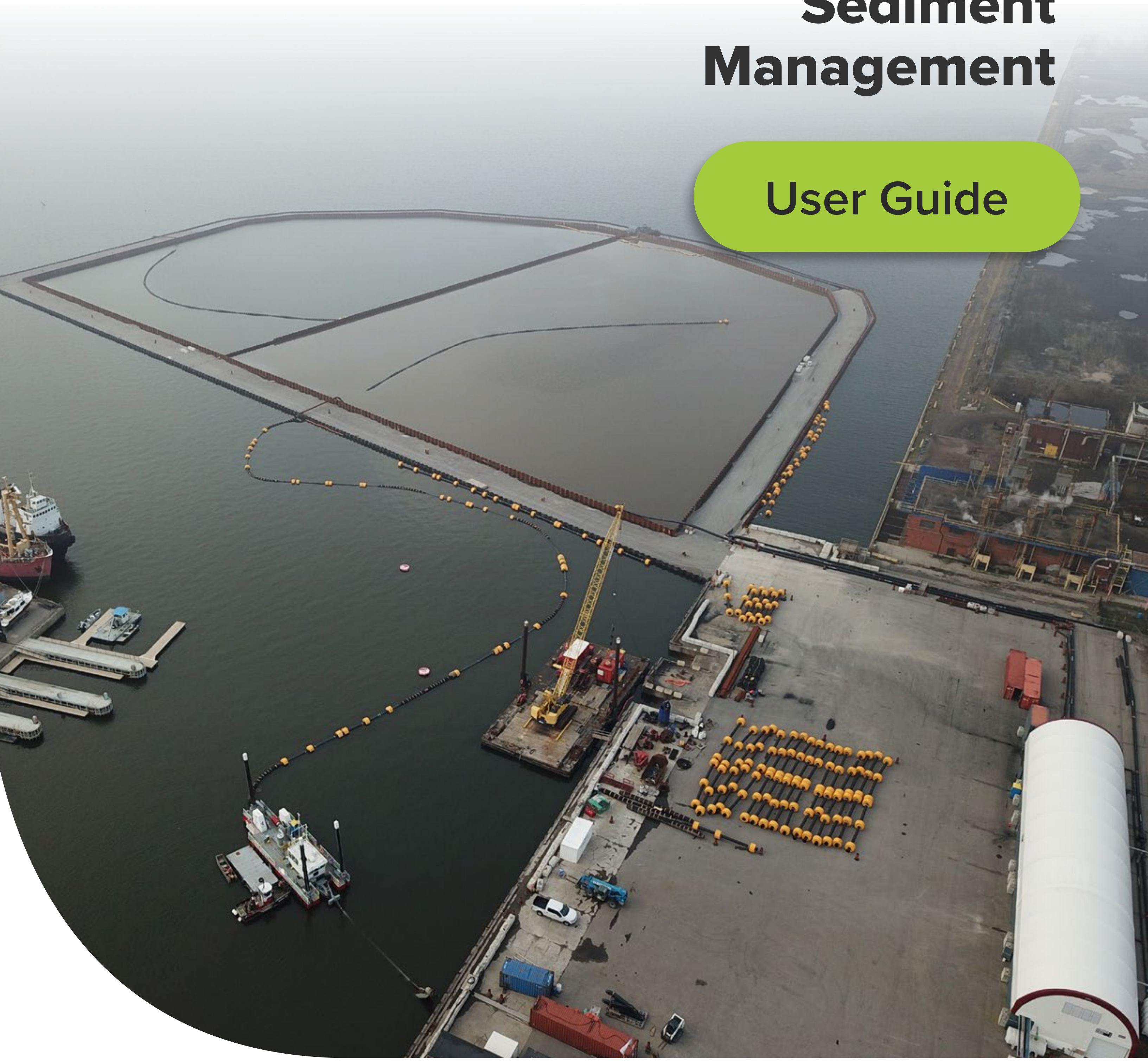
Evaluation of Project Designs for Contaminated Sediment Management

User Guide



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Preface

The management of contaminated sediment is usually a complex endeavour. Aquatic contaminated sites are highly dynamic environments requiring an in-depth understanding of numerous chemical, physical, biological, and socio-economic aspects in order to develop a safe, responsible, and effective management solution. The objective of this document is to outline the key factors that should be considered in the design and management of contaminated sediment. This document summarizes the experience gained during the Great Lakes Areas of Concern (GLAOC) sediment management projects and provides references for project managers who are asked to manage, review, or provide advice on developing a sediment management design for a particular site.

Table of Contents

List of Figures

List of Tables

1. Introduction

The number of contaminated sediment management projects completed within Canada to date is limited in comparison with larger jurisdictions such as the United States. As a result, the existing knowledge base in the Canadian public and private sector is limited. A number of the larger and more significant sediment management projects within Canada have been completed and/or are underway as part of the Great Lakes Areas of Concern (GLAOC) program or the Federal Contaminated Sites Action Plan (FCSAP), along with private sector projects.

In 1987, under the Great Lakes Water Quality Agreement, Canada and the United States designated 43 sites within the Great Lakes as Areas of Concerns (AOCs), 12 of which are Canadian and five of which are binational. Since 1987, the Government of Canada has supported action to clean up and “de-list” AOCs. De-listing an AOC is achieved through the removal of beneficial use impairments (BUIs) which exist within each AOC.   Certain BUIs relate directly to impacts from contaminated sediment such as: degradation of benthos, degradation of fish and wildlife populations, fish tumours and other deformities, restrictions on fish and wildlife consumption and restrictions on dredging activities. Environment and Climate Change Canada (ECCC), working with the Province of Ontario and other stakeholders, has a leading role in developing and implementing contaminated sediment management strategies in order to improve water quality and ecosystem health, and ultimately, lead to the removal of a site of the Areas of Concern list. Restoration of water quality and ecosystem health in Severn Sound, Collingwood Harbour and Wheatley Harbour allowed the Government of Canada to remove these sites from the list of AOCs.

Contaminated sediment management projects have been completed in the St Clair River (Sarnia), Collingwood, Severn Sound, Niagara River (Welland River), Thunder Bay (Northern Wood Preservers site), Detroit River (Turkey Creek), and the Peninsula Harbour Area of Concern. The Randle Reef Sediment Remediation Project, the largest aquatic contaminated site in Canada, is currently underway in the Hamilton Harbour AOC. The project began in 2015 with the construction of an engineered containment facility (ECF) that was completed in 2017. Contaminated sediment is currently being hydraulically dredged and placed within the ECF. Dredging is expected to finish in 2021, after which the ECF will be capped and the project completed by 2023. Monitored natural recovery is also underway in St. Lawrence River (Cornwall) and Niagara River (Lyons Creek East). As of 2021, approximately 1.3 million cubic meters of contaminated sediment will have been managed under the GLAOC program.

The management of contaminated sediment is usually a complex endeavour. Aquatic contaminated sites are highly dynamic environments requiring an in-depth understanding of numerous chemical, physical, biological, and socio-economic aspects in order to develop a safe, responsible, and effective management solution.

Many sites utilize blended remedies, combining two or more different sediment management techniques to suit the specific site conditions and management objectives in the best manner. As a result, knowledge of the key technical aspects of a number of different management techniques is required when reviewing proposed sediment management designs.

1.1 Purpose

The objective of this document is to outline the key factors that should be considered in the design and management of contaminated sediment. This document summarizes the experience gained during the GLAOC sediment management projects and provides references for project managers who are asked to manage, review, or provide advice on the development of a sediment management design for a particular site.

This document is divided into the common sediment management techniques that are currently in practice: environmental dredging, confined disposal facilities, isolation capping, thin-layer capping (enhanced monitored natural recovery), *in situ* remedies, and monitored natural recovery. It also outlines key factors and considerations that a reviewer should ensure are covered.

As previously mentioned, many sediment management projects utilize a blended remedy approach, and as such, a review will require the examination of several approaches covered in this guidance document. It is assumed here that any sediment management design under review is supported by a thorough site and sediment characterization, risk assessment, and management options evaluation, and that the reader is seeking to ensure that the chosen design has addressed all the important elements described in each of the sections (environmental characteristics, geotechnical characteristics, construction requirements).

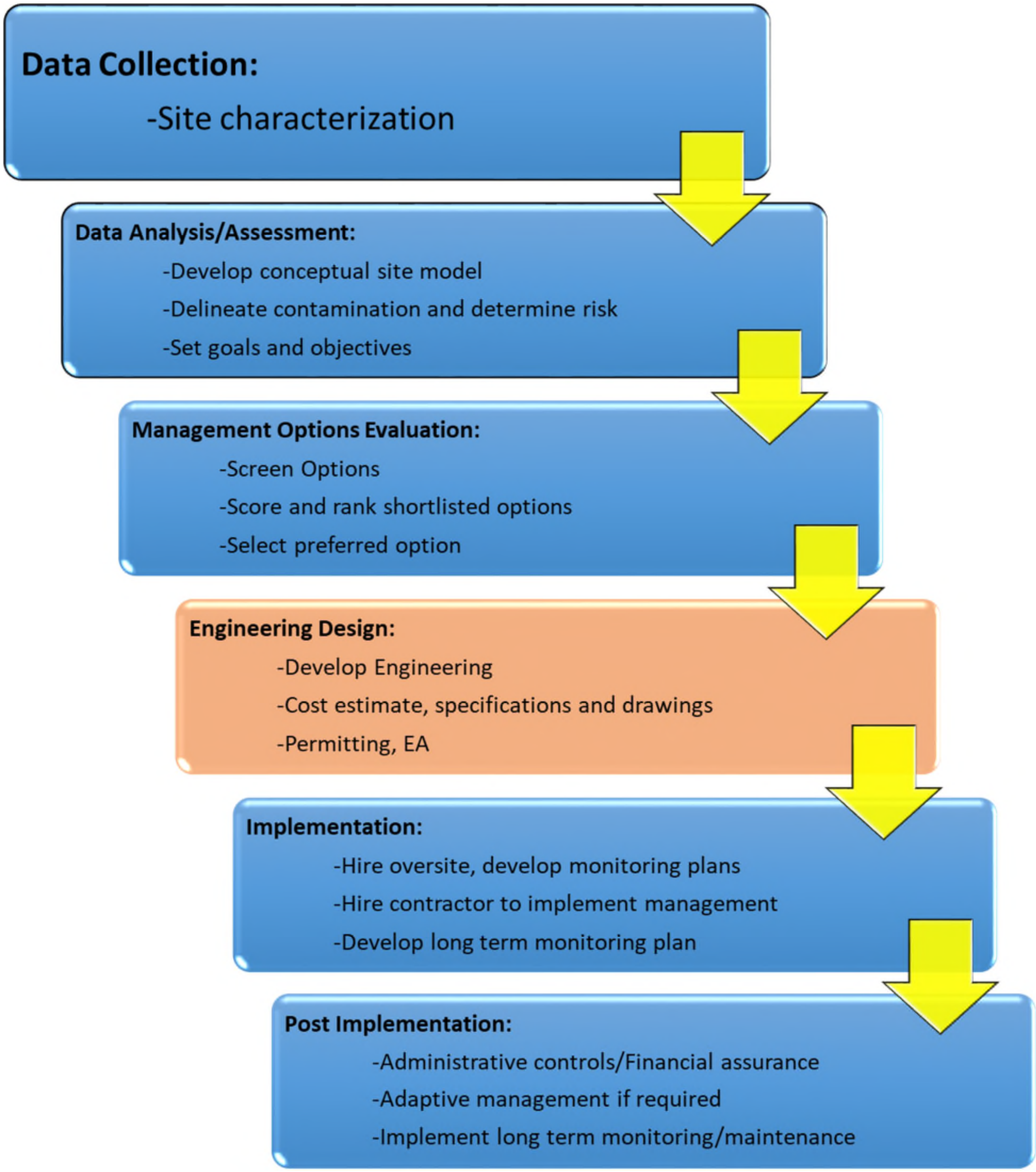

Figure 1-1: Generalized overview of the sediment remediation process.

1.2 Organization of This Document

This document is divided into nine sections, followed by references and appendices:

1. Introduction
2. The Contaminated Sediment Management Plan: General Considerations
3. Environmental Dredging
4. Confined Disposal Facilities
5. Isolation Capping
6. Thin-Layer Capping (Enhanced Monitored Natural Recovery)
7. *In situ* Management Techniques
8. Monitored Natural Recovery
9. Monitoring

Canadian guidance to develop sediment management strategies is presented in Appendix A.

The document has been organized so that items applicable to all remedies are captured under Section 2, The Contaminated Sediment Management Plan: General Considerations. It is important to note, however, that while each remedy section has the same headings as those listed in the general considerations, the information provided is remedy-specific and is intended to complement the generic information already provided.

2. The Contaminated Sediment Management Plan: General Considerations

This section outlines the general steps required to get to the design stage of a project. It also discusses the general considerations to take into account when preparing or reviewing design-level documents. Design-level documents may include 30%, 60%, and 90% design documents, in addition to project plans and specifications, although for an accelerated project, some of these steps may be bypassed. A basis of design may also be developed separately. The considerations listed in this section apply to all sediment management strategies. Additional considerations specific to each management strategy are provided within each section.

2.1 Sediment Management Options

Prior to the completion of any design work, a sediment management options (SMO) evaluation should be completed. The Interstate Technology and Regulatory Council provides guidance on the SMO process (ITRC 2014). In some ways, this is actually an early step in the design process. Sufficient data collection and site characterization would have been available to allow a reasonable comparison of SMOs. These preliminary designs used in the SMO assessment are conceptual. The SMO evaluation is intended to narrow the scope of potential sediment management options by highlighting both the advantages and challenges facing particular approaches.

Irrespective of what management option or combination of options are chosen for a given site, there are a number of key considerations common to all.

2.1.1 General Considerations

The key to successfully evaluating a project design is to determine that all technical aspects have been adequately addressed and the implications for project implementation are properly understood, taking into consideration the following elements:

- Effectiveness (i.e., the ability to achieve the sediment management goal),
- Feasibility (i.e., the ability to construct/implement),
- Schedule,
- Regulatory compliance,
- Community acceptance,
- Long-term monitoring, ownership and maintenance, and
- Cost.

The reviewer should keep these in mind throughout the review of the project design. It can sometimes be beneficial to have a design peer review, a constructability review, or value engineering completed by another qualified firm/practitioner or contractor.

2.1.2 Site Characterization

The accurate characterization of the site, including the establishment of the contaminants of concern (COCs) and the delineation of the spatial (horizontal and vertical) extent of the contamination and associated risk are the key pieces of information determining the requirements of sediment management and which SMOs would be applicable. The establishment of COCs is initially based on a review of available historical documents reports, images (shore-based and aerial) and site visits and should include surrounding properties. The COCs are subsequently refined throughout the investigative stages leading up to the decision to remediate or manage.

2.1.3 Definition of Project Objectives, Goals and Determination of Clean-Up Levels

The completion of any project design must ultimately meet established objectives, goals, and clean-up levels (CULs). Sediment management objectives are typically derived from the conceptual site model to address the significant exposure pathways. They are intended to provide a general description of what the cleanup is expected to accomplish, identify the anticipated lifespan, and help focus the development of SMOs (EPA 2005). Examples of project objectives are as follows:

- To reduce to acceptable levels the risks to humans from direct exposure to contaminated sediment or from ingestion of contaminated fish or shellfish; and
- To reduce to acceptable levels the transfer of contaminants to benthic invertebrates and fish at the site and to birds and mammals that feed at the site.

Sediment management goals may be set for each medium of concern (e.g., sediment, water). Such management goals form the basis for setting CULs. They should be represented as a range of values within acceptable risk levels. The cumulative risk from other exposure pathways should also be considered when selecting the final CULs for specific contaminants.

Project Success Criteria

It is important that the design documents clearly indicate how success will be defined and verified.

The project CULs are the extension of the overall project objectives into tangible project goals. The CULs pertain to specific measurable chemical concentrations that the project is designed to achieve. Surface sediment concentrations are the most common CULs used in sediment management. A surface sediment concentration for an established area is usually determined using a surface weighted average concentration (SWAC) calculation. SWAC is a process whereby individual sample concentrations within an overall established area are assigned a weight based upon the portion of that area they represent. This can be achieved by establishing an area each sample represents (e.g., using Thiessen polygons[1] or other similar methods) for each sample result within the overall area. Averaging the concentration in the sediment in the area using both the sample results and their respective weights determines the SWAC. More advanced interpolation techniques (other than Theissen polygons) can be utilized and these often have a capacity to assess confidence in the estimates.

Where there is a biological objective, such as fish tissue concentrations, the tissue concentration must be quantitatively related back to an established sediment and/or surface water concentration. It is important to note that it may take several years to meet that type of management objective, even though the CUL has been met.

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[1] Thiessen polygons (TPs) are often used to characterize sediments by assigning chemical concentrations or other values to areas where no actual data exist. TPs are created by drawing straight lines equidistantly between neighbouring stations, and whole polygons are then assigned the sediment chemistry concentration value of the station falling within each polygon.

Short-term and long-term monitoring post-management typically uses biological, chemical, and/or physical monitoring to determine if sediment management objectives have been achieved. Establishing the CUL defines what the remedy is designed to achieve in order to meet the overall project objective. It is important to note that any CUL for a remedy should take background considerations into account. If a CUL is lower than background concentrations, the remedy will be unsuccessful in the long term due to recontamination.

2.1.4 Source Control

Before any sediment management option is implemented, a site must be characterized such that all the sources of contamination are known and have either been stopped or managed in a way that will not result in recontamination above the CUL. This is especially important in sediment management because sediment is not static. Sediment movement occurs over time both laterally and to some extent vertically (e.g., resuspension, bioturbation and mixing). New sediment may be migrating into the site and the quality of that sediment could impact the site conditions. Without proper source control, the effectiveness of any sediment management project will be limited. Sometimes more specialized techniques can be required. Examples would include the use of hydro-acoustic techniques, underwater video and thermal imaging.

2.1.5 Conceptual Site Model

A well-developed conceptual site model (CSM) is essential during early planning stages for the development of a sediment management strategy, and should be periodically updated throughout the life of the project with new data. The CSM presents a comprehensive and concise understanding of the site conditions, including the contaminant source, COCs, pathways and receptors, and is a key element in risk assessment. In order for the sediment management option to be effective, it will have to account for the interaction of all these components of the CSM. For example, at a contaminated sediment site, it is important to know if there is any vertical movement of groundwater in the contaminated sediment, and if so, the rate of movement.

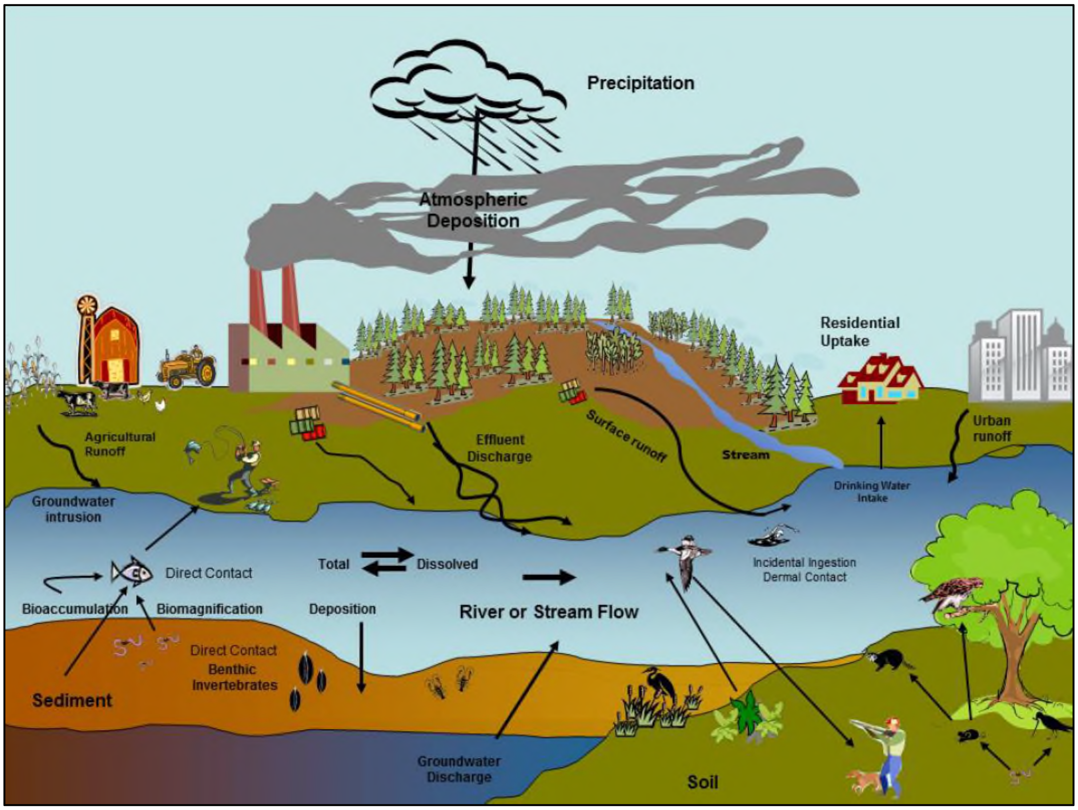

Figure 2-1: Generalized conceptual site model for biological characterization (CCME 2016).

Contaminant Fate and Transport

Contaminants can undergo both physical and chemical changes, depending on the remedy selected. This can happen before, during, and/or after implementation activities are complete.

Physical changes for contaminants bound to sediment particles can include erosion, resuspension, mixing, transport, and deposition downstream. In addition, potential contaminant transport pathways associated with the implementation and the lifespan of the remedy must be identified.

2.2 Characterization of Site

While each management option has specific aspects of site characterization that are more important than others, there are a number that are common to all. It is important to confirm that all aspects of site characterization, including site conditions, sediment characterization, and a CSM, have been appropriately addressed and form a suitable basis for any further characterization and remedy design.

2.2.1 Sediment

This section discusses the aspects of site characterization specific to sediment.

Geotechnical

In general, six key geotechnical parameters that are important in any sediment management project are grain size, water content, Atterberg limits, density, stratigraphy, and shear strength. These must be characterized across the site as well as vertically. The stability of the surrounding surface and subsurface sediment and soils can be a complicating factor for sediment management and should be considered in the design. The following list describes each of the six parameters:

1. **Grain Size Distribution:** Grain size will affect density, shear strength, and water content. Grain-size distribution will also influence sediment stability, resuspension, and transport. Sediment contamination is usually associated with the finer-grained particles.
2. **Water Content:** This refers to the quantity of water in the sediment and is affected by the grain size, lithology, and porosity.
3. **Atterberg Limits:** These indices are used to determine the nature of fine-grained soils (and sediment) with varying water content, expressed in terms of shrinkage limit, plastic limit, and liquid limit.
4. **Bulk Density:** The bulk density of sediment can vary widely based upon the degree of consolidation. Loose unconsolidated sediment located at the sediment/water interface can be partially suspended in the water column.
5. **Stratigraphy:** Sediment will vary vertically, transitioning from the soft surface sediment to dense underlying material. In some cases, multiple distinct sediment layers can be present. Sediment contamination may be associated with specific layers and the characteristics of the different layers may affect management decisions. Some remedies require geotechnical knowledge of the material underlying the contaminated sediment, as settlement of foundation soils beneath the contaminated area may affect the long-term behaviour and performance of the remedy.
6. **Shear Strength:** The shear strength of fine sediments depends on the cohesiveness and water content of the sediment in question. Consolidated fine-grained sediment, such as silts or clays, will be more cohesive (i.e., will cling/bind together) as compared with coarser-grained sandy sediments. Generally, contaminated sediment has high water content and low shear strength. Shear strength can have impacts on bank stability, the bearing strength of sediment or adjacent soil, and limit dredge depth.

General geotechnical standards for testing and evaluation procedures can be found in American Society of Testing and Materials (ASTM) documents:

https://www.astm.org/Standards/geotechnical-engineering-standards.html

Contaminants of Concern

COCs are the chemical stressors present at the site of interest. They typically start as a longer list of potential contaminants of concern (PCOCs) based on assessments covering historical site use, surrounding site use, and other historical information gathered. In order to ensure that all PCOCs are captured, thorough studies of the site and site history must be completed; the studies should identify previous (and current, if any) industrial and municipal discharges of contaminants and types of contaminants associated with those discharges.

PCOC concentrations at the site are then screened against applicable chemical screening criteria (usually toxicologically based) and are considered COCs if screening guidelines are exceeded. The *Framework for Addressing and Managing Aquatic Contaminated Sites under the Federal Contaminated Sites Action Plan (FCSAP)* (Chapman 2011) details the steps required to determine COCs. The three essential questions in that assessment are as follows:

1. Are contaminants present that pose a risk of acute or chronic toxicity to ecological receptors?

2. Are contaminants present that pose a direct risk of harm to human health or through bioaccumulation in seafood?
3. Are the contaminants present at levels above background or reference levels?

The list of COCs is often reduced further through a more detailed risk assessment process. Adequate and thorough characterization of sediment chemistry, both vertically and horizontally, must also be conducted to ensure the spatial extent and the magnitude of contamination are known. The COCs are then used to determine the applicable CULs for management of the site. Often there is one COC that becomes the driver for the site, typically due to its toxicological characteristics. For instance, a site contaminated with polyaromatic hydrocarbons (PAHs) and metals may only have a PAH criterion because cleaning up the PAHs also addresses metals of concern.

It should be noted that for contaminated sediment sites the bulk of the contaminant mass is generally located within the fine-grained sediments.

Total Organic Carbon Content

Organic carbon content is a key parameter affecting fate and transport of contaminants and many other aspects of sediment management design, including the ability to compare to certain regulatory criteria for organic contaminants. Organic carbon affects the availability of contaminants to certain receptors because the contaminants are often bound to the organic fraction.

Biological Assessment

Biological lines of evidence refer to the ability of a substance to adversely affect an organism (human or ecological). These lines of evidence include the potential for bioaccumulation, biomagnification, and toxicity as well as the examination of benthic community densities and composition. It is well established in the contaminated sediment literature that toxicity to aquatic organisms is related to contaminants in the porewater. Toxicity in sediment investigations is useful as a line of evidence in determining if sediment management is required. It is also used in prioritizing sediment for management, as well as helping to define site-specific CULs.

The GLAOC program utilizes biological information to determine risk of contaminants to aquatic ecosystems at Great Lakes sites. The governments of Canada and Ontario developed a step-by-step science based guidance document known as the Canada-Ontario Decision-Making-Framework for Assessment of Great Lakes Contaminated Sediment (COA Sediment Task Group Members 2007). This document combines biological and chemical lines of evidence to assist the user in arriving at a decision on whether or not management of contaminated sediment is required. In order to utilize this framework, ECCC follows an assessment process known as the BEAST (BEnthic Assessment of SedimenT). The BEAST process is essentially a combination of the Sediment Quality Triad (Chapman 1990) and the Reference Condition Approach (Bailey et al. 2004). As part of this approach, ECCC routinely collects reference (‘clean’) data (benthic invertebrate community structure, sediment and overlying water physico-chemistry, sediment toxicity) from a number of nearshore locations on the Great Lakes to provide a large suite of reference sites for use in comparison with contaminated sites. The large reference suite allows for the best matching of contaminated sites to reference sites based on non-anthropogenic habitat variables.

2.2.2 Site Setting

Full assessment of the current and future influencing factors impacting the site must be included — factors such as environmental conditions, climate change, adjacent land use and waterway usage. Both the effect of the sediment management project on these factors and their effect on the project need to be assessed. Evaluating the surrounding area is typically done as part of an environmental impact assessment.

Environmental Conditions

Environmental conditions (e.g., meteorological, hydrological, geological, and ecological conditions) will influence the project in many ways and require consideration.

Climate Change

All sediment management designs should be evaluated for vulnerability to climate change. According to the USEPA (2015), this evaluation should encompass (1) identification of potential hazards posed by climate change (e.g., flooding and risks to cap/backfill integrity), (2) characterization of the system's exposure and sensitivity to those hazards, and (3) consideration of factors that may exacerbate the exposure and sensitivity, such as the length of time the remediation is designed for or the size of adjacent flood plains. The main aspects that are expected to be influenced by climate change are changes and possible extremes in precipitation, temperature, and wind. This will contribute to sea-level rise and possible increases in the number of wildfires. These, in turn, would result in increased runoff amounts and intensities.

In-Water and Shoreline Infrastructure Survey

The impacts of the project on existing and future infrastructure, and vice versa, must be understood and mitigation incorporated into the design. Contaminated sediment sites are frequently located in active, urban, commercial, and industrial harbours and waterways. Common infrastructure often includes:

- Water intakes,
- Commercial/industrial outfalls,
- Combined municipal sewer discharges,
- Dock structures,
- Abutting shoreline structures, and/or
- Underground/underwater pipelines or utility lines.

Intakes often have water quality parameters that need to be met, and outfalls and discharges cannot be blocked. It is also important to determine the proximity of structures to the shoreline, the risk of failure due to potential sediment removal by dredging, and the potential for shoreline erosion.

Debris

The presence of debris and its implications must be accounted for in the design. Sufficient surveys should be completed in order to determine the presence or absence of debris and the nature of the debris.

A number of different technologies can be used to complete debris surveys, and some are more suited to detecting surface debris while others are needed for buried debris. Side-scan sonar and underwater video are examples of technology that can be used to detect debris located at the sediment surface.

Magnetometer and sub-bottom profiling surveys are examples of technology that can be used to detect buried debris.

Since the presence of debris can have a significant impact on the implementation and effectiveness of sediment management work (dredging or capping), a fair amount of liability lies with the party that conducts the debris survey. Debris surveys should be completed in support of sediment management design work, and it is also common to have contractors complete debris surveys prior to implementation to ensure they take responsibility for adequate debris removal and work planning.

Site Access

Sediment management projects typically require significant amounts of equipment for any active management; therefore, site access can significantly affect the feasibility and cost associated with the project design. Factors noted above, such as water depth and surrounding infrastructure, can limit accessibility. Sediment sites can range from urban ports, where ongoing activities limit access, to remote locations with little to no access.

Waterway Usage

It is important to know the types of vessels that are and will be using the waterway at the site (e.g., commercial vessel traffic, vessel mooring/docking, recreational vessel traffic). These vessels have different drafts and create different stresses on the bottom sediment. It is also important to know if dredging will ever be required in the future as well as any other waterway plans.

Understanding the current and potential future use of the adjacent property is also important, as these activities can impact the project, and the project can also impact these activities. The implications of both situations must be carefully accommodated in a project design.

With regards to vessel traffic and mooring, a right-of-way or specific access times may need to be established and clearly stipulated to all parties. Either project activities or existing activities would need to take precedence, but also make accommodation for the other.

2.2.3 Ecological

Assessment of the current and future surrounding ecological resources (i.e., in the background or reference area) must be included, looking at items such as proximity to sensitive ecological environments/receptors. Baseline studies of the existing biological characteristics and the health of the ecological resources of the site and surrounding area will help identify risks that any proposed sediment management project may pose to the local ecosystem and can be used post-implementation to demonstrate the benefits to ecological resources. Ecological resources to be considered will already have been identified in the conceptual site model.

Reference areas are locations with similar conditions to the project site, but they are relatively free of contamination. Such sites are often challenging to find. In a river system, they are usually represented by upstream conditions. In harbours, the ideal reference condition would be a harbour that is as similar as possible to the site of interest (e.g., similar in substrate type, water depth, and wave action), but without the COCs.

Aquatic Habitats and the Benthic Community

Aquatic habitats and the benthic community should be enumerated and characterized using appropriate sampling techniques and consider temporal / seasonal spatial characteristics. The habitat assessment should also include physiochemical properties such as flow regime, sediment size, sediment stability and water quality parameters as well information pertinent to fish such as proximity to spawning, feeding, nursery, migration, and other important habitat features.

