higher than the base case value of 5%. The alternative percent loss calculation, which used contaminant concentration as a tracer, resulted in a range of 3.3% to 6.7%, depending on the analyte, with an average of 4.6%.

Uncertainties are associated with both methods of estimating the percent loss during dredging. For both methods, the key uncertainty is heterogeneity in sediment conditions that results in localized variations in sediment concentrations and depth of contaminated sediment. Localized variation in conditions can also contribute to the amount of missed inventory, which (if not redredged) could bias these percent loss estimates high. Similarly, contaminants that have elevated concentrations occurring naturally would also affect the estimated percent loss. Comparing the measured concentrations to the predicted concentrations is also limited by the degree to which the predictions can anticipate actual dredging processes. For example, the percent loss is based on multiple dredge cuts in areas with thicker deposits of contaminated sediment; however, the actual number of dredge cuts is determined by the contractor in the field based on field conditions and likely varies from the assumptions used for the calculation (i.e., a maximum 1.2-m dredge cut per pass). For the alternative percent loss calculation, the assumption that the surface grab is always comprised of two layers (generated residuals and undredged sediment) could be incorrect in some locations because the residuals thickness could constitute the entire thickness of the grab sample. This uncertainty would tend to bias the percent loss low, because not all the residuals are accounted for the in the calculation.

For EGD, higher percent loss could have resulted from the use of a silt curtain, which may have resulted in additional resuspended sediment settling in the dredge area compared to other sites, thereby reducing movement of sediments away from the site by currents. Some nearshore areas also contained bedrock or hard material, which reduces the effectiveness of redredging, and can increase the percent loss. Considering all of these uncertainty factors, the calculations provide a reasonable best estimate of the percent loss as presented by the data. Overall, the two estimates of dredge residuals are similar to the 5% used as the base case for residuals predictions.

EFFECTIVENESS OF RESIDUALS MANAGEMENT CONTINGENCY ACTIONS

The intensive sediment sampling program at EGD also provides a controlled comparison of surface sediment concentration before and after residuals management contingency actions, which included contingency redredging (for residuals or missed inventory) and placement of RMC.

Comparison of Predicted and Measured Surface Sediment Concentrations Following Residuals Management Cover

Table 3 and Figure 9 provide data related to the effectiveness of RMC sand placement following dredging, and include contaminant concentrations in sand, contaminant concentrations prior to sand placement, and contaminant concentrations following sand placement (both Year 0 and Year 1). These data are used to analyze the following two processes at the site:

1. During sand placement, it is expected that some less-dense residuals will resuspend due to the disturbance to the water column, and then resettle on the surface of the RMC layer. The degree to which this process occurred is evaluated in the table by estimating the contribution of residuals to the Year 0 post-RMC surface sediment concentration.
2. Following initial sand placement, propwash is expected to mix underlying residuals into the RMC sand layer. Meanwhile, newly deposited sediment will settle and mix into surface sediments. Over the long-term, both processes are expected to increase surface sediment concentrations. To identify the impact of these processes, the trend in surface sediment conditions form Year 0 to Year 1 is presented.

Table 3. Analysis of surface sediment concentrations following RMC placement.*

Item[1]	tPAH	tPCB	As	Cd	Cu	Pb	Hg	Zn	Average
NRAO:	*20*	*0.189*	*41.6*	*4.2*	*108*	*112*	*0.7*	*271*	
Concentrations									
RMC Sand[2]	ND	ND	3.1	0.09	13	2.5	0.02	37	--
Pre-placement (Post-production Dredging and Redredging)[3]	3.25	0.288	15.2	1.45	87	54.6	1.01	136	
Post-RMC Placement – Year 0[4]	0.09	0.022	2.8	0.25	15	3.0	0.06	39	
Post-RMC Placement – Year 1[5]	0.11	0.023	3.3	0.23	16	3.2	0.07	40	
Percent Residuals Re-suspension and Resettling during RMC Placement[6]	1.7%	4.7%	0%	7.3%	1.5%	0.6%	2.5%	1.4%	2.5%
Percent Increase in Concentration from Year 0 to Year 1 Post-construction	26.0%	4.7%	15.9%	-7.1%	11.4%	5.3%	13.4%	2.6%	9.0%

Notes:
* Units are milligrams per kilogram dry weight unless otherwise noted.
1. Tributyltin (TBT) and dioxins/furans were not included in the analysis because of smaller sample datasets (both chemicals) and the high number of non-detect samples (TBT).
2. Residuals management cover (RMC) sand concentrations are based on laboratory analysis of quarry samples submitted during construction.
3. Pre-RMC placement values are the same as the post-dredging values presented in Table 2.
4. Post-RMC placement (Year 0) values are the average of 43 surface sediment samples.
5. Post-RMC placement (Year 1) values are the average of 60 surface sediment samples.
6. Percent re-suspension is calculated assuming that non-detects are equal to 0 and are estimated with a mass balance of the residuals concentration that would be mixed with the RMC sand in the surface to achieve the Year 0 post-RMC placement concentration.
As: arsenic; Cd: cadmium; Cu: copper; Hg: mercury; ND: non-detect; NRAO: numeric remedial action objective; Pb: lead; tPAH: total polycyclic aromatic hydrocarbons; tPCB: total polychlorinated biphenyls; Zn: zinc