Terrestrial Habitat

Projects requiring land-based operations such as staging areas, sediment handling and dewatering and water treatment, need to consider terrestrial habitats such proximity to nesting sites and feeding. This is specifically important for species at risk.

Fisheries Resources

A description of fisheries resources, including known sensitive species, species at risk (e.g., those listed on the *Species at Risk Act* [SARA]), fisheries communities, and migratory species in the vicinity of the management site, should be completed. Temporal/seasonal and spatial characteristics should be considered to identify potentially critical times or circumstances when sediment management actions should not take place, including:

- Periods of migration from one part of an ecosystem to another and
- Growing, feeding and spawning periods of sensitive or threatened species.

2.2.4 Surface Water

Background and Reference Conditions

Background conditions (Environment and Climate Change Canada, 2020) are generally those that exist in areas that are outside the direct influence of the contamination. In the context of aquatic ecosystems, areas that are completely free of contamination do not exist in reality. Even remote areas are affected by atmospheric deposition of contaminants. Some contaminants are also naturally occurring, such as arsenic. As a result, background conditions refer to the conditions that could be expected away from the influence of the COCs that are associated with the site of interest. In some areas, such as a large harbour where there are many other contributions of contaminants other than the site of interest, background levels will often be elevated above natural levels.

Reference areas are locations with similar site conditions as the project site but are relatively free of contamination. Factors that need to be considered are stated in Section 2.2.3.

Water Depth / Bathymetry

Water depth affects many components of design and also affects remedy costs. Understanding the water depth and various slopes of the sediment bottom is important for all aspects of sediment management design. Variations in bathymetry over a management area directly relate to the volume of sediment requiring management. This has obvious scope, schedule, and budget implications. Bathymetry combined with point measurements or additional low frequency sonar (Sub-bottom profiling) can be used to define sediment thickness. Surface bathymetry will also determine what methods will be required during implementation. Water lots with steep slopes will require a different approach than those with relatively flat bathymetry. Bathymetry and water depth may make certain remedial approaches or the use of certain equipment unfeasible.

It is also important to understand the stability of sediment in terms of waves, ice, and currents interacting with the sediment, as well as the effect of scour from vessels on the bottom sediment.

Hydrodynamics

Hydrodynamics is the study of the motion of fluids and the forces acting on solid particles immersed in fluids. This has many implications in sediment management projects.

Wave-produced orbital motion through the water column can agitate bottom sediment or cap materials. Waves can serve to induce a pumping-like force in the upper few centimetres of sediment caps (Eek et al. 2008). Wave climate studies should be conducted for at least one year to account for storm events and seasonal periods of high energy. Since wind is the dominant factor controlling waves, historical wind data closest to the site of interest should also be examined to obtain an idea of the expected wind speed ranges, the predominant wind directions, seasonal periods of the highest energy and frequency of occurrence. This enables an estimation of the expected wave climate as well as for modeling more extreme conditions.

Currents (from wind or tidal forces) above the sediment/water interface can erode bottom particles, depending on the current velocity, the grain size and lithology of the material. Localized currents may or may not follow the wind direction and are often complicated due to the interaction of dock walls and other underwater structures.

At marine sites, the influence of tides must be considered. Tide fluctuation will have a significant influence on a project, based upon changing water depths and the potential for complete exposure of sediment to the air. Under some circumstances, lake sites could be affected by tide-like conditions resulting from strong winds consistently blowing in one direction. This fluctuation in water level is known as a seiche and should be a consideration for locations where seiches are a relatively common occurrence (e.g., on Lake Erie).

2.2.5 Hydrogeological

Hydrogeology is the study of the distribution and movement of water in the soils and rock of the earth. There are a number of key aspects that are important to sediment management, including groundwater flow, groundwater / surface water interface, and groundwater quality.

Groundwater Flow

Groundwater flow refers to the movement of water through different geological media. The flow is affected by the porosity of the material and the driving force (hydraulic head). Groundwater is a pathway for contaminant migration and can affect sediment sites. Where groundwater discharges through sediment into a waterbody, the groundwater can be responsible for transporting dissolved contaminants from an off-site source, impacting the porewater quality in the on-site sediment itself, or transporting contaminants out of the on-site sediment into the surface water at the site.

Groundwater / Surface Water Interface

At the bottom of waterbodies, where surface water becomes groundwater, there is usually some interaction. The exchange can be in the form of groundwater recharging the surface water (upwelling) or the surface water recharging the groundwater (downwelling). This is controlled by the driving forces (hydraulic head) in the area as well as the hydraulic conductivity of the geological media. In terms of contaminated sediment sites, the groundwater / surface water interface is an important part of the conceptual site model because this interface can be a form of contaminant transport and the point of exposure for receptors.

Groundwater Quality

In the context of contaminated sediment management, groundwater quality refers to the chemical makeup of groundwater and the potential for dissolved contaminant loading to be discharged at the site. Groundwater quality can impact both the sediment (in terms of porewater) and the surface water it discharges to.

2.3 Construction Management Risk

There are inherent financial and liability risks to any sediment management project. Through the use of the contract documents and specifications, the responsibility for the risks can be allocated proportionally to relevant participants in the management of the project (i.e., the site owner, the contractor, the designer, and sometimes an oversight consultant). It is important to understand the risks, their probability of occurrence, the resulting impact on the project, and the placement of responsibility for the risks. A design can be set up to minimize risk to the project owner and transfer the risk primarily to the contractors. The advantage is that this provides a level of cost certainty for the owner, and during implementation, the contractors are better positioned to manage risk as the work progresses. The disadvantage is that the contractors may inflate the cost in order to account for the unknown risk that is transferred to them. A design can also be set up for the owner to retain risk but limit potentially higher costs. Some examples of management design components that affect risk are as follows:

Prescriptive vs. Performance-Based – Specifications can be written in a prescriptive manner whereby they detail how a certain goal will be achieved, or they can be written in a performance-based manner whereby a certain goal is presented and the method to achieve it is left to the contactors, providing more flexibility. An example of this is providing a full water treatment design (prescriptive) vs. providing discharge criteria (performance-based). Providing a full water treatment design places the risk with the owner or designer, whereas providing only discharge criteria places the risk with the contractors.

Owner-Supplied Material – On certain projects, there may be an advantage to the site owner to supply materials, if the owner can procure certain materials at low cost. This creates a potential issue when the contractor encounters problems that can be related to the product. The owner now has responsibility for the risk. If material is supplied by the installing contractor, the contractor takes on the risk. The quantity and quality of owner-supplied material will determine how risk is allocated proportionally amongst the project owner and contractors.

Owner-Supplied Information – Information provided by the owner to the contractor can be supplied for one of two main purposes: either to be relied upon or to be used as reference only. When information is to be relied upon, the risk remains with the owner. When information is to be used as reference only, the risk is borne by the contractor (e.g., debris surveys conducted by the owner are provided as reference only). The quantity and quality of owner-supplied information will determine how risk is allocated proportionally among the project owners and contractors.

Design-Build – On certain projects, contractors are retained before the completion of the design (~60% design) and are involved in the finalization of the design work. By involving the contractors in the completion of the design, efficiencies can be achieved. For example, aspects of the design can be tailored to the equipment the contractor has available. Also, having the contractor involved at this stage potentially identifies and eliminates disputes over risk, as all parties are involved in design development.

The principles of design-build can also apply where bench-scale and pilot-scale tests are required in order to finalize a design and specifications. The contractor successfully completing the bench-scale and pilot-scale tests would then proceed with full-scale implementation.

The design document can also limit risk to the owner by specifying the contractor has responsibility for risk management in specific areas and pre-establishing limits on contractor's change orders related to shutdowns or delays.

2.4 Administrative Controls

Administrative controls, also referred to as institutional controls (IC), are an administrative tool that establishes administrative procedures/approaches to ensure exposure to contaminated sediment is minimized and contaminated sediment is not disturbed, exposed, or resuspended. Some in-water developments, site alterations, emergency activities, and recreational activities that involve dredging, filling/covering, piling, and scouring have the potential to disturb, expose, or resuspend the contaminated sediment. No-anchor zones, reduction in vessel speed, no-fishing zones, fish advisories, and a ban on in-water development are examples of administrative controls.

Figure 2-2: One type of administrative control (courtesy of ECCC).

Figure 2-3 outlines the life cycle of an administrative/institutional control (IC). The first row in the figure outlines the steps required when applying an institutional control to a site. The remaining rows outline other activities that need to take place simultaneously with the steps in the first row. For more information on administrative controls and the elements shown in Figure 2-3, an excellent resource for application of administrative controls is Long-Term Contaminant Management Using Institutional Controls (ITRC 2016).

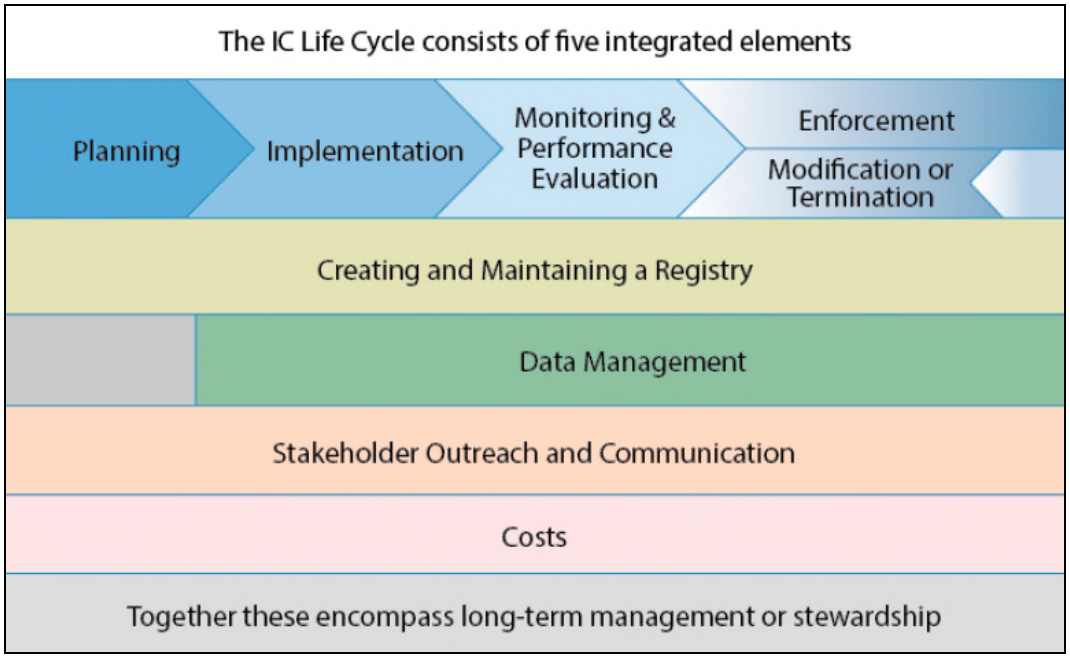

Figure 2-3: Integrated activities in an IC life cycle (ITRC 2016).

2.5 Adaptive Management

Adaptive management addresses uncertainty in project design and implementation. It is a formalized iterative process that allows implementation of alternative management approaches to meet the goals and objectives of a project. It can also allow for a tiered approach to remediation when multiple strategies are utilized over a longer period. When either monitoring during a project or long-term monitoring after completion shows the goals and objectives of the project will not be met in a reasonable time frame, then the adaptive management approach provides for the implementation of changes in management actions.

The following steps outline the adaptive management process for contaminated sediment sites (Fischenich 2012):

1. **Plan:** Defining the desired goals and objectives, evaluating alternative actions, and selecting a preferred strategy with recognition of sources of uncertainty.
2. **Design:** Identifying or designing a flexible management action to address the challenge.
3. **Implement:** Implementing the selected action according to its design.
4. **Monitor:** Monitoring the results or outcomes of the management action.
5. **Evaluate:** Evaluating the system response in relation to specified goals and objectives.
6. **Adjust:** Adjusting (adapting) the action, if necessary, to achieve the stated goals and objectives.

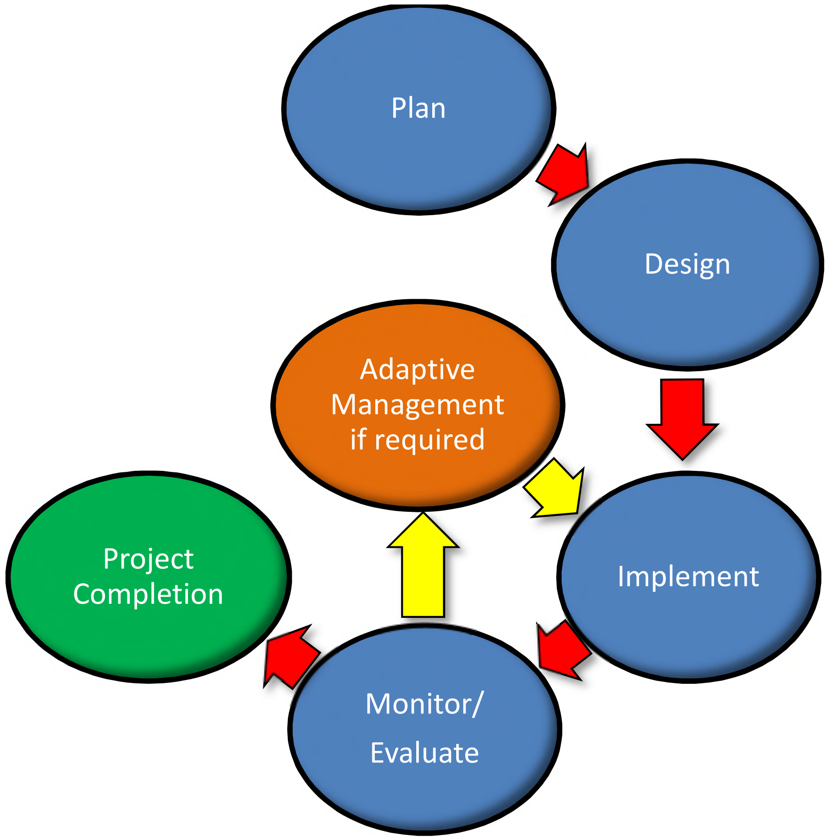

Figure 2-4: Adaptive management process.

The initial design of a sediment management project may not be able to fully incorporate what type of adaptive management action will be required. Adjustments to the design and implementation aspects will only be fully understood once monitoring reveals the scope of the issue to be addressed. In some cases, a specific action or a general understanding of what might be required can be specified upfront if an outcome is not achieved as planned (e.g., monitored natural recovery [MNR]may require some eventual thin-layer capping or hotspot dredging). Optimally, an adaptive management plan should include the alternative actions and preliminary design detail to the level possible. At a minimum, the scope, schedule, and budget/resources associated with the alternative actions should be included. For projects such as MNR sites, the adaptive management plan also needs to establish who is responsible for initiating the plan if remedial goals are not reached within an acceptable time frame. An adaptive management plan should have financial assurances in place before the project is implemented.

3. Environmental Dredging

It is the intention of the authors that this section be read in conjunction with the discussion of site characterization and long-term monitoring included in Section 2 and 9. It is noted that the subheadings are the same in this section, but this section includes specific information on site characterization and long-term monitoring pertinent to environmental dredging.

3.1 Introduction

Environmental dredging is conducted for the specific purpose of removing contaminated sediment from a water lot. Environmental dredging as a management approach is a multi-step process that can take a variety of forms and requires off-site or on-site disposal of the dredged sediment. Both environmental dredging and associated disposal are addressed in this section. Many aspects of environmental dredging differ from traditional dredging required for navigation, especially in how clean-up targets are set, how dredging equipment is selected/operated, how success is measured, and how potential environmental impacts are monitored.

In Canada, the number of environmental dredging projects has been limited to date, and most dredging contractor and marine engineer experience relates to navigational dredging. It is therefore important to ensure that the engineering design for an environmental dredging project has carefully taken into account the requirements specific to environmental dredging work.

The information provided in this section is intended to highlight the technical points to consider during evaluation of environmental dredging design documents.

3.2 Goals and Objectives

The overall objectives of a sediment management project will have already been set. Goals, however, can be specifically oriented to environmental dredging.

3.2.1 Dredging Goals

Once dredging is determined to be the remedy for the site (or a portion of the site), the design then needs to establish goals specific to the dredging process. Specific dredging-related goals will translate into defined and quantifiable clean-up levels, which are discussed later.

Dredging goals should normally reflect the following:

1. Accurate dredging: Dredging will need to be completed in a timely and cost-effective manner consistent with expectations for the transport and disposal of contaminated sediment. Minimizing the amount of extra “clean” sediment that is removed in the process of removing contaminated sediment is important for controlling project costs.
2. Limiting residuals: A characteristic unique to environmental dredging is the creation and management of residuals. Residuals are contaminated sediment that remains in place after the initial dredging, or bulk removal, is complete. During the bulk removal of the contaminated sediment, residuals can be generated in a number of ways: the resuspension and re-settling of contaminated sediment by the dredge itself, spillage of material from the dredge/barge, and the sloughing or movement of contaminated sediment into dredged areas from adjacent areas. Residuals can also be deeper pockets of material missed during the bulk removal. The design will

need to include an appropriate process for assessing residuals and a protocol for managing them.

3. Limiting sediment resuspension and contaminant release: All dredging projects have a potential for impact on the surrounding aquatic environment from resuspended sediment. For environmental dredging projects, this risk is elevated due to the significant contamination present within the sediment being dredged and the potential for this sediment to be distributed into the water column and transported away from the site.

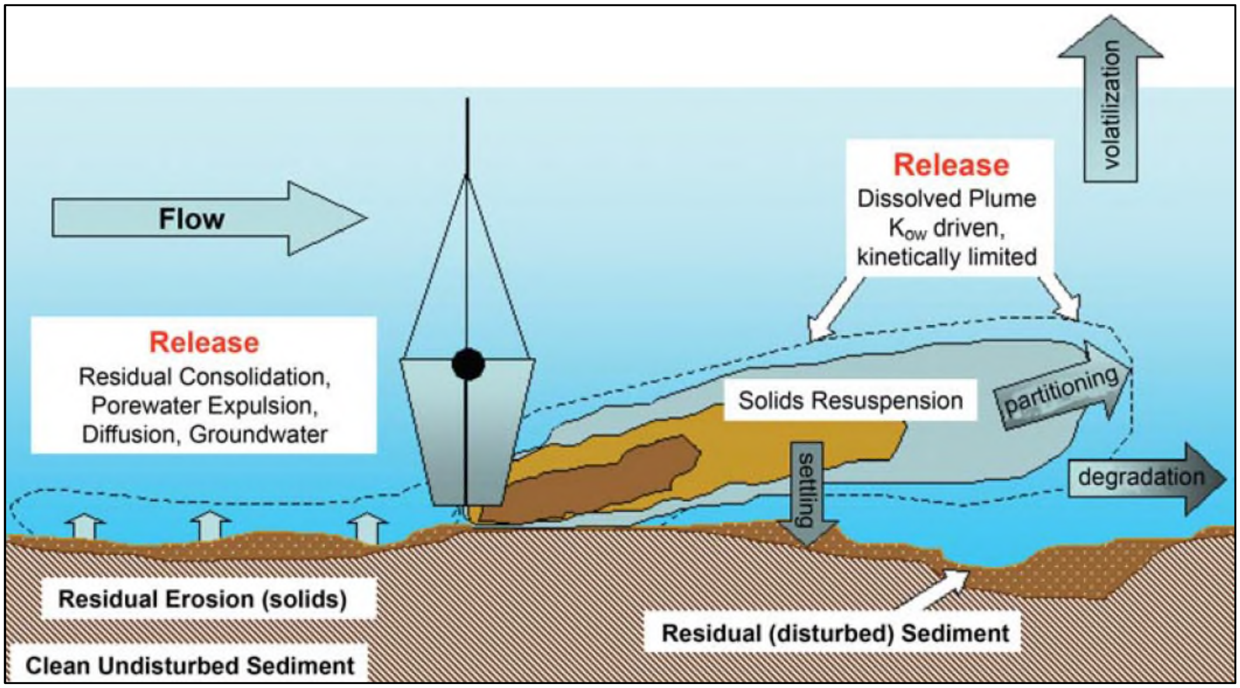

Figure 3-1: Dredging resuspension, residuals, and releases (Bridges 2008).

The design will have to set performance standards for a dredging project as a way of ensuring the overall goals and objectives are met. Dredging clean-up levels have numeric limits or criteria, typically sediment concentrations that need to be achieved either post-dredging or post-backfilling. Clean-up levels combined with well-defined vertical extent of the contamination help determine target dredge elevations (or depths), which is the primary way in which a design document establishes the scope of work for the contractors. Pre-established dredge elevations coupled with appropriate post-dredging residuals management are often preferable to dredging to a clean-up level. The issue associated with dredging to a specific clean-up level is that residuals contribute greatly to the post-dredging surface sediment concentrations, and other means of residuals management, such as thin-layer backfilling, may be more cost-effective.

There may be other standards related to dredging production rate, efficiency of material removal, etc. As noted in the USACE *Technical Guidelines for Environmental Dredging of Contaminated Sediments* (Palermo et al. 2008), performance standards can include one or more of the following:

- Removal of sediment to a specified elevation within specified areas,
- Removal of all sediment having contaminant concentrations above a specific action level,
- Reduction of the surface weighted average concentration (SWAC) to achieve the sediment clean-up level,

- Limits on the surficial contaminated sediment mass remaining as residuals following dredging,
- Limits on sediment resuspension generated by the operation, and limits on the suspended sediment and release of dissolved contaminants reaching some distance downstream from the dredging operation,
- Limits on contaminant releases to air,
- Limits on solids content and/or volume throughput for subsequent treatment/disposal, and
- Constraints on allowable time for project completion.

3.3 Characterization of Site

For dredging projects, the physical characteristics of the site, along with the characteristics of the contaminated sediment, heavily influence the design of the project. Ensuring the physical characteristics of the site have been properly assessed helps confirm the adequacy of the design. When assessing the design of a dredging project, sufficient information must have been gathered, and that information must have been properly utilized in the design.

3.3.1 Sediment

Characterization of the sediment and delineation of the required dredge areas and dredging depth is the obvious focus of any environmental dredging design. Ensuring this element has been adequately addressed is the key to establishing the proper scope of a dredging project. Areas to be dredged, dredge depths, sediment volumes, equipment requirements, monitoring requirements, and overall construction planning hinge on a proper assessment of sediment characteristics.

Geotechnical

Properly establishing the geotechnical properties of the target sediment with respect to dredging has important implications for many facets of the design: dredgeability, selection of the correct equipment for removal, pumping requirements (for hydraulic dredging), transport by barge and staging areas, anticipated production rates, de-watering requirements, and water treatment requirements. Geotechnical parameters of importance and their potential influence on dredging and the consolidation of dredged material include:

- **Grain-Size Distribution:** Grain size will affect transport (pipeline flow requirements for hydraulic dredging), de-watering, and the feasibility of post-dredge treatments such as de-sanding.
- **Density:** Loose unconsolidated sediment can be dredged with minimal mechanical force or agitation and suction. Conversely, highly consolidated denser sediment (which would probably be encountered where contamination is present at greater depths) will require a higher degree of mechanical force to both penetrate and extract.
- **Stratigraphy:** Sediment will vary vertically, transitioning from the soft surface sediment to dense underlying material. In some cases, multiple distinct sediment layers can be present. Sediment contamination may be associated with specific layers and the characteristics of the different layers may affect management decisions. Dredging projects require geotechnical knowledge of the material underlying the contaminated sediment, as this will relate heavily to dredgeability.
- **Shear Strength:** The more cohesive the sediment, the higher the shear strength and the more force required to remove it during a dredging operation. In general, contaminated sediment is

expected to have low shear strength. Shear strength of the sediment also relates to bank stability and possible limits on dredge depth.

- **Atterberg Limits:** The plasticity of the sediment affects its behaviour and has important implications for dredgeability, and from the perspective of a hydraulic dredging operation, implications for ease of transport.
- **Water Content:** Sediment water content affects the feasibility of certain dredging approaches. For mechanical dredging operations, high water content will mean greater amounts of water on barges and the need for de-watering and water treatment efforts.

In assessing the adequacy of the design, one must consider whether the geotechnical properties have been sufficiently assessed to include the preceding parameters and whether the design of construction components such as dredgeability, production rates, side slopes/sloughing, stratigraphy of the sediment and underlying material, resuspension, residuals, water quality, volume changes, and disposal have taken these findings into account.

The geotechnical characteristics of the underlying material determine how the dredging itself is best performed, including the type of equipment utilized. Depending on the source, contamination is often present within specific layers of sediment. The thickness and consistency of the contaminated sediment layers determine the required depth of dredging, dredging approach, and equipment.

The geotechnical properties of any thin-layer backfilling (residuals capping) materials should also be understood in order to ensure they are appropriate for use at the site.

Additional geotechnical considerations that factor into dredging include:

- The bathymetry/topography and water depth at the dredge area,
- Potential challenges presented by underlying material (i.e., soft sediment, hardpan) related to dredgeability, residuals generation, and the implications for overdredging excessive clean sediment volumes, and
- Construction of project-related infrastructure, such as the de-watering laydown area, the water treatment plant, and the disposal facilities (if needed), will require geotechnical information to ensure sound construction.

Dredgeability

The dredgeability of the sediment is a key factor in developing the dredge design, determining the feasibility of the work, and selecting the correct equipment for removal. The shear strength of the target sediment will be a prime factor to determine the requirements of dredge equipment and possibly rule out some equipment not capable of adequately performing the work. If the contamination extends deeper into stiffer, more-consolidated material, the dredge bucket or cutter head would need to have the capability of cutting into this material. Alternatively, if the contamination is restricted to sediment layers that are less consolidated and weaker, then smaller or different equipment (e.g., a vertical auger) may have advantages (Palermo et al. 2008).

Contaminants of Concern

The characterization of the nature, degree and extent of the contamination is key to developing specific aspects of a dredging project. Identification of chemicals of concern, their concentrations, and their location is critical to the dredge design. The lateral and vertical extent of the contamination determines basic requirements. More so than capping remedies, a dredging project requires accurately defined vertical extent of the contamination across the entire area of the site in order to determine required dredge depths and volume, so that accurate volume of material requiring handling, de-watering, and disposal can be determined.

The contaminated sediment targeted for removal could be limited to the surficial layer, may extend deeper into subsurface layers, and may be stratified. The depth of contamination and the sediment layers affected depend on the source of contamination, the age of contamination, site usage, and the physical processes (e.g., porewater movement). These factors may actually vary across larger sites, resulting in contamination at a variety of depths. The dredge design must be based upon a sampling program robust enough to define the vertical and horizontal extent of contamination across the dredge area. The vertical extent, or clean line, will determine the ultimate dredge depths required to achieve the clean-up level. The dredge area will be divided into separate dredge subareas, each with their own respective depths. The subareas and associated depths combine to form dredge prisms, which in turn determine the volume of sediment requiring actual management (geotechnical considerations in determining dredge prisms are covered in Section 3.4.3.). Definition of a dredge prism may also require transitions between subareas to account for geotechnical stability and constraints related to dredge operation. Sediment cores assessing sediment chemistry at depth must therefore be distributed in a manner to have adequately defined the clean lines in each of the dredge subareas.

The exact nature of the contamination is critical to how the dredged material is handled, stored, transported, and disposed of. Because a dredging project involves the removal and off-site disposal of the dredged sediment (unless an on-site facility is constructed), knowing the type of contaminants and the range of concentrations is critical in terms of where and how dredged sediment is disposed of. For certain contaminants, such as PCBs, special disposal requirements exist for higher concentrations. Off-site disposal of highly contaminated material is often one of the chief cost drivers for a dredging project; therefore, it is critical to ensure the project design considers the detailed chemical characterization of the sediment being dredged. The design must also establish proper decontamination, worker health protection, and safety components based on the nature of the sediment.

Sediment chemistry also contributes directly to the potential environmental impacts of the project, specifically on the aquatic ecosystem and air quality. As dredging of sediment is ongoing, there is always a risk of resuspending the contaminated sediment, with the subsequent transfer, or release, of dissolved contaminants into the water column, with attendant downcurrent impacts.

Depending on the type of dredging equipment, conducting a Standard Elutriate Test (SET) (which correlates to the Effluent Elutriate Test in Section 4.4.1) or a Dredging Elutriate Test (DRET) or developing a model based upon contaminants within the dredged sediment helps determine risk of impacts on water quality and potential impacts on surrounding ecological resources. Typically the SET test, which is more conservative, is considered a good representation of dredging with mechanical equipment, since the procedure is thought to simulate discharge which occurs from the scows/barges used on mechanical dredging projects. The SET test is also considered a good option for predicting the impact of dredge related activities such as anchoring/spudding, propeller wash and debris removal. The DRET focusses primarily on the impacts of continual resuspension of sediment by the dredge head and is therefore preferred for predicting the impacts of hydraulic dredging (Vicinie et al. 2011). Depth of contamination determines depth of the dredge cut, and deeper dredge cuts are more likely to have greater resuspension.

Prior to the completion of the design, a SET or DRET should be completed to simulate contaminant release to the water column from both sediment-bound and porewater contaminants at the point of dredging. Site water and a composite sediment sample are mixed to form a slurry and allowed to settle. The supernatant is collected and analyzed for contaminants. The results can be used to determine the short-term surface water quality during dredging and to evaluate mixing zones. A SET or DRET is used to predict the impacts of dredging a particular site, and it will consider the effects of solids concentration, aeration time, and settling time on contaminant concentrations (soluble and particulate) in the water (USACE 2008).

Application of the Dredging Elutriate Test (DRET)

For the Randle Reef Sediment Remediation Project, a modified DRET procedure was used to examine potential chemical and toxicological impacts with Randle Reef sediment at 3 TSS levels (25, 50, and 75 mg/L). The modified DRET procedure allowed the establishment of a site-specific TSS criteria protective of the environment. (Watson-Leung et al. 2016).

The predicted elutriate concentrations would be considered in a dredge design, along with other factors such as resuspension, waves, and currents, to help establish appropriate mitigation measures (e.g., silt curtains) or alterations in the equipment or approach. It is advisable, however, that dredge designs account for the possibility that the true elutriate concentrations during implementation may exceed those predicted by the SET or DRET.

The presence of certain contamination such as NAPL (non-aqueous phase liquid) can result in floating oils or sheen being produced during the dredging process. Specific mitigation, such as oil boom usage, would need to be accounted for in the design where this type of contamination has been noted.

The de-watering of dredged sediment will mean that treatment of the resulting water will most likely be required before that water can be discharged back into the environment. The system must be designed to treat the anticipated contaminants that will exist in the water as suspended material and in the dissolved phase, which would primarily be determined by the COCs in the sediment to be dredged.

Impacts to air quality may also need to be considered when volatile organic compounds are present within the sediment to be dredged.

3.3.2 Site Setting

Beyond the characterization of the sediment that is set to be dredged, the site and surrounding environment must be considered. Aspects such as the underlying material and overlying waters have a direct effect on the dredging activities. The potential impacts of dredging on the surrounding environment and possible resulting restrictions on project activities must also be considered.

Infrastructure and Waterway Usage

Existing activities at the site, specifically the water lot, need to be considered by a dredge design.

Protecting intakes/outfalls from dredging activities could involve dredging offsets, physical barriers, and protective actions to ensure the project does not interfere with their use. The best strategies and the exact requirement of such protection would be determined in the design.