The results indicate that the percent of re-suspension and redeposition of residuals ranges from 0% to 7.3%, depending on the analyte. The average percent loss is 2.5% of the deposited residuals. The range of the results is likely attributable to multiple factors at the site, including the impact of underlying sediment concentrations, variation in sand concentrations across the quarry, and how widespread the contaminants are across the site. The contractor placed RMC sand using an environmental bucket and placed material below the water surface in the lower water column in a slow manner. However, the elevation that sand is released in the water column and the rate of sand material placed likely affects the amount of fine-grained dredge residuals that resuspend and resettle on the RMC layer.

The percent increase from Year 0 to Year 1 may be attributable to deposition of sediment from unremediated portions of Esquimalt Harbour, or from episodic and localized mixing of sediments from propwash. One small area could not be dredged or covered near the graving dock mouth due to stability concerns of the graving dock sill. This sediment could also have been redistributed onto the RMC layer between RMC placement and Year 1 monitoring.

Comparison of Effectiveness of Contingency Residuals Management Actions

Table 4 presents concentrations before and after contingency redredging (only for redredge areas) and before and after placement of RMC material. For contingency redredging, surface sediment concentrations declined by 50% on average. The highest concentrations that were above NRAOs prior to redredging were for total PCBs, copper, and mercury, which showed a reduction of 57%, 58%, and 65%, respectively. Other COCs were below the NRAO prior to redredging and similar to background or native material concentrations. The moderate reductions in surface sediment concentrations (50% to 70%) is consistent with dredging as an effective means of mass-removal, but less effective at completely removing thin layers of residuals.

Table 4. Comparison of surface sediment concentrations before and after contingency residuals management actions.*

Item[1]	**tPAH**	**tPCB**	**As**	**Cd**	**Cu**	**Pb**	**Hg**	**Zn**	**Average**
NRAO	*20*	*0.189*	*41.6*	*4.2*	*108*	*112*	*0.7*	*271*	
Contingency Redredging									
Post-production Dredging (Redredge Areas Only)[2]	7.6	0.43	15.6	1.7	163	108	1.75	193	--
Post-contingency Dredging (Redredge Areas Only)[3]	2.4	0.18	9.7	1.6	69	38	0.62	107	
Percent Reduction in Concentration	69%	57%	38%	7%	58%	65%	65%	45%	50%
Residuals Management Cover									
Post-contingency Dredging (All Areas)[4]	2.4	0.15	9.5	1.5	65	41	0.63	106	--
Post-RMC (All Areas)[5]	0.041	0.020	2.7	0.22	13	2.3	0.050	38	
Percent Reduction in Concentration	98%	86%	71%	86%	80%	95%	92%	64%	84%

Notes:
* Units are milligrams per kilogram dry weight unless otherwise noted.
1. Tributyltin (TBT) and dioxins/furans were not included in the analysis because of smaller sample datasets (both chemicals) and the high number of non-detect samples (TBT).
2. Post-production Dredging (Redredge Areas Only) are based on the median of 71 surface sediment samples.
3. Post-contingency Dredging (Redredge Areas Only) are based on the median of 74 surface sediment samples.
4. Post-contingency Dredging (All Areas) are based on the median of 148 surface sediment samples.
5. Post-RMC (All Areas) are based on the median of 71 surface sediment samples.

As: arsenic; Cd: cadmium; Cu: copper; Hg: mercury; NRAO: numeric remedial action objective; Pb: lead; RMC: residuals management cover; tPAH: total polycyclic aromatic hydrocarbons; tPCB: total polychlorinated biphenyls; Zn: zinc

As shown in Table 4 and Figure 9, for RMC placement, surface sediment concentrations showed a larger reduction for all chemicals, with reductions ranging from 71% for arsenic to 98% for total PAHs. While the average concentration was below the NRAO for all COCs following all dredging, a number of sample locations contained concentrations above NRAOs. RMC was very effective at reducing concentrations, which is consistent with evidence on other projects that RMC is a more effective method for reducing surface sediment concentrations following dredging (e.g., Patmont and Palermo, 2007). Reductions were also maintained in the Year 1 post-construction surface sediment conditions. Future monitoring events will measure impacts from mixing of underlying contamination and the input of newly deposited sediment.