Structural components such as piers that impinge on the site, pipelines that run beneath a site, and dock walls that abut a site can all limit dredge activities both laterally and vertically. Piers represent a physical barrier, which may also require an offset or limitation on dredge depth in order to protect the structural integrity. The same issues exist for adjacent dock walls and sometimes for large equipment or structures that might be situated close to the water's edge. A design may sometimes need to include refurbishing, strengthening, or temporary bracing of these items in order to enable the scope of work to be completed. Pipelines and utility lines may limit the type or depth of dredging. Depending on the nature of the line location and function (e.g., high-pressure gas line, electrical line) and the construction techniques (e.g., depth below sediment, trenched or drilled), an offset on either side may be required.

Adjacent property use can either impact the project or be impacted by the project. Industrial/commercial activities with environmental or health and safety considerations (e.g., noise, dust, air emissions) are a key consideration in any design. The combined impacts from adjacent properties/projects and the dredging project are assessed in the environmental assessment stage, and those findings will need to be incorporated in the design.

Vessel traffic and anchorage in or around a project can impact implementation. Optimally, these activities can be curtailed during implementation, but this is not always the case, especially in commercial harbours. Project activities may need to be adjusted to account for waterway usage such as vessel traffic. Marine safety related to the interactions between project vessels and outside traffic should factor heavily into the project design. Marine equipment needs the appropriate lighting or markings to be evident to others moving through the water lots. Components such as floating pipelines associated with hydraulic dredging can be a hazard to outside traffic as well as being vulnerable to damage from outside traffic. When working in areas where non-project vessels and equipment are present, arrangements/agreements may need to be in place to move moored vessels so that the project has access to sediment adjacent to wharfs and dock walls. If work areas are potentially accessible to public vessel traffic, notices should be issued to ensure the public is aware of the activities and any speed or route restrictions on passage. For larger spread-out projects, features like lift bridges may restrict the movement of project equipment at certain times.

Quality-of-Life Issues

The design will also need to account for potential adjacent receptors of project impacts and ensure appropriate mitigation is included. When these receptors include institutions (e.g., hospitals, schools), residential areas, or public areas, the potential impacts from the project on quality of life should be considered (e.g., noise, lighting at night, increased traffic, and odours). Minimizing these impacts may result in limitations to the project, such as restricted working hours.

Debris

The presence of debris, or even abandoned infrastructure, on the floor of a lake/harbour/river or buried with the sediment can present a serious challenge to the completion of a dredging project. Debris can affect the dredging production rate, damage equipment, increase resuspension and residuals, and result in additional decontamination and disposal cost. Debris issues can result in substantial delays to a project and significant cost overruns if not accounted for in the project planning and design. Since most environmental dredging projects take place within urban waterways, the presence of some sort of debris is virtually guaranteed.

A dredging design should either incorporate the findings of a debris survey or clearly state the need for a contractor to assess debris as part of the contractor’s own work plan. A number of survey tools can be used to assess debris including sonar (side-scan, multi-beam), sub-bottom profilers, magnetometers, and underwater video. It should be noted, however, that there are a number of limitations with these methods. Side-scan sonar cannot see buried items and magnetometers can be affected by nearby docks, structures, and industrial slag in the sediment.

The nature and extent of debris may require a dedicated debris-removal operation prior to or during sediment dredging. If a debris survey has not been completed prior to dredging, the design should clearly establish the process for debris removal, who is responsible, and how suspended sediment will be minimized. Elements of this plan would include debris transportation (on-site and, if required, off-site), decontamination, and disposal.

Access and Staging Areas

Dredging projects require an allocated staging area onshore for mobilizing equipment and supplies, and for serving as a location for material decontamination, re-handling, sediment de-watering, and water treatment. The staging area will need to suit the needs of the project in terms of both water and land accessibility. Optimally, the staging area will be easily accessed from the dredging location. The staging area may be leased, purchased, or contributed to the project by a proponent or stakeholder. Depending on the situation, a number of legal agreements would need to be enacted.

All property utilized during an environmental dredging project may also need to be characterized before the project begins. Geotechnical characterization supports any required construction while environmental characterization would serve as the baseline condition of the staging area prior to project use. Establishing baseline condition becomes important if the use of the property by the project is believed to have resulted in environmental impacts.

Ecological

The existence of ecological resources and habitat adjacent to any dredging work requires consideration. Wildlife habitat may be adversely impacted by the project and require protection. Habitat that is home to species at risk or sensitive wildlife will require very special consideration. Minimizing these impacts may result in specific constraints and implementation of specific management approaches for the project.

3.3.3 Surface Water

Water Depth / Bathymetry

Water depths will specifically affect the ease of dredging, the selection of equipment, the risk of sediment resuspension, and the generation of residuals. At larger sites with varying water depths, different strategies and equipment may need to be considered for different sections.

Hydrodynamics

Wind, waves, and currents can impact the ability to perform the dredging work safely/effectively, the ease of access/transportation, the movement of resuspended contaminated sediment generated by the dredge, and mitigation methods required to prevent impacts to water quality.

In any dredge operation, resuspended sediment is considered to exist in three potential zones: the initial mixing zone, the near-field zone and the far-field zone (Bridges et al. 2008). The initial mixing zone is dominated by the influence of the dredging activities themselves, but the wind, wave, and current conditions of the site are the predominant factors affecting sediment transport in the near-field and far-field zones.

Predicting and incorporating the effects of currents into the design is straightforward at some sites and more complex at others. Large strong-flowing rivers have predictable current and usually an abundance of data available (including variation in flow related to storm events). Nearshore areas within the river, such as small embayments, tributary mouths, and shallow reefs/shelves may require additional investigation since they can have unique and localized conditions and typically lack data.

Smaller river systems have a much greater variance in flow pattern, and additional monitoring and modelling may be necessary to predict the possible conditions that could affect the project. The open water of larger lakes often has a dominating current; however, harbours and embayments are influenced to a much greater extent by the geography (e.g., shoreline features and tributaries that may result in eddying) and weather conditions.

Waves are generated as a result of the amount of open water, the wind direction, the water depth, the nature of the shoreline, and the energy of storms. If the predominant wind direction comes at the project site from a large stretch of open water, then more powerful waves will be generated. A hardened shoreline will reflect waves, thereby increasing choppiness. Rough conditions may slow dredging rates and complicate work activities.

Tide fluctuation will have a significant influence on how and when dredging is conducted, based upon changing water depths.

Brackish waters, where salt and fresh waters mix, can also create unique circumstances that need to be fully understood.

The accurate assessment of water movement by any of these processes is required in order to make quantitative predictions in terms of the transport and dispersion of sediment plumes from a dredging site. Meteorological data combined with site observations related to water temperature, salinity, suspended material concentration, flow speed, and direction should be the basis for design elements related to the control of sediment transport (Bridges et al. 2008).

3.4 Construction

For dredging projects key design components related to implementation of dredging projects are covered in this section.

3.4.1 Selection and Operation of Equipment

The project design may specify the type of equipment required to complete the job <u>or</u> cite design criteria and leave equipment selection to the contractor (the preferable approach for most projects). However, the owner should evaluate the potential equipment types in developing cost estimates and determining project requirements such as staging areas and re-handling facilities. Environmental dredging can be performed using a variety of equipment types. Generally, consideration of dredges will fall into one of two types (mechanical or hydraulic), based upon the method of sediment capture and removal from the sediment bed. A dredging design should consider the advantages and disadvantages of the various options in terms of feasibility, effectiveness, and economics. Designs for larger projects may need to include multiple types of dredging equipment, approaches, sizes, or types.

Equipment Operation

Selection of dredging equipment and the methods used to perform the dredging depends on the following factors:

- Physical characteristics of material to be dredged,
- Quantities of material to be dredged,
- Depth of material to be dredged,
- Method of disposal or placement,
- Distance to disposal site or staging area,
- Physical environment of the dredging area(s),

- Physical environment of the disposal area(s),
- Level of contamination of material to be dredged, and
- Dredge production capacity.

In addition, other considerations in selecting equipment include: removal efficiency, production rate, resuspension of sediment and contaminant release during the dredging process and transport off-site, residual sediment left in place following dredging, compatibility with transport, treatment, and disposal options and costs (Palermo et al. 2008).

Equipment will also need to be selected for transporting the dredgeate from the dredging area to the de-watering area and then to the disposal site or off-site. Equipment will be required for water treatment and the movement of supplies around the work area. The design detail will need to determine how all of the selected equipment will work together to efficiently complete the project tasks.

Mechanical Dredges

Mechanical dredging is the physical removal of sediment by application of direct mechanical force to dislodge and excavate the sediment. Cohesive sediment that is mechanically dredged usually remains intact, with large pieces retaining their in-situ density and structure through the dredging and disposal process. Sediment excavated with a mechanical dredge is generally placed on a haul barge or scow for transportation from the dredging site to the re-handling or disposal site.

Figure 3-2: Mechanical dredge bucket deployment from a crane (courtesy of ECCC).

The most common form of a mechanical dredge is a clamshell bucket, which can either be deployed from a crane or an articulated arm. The choice of how a bucket is deployed relates to factors such as water depth, obstacles, and required precision. Other configurations exist and mechanical dredges can also be as simple as a barge-mounted excavator.

Mechanical buckets can come in any number of sizes, and selection would be based on the required dredge depth and precision. The standard clamshell bucket is an “open” bucket, with less containment of materials within the bucket. This type of bucket is used for the dredging of uncontaminated sediment or placement of clean material such as capping material. Clamshell buckets can be deployed either from a crane cable or at the end of a fixed arm. The fixed-arm method provides better maneuverability and accuracy for targeted dredging. A fixed arm may also be better able to dredge around obstacles such as overhangs. Cable-mounted clamshells allow dredging in greater water depths but are restricted by the need to deploy directly over the intended point of dredging. Water movement through the water column will impact the accuracy of a cable-mounted clamshell.

As a mechanical bucket cuts through the sediment and travels back up through the water column, “fallback” sediment material often drops back down from the bucket. This is a significant source of the generated residuals layer. Environmental buckets, such as the bucket shown in Figure 3-3, were designed to mitigate sediment resuspension and creation of residuals. Environmental buckets are buckets that essentially close so that the dredged material and water cannot escape as they are pulled upward through the water column. The use of cable-mounted (also referred to as wire-supported) environmental buckets to mechanically remove sediment at greater depths is the common approach, but this method of operation has disadvantages related to the control of cut depth. Fixed-arm mechanical equipment has better control of cut depth. Articulated fixed-arm excavators with level-cut hydraulic operated buckets have also proven very effective.

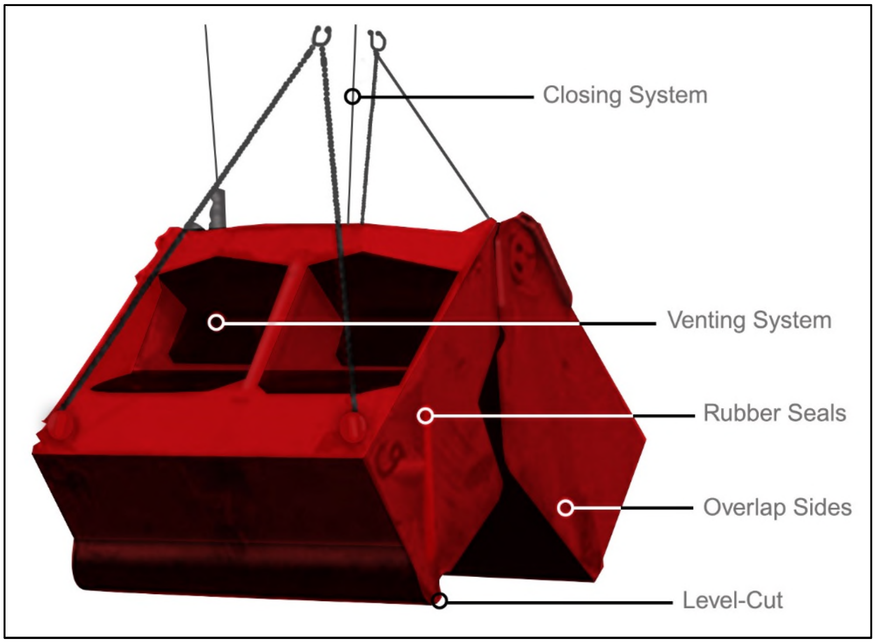

Figure 3-3: Environmental dredge bucket features (Cable Arm).

Key features of environmental buckets include:

- The ability to complete a level cut,

- The ability to close, which limits emissions of volatile organic chemicals into the air, and
- Seals and vents designed to limit water and sediment outflow from the bucket, which limits resuspension and residuals generation.

Mechanical dredging has often been characterized as having higher resuspension rates than hydraulic dredging. This was true in the past when only conventional clamshell buckets were widely available. However, the present availability of enclosed buckets and articulated fixed-arm excavators has improved mechanical dredging performance with respect to resuspension.

A mechanical bucket can have issues related to fallback, particularly when the bucket is prevented from fully closing, which can occur when debris prevents the bucket from properly closing and a portion of the dredged sediment is lost as the bucket is retrieved.

In addition, sediment that adheres to the outside of the bucket can come loose as the bucket travels back up through the water column, and either fall back down to the bottom or be re-suspended in the water column.

Scows and Barges

In mechanical dredging projects the dredged sediment is typically placed in a scow for transport to the de-watering area, confined disposal facility (CDF), or upland disposal site. The size and number of scows should be selected to optimize the productivity of the project, and filling should be conducted in a manner that avoids overflow. Once filled with sediment and the associated overlying water, the scows travel to the unloading area, where they are emptied mechanically or hydraulically (requiring designated equipment for that purpose). The dredged sediment then receives further treatment or is transported to a disposal site. A dump scow has a hopper bottom, where the hull splits, allowing the sediment to be “bottom dumped” when the doors are opened. This practice is common in navigational dredging projects where open-water disposal is permitted and sediments are not contaminated, based on applicable management criteria. In environmental dredging projects, bottom dumping for open-water placement would be problematic, given the resuspension of sediment, which would occur during the release, and the re-introduction of contaminants back into an aquatic setting.

Figure 3-4: Mechanical dredge with scow (courtesy of ECCC).

Work barges would also be utilized as the working platform for cranes and excavators used in mechanical dredging. Barges can be outfitted with spuds which are piles that can be raised and lowered to hold the barge in place, providing stability during the dredging activities. Barges would also be used to transport equipment and materials (e.g., capping material) between the dredge area and the staging area.

Figure 3-5: Work barge with raised spuds and anchoring system (courtesy of ECCC).

Hydraulic Dredges

Hydraulic dredges use a cutting mechanism and suction to collect both sediment and water, creating a slurry material which is then transported to a de-watering facility or disposal area via pipeline.

Figure 3-6: Hydraulic dredge (courtesy of Pacific Productions).

Figure 3-7: Hydraulic dredge (courtesy of ECCC).

The cutting mechanism is installed at the dredge head, which is located at the end of a “ladder” that is lowered to the sediment. A number of cutting mechanism options are available:

- **Cutter Heads:** A rotating cone-shaped dredge head that is equipped with teeth to cut into and loosen the sediment,
- **Horizontal Augers:** A rotating horizontal auger that can replace the cutter head. The auger is less aggressive in its ability to cut into the sediment, but is well suited for flat dredge cuts into loose material,
- **Hydraulic Jets:** Not recommended for environmental dredging unless conducted within containment. High-powered water jets are used to cut into the sediment as an alternative to mechanical means, and
- **Plain Suction:** Hydraulic dredges that operate without a mechanical action to loosen the sediment.

The shearing action of a cutter head or auger dredge through sediment disturbs material, which falls down and away from the bank, forming a spillage or fallback layer. This is a significant source of the generated residuals layer for hydraulic dredges. The thickness of these residuals is largely dependent on the sediment characteristics, operation of the dredge, and dredge setup (cutter head and suction pipe positioning, intake pipe velocity, and cutter head revolution speed). As a rule of thumb, the thickness of the spillage layer for a conventional cutter head dredge can be about 0.2 times the cutter head diameter or 0.5 times the discharge pipe diameter (Palermo et al. 2008).

Hybrid Dredges and Specialty Dredging

Hybrid dredges combine features of mechanical and hydraulic dredges. The Amphibex is an example, where a dredge head/bucket combination is affixed to an articulated arm, to give the advantages of an excavator and auger, and works under positive pressure.

Figure 3-8: Amphibex hybrid dredge (courtesy of ECCC).

Other hybrid approaches include (a) placing sediment on a barge by mechanical dredging and then slurrying the sediment in order to pump it via pipeline to the treatment site, where the sediment is de-watered prior to disposal and (b) placing sediment in a hopper of a positive displacement pump for discharge at low velocities and with minimal water content.

Other hybrid approaches combine the use of both mechanical and hydraulic dredging at one site. Depending upon the site characteristics, hydraulic dredging may be advantageous in one part of the site and mechanical dredging more effective in another part.

Pumps and Pipelines

Hydraulic dredging relies on pipelines to transport the dredgeate to its disposal or de-watering locations. These pipelines can be floating or submerged, depending on the needs of the project.

Figure 3-9: Floating pipeline (courtesy of ECCC).

If pipelines extend for a considerable distance, then additional booster pumps are required in order to maintain the velocity of the dredgeate within the pipeline. If the velocity drops within a pipeline, the sediment will begin to settle, creating clogs.

Figure 3-10: Booster pump configuration (courtesy of ECCC).

A number of different pump types can be utilized to generate the suction required to capture and transport the sediment/water slurry. Transport of the sediment/water slurry to either a confined disposal facility or a de-watering area will be via pipeline. The dredge design will need to define the pipeline specifications based upon the sediment characteristics (sand vs. silt/clay), solids concentration of the slurry (commonly, 10%–20% solids), the distance to be pumped, and elevation rise (in the case of upland de-watering/disposal areas). Elements of this design component would be pipeline diameter, pipeline routing, and booster pump requirements. The number of required pumps, their positioning, and their size/power all need to be considered by the design.

Auxiliary Construction Equipment

Numerous vessels are required at a dredging project. Tugboats are required to move barges and scows around the site. Survey vessels are required to conduct post-dredge bathymetric surveys. Other vessels may be required to complete water and sediment sampling, ferrying equipment and crew around the site, and managing turbidity curtains, if deployed.

Propeller wash causes a great deal of sediment resuspension when tugboats are pushing the dredge into place and then moving it again, and moving the barge(s) used for the dredged material alongside the dredge. Other service boats, which move crew, equipment, and supplies, also contribute to propeller wash and resuspension of sediment. The design needs to take any resuspension caused by the spread into account.

Other heavy equipment will be required to transport material around and to and from the staging area to off-site locations. Equipment could include additional cranes, forklifts, Bobcats, and transport trailers.

De-watering can be performed passively where the only mechanical equipment required would be along the lines of an excavator to stockpile dredged material (from a mechanical dredge) on land for draining (and possibly turning over the stockpile or mixing in solidification agents). Active de-watering would require mechanical equipment such as belt or filter presses. De-sanding can also be performed using equipment such as centrifuges. Water treatment may utilize settling cells, sand filters, and activated carbon filters (or technology that performs the equivalent treatment). De-watering, de-sanding, and the water treatment system will all require a number of pumps, piping, valves, and sensors.

3.4.2 Mobilization and Demobilization

With the establishment of the work area, staging area, site access, and equipment, the requirements and scheduling of mobilization to the site will need to be determined. Specialized equipment may require quite a bit of preliminary time to obtain the equipment and then move it to the site. Also, site access and staging area access have to be established far enough ahead of the in-water work to allow for the delivery and possible assembly of the required equipment and materials (dredges, de-watering lay down areas, water treatment facilities). Careful scheduling of mobilization will ensure the in-water work can be performed on schedule.

3.4.3 Management Units and Dredge Prism Design

The overall delineated area of contaminated sediment to be dredged should be subdivided into smaller subunits. The establishment of sediment management units (SMUs) will be based on factors such as water depth and physical sediment characteristics. The SMUs will in turn be subdivided into dredge management units (DMUs) that will be based on factors such as work sequencing, the tracking of work progression, and the final dredge depth/cutline (Palermo et al. 2008). Defining dredge prisms and associated SMUs and DMUs is necessary to confirm accurate dredge depths/cutlines and the overall volume of sediment to be dredged. A dredge prism could include multiple DMUs with differing cut depths, or multiple DMUs all at the same cut depth, depending on the site.

The dredge prism represents the three-dimensional volume of sediment to be dredged from the various DMUs. An accurate characterization of the sediment profile throughout the proposed dredging area is critical to properly defining the dredge prism. Chemical and physical characteristics of the sediment affect the dimensions of the dredge prism, specifically the bottom and sides. The depth of contamination to be managed will determine the vertical limits of the dredge prism (i.e., the dredge depth). The lateral and vertical extent of the dredging form the basis of each prism, but some additional factors also determine its shape. The physical characteristics of the sediment and related issues, such as potential sloughing or the need to transition from one dredge depth to another, will determine the angles of the prism's sides.

Transitions

The required transitions from one area to the next affect prism dimensions. The angle of the side slopes may be specified in the design, and will be based upon the geotechnical properties of the sediment (and potentially the existing bathymetry). Sloping of the side walls along the edges of a dredge area, where the dredge prism meets adjacent subsequent dredge areas, or the surrounding of uncontaminated material is required to ensure stability and avoid sloughing and erosion. The prevention of sloughing and erosion ensures completed dredge areas are not re-contaminated by surrounding contaminated sediment.

Overdredge Allowances

A dredge design may also include a degree of overdredging, where a certain amount of sediment below the vertical limit of contamination is removed. The advantages of this can be a reduction in contaminants left undisturbed, reduction in residuals generation and increased effectiveness. The disadvantage of over dredging is the increase in sediment volumes for de-watering, treatment, and disposal, along with an increase in costs. Overdredge allowances in an environmental dredging design are expected to be tighter than they are for navigational dredging, based upon the precision of the equipment (Palermo and Hayes et al. 2014). The dredge design must have sufficiently considered the advantages/disadvantages of overdredging, based upon the sediment/site characteristics, and selected overdredge allowances accordingly.

3.4.4 Sequencing and Acceptance of Work

Horizontal and vertical sequencing of work should be clearly defined by the project design. The order in which the DMUs are dredged determines the horizontal sequence. It is common for the horizontal sequencing to be prioritized according to the level of contamination; however, other site conditions also factor in. Locations of DMUs upstream vs. downstream, dredge depths, and physical sediment characteristics can all be considerations. Dredging by DMU is typically sequenced from upstream to downstream for unidirectional current conditions, as in a river. Dredging by DMU is also typically sequenced from upslope to downslope to minimize sloughing of contaminated material into dredged areas.

Vertical sequencing of work refers to the number of dredge passes and the thickness of each of these cuts within a DMU. The sediment conditions (both chemical and physical) within a DMU will help determine appropriate thicknesses of dredge cuts, which in turn determine the number of dredge passes required to reach the final depth in that DMU. Dredge size can also be a determining factor for cut thicknesses.

The initial acceptance that dredging in the DMU has been completed is based upon bathymetric surveys, which confirm the final depth has been achieved. The project will also include verification sampling to ensure sediment chemistry meets the pre-established project-specific clean-up level. Follow-up actions such as second-pass dredging or thin-layer backfilling (residuals capping) are triggered when the dredged areas do not meet the acceptance criteria.

3.4.5 Anticipated Production Rates

Another critical aspect of the dredge design is an accurate prediction of the dredge production rate, the rate at which the contaminated sediment can be effectively removed, transported, processed, and disposed or contained. All of these aspects are interlinked and affect how quickly the contractor is able to complete the work, which in turn forms the basis of the anticipated project schedule and budget. As noted above, the geotechnical properties of the sediment determine how it needs to be removed; these properties also determine how quickly the removal can be completed (i.e., what volume of sediment can be moved in a given time).

Assuming the dredgeability has been established, these other factors need to be assessed as part of the design process:

- **Pumping Requirements (for hydraulic dredging):** If dredging is conducted hydraulically, then the dredged sediment is mixed with water at the dredge head to form a slurry for transport. Geotechnical characteristics such as cohesiveness and grain size can affect the ease with which this material is pumped through a pipeline. Cohesive materials such as clay can clump, or “ball up,” disrupting the pumping process. Coarser-grain sands can settle out in the pipeline. Without a proper design, production rates can be slowed or stopped by partially or fully blocked pipelines. The design of the pumping system will need to accommodate for the geotechnical properties and distance to the disposal site, with the number of required pumps, the size/strength of the pumps, and proper placement of booster pumps,
- **Re-handling Requirements (for mechanical dredging):** Mechanically dredged sediment is normally placed on barges or scows for transport to a re-handling or de-watering facility prior to further transport for disposal. The transport distance, number and size of barges used, and other factors may influence the overall production rate. Production rate can also be determined by the capacity of the off-loading facility and/or treatment and de-watering process. All such factors should be accounted for in the design, and consideration should be given to redundancy regarding critical equipment in order to avoid bottlenecks in the overall throughput,
- **De-watering Requirements:** Whether the dredged sediment is to be disposed of off-site or placed in an on-site containment cell (either land- or aquatic-based), the majority of projects will require this material to be de-watered first. For mechanical dredging projects, the water content of the dredged sediment is much less than if hydraulically dredged. For hydraulic projects where the sediment has been slurrified, de-watering will depend on the method of placement and treatment. Material pumped directly to a containment cell will undergo settling and consolidation. Material pumped to a mechanical de-watering/treatment plant may be de-watered using clarifiers or filter presses,
- **Water Treatment Requirements:** The de-watering of dredged sediment will therefore mean that treatment of the resulting water will be required before that water can be discharged back into the environment. Sediment with a larger portion of fine-grain material may produce an initial effluent with a greater concentration of suspended solids, and

- **Beneficial Reuse:** Separation and beneficial reuse of the clean portions of the dredged sediment can be achieved through a de-sanding, or soil-washing, process, where coarse-grain sediment is separated from the fine-grain sediment that the contaminants have bound to. This would involve the dredge effluent being treated by a series of steps that can involve settling tanks, centrifuges, polymer addition, filters, and presses. The time requirement for this process could limit dredging production, depending on the scale of the treatment plant and/or the stockpiling capacity for dredged sediments.

Production rates are also determined by the active time of the dredger. This active time can be measured on a daily, weekly, monthly, or yearly basis. Many factors can have an influence (e.g., equipment and personnel capacity, accommodation of other site activities, seasonal considerations, and municipal bylaws related to noise).

3.4.6 Resuspension, Fate and Transport, Residuals

Resuspension is defined as the processes by which a dredge and attendant operations dislodge bedded sediment particles and disperse them into the water column (Bridges et al. 2008). Once suspended in the water column, sediment can be transported off-site by local water currents. The generation of significant resuspension can result in residuals as the suspended sediment re-settles. The geotechnical properties of the sediment being dredged, type of dredge, and method of operation are primary factors determining resuspension. These properties include bulk density, particle-size distribution, and mineralogy. The design should include a proper assessment of these properties and then take them into account in terms of resuspension potential.

The associated residuals generation also needs to be accounted for by the design, with appropriate monitoring, mitigation, or estimate of how much additional dredging or thin-layer backfilling (residuals capping) will be required.

3.4.7 Water Quality

Sediment resuspension in the water column is an issue, as water quality may be impacted. The primary impact will be from contaminants that are bound to the suspended particles. Suspension of contaminated sediment may also increase the quantity of dissolved contaminants within the water column.

3.4.8 Volume Changes

The volume of sediment dredged will differ from the final volume placed for disposal, depending on the type of dredging (hydraulic vs. mechanical) and the methods for re-handling, transport, dewatering, and disposal. Estimates of these volumes can be based on treatability testing or column settling tests (see Section 4).

Dredging beyond the overdredge allowances can also contribute significantly to an increase in the volume of dredged materials. Design documents can address this issue by establishing penalties or incentives aimed at limiting overdredging.

3.4.9 Management Actions and Contingencies

Contingency planning is an important aspect to all projects, and details should be included in the design. For dredging projects, unexpected issues such as the presence of buried debris, hardpan, unidentified infrastructure, equipment failure, contractor performance issues, unexpected contamination, and weather conditions can contribute to a number of challenges to overcome. These challenges include but are not limited to: unacceptable sediment resuspension, contaminant release, residuals generation, failure to achieve the clean-up levels, air quality impacts, impacts to ecological resources (e.g., fish kills), noise complaints, impacts to public welfare, interference with navigation, and safety issues. An adaptive management plan should be developed during the design to address uncertainties. The monitoring plan needs to be combined with management actions that will be adopted to overcome these challenges and mitigate the associated negative consequences.

3.4.10 Prediction of Resuspended Sediment / Residuals

The generation of resuspended sediment and residuals during an environmental dredging project can hamper the long-term effectiveness of the completed work. Residuals are a thin layer of contaminated sediment left behind after the completion of dredging. These residuals are often fine-grain sediment to which the majority of contaminants have adhered; therefore, the post-dredge surface sediment can still have contaminant concentrations close to or even higher than the original pre-dredge surface. Despite the fact that residuals usually constitute a thin layer of material, because they form the new sediment surface, their exposure to the ecosystem is significant. Dredge-generated residuals are also considerably less stable than any pre-existing sediment; therefore, the risk of erosion and resuspension is significantly higher than in undisturbed sediment. This can present an increased risk to water quality and potential for contamination to be transported downcurrent to new depositional areas. Controlling and managing residuals is recognized as one of the key challenges any dredge design must address.

The magnitude of sediment resuspension and potential for off-site transport of contaminants during a dredging operation are influenced by many factors, including the following (EPA 2005):

- Physical properties of the sediment (e.g., grain-size distribution),
- Vertical distribution of contaminants in the sediment,
- Water velocity and degree of turbulence,
- Type of dredge,
- Methods of dredge operation,
- Skill of operators,
- Extent of debris,
- Water salinity,
- Extent of workboat/tugboat activity,
- Steepness of dredge-cut slopes,
- Amount of contaminated sediment resuspended by the dredging operation,
- Extent of controls on dispersion of resuspended sediment (e.g., silt curtains, sheet piling),
- Vertical profile of contaminant concentrations in sediment relative to the thickness of sediment to be removed,
- Contaminant concentrations in surrounding undredged areas due to possible agitation effects of dredges, and the spread,
- Characteristics of underlying sediment or bedrock (e.g., whether overdredging is feasible), and
- Obstructions or confined operating area (e.g., which may limit effectiveness of dredge operation).

Residuals can be generated during dredging as the sediment is stirred up, partially falling back down from the dredge or sloughing in from adjacent areas. Pockets of contamination that dip below the established dredge grade can also be considered residuals and are referred to as undisturbed residuals. Undisturbed residuals are often related to obstacles to dredging such as debris, hardpan, infrastructure, or incomplete vertical characterization (Bridges et al. 2008).

Effectively predicting and establishing a method of managing generated residuals is one of the greatest challenges an environmental dredging design has to tackle. As noted above, the geotechnical properties of the sediment being dredged contributes directly to the predicted amount of residuals. Other factors, such as the equipment type and skill of the dredge operator, also contribute to this amount.

The calculation of the expected volume and concentration of residuals will provide the dredge design with a good starting point for planning the required residuals management. Approximate contaminant concentrations within a residuals layer can be predicted, based on the average sediment concentration in the final production cut profile (Palermo et al. 2008). The range of residuals mass has been confirmed by analysis of detailed post-dredging data sets, which indicate a range from 1% to 11%, with a higher percentage of residuals mass for a higher average in-situ density of material dredged (Patmont et al. 2017). However, there is no guaranteed method of predicting residuals volumes or concentrations, and true residuals generation will only be known upon completion of the dredging work.

3.4.11 Residuals: Preventative and Management Measures

Residuals will occur in every cleanup of a dredging site. Focus on the prevention or minimization of residuals and resuspended sediment should be a key part of every dredge design, as well as a focus on the management of created residuals. Operational controls and engineering controls should be part of every dredging project design, and can be described in an adaptive manner related to the project's overall progress and the generation of residuals.

Operational controls involve adjusting dredging equipment and techniques with the aim of minimizing the generation of residuals. A comprehensive vertical characterization of contaminants at the site is the most effective approach to avoiding undisturbed residuals, but pockets of contamination may still remain undiscovered. In addition, accurate and precise positioning of the dredge passes, including removal of sediment above the cut line, is clearly an effective approach. Another effective strategy for minimizing residuals production may, however, be ensuring the work is completed in a controlled and efficient manner (i.e., at an appropriate rate to ensure no undue resuspension or excessive fallback of dredged sediment). Controlled dredging techniques should reduce sediment spillage from the dredge bucket or head during operations. Vessel movement can significantly contribute to resuspension, so the management of vessel acceleration and speed, as well as appropriate selection of support vessels, is important. The correct sequencing of the dredging (upstream to downstream or from the top of a slope to the bottom) can also help reduce the residuals generated during the dredging process.

Engineering controls can be implemented to limit the spread of resuspended sediment and the generation of residuals, including:

- Selecting the appropriate type of dredge (mechanical or hydraulic) for the sediment and site characteristics,
- Using environmental dredge buckets with seals, intended to reduce resuspension and residuals generation, or outfitting hydraulic dredge heads with cowls, intended to capture resuspended sediment,
- Prohibiting overflow from scows that receive the dredged material,

- Using barriers to isolate the entire dredging site from surrounding water lots; these barriers can include:
  - Temporary steel sheet pile walls, which are removed after the completion of dredging,

Figure 3-11: Temporary sheet pile containment (courtesy of ECCC).

  - Silt curtains, which are flexible low-permeability barriers that hang down from the water surface using a series of floats on the surface and a ballast chain or anchor along the bottom and re-direct water flow (Francingues and Palermo 2005). Silt curtains will reduce the impact of turbidity on the surrounding waters, but will not necessarily contain contaminated residuals within the curtained area. Conventional silt curtain deployments are impractical or ineffective in high-flow scenarios (i.e., above 1.5 feet per second) and at depths greater than 10 to 12 feet, where loads on the curtains and moorings are excessive. Other practical limitations on the effectiveness of silt curtains (and screens; see next item) include strong currents, high winds, fluctuating water levels (e.g., tides), excessive wave height (including vessel wakes), drifting ice and debris, and movement of equipment into or out of the area. Generally, silt curtains are most effective in relatively shallow, quiescent water without significant tidal fluctuations (Francingues and Palermo 2005). Structurally reinforced curtain deployments (i.e., H-pile support) may be considered for conditions of higher flow or tidal fluctuations,

Figure 3-12: Silt curtain deployment (courtesy of ECCC).

- Silt screens, which are made of geotextile fabrics, are more permeable than the curtains just mentioned. These screens allow a significant fraction of the water to flow through, but retain a large fraction of the suspended solids (Francingues and Palermo 2005),
- Air or bubble curtains, which are created by laying sections of pipe along the sediment bed. These pipes then release air bubbles along their length to form a “curtain” of air that disrupts water flow and limits the transportation of suspended sediment across the work area. Air curtains can be used at locations with frequent vessel traffic in and out of the work area,

Figure 3-13: Bubble curtain deployment on the St. Lawrence River (courtesy of ECCC).

Figure 3-14: Bubble curtain deployment on the St. Lawrence River (courtesy of ECCC).

Figure 3-15: Bubble curtain deployment (courtesy of ECCC).

- “Moon pools,” which are constructed of weighted silt curtains deployed around the immediate area of the operating dredge, thereby limiting the spread of any resuspended sediment. While residuals generation can still occur, it is contained and more likely to be captured during the dredging of that area (see Figure 3-16), and
- Caissons, which can be temporarily installed for specialized dredging at especially sensitive sites. Dredging inside caissons is generally quite expensive and usually requires the removal and re-installation of the caissons in an overlapping pattern in order to ensure all contaminated sediment is captured.

- Rinsing buckets to remove adhered sediment before completion of a dredge.

Figure 3-16: Derrick barge with attached moon pool and drip pans in use (M. Roberts, A. Corbin, P. Doody, T. Peters, and C. Robinson 2017).

3.4.12 Specialized Dredging for Clean-Up Passes

Residuals dredging can also be completed using specifically designated equipment that is well suited to remove loose unconsolidated material. The Vic Vac dredge head is one specific example of an environmental dredge head designed to complete clean-up passes on large environmental projects such as the Fox River and Ashtabula River (Palermo et al. 2008). The design may stipulate the use of such specialized dredges to maximize the ability to remove residuals.

3.4.13 Residuals Cap or Cover

In recent years, the residuals cap or cover (thin-layer backfilling) approach has emerged as one of the primary strategies for managing dredging residuals. The design should account for when and how a residuals capping approach would be adopted. This will be determined by a decision-making process similar to the flow chart laid out in Figure 3-20. In situations where re-dredging does not make sense, such as thin layers of very loose residuals, then residuals capping could be implemented. In order to determine this, dredge verification samples must have determined both the thickness and contaminant concentration of the residuals layer. The particle-size distribution is also an important consideration related to the cap stability, movement of the thin-layer backfill (residuals cap), and the mixing with the residual sediment initially and over time. The residuals capping process is equivalent to the thin-layer capping process presented in Section 6. The most important difference is that the residual materials being capped are much less consolidated than undredged sediment and often of lesser thickness.

The design will need to indicate the requirements for the capping material, both chemical and physical characteristics. The residuals capping/cover requirements can be estimated in the design for budgetary, scheduling, and contract purposes, but the estimate is highly variable depending on the nature of the dredge-generated residuals. Placement requirements must be specified along with the process for determining the cap thickness, which is based on residuals contamination mass.

3.4.14 Dredgeate Management

De-Sanding

When the sediment composition is favourable, a dredge design may include a de-sanding process to reduce the volume and disposal cost of the contaminated sediment. The contaminants are typically bound to finer-grain sediment, while coarser sand particles are typically clean. If dredged sediment has a significant sand content, then a de-sanding process may be desirable and feasible. The separation process can be achieved in a number of ways, such as centrifuging or screening. These processes are most efficiently applied when the material is dredged hydraulically. If material is dredged mechanically, a separate slurry operation would be required. De-sanding also has the added bonus of producing a clean sand material suitable for beneficial reuse, either external to or as part of the project. Reuse applications could include construction projects, backfill material, landfill caps, and beach nourishment. Appropriate testing and evaluations should be conducted as part of the design to confirm that separated sand will be suitable for separate management and/or beneficial use.

De-Watering

All dredging design must account for some degree of de-watering. The volume and complexity of the required de-watering depends on the dredging technique, sediment characteristics, contaminants, and disposal method. The eventual disposal of the dredged sediment also factors into the degree of de-watering required. The design will either have to present the de-watering requirements or present a required method of de-watering. De-watering options can vary greatly in complexity and can range from passive de-watering to active de-watering. For mechanical dredging, simply stockpiling dredged sediment in a contained cell and allowing water to drain is the simplest option. For hydraulic dredging, the sediment slurry can be pumped directly to a CDF, into geotubes or to a sediment processing plant for mechanical de-watering. For CDFs, the slurry is pumped to a confined site where settling and consolidation provide for de-watering (see Section 4).

Geotubes (cylindrical geotextile containers) allow the slurry to drain over time, with the geotube functioning as a filter that allows water through and retains the sediment. Geotubes are commonly filled and stacked upon each other in a pyramid structure, where the additional weight of the stacked tubes further assists the “squeezing” of water out of the sediment. Additives, such as polymers, can be utilized in Geotubes to expedite settling.

Examples of mechanical de-watering primarily consist of equipment such as belt presses or filter presses, which exert a mechanical force to physically compress the sediment and remove any remaining water.

Drivers for the selection of certain de-watering options would be limited by the space available for de-watering operations, the time available, the volume of sediment, and the associated disposal cost. If, for example, the use of geotubes was specified, then the design document would have to ensure an area of appropriate size and characteristics (elevation, geotechnical considerations, surrounding properties) was available. Sufficient time would also be needed to allow for the gradual compression of the sediment-filled geotubes under the force of gravity.

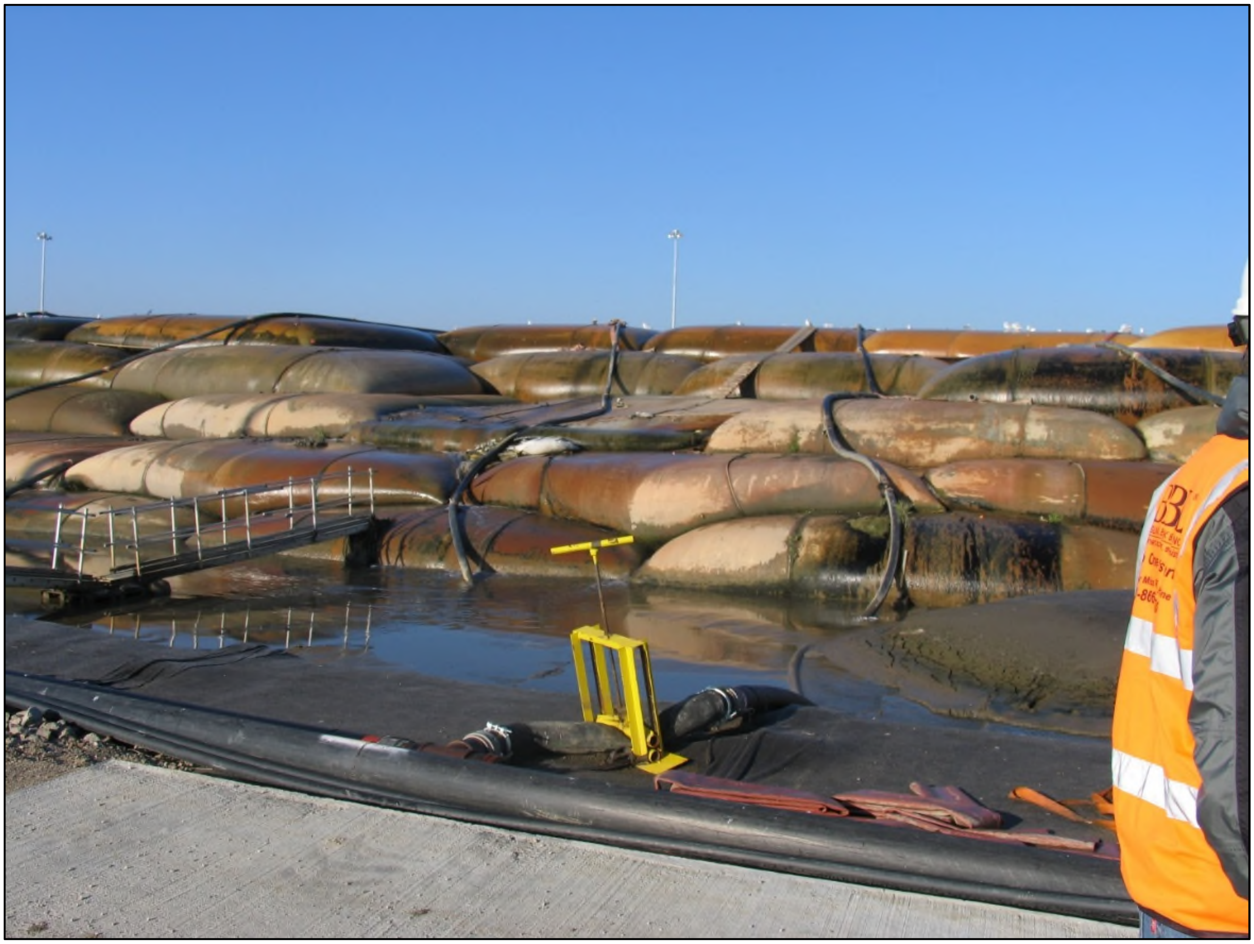

Figure 3-17: Geotube stacking (courtesy of ECCC).

Water Treatment

De-watering is a common component of dredging projects, and the project-specific water treatment requirements must be determined. Any discharges of excess water produced by the project back into a waterbody will require that pre-established water quality criteria be met. Discharge criteria can be based on both regulatory requirements and existing background conditions.

Water treatment systems address two impacts to water quality: suspended solids (and associated chemical concentrations) and dissolved chemical concentrations. Suspended solids are typically dealt with by a combination of settling cells and filters. The size of settling cells needs to be based on the volume of water requiring treatment and the rate in which it is produced. Settling of particulates within these cells can be augmented by the application of coagulants and flocculants. The settling produces waste material in the form of sludge for disposal.

Figure 3-18: Settling cells in a water treatment system of the Randle Reef Sediment Remediation Project (courtesy of ECCC).

Vessels filled with a sand medium is the most common filtration technology utilized. Remaining particulate will be removed from the water as it passes through these vessels. Eventually, any sand filter will reach capacity, at which time the sand will need to be replaced or refreshed through a backwashing process.

Activated carbon is most commonly used to treat the dissolved contaminants that remain in the filtered water. This can be achieved by using filtration vessels filled with activated carbon or via application of the activated carbon into the water and continuing agitation. Eventually, activated carbon will also reach capacity and be exhausted. The used carbon would then either be a waste material or potentially undergo a reactivation process where the accumulated chemicals are stripped back off.

Figure 3-19: Sand filtration and activated carbon vessels in a water treatment plant (courtesy of ECCC).

Sediment Treatment

Sediment treatment technologies may be included in a dredge design as an alternative to disposal or as a pre-treatment prior to disposal. For dredging projects, this would be completed off-site after de-watering has occurred. Where multiple contaminants exist, a treatment process may address some but not all contamination. Pre-treatment may lessen the costs for sediment disposal, which would otherwise be considered hazardous waste. Possible treatment technologies include the following (Palermo et al. 2014):

- Bioremediation,
- Thermal desorption,
- Extraction/washing,
- Chemical treatment, and
- Stabilization/solidification.

Sediment treatment technologies (with the possible exception of stabilization/ solidification) are dependent on the specific requirements of a project to determine if they are viable. A scenario with restricted disposal options may encourage the use of sediment treatment technologies. The effectiveness of treatment technologies is often unproved and requires upfront testing in the form of bench-scale and pilot-scale projects. The more advanced or experimental technologies listed above can also be expensive and/or require longer treatment periods (bioremediation).

Disposal

The design document should establish the requirements for the ultimate transport and disposal of the final waste sediment. Transport to both on-site and off-site disposal facilities can take many forms, such as pipelines, scows, trucks, or trains. The assessment of potential routes should be based on distance, potential hazards, and the impacts on surrounding properties. If the transportation route crosses private property, then agreements will likely be required.

Upon completion of de-watering and possible pre-treatment, the remaining contaminated sediment will require disposal in either an existing or project-specific facility. Disposal facilities can be upland or aquatic. Aquatic containment cells are discussed in Section 4.

Specially constructed upland facilities and existing landfills will all have specific requirements in order for waste material to be accepted. From a physical perspective, the water content of the material needs to be low enough to establish the material as a solid waste for placement in a landfill. For example, in Ontario, subjecting the de-watered sediment to the equivalent of the “concrete slump test” (ASTM C143) is a requirement for landfill acceptance.

The chemical characteristics of the waste sediment also determine what landfills can accept. Certain contaminants and their concentrations are subject to regulatory constraints, which may limit possible disposal destinations. In Ontario, waste is subjected to the Toxicity Characteristic Leaching Procedure (TCLP) [as defined in Ontario Regulation 558/00] in order to confirm whether or not it is designated a “hazardous waste.” Hazardous waste requires disposal in specialty landfills. Sediments with 50 mg/kg or more of PCBs would be subject to restrictions under the *Environmental Protection Act* PCB Regulations-SOR/2008–273.

3.4.15 Project Monitoring and Mitigation

Monitoring should be conducted at contaminated sediment sites for a variety of reasons, including:

- To assess compliance with construction design and performance standards,
- To assess short-term-remedy performance and effectiveness in meeting sediment clean-up levels, and/or
- To assess long-term-remedy effectiveness in reducing risk to human health and/or the environment (EPA 2005).

The monitoring plan should be integrally designed with the adaptive management plan to provide feedback to dredging contractors so that they can adaptively manage the project operations, as needed, to improve the outcomes.

Post-Dredging Verification

The methodology for verifying the completion of environmental dredging should be included in the dredge design to address bathymetry and contamination. Typically, dredging will be completed within a specific dredging area or unit, whereupon post-dredging bathymetry will be required to determine if the design’s cut elevations have been achieved.

The collection of verification samples throughout the SMU are required to confirm contamination above the project clean-up level has been removed or managed (with post-dredge capping).

The project design will need to stipulate how verification results are considered and what constitutes meeting the project clean-up level. Using surface weighted average concentrations (SWACs) is a common approach, where the SWAC results are compared to the clean-up level rather than individual sample results. Most environmental dredging designs will establish a decision-making process that clearly describes the steps in a verification sampling program to determine if a completed dredge area has met the clean-up level and to determine what to do next. The following flow chart, used for the Randle Reef Project, is an illustration of this kind of decision-making framework.

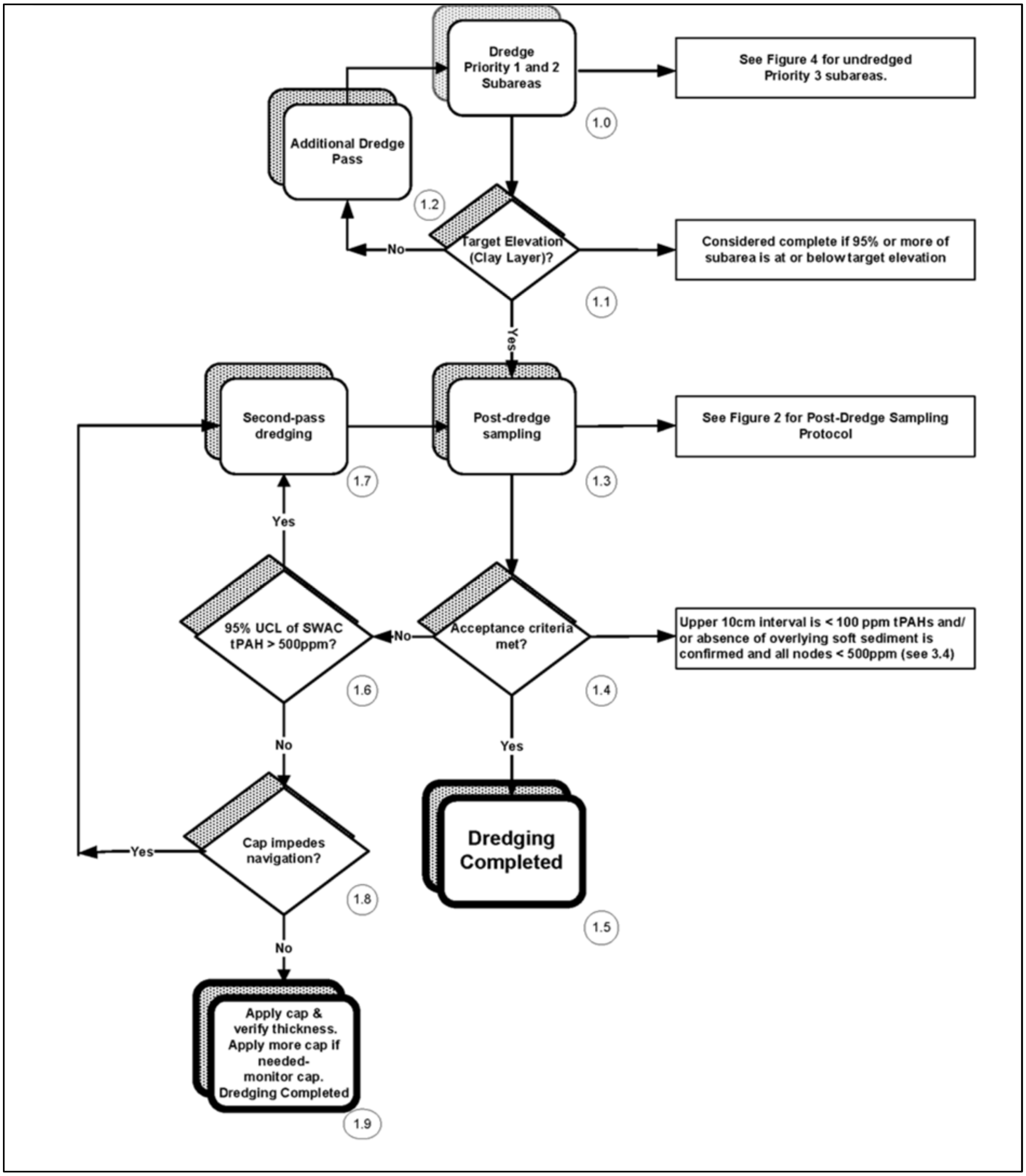

Figure 3-20: Dredging Design Decision-Making Framework.

This type of decision-making framework helps establish a consistent approach to determining the next steps after assessing verification sample results. Other factors, such as the thickness of any residuals layers, may also be considered in the framework.

The dredge verification sampling can consist of a mix of grab and core samples. The collection of core samples will allow for the assessment of the thickness of any residuals layer (if it exists). Thickness is important because a thick layer with the same contaminant concentration as a thinner layer contains much more mass of contaminant that has the potential to migrate via groundwater flux or mixing into surface waters.

Contaminant concentrations in either all samples or the SWAC for an area must meet the project clean-up level in order for management actions to be considered complete. Failure would require either additional dredging or management via thin-layer backfilling.

Water Quality

Water quality monitoring programs are a key component of the project, ensuring minimal negative impacts to the ecosystem occur and triggering management actions when required. In general, impacts to water quality are monitored using these three approaches:

1. **Total Suspended Solids (TSS):** The resuspension of solids in the water column can have an impact on aquatic life regardless of the chemical concentrations within that sediment. TSS is measured by collecting grab samples and determining the mass of solids in a volume of water. Criteria exist for TSS in order to protect aquatic life.
2. **Turbidity:** Turbidity is the measurement of light penetration through the water. A correlation between turbidity and TSS (and by extension water chemistry) can be established. Turbidity can be measured in real time, and therefore carries the advantage of measurements in real time. Turbidity is therefore used for continuous monitoring of dredging activities. Monitors are typically deployed with one upcurrent (to give a reference value) and a number of monitors downcurrent (at various angles). Turbidity monitors deployed around a dredging location would need to move in concert with the progression of dredging. Variability can exist between different models of turbidity meters, and the monitoring program should account for this and ensure a consistent approach.
3. **Chemistry:** The COCs within the sediment impact the water quality when the sediment is resuspended. Contaminants will also pass into the dissolved phase. The collection of grab samples and analysis of the whole water sample for chemical concentrations will measure both of these components. Water chemistry will be directly influenced by variations in the TSS produced by dredging activities.

Water quality monitoring will show whether control measures are required. Threshold values will need to be established for each type of monitoring conducted. The dredging project design could detail the specific mitigation methods/details or rely on contractors to submit mitigation plans to meet the required criteria.

Air Quality

The impacts of environmental dredging on air quality are highly variable and project-specific. Sediment chemistry, equipment type, dredging process, and de-watering requirements are key factors that can determine risks to air quality and to operator health risks. Many major contaminated sediment dredging projects will have an air quality monitoring component. Air monitoring shares similarities with water quality monitoring. Grab samples (using SUMMA canisters, Tedlar bags, etc.) can be collected and analyzed to determine the actual chemical concentrations of volatile compounds. Other components, such as metals or non-volatile PAHs, may require the collection of airborne particulate samples (if this is considered a risk for the project).

Real-time air monitoring can be conducted using equipment to detect total volatile organic compound concentrations in the air (e.g., a photoionization detector). The results from this type of monitoring are not specific to any one contaminant of concern and a correlation needs to be established beforehand.

Beyond the actual chemical concentrations emitted from a dredging project, any odour generated from the project can become an issue, particularly in urban areas with residential or public areas close by. Odour may be associated with the COCs, but can also be related to the organic material within the dredged material and the generation of gases such as hydrogen sulfide. Odour monitoring is a challenge because of the subjective nature of what is considered unpleasant odour. Monitoring approaches have adopted the use of odour panels and/or olfactometers in order to try to quantify odour impacts.

3.5 Long-Term Monitoring and Maintenance

In general, an environmental dredging project successfully implemented will have fewer long-term monitoring requirements than other types of sediment management, such as capping. If residuals capping (thin-layer backfill) is required, long-term monitoring similar to a thin-layer capping project should be adopted. However, capped dredge-generated residuals usually represent only a thin unconsolidated layer of remaining material, and long-term monitoring is often not a requirement. Specific circumstances related to a project's residuals management may prompt the inclusion of long-term monitoring. As mentioned, the monitoring plan should be thought through so that monitoring results can guide actions to adapt to unknown conditions or results of monitoring.

3.6 Challenges and Uncertainties

The degree to which additional dredging or thin-layer backfilling will be required to manage residuals will always be an unknown until project implementation. Because the dredging work is completed from a vessel, weather conditions, particularly wind, waves, and currents, represent an unknown impact to the project. Despite any completed debris surveys, a certain amount of unidentified debris can always be encountered. Malfunctions and equipment breakdown are an uncertainty for any project. A robust design must account for some of these uncertainties where possible. The design and associated cost estimate must also include sufficient construction contingency to cover a reasonable prediction for extra costs. Construction contingency for dredging projects should be based upon the individual factors for each project/site and the degree of risk. If sediment management challenges prevent the project from successfully meeting its intended goals, then the adaptive management plan should be implemented.

4. Confined Disposal Facilities

It is the intention of the authors that this section be read in conjunction with the discussion of site characterization and long-term monitoring included in Section 2 and 9. It is noted that the subheadings are the same in this section, but this section includes specific information on site characterization and long-term monitoring pertinent to confined disposal facilities and containment cells.

4.1 Introduction

A confined disposal facility (CDF) is an engineered structure consisting of dikes or walls that extend above any adjacent water surface and enclose a disposal area for containment of dredged material to isolate the dredged material from adjacent waters or lands. The dikes or walls are often constructed of sand and stone, and allow for water to be discharged over a weir structure or filtered through the walls. CDFs have been typically used for disposal of contaminated dredged material from navigational dredging; however, in more recent times have also been used for disposal of contaminated sediment from environmental dredging projects.

CDFs can be constructed in three ways:

1. **Nearshore CDF –** The facility is located along the shoreline such that one of the walls is comprised of the shoreline itself.
2. **Island CDF –** The facility is completely surrounded by water.
3. **Upland CDF –** The facility is not located in water, but on land. This can also include an engineered landfill. The type of landfill required (i.e., sanitary or hazardous waste) is dependent on the contaminant type, concentration, and leachability. Landfills require the sediment to be de-watered before acceptance for disposal.

A CDF can also be a structure that is fully contained and hydraulically disconnected from the surrounding waterbody. These types of CDFs are typically constructed of sheet pile walls and have also been referred to as engineered containment facilities (ECFs) (Graham et al. 2012). CDFs can also include instances, for example, where a former ship berth has been used to contain and isolate contaminated sediment from the adjacent waterbody.

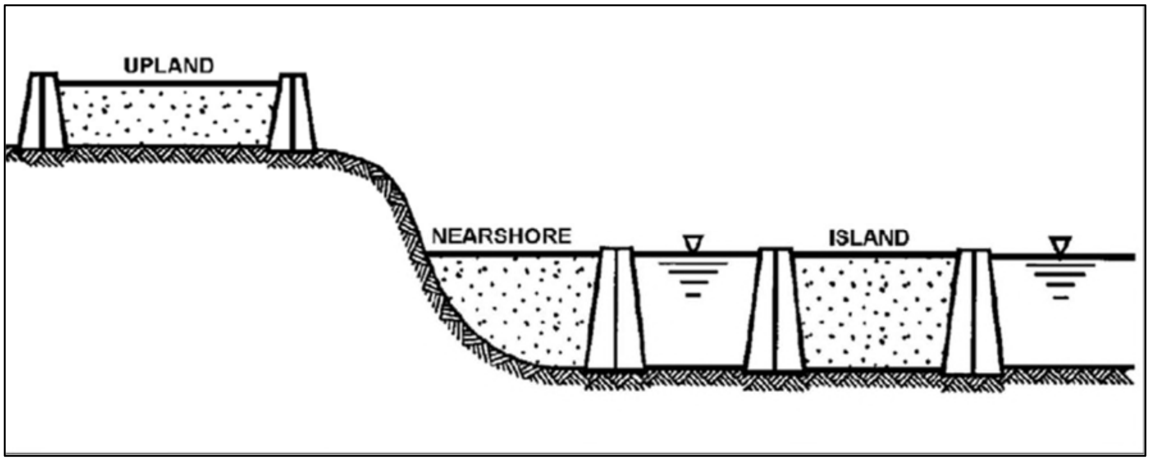

Figure 4-1: Upland, nearshore, and island CDFs (USACE 2015).

A CDF may contain a large containment cell for material disposal and adjoining containment cells for retention and decantation of turbid, supernatant water.

The intention of this section is to focus on the design requirements for nearshore and island CDFs. Upland CDFs are provincially regulated and would follow design criteria established for landfills.

The following list is an overview of the information that should be included in the design for placement of contaminated sediment into a new CDF or an existing CDF:

- Characterization of contaminated sediment to be disposed of in the CDF. Along with the known attributes of the COCs, the geotechnical properties of the contaminated sediment are needed,
- Characterization of the CDF site. This information should include a geotechnical evaluation, an evaluation of the surrounding setting and environment (i.e., other users of the area), and the hydrodynamics of the water and groundwater environment, and
- Evaluation of potential exposure pathways of the CDF (i.e., contaminant fate and transport). A conceptual model will assist with this evaluation, which should lead to a series of testing procedures for each potential pathway.

The following list is an overview of the information that should be included in the design of a new CDF or the modification of an existing CDF to minimize the loss of contaminants to the surrounding environment (U.S. Army Corps of Engineers 2003). This information is also critical in determining what operational controls should be used to minimize the loss of contaminants:

- The information from the potential exposure pathways, the site characterization, and the geotechnical evaluation can assist in design and construction of either a new CDF or modifying an existing CDF to minimize the loss of contaminants (U.S. Army Corps of Engineers 2003),
- Similarly, the above information is critical in determining what operational controls should be used to minimize loss of contaminants, and
- A long-term maintenance and monitoring plan. This is important to ensure CDF stability and functionality.

This information is expanded upon within this section.

4.2 Goals and Objectives

The goal of a CDF is to isolate contaminants from the surrounding environment via containment cells/structures and to minimize loss of contaminants to the surrounding environment. Minimizing contaminant loss is achieved through setting design criteria for each exposure pathway (i.e., water quality for effluent and/or runoff, air quality for volatiles, and similar considerations for groundwater quality and biological uptake). Other secondary goals may exist for certain projects (i.e., end use of the filled CDF, such as natural habitat or parkland), which should also be accounted for in the project design. As these structures are designed for the long term, they require ownership along with long-term maintenance and monitoring to ensure they are performing as expected. It is crucial that ownership of the facility is clearly identified, as the owner is legally responsible for all future operation, monitoring, and maintenance activities.

4.3 Characterization of Site

4.3.1 Sediment

Geotechnical

Prior to constructing or modifying CDFs, the geotechnical properties for both the sediment to be dredged and the containment site must be understood.

With respect to the contaminated sediment, certain geotechnical parameters will be required to conduct modelling for two separate processes that will take place within the CDF: settling and consolidation. The geotechnical evaluation should include the six parameters previously outlined in Section 2.2.1.