CONCLUSIONS

The design estimates of undisturbed and generated residuals for EGD Phase 1B dredging were compared to the post-dredging data to evaluate the accuracy of the estimates. In addition, residuals management actions are analyzed and compared. The monitoring data demonstrated the following results:

- For undisturbed residuals, more contaminated sediment was removed as missed inventory during construction than was predicted using the geostatistical tools that informed development of the dredge prism during design. Multiple potential causes were explored with the available data, and the mostly likely explanation is due to variations in the depth of contaminated sediment that was not captured by the design cores.
- For generated residuals, two methods were used to compare measured post-dredge surface sediment concentrations to design predictions. In the first method, measured concentrations are directly compared to predictions from the design sensitivity analysis and averaged 6.6% loss. In the second method, contaminants are used as a tracer to estimate generated residuals thickness and averaged 4.6% loss. Both estimates were within the range of the design predictions (2% to 9%).
- The degree of mixing during RMC placement was evaluated by comparing surface sediment concentrations before and after placement. Approximately 2.5% of residuals is estimated to have been resuspended and redeposited on the RMC surface during placement. Year 1 post-placement concentrations increased by approximately 9% from Year 0 post-placement concentrations, potentially from propwash mixing or deposition of sediment from other parts of the harbour.
- The effectiveness of two residuals management approaches was also evaluated. Redredging removed additional contaminated sediment mass and reduced surface sediment concentrations by 50% on average. RMC material placement served to reduce post-construction surface sediment concentrations by 84% on average.

Based on these results, the following conclusions can be drawn:

- Geostatistical tools, such as contaminated neatline and confidence level analysis, should be used to inform the dredge prism for remediation projects.
- Higher density post-dredge sampling programs, like the 25-m grid spacing used for the EGD remediation project, are more likely to identify missed inventory and dredge residuals. Contingencies for missed inventory and residuals redredging should be incorporated into construction planning from both a schedule and budget perspective.
- The bounding-level estimates of generated residuals (2% to 9% loss) are generally appropriate. Generated residuals predictions should be developed during design to inform design and planning contingencies.
- Careful placement of RMC can limit re-suspension and redeposition of generated residuals, resulting in low post-construction concentrations.
- Consistent with observations at other sites, RMC placement reduced surface sediment concentrations more effectively than redredging.

REFERENCES

Desrosiers, R., and C. Patmont. (2009). "Environmental Dredging Residuals – Case Study Summaries and Analyses." *Presented at 5th International Conference on Remediation of Contaminated Sediments*. February 4, 2009.

LaRosa, P., C. Patmont, and R. Desrosiers. (2007). "Effectively managing dredging residuals: Balancing remedial goals and construction costs." *Proceedings of the Fourth International Conference on Remediation of Contaminated Sediments*. Savannah, Georgia. January 22–25, 2007.

National Research Council (U.S.). (2007). Committee on Sediment Dredging at Superfund Megasites. *Sediment dredging at Superfund megasites: assessing the effectiveness*. National Academies Press. 294 pages.

Patmont, C., and M. Palermo. (2007). "Case Studies of Environmental Dredging Residuals and Management Implications." Paper D-066, in: *Remediation of Contaminated Sediments—2007, Proceedings of the Fourth International Conference on Remediation of Contaminated Sediments*. Savannah, Georgia. January 2007.

Technology News and Trends. (2008). *Innovative Dredging Technology Accelerates Removal of Residual Contamination in Ashtabula River*. Available at: http://www.clu-in.org/products/newsltrs/tnandt/view.cfm?issue=1008.cfm#1. October 2008.

USACE (U.S. Army Corps of Engineers). (2008a). *The Four Rs of Environmental Dredging: Resuspension, Release, Residual, and Risk*. Technical Report ERDC/EL TR-08-4. Vicksburg, MS: U.S. Army Engineer Research and Development Center. Available at: http://el.erdc.usace.army.mil/elpubs/pdf/trel08-4.pdf.

USACE. (2008b). *Technical Guidelines for Environmental Dredging of Contaminated Sediments*. Technical Report ERDC/EL TR-08-29. Vicksburg, MS: U.S. Army Engineer Research and Development Center. Available at: http://el.erdc.usace.army.mil/elpubs/pdf/trel08-29.pdf.

USEPA (U.S. Environmental Protection Agency). (2008). *Research advancing understanding of dredging residuals*. Issue report by the Office of Research and Development. Available at: http://www.epa.gov/ord/npd/pdfs/lrp-factsheet_dredging.pdf.

USEPA. (2009). *Land Research Program, Contaminated Sediment Research*. Available at: http://www.epa.gov/landscience/accomp-sediments.htm.

Wang, T.S., Larm, K., and Hotchkiss, D. (2002). "Evaluation of Closed Buckets for Remedial Dredging and Case Histories." *Proceeding of the American Society of Civil Engineers, 3rd Specialty Conference on Dredging and Dredged Material Management*. Orlando, Florida. 2002.

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