When dredged material is placed in a CDF, the intent is that hydraulically, it settles to the bottom of the cell. Understanding how the dredged material will behave once placed in the cell is critical in determining the initial storage capacity of the cell along with the quality of the effluent discharge. Typically, the Long Tube Column Settling Test is used to create settling curves for the cell (see Section 4.4.1 for details on this test). In addition, after the dredged sediment is placed, it will consolidate under its own weight over time. Consolidation modelling will provide both the magnitude and rate of consolidation, thereby determining the short- and long-term storage capacity of the cell. Public-domain modelling programs can be used for this purpose.

Coastal and geotechnical design aspects for retaining dikes or walls need to be considered during the sediment management option study before any CDF design is fully developed (see Section 4.1). These aspects are outside the scope of this document. In addition, the following should also be considered:

- Requirements for the end use of the facility (e.g., if it is going to be used as a port facility, what types of loading will it need to support?),
- Seismic considerations,
- Slope stability of the walls,
- Settlement of foundation soils (magnitude and time rate),
- Groundwater upwelling, and
- Permeability of foundation and walls.

Determining the settlement of foundation soils beneath the CDF is crucial to understanding the long-term behaviour and performance of the CDF. This is achieved through consolidation modelling.

Contaminants of Concern

Detailed knowledge of COCs in the sediment to be dredged should already be known from analyses leading up to the determination that sediment management is required (see Section 2.2.1). This knowledge must include which contaminants are present and at what concentrations, and whether the levels of contamination vary within the dredging site (i.e., sediments from some parts of the site may have lower or higher levels of certain contaminants, and the dredging and placement of those sediments into the CDF should consider this in terms of placement and sequence). This information can be used if selective placement or layering of highly contaminated sediment versus less-contaminated sediment, would enhance the effectiveness of isolation.

4.3.2 Site Setting

Assessment of the current and future surrounding environment must be included. In addition to the general items outlined in Section 2.2.2, consideration must be given to the potential creation of odours, air quality concerns, available area for containment, climate conditions, and adjacent land use/neighbours (e.g., determining if a CDF has the potential to block existing water intakes for a neighbouring industrial facility or interfere with the enjoyment of an adjacent park) before a CDF is placed on the site. Evaluating the surrounding environment is typically done as part of an environmental impact assessment.

4.3.3 Ecological

Knowledge of the local ecology is critical to the design of CDFs. In addition to the general items outlined in Section 2.2.3, proximity to sensitive ecological environments/receptors and attraction of waterbirds must be considered. Nearshore and island containment facilities will eliminate the aquatic habitat of the water lots where they are constructed. The design should include any required habitat compensation (e.g., creation of fish habitat to compensate for project impacts with an end result of zero net change in habitat after project completion) or mitigation actions (e.g., fish rescue). Upon construction, additional mitigation, such as bird scare, may be required during filling activities. Such activities must be conducted with the appropriate permits. This is also typically done as part of an environmental impact assessment.

4.3.4 Surface Water

While general surface water considerations are presented in Section 2.2.4, specific considerations for CDF design are presented here. When creating a nearshore or island CDF, the hydrodynamics in the vicinity of the CDF site must be understood (i.e., currents, wave energy, tides). Hydrodynamic modelling should be conducted for two scenarios: pre-CDF creation and post-CDF creation. The results should then be incorporated into the CDF design. The purpose of the pre-CDF modelling is to understand the existing conditions before the facility is created. The post-CDF modelling indicates how the construction of the facility will change existing conditions. The results of the post-CDF modelling can be used to change operational controls, if the projected hydrodynamic changes are unacceptable, or to redesign the CDF in question. The potential effects of climate change should also be included in this assessment. As with all modelling, the models should be verified as much as possible with real current measurements prior to being used for predictions.

4.3.5 Hydrogeological

Characterization of the hydrogeological conditions in the vicinity of the CDF is required. A CDF can be affected by groundwater flow, especially groundwater upwelling. Groundwater flow can present a potential contaminant pathway from the CDF, so the facility will need to be designed to mitigate any identified groundwater issues. Groundwater upwelling into the interior of a CDF could also result in a positive pressure gradient in the overlying surface water, which in turn could increase the discharge rate out of a CDF. Upwelling can also increase the water content of the placed dredged material, slowing its consolidation and potentially reducing the capacity of the CDF over time. Water may also infiltrate through the berm walls of a CDF. Consolidation of fine-grained materials can reduce the permeability of the berm walls as well as the base of the CDF. If continuing problems are found, de-watering enhancements can be considered, such as wick drains and trenching.

4.4 Construction

The design will stipulate the size, shape, and structural components. Each site-specific CDF design will be based on the physical and chemical characteristics of the contaminated sediment, the physical and environmental characteristics of the site, the potential pathways for contaminant release, the groundwater aquifers both beneath and surrounding the site, the uses of the areas surrounding the site, and the anticipated future use of the site.

4.4.1 Contaminant Fate and Transport

The design and operation of a CDF should be directed toward the goal of minimizing contaminant loss while maximizing sediment consolidation. Therefore, potential contaminant release pathways must be identified, followed by the selection of controls and structures that will limit contaminant release. As shown in Figure 4-2, common contaminant release pathways include:

- Effluent (excess water and suspended solids) from the placed contaminated sediment,
- Surface runoff from precipitation,
- Seepage and groundwater leachate,
- Volatilization, and
- Plant / animal uptake.

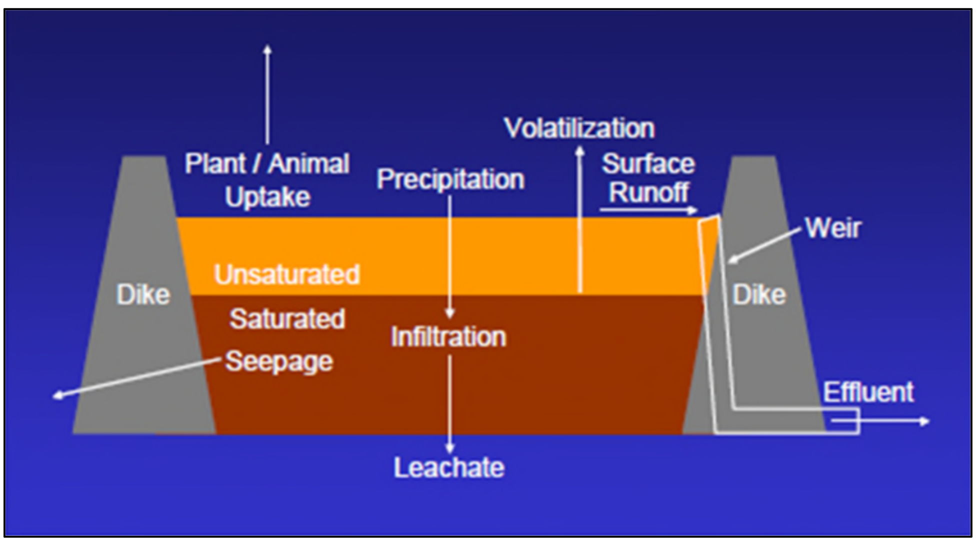

Figure 4-2: Contaminant release pathways for a CD (USACE 2003).

Contaminants placed in a CDF can undergo both physical and chemical changes (USACE/EPA 2004). Disturbance of the sediment inherent to placement can increase oxygen levels within the sediment, thereby increasing mobility of some contaminants (e.g., metals) and de-chlorination of some organic contaminants. The Evaluation of Dredged Material Proposed for Disposal at Island, Nearshore, or Upland Confined Disposal Facilities – Testing Manual, prepared by the USACE, presents a detailed evaluation structure and detailed evaluation procedures to determine contaminant fate and transport (USACE 2003). Details regarding the evaluation of the following contaminant pathways can be found in the USACE document.

Effluent

Effluent refers to the decant water from the dredged sediment within the CDF. Characterization of the effluent is needed in order to determine if treatment is required prior to discharge. Effluent water quality is a function of the dredged material flow rate, contaminant concentrations, and solids content / grain size, in addition to the containment cell configuration and volume. Determination of the total decant water residence time in addition to the TSS content of the effluent is essential in determining any treatment requirements prior to discharge.

Bench-scale tests are performed to estimate the effluent quality to be discharged from the CDF. These tests typically include composite samples of the sediment to be dredged mixed with water from the site. Bench-scale tests can include the following:

- **Long Tube Column Settling Test (LTCST) -** This test is used to evaluate TSS concentrations and total concentrations of COCs in effluent. Site water and a composite sediment sample are mixed to form a slurry and are then vigorously aerated. Samples for TSS, turbidity, and COCs are then taken at various depths within the column over time to estimate expected concentrations and to create settling curves (see Figure 4-3), and
- **Effluent Elutriate Test –** This test is used to determine the water quality expected after passive settling within the facility. Site water and a composite sediment sample are mixed to form a slurry, aerated for one hour, and allowed to settle for 24 hours. The supernatant is then analyzed for contaminants (see Figure 4-4).

In addition, the USACE has developed a computer program that reduces the LTCST data and interprets the design requirements for initial storage and solids retention. The program is called SETTLE (Computer-Assisted Settling Data Analysis), and it predicts effluent TSS concentrations for various ponding and flow-rate conditions within the CDF (USACE/EPA 2004).

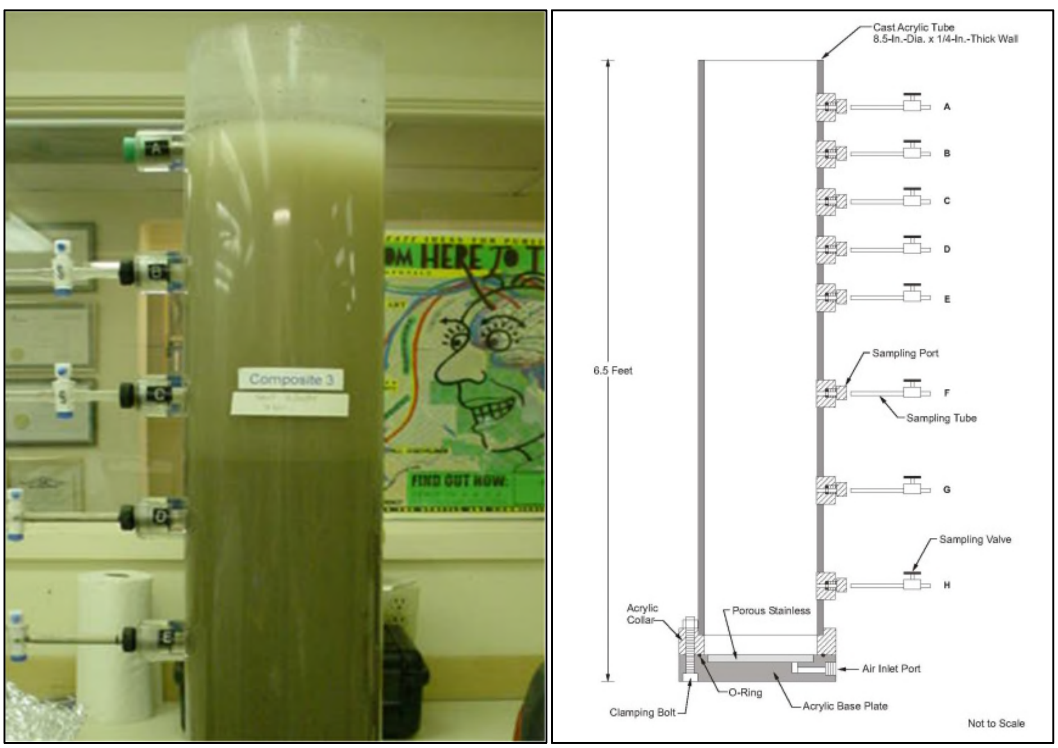

Figure 4-3: Long tube column settling test (Blasland, Bouck & Lee Inc. et al. 2006).

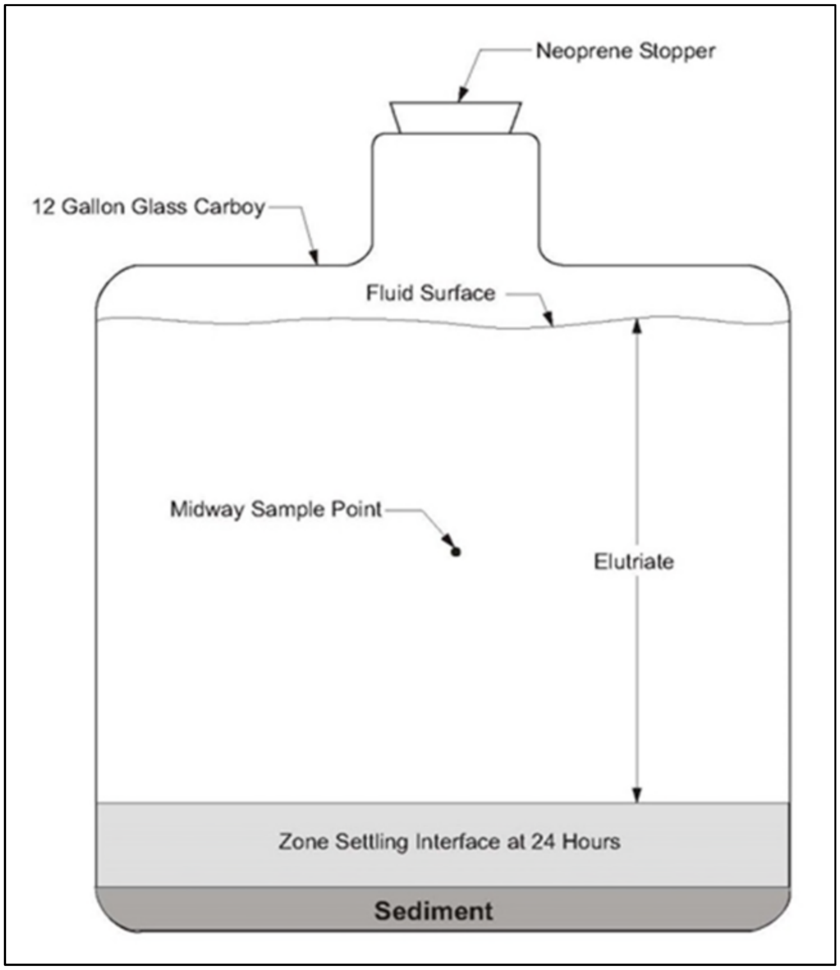

Figure 4-4: Effluent elutriate test apparatus diagram (Blasland, Bouck & Lee Inc. et al. 2006).

Surface Runoff

In a CDF, when contaminated sediment is still exposed, precipitation will cause runoff from the surface of the CDF. Once a CDF is full, the ponded water on top of the dredged sediment is decanted. This exposes the contaminants to oxygen in the air, and they can become more soluble and thus mobile during precipitation events.

Surface runoff quality can be initially screened using equilibrium partitioning principles and mixing zone assumptions. If a more detailed approach is required, the following tests can be conducted:

- **Simplified Laboratory Runoff Procedure (SLRP) –** This procedure predicts runoff quality using various exposure characteristics. It also takes long-term drying of dredged material into account by evaluating the potential oxidation and resulting increase in metals solubility, and
- **Rainfall Simulator / Lysimeter System (RSLS) –** This system simulates runoff quality by using a mechanical rainfall simulator to “rain” onto the dredged sediment. Runoff quality and rates are then directly measured.

If a cap is engineered for the facility when the CDF is full, surface runoff will no longer make contact with the contaminants and will no longer be a pathway for contaminant transport. The project design will, however, have to account for the intermediary stages where contaminated sediments could/will be exposed.

Seepage and Groundwater Leachate

Leachate from the facility can be created by groundwater flow, precipitation, and gravity drainage. It can migrate through the bottom or sides of the CDF. The quality of the leachate is a parameter that must be known. Leachate quality can be initially screened using equilibrium partitioning principles. The following tests are used to acquire data for input into groundwater flow and solute transport modelling:

- **Thin-Layer Column Leaching Test (TLCLT) –** This test simulates contaminant leaching from dredged material within a confined facility (under anoxic conditions). Distilled water is passed through a composite sediment sample for a set number of pore volumes. The leachate is then analyzed for contaminants. Site-specific sediment/water partition coefficients can also be determined using this test (see Figure 4-5),
- **Sequential Batch Leachate Test (SBLT) –** This test is used to produce contaminant desorption isotherms by mixing the sediment with distilled-deionized water. The sediment and water are brought to equilibrium, centrifuged to remove the water from the sediment, and then analyzed for contaminants. The process is repeated several times to produce the isotherms. The contaminant-specific isotherms can then be used to produce equilibrium distribution coefficients. This test is recommended for freshwater sediment only (see Figure 4-6),
- **SBLT or TLCLT Adsorption Test –** This test is used to determine the adsorption of contaminants to clean materials, in addition to attenuation. The test is identical to the SBLT or TLCLT except that the contaminated sediment is replaced by clean materials (i.e., foundation soils or berm-construction soils) and leachate is used to pass through the clean materials, and
- **Porewater Extraction Test –** This test is used to determine the concentrations of the contaminants when in equilibrium with the sediment. Composite sediment samples are centrifuged, and the resulting porewater collected and analyzed for contaminants. Site-specific sediment/water partition coefficients can also be determined using this test. It should be noted that more recently developed techniques known as passive sampling have the ability to overcome some of the limitations and issues surrounding centrifuging for porewater, and could be considered here (see Figure 4-7).

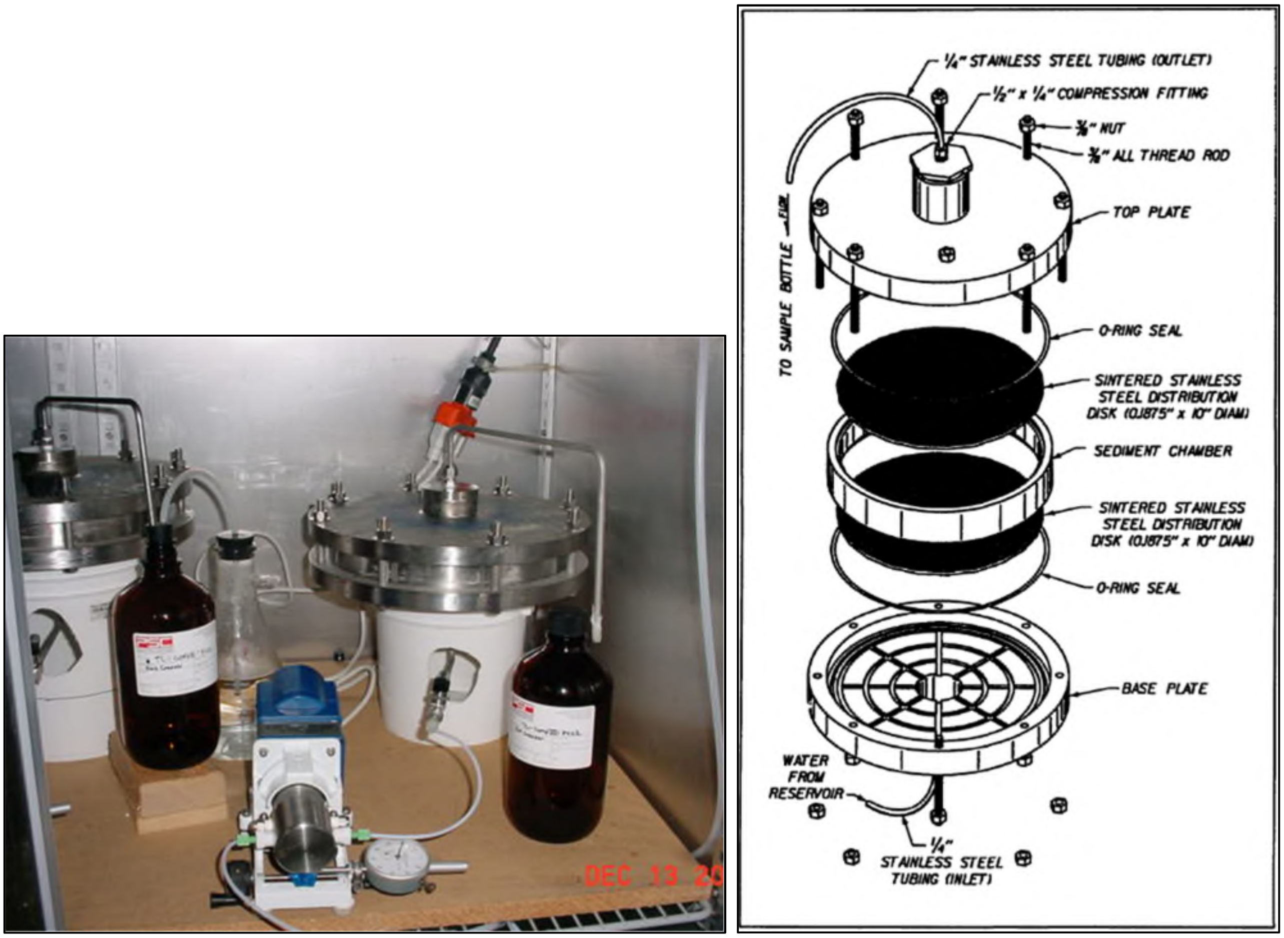

Figure 4-5: Thin-layer column leaching test (Blasland, Bouck & Lee Inc. et al. 2006; Brannon et al. 1994).

Figure 4-6: Sequential batch media adsorption test. (Blasland, Bouck & Lee Inc. et al. 2006)

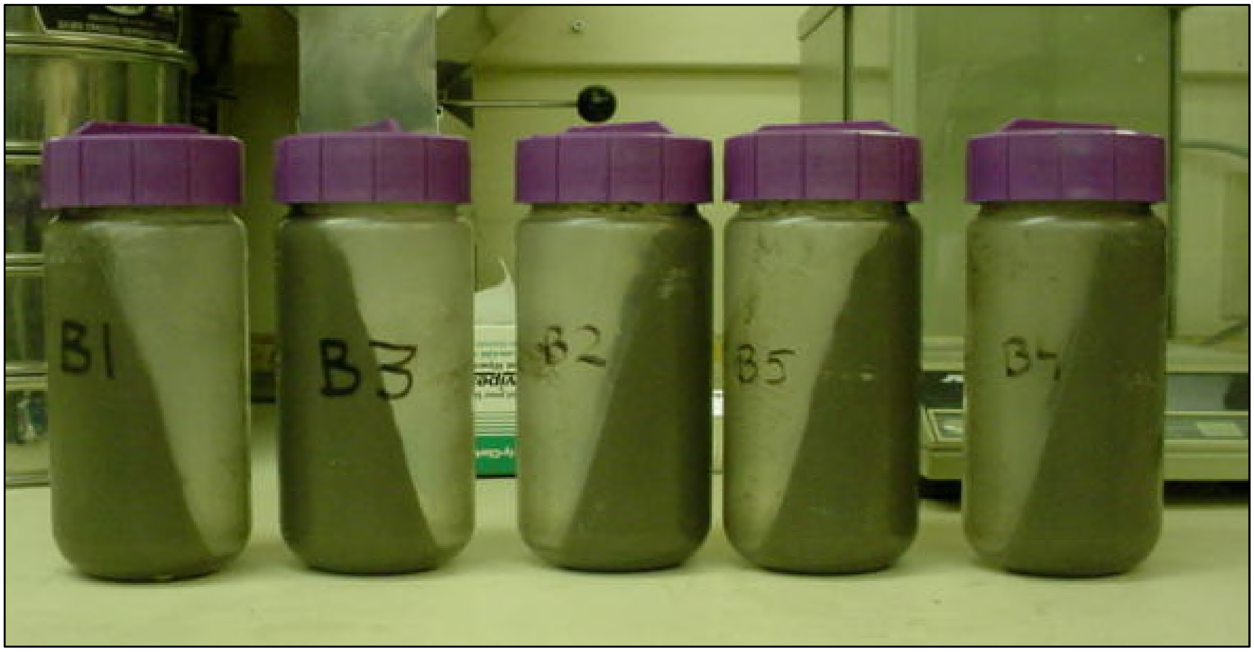

Figure 4-7: Porewater extraction test (after centrifugation). (Blasland, Bouck & Lee Inc. et al. 2006)

If the CDF includes a membrane on the bottom and sides to isolate the contaminants in the CDF, then this pathway is not an issue.

Volatilization

Volatilization is dependent upon the chemical characteristics of the contaminants. The mass transfer rates from sediment to air, water to air, and sediment to water must be known (USACE/EPA 2004). There are four potential conditions where volatilization can occur:

1. Dredged material exposed directly to air.
2. Dredging site or other water area where suspended solids are elevated.
3. Ponded CDF with quiescent, low-suspended solids concentration.
4. Dredged material covered with vegetation (USACE/EPA 2004).

Emission rates are dependent on concentrations of the contaminants at the source, the surface area of the source, and the degree to which the dredged material is in direct contact with the air. Emission rates can be initially screened using chemical partitioning assumptions. Receptor exposure to the rates identified are then evaluated to determine the associated risk.

If a more detailed evaluation is required, the following test can be used:

- **Volatile Flux Chamber Test (VFC) –** This test is used to determine the concentration of contaminants in the air after passing air over a sample of the dredged sediment.

The modelling of air emissions must always take atmospheric conditions (wind direction, wind strength, relative humidity, etc.) into account. Background air quality and the impacts from surrounding emitters, with potential for cumulative effects, should also be taken into consideration.

Plant and Animal Uptake

With a CDF, there is potential for plant and animal uptake of contaminants. This could occur when aquatic species (e.g., waterbirds) are exposed to a containment facility that is left partially filled or when terrestrial species are exposed to a containment facility that is filled and de-watered. A conceptual site model can be created and standard ecological risk assessment procedures applied to determine whether plant and animal uptake is a risk. Bioaccumulative contaminants are of particular concern when dealing with animal uptake and metals are usually of concern for plant uptake (USACE 2004). Earthworms are typically used as the indicator species when determining the potential for animal uptake. If a more detailed assessment is required, the following tests can be used to determine whether plant or animal uptake is a concern:

- **Animal Bioaccumulation Test –** This is a bioassay using worms exposed to the dredged sediment for a specified period. After exposure, the worms are analyzed to determine the concentration of contaminants in their tissues. Contaminant concentrations are then compared to reference samples,
- **Diethylenetriamine-pentaacetic Acid (DTPA) Extract Test –** This is a simple test that predicts potential plant bioaccumulation by extracting metals from sediment using DTPA. This test applies to metals only,
- **Plant Uptake Program (PUP) –** This is a computer program that predicts bioaccumulation of metals from freshwater dredged material in freshwater plants. PUP uses the results of the DTPA Extract Test as an input (USACE/EPA 2004), and
- **Plant Bioaccumulation Test –** This is a bioassay using index plants exposed to the dredged sediment for a specified period. Plant growth and contaminant concentrations in plant tissue are measured. Contaminant concentrations are then compared to reference samples.

If the CDF has an engineered cap that does not support plant or animal life, this pathway is not a concern.

Particulate Transport

In a CDF, particulate transport may be of concern. Particulates could be transported if the surface sediment is dry and there are strong winds. Tools to quantify this pathway are not well developed (USACE/EPA 2004). Particulate transport is not typically a concern if an engineered cap is placed on top of the CDF.

Contaminant Pathway Controls

If it is determined that a particular contaminant pathway cannot meet applicable criteria, contaminant pathway control measures will be necessary. Contaminant control can be achieved by the following engineering actions:

- Lining the interior of the CDF berm/wall (and possibly the bottom) with an impermeable liner,
- Installing an impermeable barrier at the core of the berm/wall (i.e., a sealed steel sheet pile wall or a reactive core, such as activated carbon, with the ability to treat contaminants before they pass through the berm/wall to the adjacent waterbody),
- Treating effluent, runoff, and leachate, if needed, and
- Placing a cap over the CDF when disposal actions are completed.

4.4.2 Engineering Considerations

A CDF typically uses earthen containment berms constructed of sand, gravel, and/or rock fill, which serves to filter escaping water while retaining the solids and contaminants. Where the release of water is not desired, a CDF can also be constructed using flat steel sheet pile walls or cellular steel sheet pile walls (sometimes referred to as ECFs). The sheet pile interlocks must be sealed in order to provide adequate containment of contaminants. In some cases, a double steel sheet pile wall has been used, with a sealed inner wall providing isolation and an outer wall providing structural stability (Graham et al. 2012).

Engineering factors to be considered during design may include the following:

- Geotechnical characteristics of the CDF foundation,
- Dike construction and height,
- Subdivision of the CDF into separate containment cells,
- Surface area and depth of the CDF,
- Life of the CDF (including application of coatings or cathodic protection for steel structures),
- Anticipated frequency of use, and
- Anticipated use of the CDF after filling.

These design considerations will determine the surface area and ponding depth required to achieve effective sedimentation, the required containment volume for storage (including required freeboard), and the proper sizing of weir structures.

Structural design elements should consider all appropriate processes, such as wind pressures, wind-generated waves and surface currents, wave action and erosion, ice loading, and expected live loads. Climate change and, for certain locations, sea-level rise, are also important factors. Typically, the design elements are modelled using the conditions representing the 100-year return period (or longer). The return period will be determined by the desired design life for the structure.

Containment Dike / Wall Height

The height of the containment walls will be dependent upon several factors, such as wall stability, anticipated end use, and water levels. The design water level for the site must factor in the mean monthly water levels along with high and low short-term and long-term averages, minimums and maximums. The design needs to take into account the ponding and freeboard requirements for filling, the potential for overtopping due to wave action, the potential effects of overtopping, and the potential for erosion of CDF walls.

The walls must also be designed to meet the requirements for initial storage volume within the CDF, which is dependent on the *in situ* volume to be dredged, along with the increase in volume changes that will occur during the dredging placement operations. The volume changes can be determined by using the LTCST described in Section 4.4.1.

Containment Wall Permeability

The degree of permeability of the containment wall is a limiting factor in the accumulation of ponded water in the facility. Once the freeboard limit has been reached, dredge production rates would be restricted accordingly. As the ponded water filters through the dike wall, the freeboard is increased, allowing the production rate of dredging to be maintained. As containment wall permeability decreases and freeboard is reduced, the production rate is impacted. Active pumping and water treatment may be required to maintain desired dredge production rates.

For nearshore facilities, the potential for contaminant seepage into the surrounding groundwater may also be a design consideration.

Cell Subdivision

In many cases, a CDF is subdivided into cells for sediment segregation and/or effluent treatment. Segregation of the sediment allows for the control of contaminant placement (i.e., certain types of contaminants are concentrated in certain area of the CDF). Passive effluent treatment can also be achieved by using cells to increase the effluent retention time within the CDF. Cells can also provide more efficient settling and consolidation of the sediment, avoiding short-circuiting of flow from the placement point in the CDF directly to the decant water discharge point. The optimal subdivision configuration can be determined using modelling techniques.

4.4.3 Operational Controls for Placement of Dredged Material

In addition to the engineering aspects of constructing or modifying an existing CDF to minimize loss of contaminants by the pathways already evaluated, a number of operational controls need to be considered.

Dredge Production Rate

The dredge production rate is the rate at which the dredged sediment enters the CDF. The CDF design will determine the allowable inflow rates. If the size of the CDF puts constraints on the available surface area and retention time, the design should set a limit on the inflow rate. Contractors bidding on the work must be made aware of any limitations so that the dredge size and/or pumping rates can be matched with the CDF capacity.

The required rate of effluent treatment is directly influenced by the dredge production rate. If the effluent discharge does not meet water quality standards, the design must include required changes. While not desirable, one such option is to reduce the rate of dredging and thereby reduce the inflow and outflow rates from the CDF. Additional information on the dredge production rate is provided in Section 3 (Environmental Dredging).

Transport to Confined Disposal Facility

Ideally, the CDF should be located in close proximity to the contaminated site. Minimizing the distance between the disposal facility and the contaminated site will not only reduce costs, but also the potential for spillage. The potential impacts of transport on the neighbouring properties along the haul route must also be considered. Considerations include interference with navigation/marine traffic, odour, and visual aesthetics. Typical transport mechanisms include direct discharge via pipeline when hydraulic dredging is used and direct placement via mechanical dredge or hydraulic off-loading (slurrying and pumping the sediment) when mechanical dredging is used.

Selective Placement

Selective placement can be used as an effective operational control during placement of contaminated material. For example, using alternating layers of contaminated sediment and clean material can aid in containing contaminants and/or provide a mechanism for attenuation (i.e., sorption). In addition, using layers of sand between contaminated layers can enhance de-watering and consolidation. Placement of lesser-contaminated material as the final layer will also aid in controlling contaminant losses through surface run-off, plant and animal intake and volatilization.

It is also important to note that placement of fine-grained material typically results in a self-sealing effect, as the permeability of the material will decrease significantly once it has consolidated. It also serves to decrease the interstitial spaces of the berms/walls over time, making them hydraulically tighter. Decreasing the ponded water above the dredged material will also result in reduced hydrostatic pressure or an inward hydraulic gradient and ultimately reduce or eliminate contaminant migration via leachate from the CDF.

De-Watering of Sediment

CDFs use a passive de-watering method by using gravity and consolidation under self-weight to remove water. Passive de-watering takes much longer than mechanical methods. More detail on de-watering sediment is provided in Section 3 (Environmental Dredging).

Increased Retention Time

If the effluent will not meet water quality standards, consideration of increasing the ponded area and depth of the CDF is an option, as well as relocation of the inflow and effluent discharge points, with the objective of increasing retention time. An evaluation of short-circuiting should be conducted.

Effluent Treatment

If the raw effluent does not meet established discharge criteria for the site, treatment is required. Evaluation of physical treatment to remove suspended solids and the attached contaminants, as well as treatment to remove dissolved contaminants, should be conducted, if needed. Treatment systems would utilize technology similar to what is described in the environmental dredging section. Bench-scale treatability tests should be performed to determine the most appropriate method of treatment prior to finalizing the design. The following are typical bench-scale tests:

- **Flocculation Jar Test –** Site water and a composite sediment sample are mixed to form a slurry and allowed to settle for one hour. The resulting supernatant is then separated and combined with various flocculants/coagulants to determine their effectiveness (see Figure 4-8),
- **Column Settling Test -** Site water and a composite sediment sample are mixed to form a slurry and vigorously aerated. Flocculants/coagulants are added, and samples for TSS and turbidity are then taken at various depths within the column over time to create settling curves. This also helps to determine the effectiveness of the flocculants/coagulants,
- **Column Media Filtration Test –** This test uses the supernatant from the Effluent Elutriate Test to pass through various filtration/adsorption media (e.g., sand, granular activated carbon) in order to determine the effectiveness of the treatment media on removing dissolved contaminants (see Figure 4-9), and
- **Batch Media Adsorption Test –** This test is used to determine the adsorptive capacity of a selected medium (e.g., granular activated carbon) by determining the amount of transfer of dissolved contaminants from the supernatant to the selected medium (Brannon 1994).

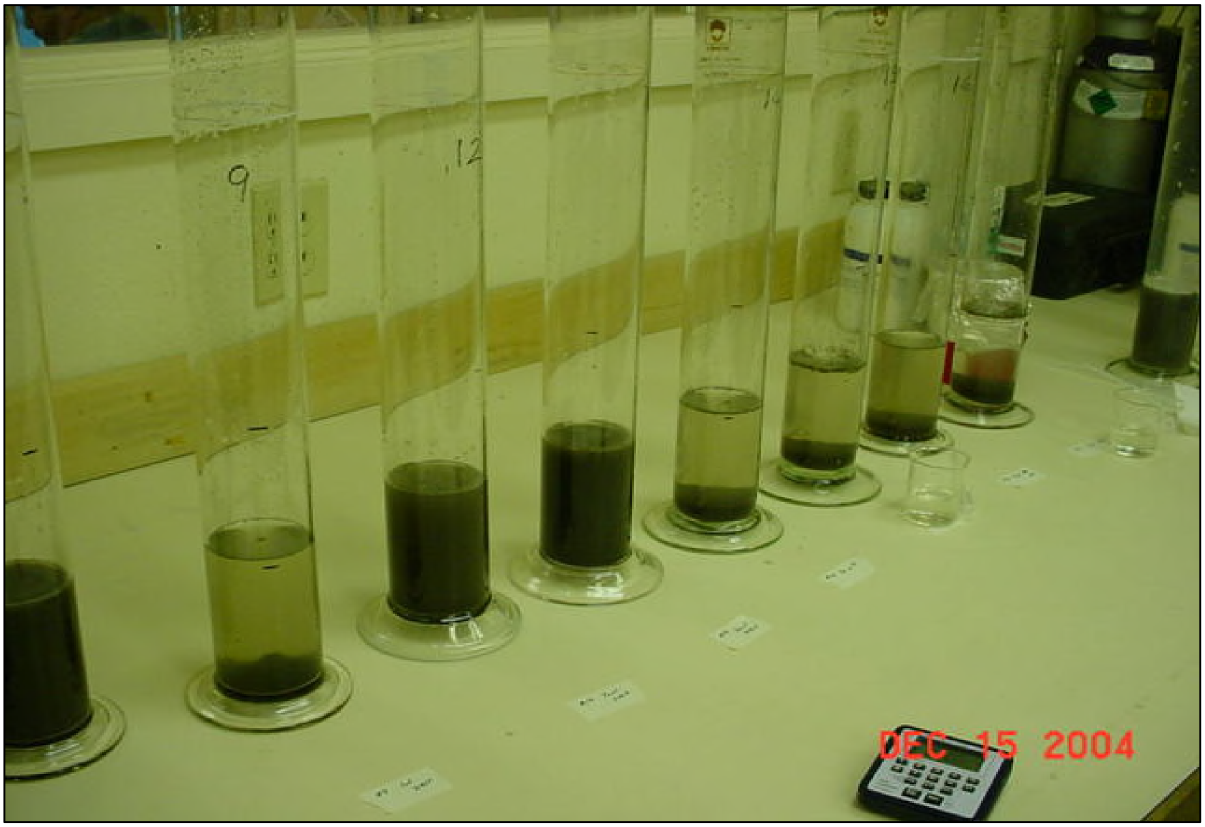

Figure 4-8: Flocculation jar test (after centrifugation) (Blasland, Bouck & Lee Inc. et al. 2006).

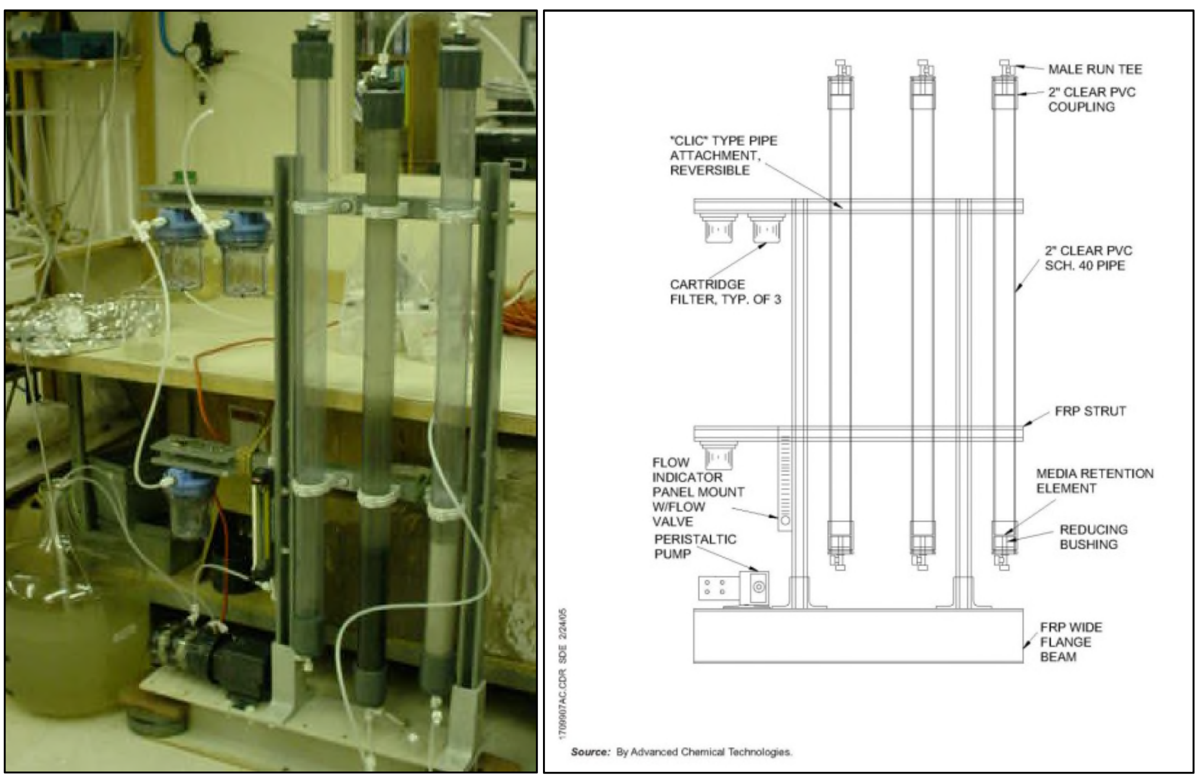

Figure 4-9: Column media filtration test (after centrifugation) (Blasland, Bouck & Lee Inc. et al. 2006).

Risk Monitoring and Mitigation

Risk monitoring and mitigation during the filling of the CDF is identical to that outlined during the dredging process. Water quality monitoring is essential to ensure contaminants are not entering the adjacent waterbody. Depending on the type of contaminants being dredged, air emissions may also need to be monitored for chemicals of concern and/or odours.

4.4.4 Confined Disposal Facility Cover

CDF cover design (thickness and materials) is dependent upon the end use of the CDF, and is typically designed to reduce the potential for impacts to the surrounding environment from surface runoff, seepage and groundwater leachate, volatilization, and plant and animal uptake. The height/thickness of the cover is related to the final design elevation for the contaminated sediment within the CDF in addition to the required design elevations and grading for the top of the facility. The cover should also be designed to accommodate long-term monitoring to ensure the facility and/or cover is performing as expected.

With a goal of long-term isolation, cover design typically involves consideration of the following:

- Anticipated contaminant flux through the cover (affects volatilization, bioaccumulation, and surface water runoff potential),
- Site hydrogeology,
- Surface water runoff,
- Geotechnical strength and stability of the dredged sediment,
- Existing and future anticipated harbour water levels, and
- Accommodation of utilities.

CDF covers can either be permeable, impermeable, or a combination of the two. A permeable cover could be suitable for a CDF with a reactive core (i.e., the walls are designed for water to pass through). An impermeable cover would be suitable for a CDF with impermeable walls that is hydraulically disconnected from the adjacent waterbody. A combination cover could be suitable for any CDF and would include a permeable layer on top of an impermeable layer, isolating the contaminants within the CDF while allowing vegetation to grow.

When installing a cover, the bearing capacity of the dredged material must be sufficient to support the load exerted by the covering material. The first layer of the cover is typically the most difficult to install due to the bearing capacity issue. If the initial bearing capacity is insufficient, various techniques can be used: structural fill, hydraulic placement (if conditions allow), surcharging with porewater extraction (i.e., wick drains), geotextiles, and geogrids. Regardless of the technique(s) used to increase the bearing capacity, consolidation of the dredged material is required, which can take considerable time (i.e., months to years).

Depending on the type of contaminants, a system to collect and convey volatile emissions may be necessary. Similarly, a groundwater collection system may be necessary if hydrogeologic conditions indicate groundwater upwelling through the cover is an issue.

Stormwater management is also an important consideration in cover design. Usually, CDFs containing contaminated sediment will require a cover that limits infiltration of precipitation. This can be achieved by grading and/or installation of a stormwater collection system.

4.4.5 Future Usage

The end use or potential end use of the facility must be known at the beginning of the design phase. This will ensure that the wall and cover designs, along with consolidation modelling, are done correctly using realistic, site-specific parameters. Ultimately, the cover and dredged material strength must be able to support the planned usage for the facility. The end use will also dictate any infrastructure required. Infrastructure needs could include road and rail access and/or utility services. Another end use may be habitat for plants and animals, a park, or a nature preserve, whereby contaminant uptake and bioaccumulation would be a concern to be considered.

4.4.6 Lifespan

The typical structural design lifespan for a CDF is at least 100 years; however, management and maintenance need to be conducted by the CDF owner in perpetuity. The 100-year design should take physical integrity into account, in addition to the 100-year storm event and any other applicable events with respect to climate change.

4.4.7 Construction Monitoring

As with all construction projects, monitoring must be conducted during construction to determine whether the CDF is being constructed according to plans and specifications, to verify the absence of contaminant releases to the environment, and to ensure the settling and consolidation reflects what was predicted.

4.5 Long-Term Monitoring and Maintenance Plans

The main objectives for the long-term monitoring and maintenance plans are to ensure contaminants remain contained and the structural stability of the facility remains sound. Such plans should be developed as part of the CDF design.

In terms of ensuring contaminants remain contained, the following techniques could be considered:

- Monitoring of the perimeter of the structure (i.e., monitoring wells installed at time of construction) for contaminants,
- Hydraulic head measurements within the monitoring wells (if present) for comparison with measurements of the water level of the adjacent waterbody to determine the potential for water flow and its direction through the walls, and
- Monitoring of contaminant levels in effluent and/or runoff discharging from the facility.

In terms of ensuring the structural stability of the facility, the following techniques could be considered:

- Topographic surveys to determine any structure movement,
- Porewater pressure gauges to determine if water is infiltrating the facility and pressure is building inside,
- Inclinometer measurements to determine wall verticality,
- Bathymetric surveys to determine any areas of scour adjacent to the structure,
- Underwater video inspections to determine visual issues under the water line,
- Visual inspections to determine visual issues above the waterline (i.e., corrosion, damage),

- Stormwater/drainage monitoring to determine if the design is functioning as intended, and
- Steel sheet pile thickness measurements (if walls are constructed with sheet pile) to determine deterioration and estimate remaining lifespan.

Monitoring should be conducted annually for the first five years following construction. If, after five years, monitoring results do not indicate any concerns, the plan can be reassessed and monitoring can be conducted at a lower frequency thereafter (i.e., every five years). If monitoring results indicate a concern, maintenance will be required to mitigate the identified concern. Management actions specified in the adaptive management plan should also be considered if monitoring indicates the facility is not performing as intended. Management actions could include operational controls, wick drains or trenching, changing flow patterns, or changes in effluent treatment to increase treatment efficiencies.

4.5.1 Administrative Controls

Administrative controls (sometimes referred to as institutional controls) refer to a set of rules and mechanisms to manage activity in and around the CDF. An example of an administrative control for a CDF could be restricted access. Restricted access is a preventative measure to help keep the site from being damaged and to reduce risks to people that may want to visit the site. Restricted access could be enforced by signage and/or fencing. Administrative controls will be governed by the location of the CDF and by adjacent land uses.

4.6 Challenges and Uncertainties

There are various challenges to overcome when building and/or operating a CDF. One of the most difficult challenges is the CDF siting process. Public acceptance of CDF construction is typically difficult to achieve. There may also be public concerns over air quality due to contaminant volatilization or odours.

Additional challenges include the dredging contractor’s ability to limit overdredging, which will also have a direct impact on the volume of sediment the CDF can hold. Challenges can also include the geotechnical qualities of the dredged material after placement. Neither the geotechnical qualities nor the rate of consolidation can ever truly be known until after placement has been completed. If sediment management challenges prevent the project from successfully meeting its intended goals, then adaptive management should be considered.

5. Isolation Capping

It is the intention of the authors that this section be read in conjunction with the discussion of site characterization and long-term monitoring included in Section 2 and 9. It is noted that the subheadings are the same in this section, but this section includes specific information on site characterization and long-term monitoring pertinent to isolation capping.

5.1 Introduction

Isolation capping of contaminated sediment involves physically and chemically isolating contaminated sediment from the aquatic ecosystem. In the context of sediment management, this is also referred to as *in situ* capping, a term that generally refers to capping contaminated sediment in its original place. Placing an engineered subaqueous cover, or cap, over an *in situ* deposit of contaminated sediment involves engineering designs that include complex chemical interactions intended to contain contaminants, rendering them unavailable to benthos and aquatic receptors and humans.

Isolation caps are also used in the closure of contained aquatic disposal (CAD) cells. CAD cells are subaqueous containments for placement of contaminated sediment removed from a location, deposited in the CAD cell, and then capped. A CAD cell may be an existing subaqueous depression such as a borrow pit or a purposely excavated cell on the water body bottom. Traditionally CADs have been primarily utilized for the disposal of navigational dredge material where contaminants present have prevented open water disposal. There are no known applications of CAD for contaminated sediment management projects in Canada.

Capping is an alternative to dredging, with a proven record of success (Reible 2014), where contaminated sediment sites have plentiful water depth, navigation is not an issue, and no other site-specific factors present issues.

5.2 Goals and Objectives

According to Reible (2014), capping is designed to achieve one or more of the following objectives:

1. Physically contain contaminated sediment to eliminate sediment resuspension risk.
2. Chemically contain contaminants in sediment to reduce migration and release.
3. Prevent the benthic community from interacting with and feeding on the underlying contaminated sediment (i.e., bioturbation).

As a result, there are variations in the design of caps that are used in the management of contaminated sediment. Objectives 1 and 3 can essentially be achieved with a simple sand cap, while Objective 2 may require sorbents or other amendments.

In areas where weather conditions are challenging or vessel traffic is present, the design should include armouring of the cap in order to provide structural protection and ensure long-term stability. Another possible design option is to place a habitat layer that is favourable to benthos and other organisms at the top of the cap. These varied objectives usually result in a cap design with multiple components. For example, a cap may include components related to habitat, stability against erosion (an armour layer), and chemical isolation.

When capping is being considered as the main management plan or a part of a broader management plan, there are many complexities that must be considered. Detailed guidance for isolation capping for the purposes of sediment management has been developed by USACE, USEPA, and others (USEPA 2005, Palermo et al. 1998a, EPRI 2008, and Reible 2014). These resource documents provide procedures for site and sediment characterization, cap design, cap placement operations, and monitoring, and should be consulted for detailed discussion of the various topics related to cap design.

A good overview of the cap design process is presented in Figure 5-1, taken from Palermo et al. (1998a). Sections outlining the main considerations for isolation capping then follow.

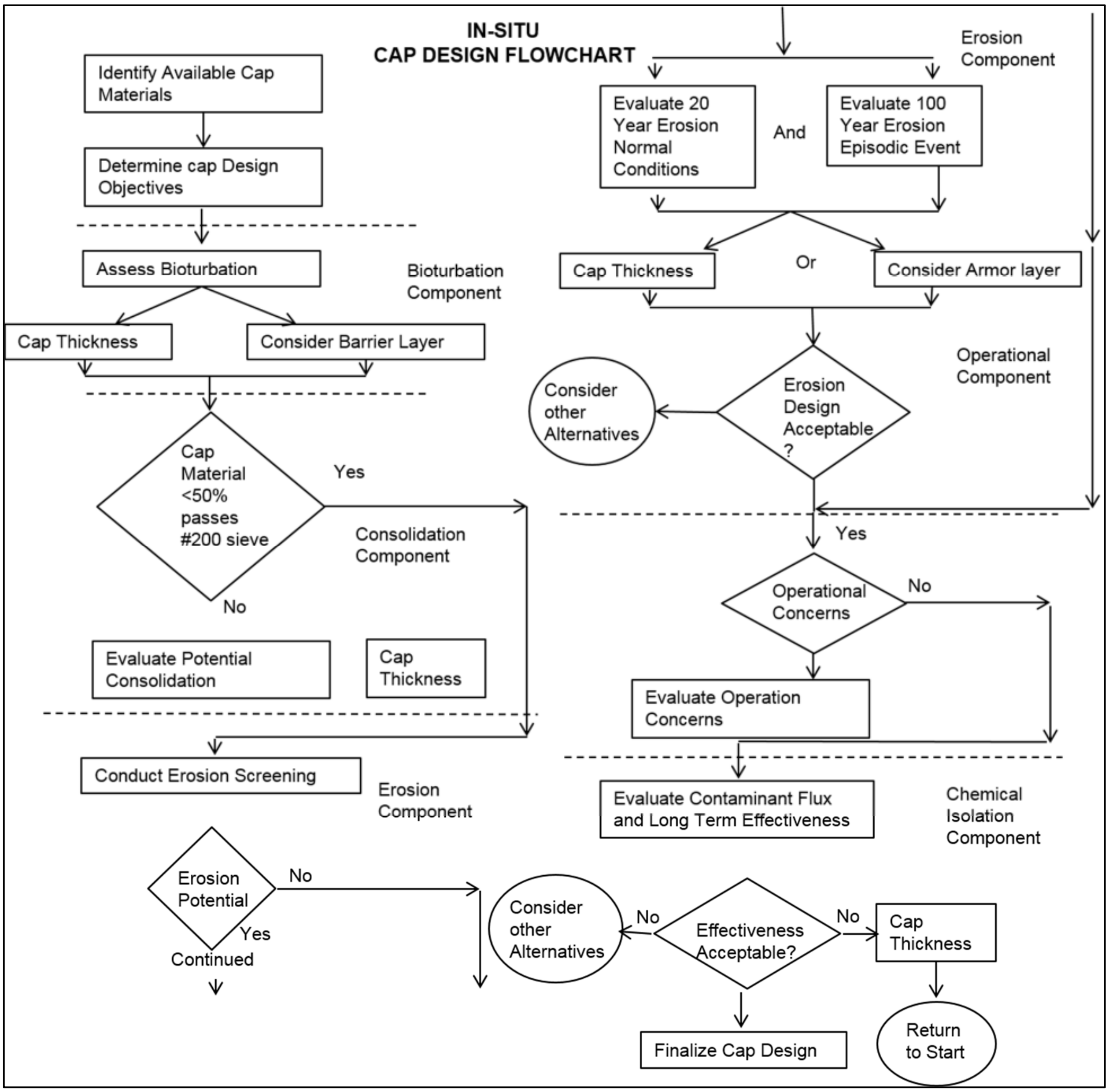

Figure 5-1: Cap design flow chart (Palermo et al. 1998a).

5.3 Characterization of Site

5.3.1 Sediment

Contaminants of Concern

Isolation caps are designed to contain and reduce the migration and release of contaminants, and a thorough understanding of the contaminants present in the sediment is required in order to properly design and select the cap materials. Dissolved contaminants under caps can migrate by two main methods:

- Advection, which is the transportation of dissolved contaminants by means of fluid movement (e.g., groundwater upwelling), and
- Diffusion, which is the migration of a substance by means of random molecular motion from high to low concentration.

Caps can be comprised of a single layer or multiple layers, which will serve to prevent migration. This is achieved by sorbing, retarding the contaminants and dispersing and dilution of the contaminants amongst the capping materials. The contaminants and their associated concentration play an important role in the modelling of how different caps are designed and how they will perform. This modelling, which is discussed in more detail later, is used to evaluate different caps and layers in order to derive an appropriate design for the site of interest.

Contaminants can be broadly classified into inorganics (most commonly metals and metalloids) and organics (e.g., PCBs and PAHs), and many sites have mixtures of the two. There are different considerations for cap design, depending on contaminants present. As an example, if a site contains sediment contaminated by metals only, the capping design could simply provide a sand cap. The burial of the metals-contaminated sediment below the sand can induce an anaerobic zone which creates reducing conditions below the cap, promoting the generation of sulfides. Sulfides are known to bind certain metals, rendering them unavailable to aquatic organisms, but they can increase mercury methylation, a contaminant of concern at some sites. Mercury methylation turns elemental mercury into an organic compound which makes it more bioavailable and increases the bioaccumulation/ biomagnification risk. If organic pollutants are the contaminant of concern, adsorbing amendments may be required. Many sites have both metals and organics present as contaminants.

Many of the organic contaminants present in sediment are hydrophobic and are thus strongly bound to the fine-grained sediment particles and organic fractions. Heavy metals, such as cadmium, zinc, nickel, lead, copper, and mercury, are also strongly associated with the sediment particles; however, the migration of metals can be highly complex. The oxidation state of metals influences their solubility and their subsequent affinity for sediment particles. Other parameters, such as Eh, pH, microbial activity, and the presence of sulfides, chlorides, and carbonates, influence migration (Palermo et al. 1998). This is important for the isolation cap design, as it affects the migration up through the cap, the possible eventual breakthrough of the contaminant, and the lifespan of the cap.

Gas Ebullition

The formation of gas bubbles in sediment can migrate contaminants to the surface through sorption. According to Reible (2014), gas ebullition is often driven by the degradation of newly deposited organic matter. Gas ebullition is likely to only be significant when it is driven by the degradation of the contaminants or the contaminant-bearing phase (e.g., NAPL). The migration and subsequent flux of contaminants through gas ebullition, if deemed to be a concern at the site of interest, requires consideration in the modelling of the cap performance.

Geochemistry and Microbial Actions

Under static conditions, only the upper few millimetres of sediment would be aerobic; however, bioturbation will account for aerobic conditions much further down (approximately 15 cm in fresh water and deeper in estuarine or marine sediment (Clark et al. 2001). Beneath this are anaerobic zones, which create reducing conditions for such compounds as nitrate. Placement of a cap relocates the bioturbation zone to the cap itself, so the old zone will become anaerobic after capping. These zones have important effects on the fate and transport of many contaminants, so site-specific knowledge is important for cap design and modelling.

Anaerobic conditions are advantageous for divalent cationic metals, as under such conditions they are bound up in sulfides through the formation of insoluble metal-sulfide complexes. In this regard, even a sand cap with very little organic content would be beneficial if the main contaminant of concern is metals. Anaerobic conditions are not ideal for mercury, however, as it tends to become methylated and bioavailable to benthos and other trophic levels. Pilot- or bench-scale testing can be used to help understand the system under study.

Sediment under anaerobic conditions, as it would be under an isolation cap, will still undergo biological degradation, and some contaminants are degraded better than others under these conditions. Chlorinated organic contaminants such as PCBs will undergo a slow microbial de-chlorination, which will result in a decrease in the flux to the overlying cap (Murphy et al. 2006). Other chlorinated contaminants can undergo more rapid de-chlorination. Care must be taken to properly understand the system and how it will respond. For example, de-chlorination is a desirable and necessary part of the process; however, it can stall under certain conditions, and daughter products (created as the chlorine atoms are removed) can be just as problematic as or worse than the parents.

The long-term degradation of contaminant concentration levels is an important consideration in an isolation cap design. Microbial degradation under caps occurs as the micro-organisms use electrons from the contaminants as an energy source. If there is not a high enough concentration of contaminant for the target degrading microbes, they can be “outcompeted” and replaced by other less desirable microbes in terms of degradation ability. This can be dealt with by the use of amendments to stimulate target microbes, and again emphasizes the need to properly understand the system at the site of interest.

Bioturbation

The upper 0–20 cm of sediment is often referenced as the biologically active zone, where benthic organisms rework the sediment and rich levels of degradable organic material are sometimes deposited (Kristensen, 2005). Bioturbation is the movement of sediment by the activities of aquatic organisms. In some cases, bioturbation is the most important natural process bringing contaminants to the sediment surface (EPA 2005). The effects of bioturbation can include the mixing of sediment layers, alteration of chemical forms of contaminants, bioaccumulation, and the transportation of contaminants from the sediment to porewater or the water column. During such activities as feeding, movement, and shelter-building, many bottom-dwelling organisms physically move sediment particles. This may result in altered sediment structure, biology, and chemistry. The extent and magnitude of this alteration will depend on site location, sediment type, and the types of organisms and contaminants present, which highlights the need for such information for the site of interest. There is much variability in the literature regarding the depth of bioturbation. ECCC’s development of the BEnthic Assessment of SedimenT (BEAST) approach for determining the need to manage contaminated sediment considers bioturbation can reach as deep as 40 cm, however, generally utilizes the top 10 cm of sediment for toxicity tests and benthic community structure (Reynoldson and Day, 1998). Sediment profile imagery (SPI) cameras (see Figures 5-2 and 5-3) are one means of visually assessing the extent of bioturbation and the types of organisms present at a site.

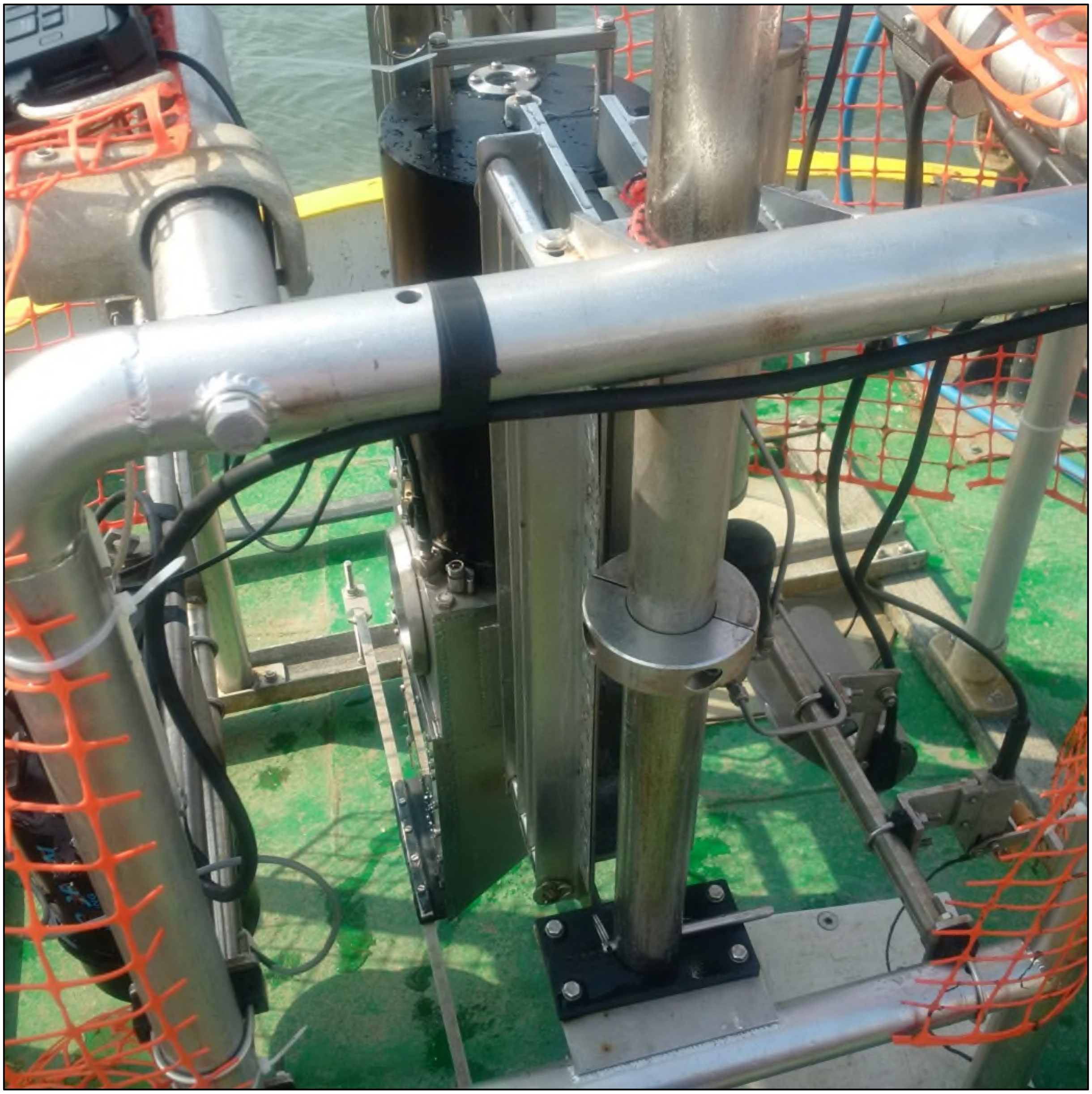

Figure 5-2: SPI camera surrounded by its housing frame. The wedge-shaped lens (centre bottom) is inserted into the sediment (courtesy of Fisheries and Oceans Canada).

Figure 5-3: SPI camera image showing the water, the sediment/water interface, and the sediment (courtesy of Fisheries and Oceans Canada).

Both an isolation and CAD cap design must ensure it accounts for bioturbation as a potential mechanism by which the intended contaminants could pass through the cap (e.g., relating cap thickness to the bioturbation zone at the site). It may be desirable to select capping materials that discourage colonization by native deep-burrowing organisms in order to limit bioturbation and the release of underlying contaminants. The most important consideration is that the cap must be thicker than the expected bioturbation depth for the site of interest so that the contaminants are not disturbed, unless concentrations are so low that the process in the bioturbation zone allows for meeting the standard. As a general rule of thumb, 15–20 cm bioturbation depth can be considered for freshwater systems, and marine systems can extend to 50 cm and beyond (Kristensen 2005). Clarke et al. (2001) provide a useful summary of recommended cap thicknesses, presented here as Table 5-1.

Table 5-1: A summary of recommended cap thicknesses for the bioturbation component of cap design. (Clarke et al. 2001)

Environment	Cap Material	Depth of Surficial zone of Sediment Mixing (cm)	Depth Increment for Mid-depth zone of Biodiffusion (cm)	Total Bioturbation Component Cap Thickness (cm)
Coastal/marine	Sands	10	10-35	20-45
	Silts/clays	10-15	10-45	20-60
Fresh water	Sands	10	10-20	20-30
	Silts/clays	10	10-30	20-40

Note: In the coastal/marine sand cap example, 10 cm would accommodate the intensively mixed surficial layer, and an additional 10–35 cm would be needed to accommodate mid-depth bioturbation, yielding a total cap thickness of 20–45 cm to adequately address overall bioturbation. Values at the lower end of total bioturbation component thickness would be justified only where sufficient knowledge of local benthos supported selection of a shallower depth.

5.3.2 Geotechnical

In addition to characterizing the contaminants in the sediment, geotechnical characteristics are important to the design of the cap. These include (EPA 2005):

- Density,
- Water content,
- Grain size,
- Atterberg limits,
- Specific gravity,
- Organic content,
- Consolidation,
- Permeability, and
- Shear strength.

Capping of sediment induces loads on the underlying contaminated sediment that is being capped as well as any other non-contaminated sediment. In the case of CAD where excavation of a depression is required, geotechnical data will be required for the sediment located below the excavation limit. Contaminated sediment is commonly fine-grain material with high water content and low shear strength, and is compressible when a cap is applied. With CAD, the placed sediment will have very low initial shear strength as a result of the disturbance from being dredged and subsequently placed. As a result of this very low initial shear strength, consideration of the stratification, the consolidation, and the hydraulic conductivity of the underlying layers, as well as the placed layers is required. On sloped surfaces, it is important to make sure capping does not induce failure of the underlying contaminated sediment, which would cause a general slope failure. The slope of the sediment surface at the site should be assessed, stability analyses should be done, and sediment strength should be modelled to calculate the slope stability factor.

Consolidation of the underlying sediment during and after the construction of a cap can introduce contaminated porewater into the cap, and holds higher potential for contaminant flux through the cap than diffusive transport of dissolved contaminants. This early flux caused by capping weight consolidation should be considered during the design/modelling of the proposed cap (Moo-Young et al. 2001). Measuring the *in situ* density of the sediments and conducting consolidation testing is required in order to properly model.

If the material used to cap the sediment is not a fine-grain material (>50% by weight passing a #200 sieve), Palermo et al. (1998) indicate that it can be assumed that the capping material itself will not consolidate and the only consolidation will be from the weight of the cap causing consolidation of the underlying sediment. If the capping material consists of fine-grain material, some consolidation of the capping material will also occur, which may result in the need for additional capping material to reach the desired thickness.

5.3.3 Site Setting

Adjacent properties may be utilized as staging areas for equipment and the stockpiling of capping sand. The nature of these properties along with associated access routes should have been properly assessed during the completion of the design.

Climate

Knowledge of the site-specific climate (i.e., temperature, precipitation, local currents, wave climate, and varying water levels, such as in the Great Lakes) is important for many reasons and interrelates with a number of the other points in this section. Seasonal flow fluctuations or ice scour are examples of climatic effects that could present a potential risk for isolation caps in shallow water, and should be accounted for in the design. The planning of cap installation should also factor in the expected seasonal weather patterns.

Waterway Usage

It is important to know the types of vessels that will be using the waterway where your cap is located, as vessels have different drafts and create different stresses on the bottom sediment (e.g., propeller wash). Required navigational depths in commercial and recreational boating areas may limit the cap thickness that can be installed. It is also important to know if dredging for navigation purposes will ever be required or if any other plans exist.

Debris

Debris in the vicinity of the cap area may need to be removed prior to cap placement. Large debris on the surface could interfere with the cap integrity. Debris that is below the surface (sometimes to be buried by the cap material) can be problematic, as the consolidation of the cap and underlying sediment may lead to this debris penetrating the cap over time. However, a design may determine with a sound rationale that it is best to leave debris in place. Regardless, waterways commonly contain debris and the presence/absence of this should be determined and accounted for in the design well in advance.

Rate of Deposition

It is important to know the rate of deposition of sediment into the area of interest. This can be helpful in terms of establishing whether or not a habitat layer on top of the cap will be necessary and what the expected rate of accumulation on the cap will be.

5.3.4 Surface Water

Water Depth

Water depth affects the degree to which waves or ice interact with the capping surface and the degree of scour from vessels on the cap material. This, in turn, affects the constructability of the cap and the types of equipment and cap materials selected for placement.

Bathymetry

Bathymetric information is also required when designing a cap. Bathymetry examines the surface to be capped and determines if there are any stability concerns with sloping. Thicker caps also need to consider the sloping of the edges of the cap to form a transition zone, which eliminates the potential for slope cap failure and erosion. It is also important to know the stability of the underlying sediment in these sloping areas. Caps add large masses of materials, so the sediment slope stability becomes important. In terms of CAD, natural depressions reduce the need to excavate prior to disposal of contaminated sediment. Areas that are flat or have gentle slopes are preferred for CAD, as they reduce potential horizontal migration upon placement of the contaminated sediment.

Hydrodynamics

Wave-produced orbital motion through the water column, which can serve to agitate bottom sediment or cap materials, is generally negligible at a depth equal to one-half the existing wave length (Masselink and Hughes 2003). Waves can also serve to induce a pumping-like force in the upper few centimetres of the sediment caps (Eek et al. 2008). Wave force affects the constructability of the cap and the type of cap materials selected for placement.

Currents above the sediment/water interface can erode bottom particles, depending on the velocity and the grain size and lithology of the material. Currents may or may not follow the wind direction and are often complicated due to the interaction of seawalls, bulkheads, and other underwater structures. Tidal currents are obviously more predictable in terms of direction and timing.

5.3.5 Hydrogeological

Groundwater / Surface Water Interface

Aquatic sediment environments are often not static in the vertical dimension. Some form of flow is usually present between the porewater in the underlying sediment and the overlying surface water, and can be upward or downward. Establishing this direction as well as quantifying the flux is essential for cap design, as this affects the transport of contaminants through the capping materials. The vertical gradient and flux are important pieces of information, as contaminated sediment environments that are dominated by diffusive transport can be chemically contained by sand caps for hundreds of years (Murphy et al. 2006).

When vertical groundwater/porewater movement is not present and diffusion is the rate-limiting transport mechanism of contaminants through the cap, passive materials such as sand can be effective capping materials due to an increased diffusive path length, and hence increased dilution, above the capped sediment (Eek et al. 2008). However, there are many instances where mechanisms other than diffusion are prevalent: natural groundwater upwelling, induced porewater upwelling by the weight of the new capping materials, and bioturbation. It should be noted that the effects of upwelling due to the weight of the cap can be minimized by using a cap that has sufficient thickness to contain the entire volume of porewater that is squeezed out of the sediment (Palermo 1998). However, with the use of amendments becoming more common, this concern can be mitigated. This is particularly useful for sites where groundwater upwelling is negligible or under a negative gradient.

A common and relatively simple method utilizing a seepage meter is described by Lee (1977) and has been utilized by the authors on more than one occasion to measure porewater flux (see Figure 5-4). Other means in shallow systems include the use of piezometers as well as more sophisticated seepage meters. These also allow for samples of the porewater quality, if desired.

Figure 5-4: A seepage meter of Environment and Climate Change Canada (courtesy of ECCC).

5.4 Construction

Caps are designed to physically and chemically isolate contaminated sediment and limit the exposure to aquatic organisms and the aquatic environment. The composition of caps and the depth of caps are the primary design elements. To determine these elements, a number of variables need careful consideration, including sediment and site characteristics and specific engineering factors, as noted next.

Caps should generally be constructed in thin lifts to avoid overstressing small areas of the underlying contaminated sediment. Lift thickness considerations will depend on the overall thickness of the cap and the bearing strength of the underlying sediment, which is site-specific. The idea is to start gradually and slowly build up the cap in layers, and methods that displace or mix with the contaminated material should generally be avoided. Equipment used can also produce constraints. For example, the minimum thickness of a layer using a clamshell bucket for delivery is on the order of 0.15 m, while other means, such as sand spreaders, can apply material in thinner lifts.

5.4.1 Estimating Stresses Exerted on Cap from Propellers, Waves, River Currents, and Tidal Currents

Common stresses placed on caps include propeller wash from boats and ships, currents, and orbital agitation from waves (wind generated and vessel generated). Cap materials are at risk when the critical shear stress required for erosion of the cap materials is exceeded by the stressor at play.

Stresses exerted on caps from boats and ships can be estimated utilizing a common formula developed by Blaauw and van de Kaa in Palermo et al. (1998), which requires information on engine horsepower, propeller diameter, draft, and site bathymetry. The formula allows the calculation of bottom velocities generated by propeller wash, and these can then be converted to a shear stress, which is then related to the critical shear stress for erosion of the capping material.

In cases where a navigational channel occurs in close proximity to an isolation cap, the characteristics of the channel (i.e., width, depth, and vessel turning radius) can have an effect on the force exerted on the capping material. A guidance document that covers these variables is available from Transport Canada (2009).

Stress exerted on caps from currents and waves can be estimated by deploying current meters and calculating the subsequent shear stress using the logarithmic profile method (law of the wall) (Masselink and Hughes 2003). This approach for measuring currents only provides information for the period in which the instruments are deployed as well as the specific location of the instruments; so modelling is usually required to extrapolate the information to more extreme periods of wind force that may occur over the longer term or at less frequent intervals.

The US Army Corps of Engineers (USACE 2014) provides advice on modelling to help evaluate the long-term fate of sediment or cap deposits, as well as other guidance. The reader is also directed to the work of Soulsby and Clark (2005), who developed a method of calculating the combined bed shear stress of waves and currents using explicit algebraic equations.

Although many models can be used with just wind data and bathymetry, this is not advisable. Instead, current meters, such as Acoustic Doppler Current Profilers, allow verification and calibration of the model before any extrapolation is conducted. This will allow a “design wind” to be chosen and then modelled using a model that has been verified by in-field instrumentation.

Currents generated by tides will need to be measured, and again a "design tide" may need to be chosen to represent more extreme events, with consideration of the possible effects of climate change.

5.4.2 Estimating the Critical Shear Stress for Erosion of Cap Materials

Establishing reasonable estimates of the critical shear stress for granular materials is relatively straightforward; it can be found utilizing mathematical expressions of the Shields curve. For example, daSilva and Bolisetta (2000) developed an approximate analytical expression for the Shields diagram, and this is utilized in Graham et al. 2013.

Non-cohesive materials behave in a much more complicated manner due to cohesive forces between the sediment grains, and the best way to understand the critical shear stress associated with these is to conduct *in situ* testing using portable flumes or extract cores for later testing in laboratory-based flumes (see Figures 5-5, 5-6, and 5-9).

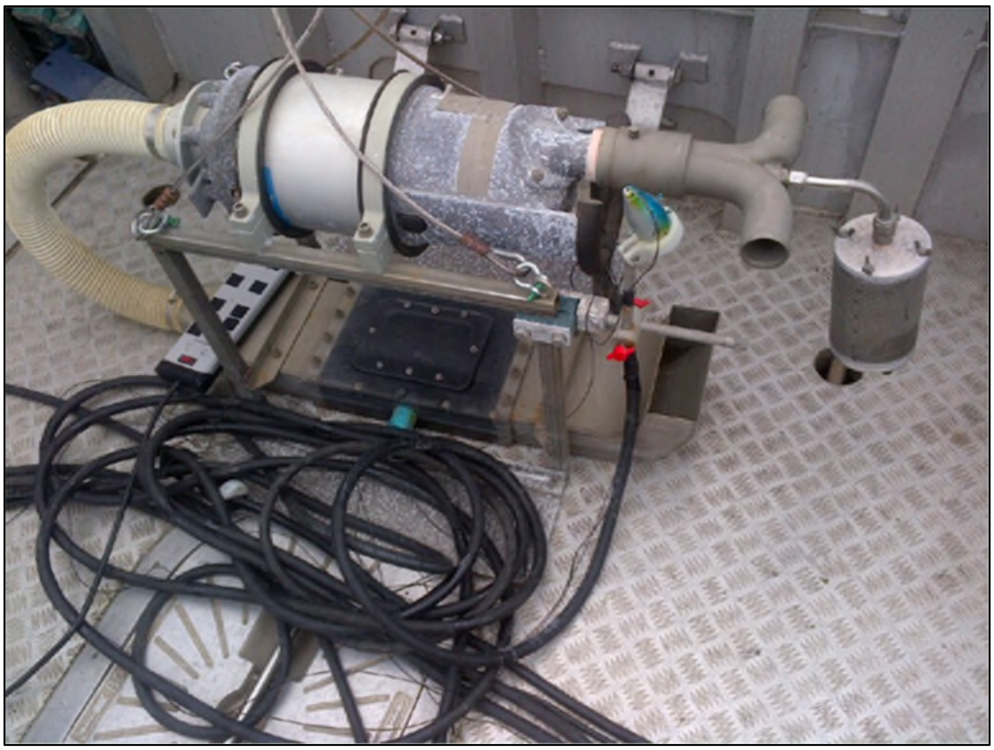

Figure 5-5: A Portable flume of Environment and Climate Change Canada (courtesy of ECCC).

Figure 5-6: A Portable flume of Environment and Climate Change Canada (courtesy of ECCC).

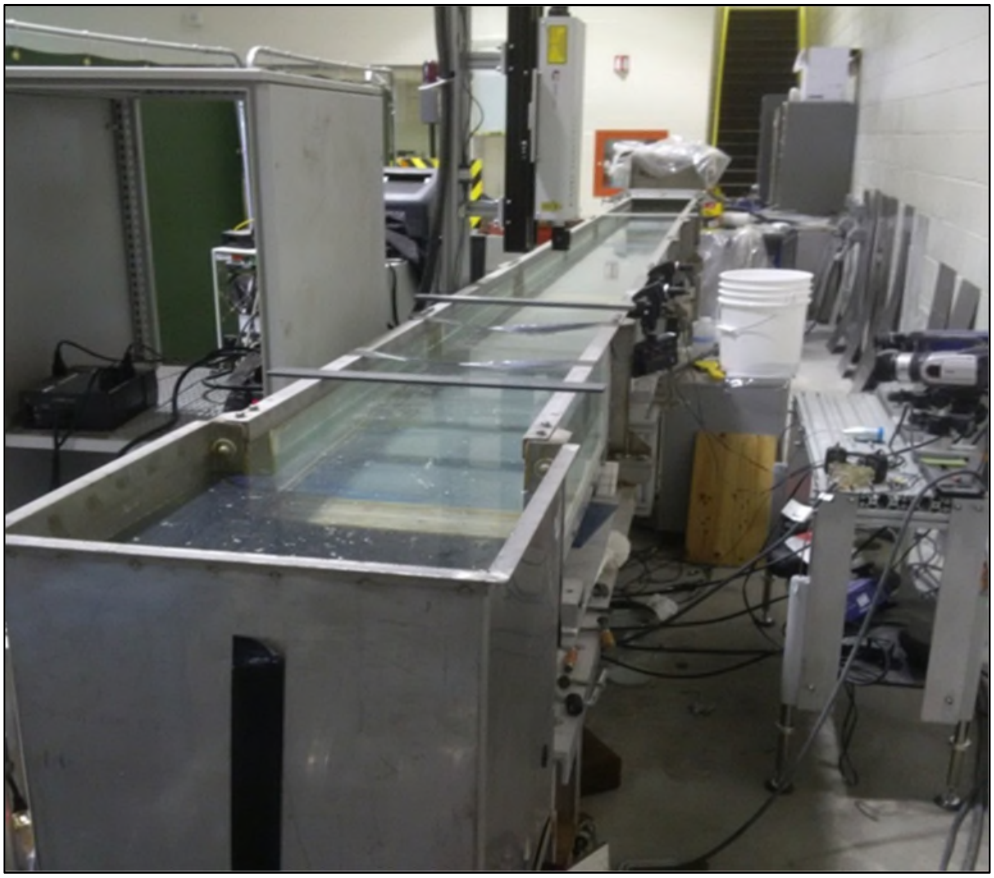

Figure 5-7: A linear flume of Environment and Climate Change Canada (courtesy of ECCC).

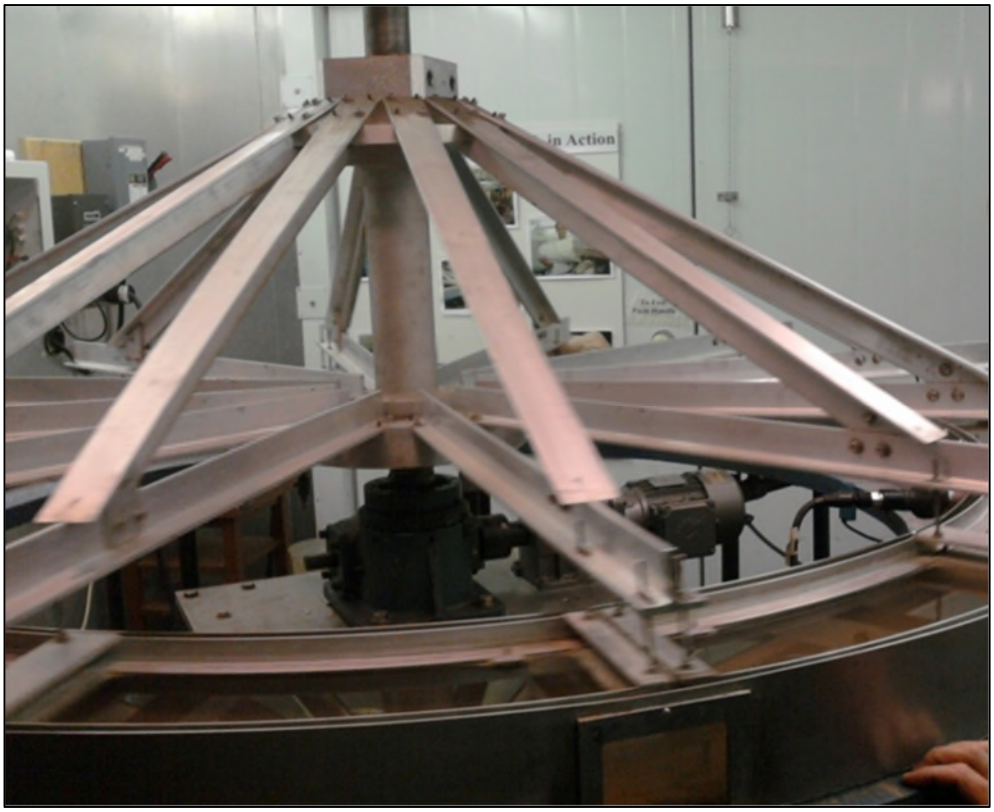

Figure 5-8: A circular flume of Environment and Climate Change Canada (courtesy of ECCC).

Figure 5-9: A core sample for use in the circular flume of Environment and Climate Change Canada (courtesy of ECCC).

5.4.3 Contaminant Flux Modelling

Caps must be designed to retard and control the rate of contaminant flux such that the cap objectives related to chemical isolation are maintained in the long term. This aspect of design relies on contaminant flux modelling. Reible (2014) presents a good detailed overview of contaminant transport modelling concepts. In order to properly assess and design caps for contaminated sediment, models are needed. The models are used to estimate the fate and transport through various layers and then design scenarios. Models are well developed in the groundwater flow field; however, not so well developed for contaminated sediment caps. According to Reible (2014), the reasons for this is that the benthic layer that develops at the cap surface is subject to significantly different transport processes and rates than those in groundwater or in layers of sediment under the cap. In addition, there are sometimes multiple layers in a cap, sharp gradients in redox conditions in the cap layers, the presence of bioturbation, and the effects of erosion, deposition, and consolidation. Due to the small vertical scale of interest, the fate and transport of contaminants in sediment caps can usually be modelled using a one-dimensional advection diffusion reaction equation with sorption. Dr. Danny Reible has developed a model, which has evolved from a spreadsheet to a full interface model (CAPSIM) and can be accessed at:

https://www.depts.ttu.edu/ceweb/research/reiblesgroup/downloads.php

A number of sediment management projects have utilized this model in their design.

5.4.4 Key Modelling Processes

The approach generally involves the assumption that a cap is composed of multiple homogeneous layers where various processes occur. Any models used in designing and assessing the performance of caps must consider these processes.

Sorption

Sorption is the adhering or attaching of contaminants to solid particles in the cap matrix. If contaminant concentrations in the surrounding water drop, contaminants can desorb; however, it also depends on the strength and nature of the attachment bond. Adsorption causes a “retardation” of levels of contaminant relative to porewater/upwelling groundwater. The adsorption process can be linear or non-linear. Caps composed of granular material would have very little adsorption, because the presence of fines and organic matter is usually very low.

Advection

The transportation of dissolved contaminants due to fluid movement also causes dispersion due to particles in the cap matrix, creating varying pathways as a contaminant is transported through by porewater. This causes a longitudinal and transverse spreading of the contaminant plume.

Decay

This is the degradation of contaminants over time (e.g., the de-chlorination of chlorinated solvents). This is a complicated process that is affected by such factors as the contaminant, the microbial environment, and the presence and absence of oxygen. The simplest reactions are first-order decays. Degradation of contaminants in caps is generally problematic, as the cap itself reduces the influx of organic matter and nutrients, which are important to microbial growth, which in turn is important for degradation. The formation of anaerobic conditions also slows down the degradation of many contaminants; however, anaerobic conditions do encourage metals containment and sequestration. Degradation of contaminants in caps is an area that requires further research. For most designs, it is appropriate and conservative to simply ignore decay.

Boundary Conditions

All flow models require boundary conditions to define the conditions at the edges of the spatial environment. In the case of sediment caps, it is important to define initial boundary conditions.

Diffusion

Molecular diffusion is the migration of a substance due to random molecular motion, and can be important in the modelling of contaminant transport through a cap. It is a function of temperature, viscosity of the fluid, and the size of the molecule (Reible 2014) and produces a flux direction from high to low concentration. Reible also points out that in a sediment cap, molecular diffusion must be corrected for the tortuosity and porosity of the diffusion pathways in the porous medium. There are various ways of doing this, some of which are described in Reible (2014), and these should be covered by whichever model is used in the design. When diffusion is the rate-limiting transport mechanism of contaminants through the cap, passive materials can be effective capping materials (Eek et al. 2008) due to an increased diffusive path length above the capped sediment. However, there are many instances where mechanisms other than diffusion are prevalent: natural groundwater upwelling, induced porewater upwelling by the weight of the new capping materials, and bioturbation.

Benthic Boundary Layer

A capping model needs to consider the transport of the contaminant mass through the sediment/water interface and the turbulence and velocity of the overlying waters. Bioturbation is an important consideration that must be included in any modelling.

Transient vs. Steady State

In general, a transient state is an interim state where a system produces output that is variable, depending on the inputs. A steady state exists when the system’s output is no longer variable (i.e., output does not change over time). According to Reible et al. (2008), a serious limitation with transient models is the assumption that the analytical solutions are applied to the chemical isolation layer of the cap. However, the protectiveness of a cap is largely defined by the contaminant behavior in the biologically active zone, which is subjected to much differing transport processes and rates than the underlying layers.

Transient models are still useful as (a) first approximations for a single isolation layer, as analytical solutions are readily available, and (b) an estimate of concentration profiles in a cap before the contamination reaches the bioturbation layer. An alternative approach is to consider only steady-state conditions, where is it possible to consider the complexities of the upper boundary, but still employ relatively simple analytical solutions to the chemical transport equations. This is a conservative approach, as the flux of contaminants at the steady state is at the maximum.

Deposition

Depending on the aquatic environment of interest, deposition may be occurring and should be considered in the modelling. Reible (2014) cautions that it is likely unrealistic to assume measured depositions will continue to occur for long periods, as these can result in unrealistic cap thicknesses. Instead, a definition of what could be an equilibrium sediment surface could be used.

Data Requirements

Cap modelling requires a large amount of input data, some of which is site-specific and some in which defaults can be used. As a reviewer of a design involving the use of cap modelling, the reader should refer to the aforementioned CAPSIM model, produced by the Reible Group out of Texas Tech University, for an idea of the inputs and requirements, and assess how the design under review has addressed them. The design should discuss what parameters were adjusted and how they were adjusted to vary the output (e.g., breakthrough time) in order to meet the requirements of the project.

The reader is directed to Reible (2014) for more detailed descriptions of the equations used and other useful approaches and references.

5.4.5 Construction Equipment and Materials

When placing an isolation cap, the goal is to accurately place the required material in a controlled manner, avoiding any mixing with the contaminated sediment that is being managed. It is also desirable to avoid any resuspension of contaminated materials into the water column as well as creation of excessive suspended solids from the capping materials themselves.

Cap Materials

The cap design should determine the appropriate cap material, based on many of the concerns outlined above (cap stability, contaminant migration, bioturbation etc.). Two key physical traits of the cap material will be grain-size distribution. This will affect the effectiveness of cap placement in the short term and the cap stability in the long term.

Where amendments are used, the cap material density, cap material grain size distribution, and the method of cap placement will affect how uniformly the amendment will be distributed throughout the cap upon application. When amendment and cap matrix densities differ greatly, stratification can occur and amendments may even be lost during application.

The chemistry of any candidate cap material must also be considered in order to confirm that chemical concentrations (particularly inorganics) are acceptable for deposition at the site. Remote locations can present some challenges to obtaining capping materials; most of the challenges in this regard are related to higher costs associated with transportation. Capping materials used for the isolation of contaminated sediment need to be free of contaminants themselves, and thus the source is important. Most sites source material from local pits and quarries, and generally the only concern with these is the concentration of naturally occurring metals. Materials from these and other sources must be carefully examined and tested to ensure they are appropriate. Testing of the materials should include:

- Test data that demonstrates the source is of suitable physical and chemical quality and available in the quantities necessary to meet the requirements of the project,
- Chemical and physical tests (carried out at certified laboratory facilities), including the required testing frequencies, which should be specified on a cubic-metre basis (e.g., 1 sample/3,000 m^3), and
- A minimum number of locations to sample within a stockpile (if capping material is stockpiled), a minimum number of subsamples, a minimum number of composite samples, and minimum volume. Capping material (e.g., sand), if stockpiled, should be obtained from a point in the stockpile deep enough to be uninfluenced by precipitation washing out the fines.

One other consideration is that the grain size of capping materials can affect sorptive capacities, the amount of turbidity during deployment (as fines content is increased), and erodibility.

Geomembranes, which serve to prevent flow through caps, are not commonly employed in cap construction. Geotextiles can be used to increase the structural stability of caps and segregate different cap layers in order to prevent mixing.

Equipment

The placement of caps can be conducted using conventional dredging equipment such as clamshell buckets (see Figure 5-10) or even excavator buckets. Other systems utilized are tremie tubes for a target placement at the discharge of a pipe; or spreaders (similar to winter salters/sanders) which “rain” the cap material down through the water column; direct water-jet washing from barges; or surface release from barges. The delivery mechanism generally depends on site conditions such as water depth and currents; physical characteristics of the *in situ* contaminated sediment, which in turn determines the material being delivered; and the type and thickness of layer being placed. Further examples and discussion on the various techniques can be found in Palermo (1998a) and Bailey and Palermo (2005). With some layers, it is not desirable to have the material fall for great distances in the water column due to differential settling velocity (discussed further on). Turbidity created during placement can also be reduced by lowering the point of release.

Whatever equipment is chosen, accurate positioning is very important. The method to locate and control capping position should include a range of electronic positioning systems. The horizontal accuracy of the system chosen should be provided (e.g., +/- 1 metre). Real-time kinematic GPS, or equivalent, is the current standard. Accuracy of water depth should also be specified (e.g., +/- 0.1 metre).

Figure 5-10: Capping using a mechanical clamshell (courtesy of ECCC).

Figure 5-11: Spreader used for capping at the Fox River site, Wisconsin (courtesy of J.F. Brennan Company, Inc.).

Figure 5-12: Flat-pan spreader barge used at Mock's Pond, Indiana (courtesy of M. Palermo and C. Vogt).

Figure 5-13: Angled-plate hydraulic spreader barge operating at the Fox River site, Wisconsin (courtesy of M. Palermo and C. Vogt).

Common Capping Amendments

Amendments can be required to meet environmental objectives or to handle constraints (e.g., on thickness). Common amendments include carbon, biochars, reactive core mats, and organo-modified clays.

These amendments all rely on an organic fraction to adsorb contaminants, and most native sands will have some organic component, albeit a small one. The tendency for hydrophobic organic contaminants to adsorb to organic fractions is well documented in the literature (Murphy et al. 2006). Performance of the various carbon-based amendments does vary, however. Murphy points out that amendments such as coke and activated carbon have demonstrated non-linear sorption isotherms and extremely high equilibrium sorption partition coefficients for PCBs. It has also been shown that PAHs and PCBs bound to coke and activated carbon are less bioavailable than when bound to organic carbon.

Sorptive capacity is dependent on the type of amendment (or the characteristics of the capping material), its surface area, and the chemical makeup of the water / porewater that is being exposed. Sorptive capacities should be measured on a site-by-site basis using column breakthrough tests.

In general, activated carbons have the highest sorptive capacity due to their extremely high surface area; however, they are a manufactured product, and as such, come with a higher price tag. Activated carbon is integrated into a number of commercial products designed to mimic the fall velocity of common capping materials such as sand. Many of these products are designed so that the surrounding material (in which they are encased) dissolves, leaving just the activated carbon.

Biochars are generally produced from animal dung, which is thermochemically decomposed using pyrolysis to form a charred carbon product. Gomez-Eyles et al. (2013) evaluated a number of carbon sources, including activated carbons and unactivated biochars, for their ability to adsorb organic contaminants, including PAHs. The study indicated that the ability for activated carbons to adsorb organic contaminants was consistently one order of magnitude higher (and often closer to two). While biochars are less costly, significantly more mass is required to achieve the same adsorptive capacity as activated carbon. Gomez-Eyles et al. (2013) also discussed the presence of native black carbon material (e.g., soot and coke). These materials are very common in contaminated sediment and soils impacted by PAHs. The presence of the black carbon along with sorptive attenuation effects could result in unactivated biochar amendments having little to no effect on organic contaminant bioavailability, significantly reducing the ability of the biochar to adsorb contaminants. This is an area that requires more research.

Organo-modified clays (OMCs) are clays subjected to cation exchange sodium (Na) for organic molecules. These molecules then serve as organic sorbents. According to Reible (2014), the sorptive capacity of OMCs is less than that of activated carbons, but the potential for fouling of the OMCs is less than one-half of that for carbon. In general, activated carbons are more effective sorbents of dissolved hydrophobic organic contaminants and OMCs are more effective sorbents of NAPLs. Where NAPLs are present in part of an area to be capped, the process for potential contamination migration should be carefully considered. NAPLs may be mobilized by consolidation-induced or groundwater-induced advective forces. OMCs can also be placed into mats when space or vessel draught is an issue.

It has been noted by several researchers that ingestion and foraging of benthos in contaminated sediment where contaminants have been concentrated into amendments is a concern. This highlights the need to consider the potential contact of benthos with layers of the cap where treatment is occurring. Protective measures can include a physical barrier or minimum depth of cover over top.

Mixing vs. Layering

Where amendments are being used in capping materials, they can be placed as discrete thin layers or mixed with sand or some other capping material (see Figure 5-14). The key is to ensure that the volume of the amendments and surface area presented is adequate to achieve the capping objectives.

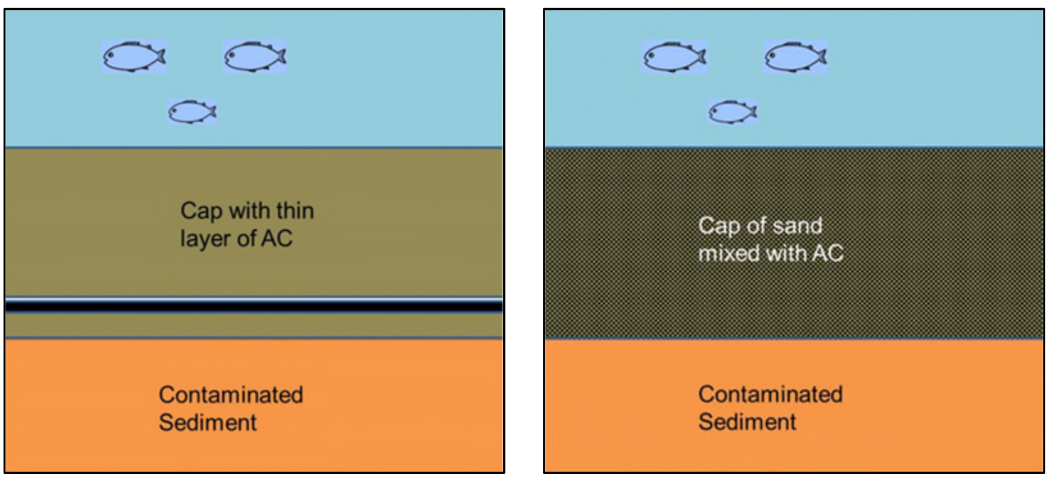

Figure 5-14: Example of different ways of applying an amendment.

Permeability Control Layers

Permeability can be controlled within caps through the use of low-permeability layers; however, such layers serve to divert rather than remove groundwater upwelling. Upwelling groundwater will simply migrate around or find an alternative pathway. These layers would only be effective with a CAD cell or small isolation cap where they could be used to divert groundwater around the placed contaminated sediment and capped area.

Erosion Control and Habitat Layers

Once erosive forces (discussed under site conditions) are determined, the need for armouring and the type of armouring can be determined. Armouring consists of placing a protective layer or layers which can be made up of granular material (e.g., gravel, clear stone, or boulders) or manufactured products (e.g., marine mats). Smaller grain sizes can be placed on top of the armour layers to encourage the rehabitation of the area; however, these habitat layers are exposed to erosive forces. Armoured caps generally attract greater diversity of macroinvertebrates than straight sand caps (Palermo et al. 1998). The recolonization occurs as the interstitial voids of the armour layers are filled with new sediment.

Different Placement Methods

The effect of amendment densities and fall velocities can further complicate the delivery and placement of amendments when combined with the delivery mechanism. Release depths and delivery mechanisms can alter the final amended cap mixture, and this must be considered in the design. All the commonly used amendments (e.g., activated carbons, biochars) and other lesser-used products (e.g., compost, mulch, and other organic sources) are less dense than sands. When being mixed with sands for use in a cap, this difference in fall velocity must be accounted for, as it can result in uneven delivery and placement, which in turn can decrease the effectiveness of the cap. Presoaking activated carbon for at least eight hours increases its density and its fall velocity to a certain degree. As noted previously, commercial products that incorporate amendments but are encapsulated within a material designed to mimic the fall velocity of the capping material, are becoming increasingly available.

Edge Transitions

An edge transition zone should be provided at the cap edges to minimize risk of localized instability or lateral squeezing of the sediment at the cap perimeter. An edge transition zone includes the edge of the cap and allows cap thickness to be gradually reduced. The slope to bed sediment and a minimum sand thickness at the limit of the edge transition zone should be specified in the design (see Figure 5-15).

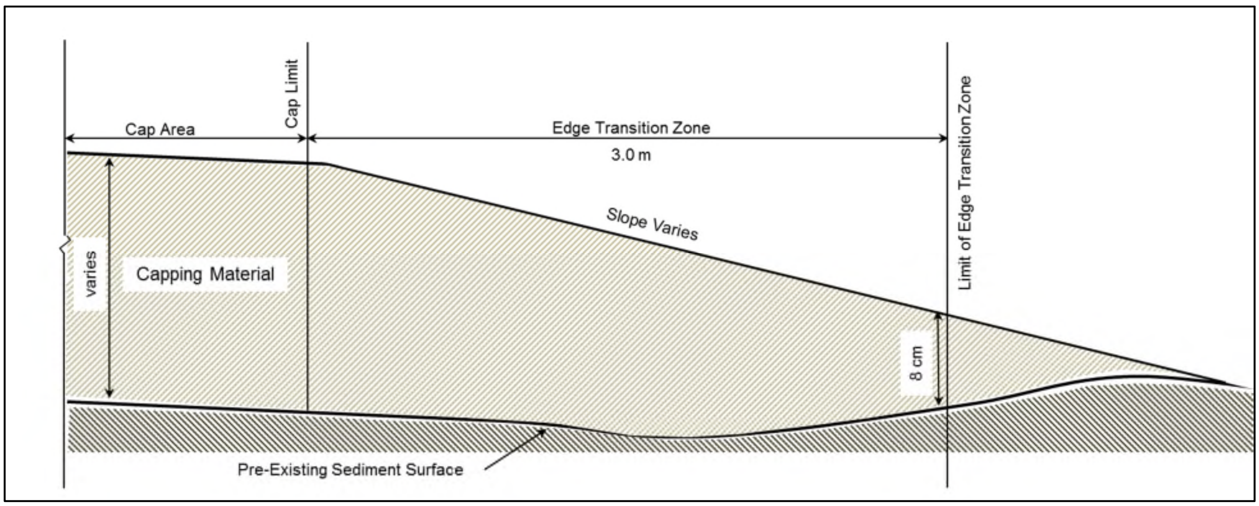

Figure 5-15: Edge transition example, as used in Peninsula Harbour thin-layer capping project in Marathon, Ontario.

Resuspension Due to Cap Placement

As with all contaminated sediment projects, the potential for resuspension of contaminated sediment is a concern, and one that should be minimized as much as possible. Resuspension concerns related to cap placement vary, depending on the grain size and density of the contaminated sediment. The main methods for controlling resuspension are related to the means by which the capping materials are applied. Lyons et al. (2006) evaluated contaminant resuspension potential at two sites on the east coast of the United States. They found that the resuspension of contaminated sediment was measurable but relatively low when capping was conducted over uncapped sediment, and the magnitude of resuspension decreased with successive capping layers. They concluded that resuspension during capping can be minimized by placing the cap material in lifts, using techniques that minimize potential disturbance. Subsequent lifts can be placed more aggressively than the initial one. Silt curtains can also be utilized to control the spread of resuspended material in discrete or whole areas of isolation capping. Silt curtains are generally useful for areas with water depths up to 10 m (Ogilvie et al. 2012). After this, they become more challenging to install and maintain. Common problems include gaps at the bottom, which allow for the escape of suspended sediment along the bottom or scouring caused by current flows through this gap area. The stability of silt curtains is also limited by currents. Further information on silt curtains can be found in Ogilvie et al. 2012.

5.4.6 Construction Monitoring

As with all construction projects, monitoring must be conducted during construction to determine whether the cap is composed of the correct materials, is placed correctly, does not mix with the contaminated sediment, and does not result in excess resuspension or turbidity in the water column. Monitoring must also determine whether consolidation occurs as predicted through such methods as bathymetric surveys and / or surveyed settlement plates.

5.5 Long-Term Monitoring and Maintenance

5.5.1 Physical Monitoring

The physical integrity of caps should be monitored over time to ensure the cap is not eroding and slumping in any unwanted manner. This monitoring should occur at least once per year for a few years, and then at longer intervals until long-term stability has been confirmed. Monitoring plans should also include monitoring after any storm events that go beyond a threshold of intensity established in the design assumptions. Accumulating sediment on top of the cap should also be measured to determine its chemical composition.

5.5.2 Chemical Monitoring

The chemical monitoring of isolation caps primarily involves the monitoring of porewater within different levels of the cap as well as above the upper most layer over time, in order to verify that the modelling was reasonably accurate and early breakthrough or breakthrough in unacceptable levels is not occurring. Monitoring should be targeted at least yearly and can be tapered off over time to less frequent intervals as confidence in the cap is gained. Conventional methods for collecting porewater samples for chemical analysis are complicated, expensive, and not always representative of the intended porewater location or depth interval. More recently developed passive sampling techniques provide a simple, reliable, and representative approach to accurately measure concentrations of hydrophobic organic compounds (HOCs) in sediment porewater.

One of the most common types of passive sampler used in the measurement of HOCs in sediment is a low-density polyethylene (LDPE), polyethylene (PE), or polyoxymethylene (POM) rod that sorbs HOCs from the adjacent porewater into the sampler material (ESTCP 2016). The sampler is usually encased in a protective perforated casing or mesh. (see Figure 5-16).

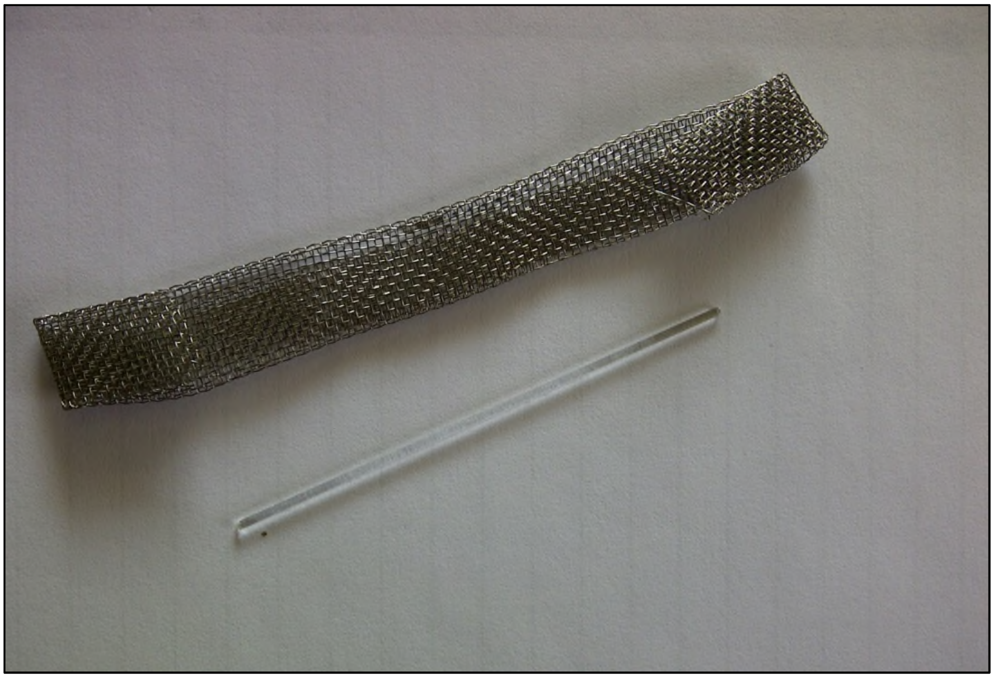

Figure 5-16: Polyethylene rod and example of protective casing (courtesy of ECCC).

The sampler is inserted to the depth of interest and then removed from the sediment after a set period. The HOCs in the sampler are then extracted using a solvent, and the concentrations of HOCs in the solvent are measured by an analytical laboratory. Polyethylene has a strong affinity for HOCs, so only a small amount is needed to achieve a detectable level in the solvent that was used to extract the HOCs from the sampler. The amount of target chemical that accumulates in the sampler, at equilibrium, is linearly related to the concentration of the contaminant of interest in the porewater The porewater concentrations of HOCs are calculated based on the contaminant partitioning coefficients, the mass of contaminant in the solvent used to extract the HOCs from the passive sampler, the mass of the passive sampler itself, and the degree of equilibrium achieved between the sampler and porewater for the compounds of interest. The methods for calculating the porewater concentration are outlined in ESTCP (2011).

The most challenging component of the analysis is determining when the sampler has reached equilibrium, which is dependent on a number of site-specific variables. Equilibrium times can be determined using laboratory microcosms to represent the cap, or more commonly, using performance reference compounds (PRCs). PRCs spanning the range of octanol-water partition coefficients (K_{ow}) of the compounds of interest to be monitored in the porewater are preloaded into the sampler at known concentrations before deployment. During deployment, the PRCs equilibrate over time between the adjacent porewater/sediment environment and the passive sampler. After collecting the samples, the fraction of each PRC remaining in the sampler compared to the original concentration is used to evaluate how close to equilibrium the passive sampler is for each PRC. Further information on the use of PRCs is provided in ESTCP (2011).

When metals are a concern, their concentration in porewater can be measured using diffusive gradients in thin films (DGT) passive samplers. DGTs are kinetic samplers, where the porewater concentrations are calculated based on the duration of time the sampler is deployed, and therefore do not need to attain equilibrium between porewater and sampler.

Passive samplers can also be used above reactive core mats if some sediment is placed above the mat to allow for sampler deployment and to act as a medium for porewater contaminants to accumulate. If these samplers indicate that contaminated porewater is leaching through, additional sampling is likely warranted, as well as re-examination of the design through the adaptive management plan.

5.5.3 Ecosystem Monitoring

Other monitoring designed to assess the recolonization of the area by aquatic plants, invertebrates, and fish should also be conducted, with the objective that the area will return to being a part of the local ecosystem.

5.5.4 Administrative Controls

Administrative controls are a key part of most capping projects. If possible, having vessels avoid capping areas will help prevent physical disturbance of caps (e.g., by deployment of anchors). Caps should be marked on nautical charts and maps, and perhaps marker buoys should be deployed, so that the presence of caps is well known. The owner/administrator needs to be committed to ensuring that monitoring and maintenance of the cap is carried out into the future.

5.5.5 Adaptive Management

The purpose of adaptive management is to identify and outline contingency measures that will be taken in case the long-term monitoring data indicate that capping is ineffective in reducing risk as projected. The adaptive management plan should include the following:

- Measures to implement as needed (e.g., additional administrative controls, placement of additional clean sediment to exposed areas),
- Time frame to implement the adaptive management actions,
- Party responsible for funding and implementation, and
- Monitoring of measures implemented.

5.6 Challenges and Uncertainties

Probably the largest uncertainty associated with isolation capping is the modelling of cap performance and possible breakthrough time. Isolation caps are often comprised of multiple levels, and the complex interaction between the COCs, capping materials, groundwater and porewater, amendments, and microbes is difficult to model. Future environmental conditions present another uncertainty. This is usually addressed by using design criteria like the 100-year storm; however, with more extreme weather, the frequency of such an event may need to be increased. Malfunctions and equipment breakdown present another uncertainty for any project.

A robust design must account for some of these uncertainties where possible. The design and associated cost estimate must also include sufficient construction contingency to cover a reasonable prediction of extra costs. If sediment management challenges prevent the project from successfully meeting its intended goals, then the adaptive management plan should be implemented.

6. Thin-Layer Capping (Enhanced Natural Recovery)

It is the intention of the authors that this section be read in conjunction with the discussion of site characterization and long-term monitoring included in Section 2 and 9. It is noted that the subheadings are the same in this section, but this section includes specific information on site characterization and long-term monitoring pertinent to thin-layer capping.

6.1 Introduction

Thin-layer capping (TLC) is the placement of a thin layer (up to 15 cm) of clean material, usually sand, on top of contaminated sediment in order to reduce chemical concentrations in the bioturbation zone and accelerate natural recovery processes to acceptable levels. The expectation is that the clean capping material will mix with contaminated sediment over time, reducing the surface chemical concentrations. Thin-layer capping is also referred to as thin-layer placement or enhanced natural recovery (USEPA 2005; ITRC 2014).

There is a clear distinction between the use of TLC as a remedial approach and thin-layer backfilling (residuals capping/cover) post-dredging. TLC is applicable to addressing *in situ* contaminated sediment where low-level contamination would extend to deeper depths in the sediment profile. The objective is to form and maintain an acceptable clean sediment surface with concentrations of COCs below the clean-up levels. In contrast, post-dredging thin-layer backfill is a placement of a thin layer of clean material on top of residual contaminated sediment.

TLC is also distinct from isolation capping, given that isolation caps are generally thicker than 15 cm and used to isolate contaminants.

6.2 Goals and Objectives

The goal of TLC is to reduce contaminant concentrations in the bioturbation zone to acceptable levels in order to protect aquatic organisms and human health. This risk reduction must be achieved within an acceptable, predetermined period. TLC is often used at sites where natural recovery would take too long to reach acceptable risk levels.

With TLC, the contaminated sediment is left in place undisturbed. TLC relies on the mixing of the cap material with the underlying contaminated sediment to achieve the clean-up level desired. TLC is not intended to completely isolate the contaminated sediment like isolation capping. TLC can be used at sites where:

- human health risks and ecological risks are low to moderate,
- the speed/rate of natural processes (i.e., degradation, transformation, and burial) to reduce the bioavailability or toxicity of contaminants in sediment would take too long to reach acceptable risk levels, and/or
- residual contaminated sediment is present from environmental dredging (known as thin-layer backfilling).

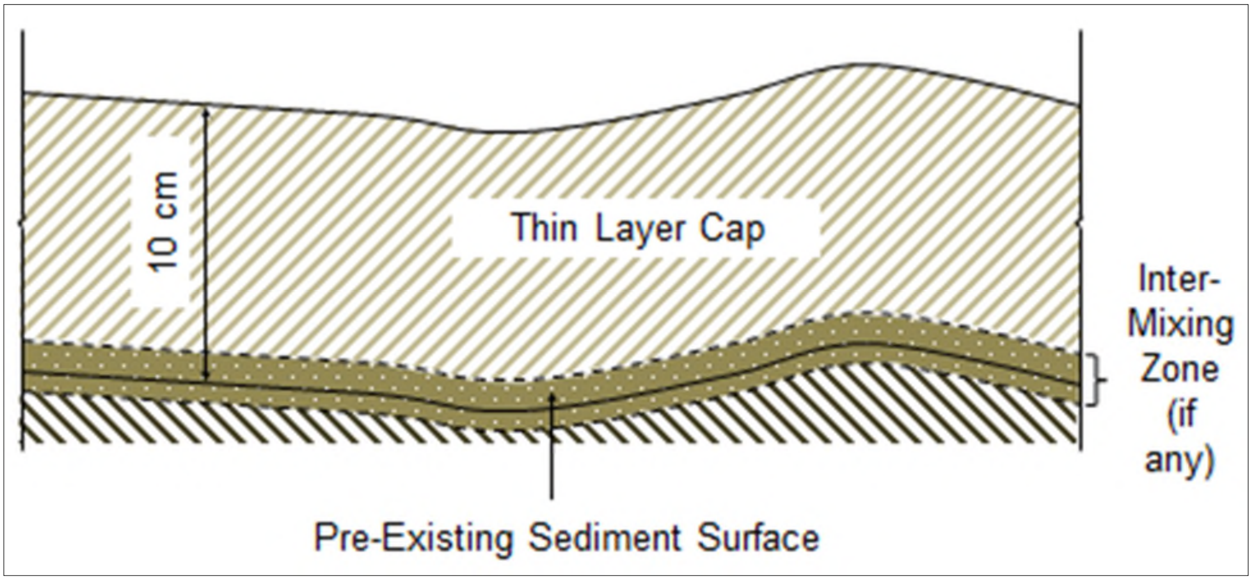

Figure 6-1: An example of a 10 cm sand thin-layer cap.

6.2.1 Performance Standards and Clean-Up Levels

The design will have to meet the established performance standards and clean-up levels for a TLC project. Clean-up levels should have been established during the risk assessment / sediment management options assessment. Clean-up levels are numeric limits or criteria, typically sediment concentrations that will determine the area to be covered with a thin layer of capping material. Performance standards for TLC can include the following:

- Covering of all sediment having contaminant concentrations above a specific action level (clean-up level),
- Cap thickness requirements,
- Limits on contaminated sediment resuspension generated by the capping activity, and
- Limits on the release of fines from the capping material from the capping operation.

6.3 Characterization of Site

It is imperative for any successful TLC design to have a detailed understanding of the physical characteristics of the site and the characteristics of the contaminated sediment, as they heavily influence the design of the project. Some sites (e.g., sites affected by erosion, heavy vessel traffic) are not suitable for TLC, and as such, sufficient local hydrological information needs to be gathered and included in the sediment management options evaluation process. Ensuring that sufficient information has been gathered and the design work has properly utilized this information helps to confirm the adequacy of the design. Guidance on site characterization is found in Section 2.2.

Effective TLC requires a thorough understanding of the physical characteristics of the site: water depth, sediment grain size / stratigraphy, bathymetry, current strength, current patterns, wave energy, climate, tides, and waterway usage. Detailed guidance on these parameters is found in Sections 2.2 and 5.3.

6.3.1 Sediment

Proper TLC design requires characterization of the sediment. Contaminant levels in sediment must be characterized in order to delineate the area that needs to be capped. If soft sediments are present, it must be determined if the existing sediment can support the weight of a thin-layer cap.

Geotechnical

The sediment must have sufficient strength to support the weight of the thin-layer cap without lateral displacement of the sediment. Geotechnical properties (grain size, density, shear strength, Atterberg Limits, water content) must be collected, and the load-bearing capacity of the in-place contaminated sediment needs to be assessed to determine the weight of cap that the site can support. The load-bearing capacity is generally not an issue. TLC requires thin layers of capping material, so this would not be a limitation in most cases, and most of the geotechnical properties are not an issue for TLC, but these properties may be important if the native sediment is soft and cannot support the weight of a cap. The degree to which the underlying sediment and the cap material mix upon placement is also a critical consideration. If the mixing leaves the surficial sediment above the clean-up level, then the design should be reviewed and redesigned with a thicker cap or a conventional isolation cap. The geotechnical properties of the sediment, therefore, can affect the thickness and number of lifts required to place the thin-layer cap. Additional information on geotechnical parameters are presented in Sections 2.2.1.

Contaminants of Concern

The designing of TLC requires a thorough understanding of the contaminants present in the sediment. Guidance on contaminant characterization is found in Sections 2.2.1 and 5.3.1. The COCs must be identified, and the extent and magnitude of the contaminated area, including “hot spots,” must be determined. The concentration and location of the contaminants will dictate the TLC design (i.e., area to be covered, type of capping material and/or thickness of the TLC).

6.3.2 Site Setting

In addition to characterizing the sediment, the influence of the surrounding environment on the TLC project and the potential impacts of the TLC on the surrounding environment, including potential restrictions on site usage, must be considered. The assessment of the surrounding environment (e.g., in-water and shoreline infrastructure, debris, access and staging areas, and waterway usage) is usually done as part of an environmental assessment process, and the results of the assessment should be included in the TLC design. Adjacent properties may also be utilized as staging areas for equipment and the stockpiling of capping material. The nature of these properties, along with associated access routes, should have been properly assessed during the completion of the design.

In-Water and Shoreline Infrastructure

In-water and shoreline infrastructure surveys must be done to identify structures, pipelines, and above-ground water-intake pipes, as they may require different equipment/methods for laying the cap. For example, pipelines positioned on or below the sediment bed will hinder the laying of the capping material due to the risk posed by anchoring or securing barges and heavy equipment. The placement of cap material may be limited in and around intakes and sea-floor/lakebed structures. Detailed plans for dealing with this type of infrastructure and other types (e.g., docks) must be included in TLC design.

Debris

A debris survey must be conducted, and a decision must be made either to remove or not remove the debris, as some debris will interfere with capping operations. For example, silt curtains are often used to control turbidity in the water column, and debris in shallow waters can restrict silt curtain movement. The design should include procedures for dealing with debris in shallow areas when silt curtains are used.

Access and Staging Areas

TLC projects require an allocated staging area onshore for storing capping material and equipment. When storing the capping material, a proper silt fence must be installed to prevent capping material from leaving the storage area.

Waterway Usage

For TLC design, it is important to know what type of vessels will be using the area, as these vessels have different drafts and create different stresses on the bottom sediment. If not properly designed, all the capping material can be eroded away by stresses such as propeller wash, exposing contaminated sediment. Larger-grain capping material and a thicker cap have been used in areas where frequent and/or large-size vessel traffic can occur to minimize cap movement offsite.

Ecological Considerations

Knowledge of the local ecology is critical to the design of TLCs. In addition to the general items outlined in Section 2.2.3, proximity to sensitive ecological environments/receptors must be considered. Nearshore sensitive areas should be identified and protected from being covered by fines in the capping material, and fish residing in the area should be protected from turbidity during the capping process. Mitigation measures such as silt curtains should be used to protect the sensitive fish habitats and fish. Mitigation measures are usually identified as part of an environmental impact assessment.

6.3.3 Surface Water

Water Depth / Bathymetry / Hydrodynamics

Water depth will affect capping equipment selection. Increased water depth results in the capping material taking longer to reach the bottom and spreading out more in the water column, which requires longer silt curtains to control turbidity. Deeper water may also require specialized equipment to place the capping material.

Seasonal hydrodynamics generally control the erosion potential of the site sediment. In order for TLC to be considered, the sediment bed has to be stable and the rate of sediment deposition should be greater than the rate of erosion. Unusual high-energy storm events, which could cause erosion of the cap, are of concern and should be addressed in the design. The dominant seasonal hydrodynamic forces should be identified and quantified, because these forces drive sediment transport. Specific profiles of currents, tides, and waves should be used to model erosion potential and sediment transport. The TLC should remain in the area, mix with existing contaminated sediment and not erode away.

If the thin layer cap area is large, there may be different hydrodynamics that require more than one type of thin layer cap (i.e., more than one cap thickness, more than one grain size for capping material). Wave orbital motion through the water column can agitate TLC depending on water depth (Masselink and Hughes 2003) and erode TLC. In areas of high energy, TLC is not recommended.

6.4 Construction

Thin-layer caps are designed so that clean capping material mixes with the contaminated sediment to reduce the exposure of aquatic organisms to the contaminated sediment. The amount of mixing upon application depends on many variables such as the capping material, the sediment being covered and the placement method. Long-term mixing is dependent on many of the same variables but also the hydrologic conditions the cap is exposed to. Models are used to design and assess the performance of caps. Various key processes and factors that affect TLC are presented in Section 5.4. Types of capping material, cap thickness, and accepted target contaminant levels in the cap, porewater, and biota should all be considered in TLC design (USEPA 2013).

When constructing a thin-layer cap, the goal is to accurately place the capping material in a controlled manner to reduce the suspension of the contaminated sediment, and to reduce the fines in the capping material from being released into the water column.

6.4.1 Capping Materials

The grain size and organic carbon content of the clean capping material to be used for thin-layer placement should be carefully considered in consultation with aquatic biologists. In most cases, natural materials (as opposed to manufactured materials) approximating common substrates found in the area should be used, when possible.

Capping materials must be tested (see Section 4.4.5 in Isolation Capping Section) and meet the local sediment quality guidelines or criteria. Analytical methods with detection limits for each contaminant of concern to be tested should be provided. In some areas, metal concentrations may be high due to natural background levels. In these cases, the natural background metal levels could be used as criteria for the capping material, if approved by appropriate agencies.

Capping material selection should be based on the *in situ* and/or the desired final habitat. In general, sand, gravel, and a mixture of sand and gravel are used most often, with the approval of regulatory agencies. The presence of fine-grain material within capping material will also need to be evaluated; a maximum amount of fines should be specified in the design, as fines will add to turbidity issues upon application.

When the physical characteristics of capping material are different from that of the native sediment, approval from government agencies may be required, as the benthic habitat will be changed. Depending on the amount of similar habitat and the value of that habitat in the area, approval may or may not be given to use the capping material that is different from the native sediment. As already discussed in this section, a very thin layer of material similar to *in situ* sediment can be applied on top of the sand and gravel used for the cap in order to encourage the recolonization of benthos. The grain size of the capping material should be selected based on the critical shear stress and erosion potential at the site, so that the cap is not completely eroded away. Further information on measuring the critical shear stress can be found in Section 4.4.1. Pending the local erosional energy regime, various grain sizes may be required for capping material.

Ideally, the capping material should stay within the cap area and mix with existing sediment. Mixing of the cap material with the underlying sediment can vary from 0% to 100% as long as the clean-up level is achieved at the surface. Flow velocity due to storm waves should be assessed at the lake/river/harbour site to ensure that cap material suitable for resisting erosion is chosen.

Availability of Capping Material

Local sources of capping material should be sought. Remote locations can present some challenges to obtaining capping materials; most of the challenges in this regard are related to higher costs associated with transportation. Capping material can be delivered to the site by land or by water. More than one source of capping material may be required, depending on the volume and type of capping material specified.

6.4.2 Cap Thickness

The objective of TLC is to reduce contaminant concentrations in the bioturbation zone to acceptable levels. Effective cap thickness should be determined by considering the level of chemical concentration, the degree of reduction desired, the type of capping material used, the anticipated degree of mixing with underlying sediment and site-specific hydrodynamic data (additional thickness can be added to compensate for losses from flows and currents).

When non-sorptive materials like sand and crushed rocks are used, TLC thickness equal to the depth of the well-mixed bioturbation layer (15 to 20 cm in fresh water) has been used, but a thinner cap may achieve the desired clean-up level.

If the proposed capping area is large, there may be multiple hydrodynamic conditions that may require different types of capping material and different cap thicknesses.

Measuring Cap Thickness

Acceptable minimum, maximum, and average cap thicknesses should be specified in the design. Cap thickness measurements using pre- and post-cap placement bathymetry can be done, but the equipment must have the precision to measure the changes in cap thickness. Accordingly, other methods for measuring cap thickness, such as coring or SPI camera surveys, or placement of measuring sticks pre-cap and taking measurements post-cap may be more practical. Cap thickness can be measured from the middle of the intermixing zone to top of the cap.

6.4.3 Capping Sequence

The capping sequence should be flexible to accommodate adverse weather and operational issues. The regional in-water work operating window (i.e., time) must be considered. If required, a request for modification to the operating window can be made to the appropriate agency, but approval may not be granted.

6.4.4 Concerns Associated with Resuspension and Contaminant Release

As with all contaminated sediment projects, the potential for resuspension of contaminated sediment is a concern and one that should be minimized as much as possible. With TLC, resuspension of contaminated sediment is a lesser issue than with isolation capping, as TLC relies on the mixing of the contaminated sediment with capping material.

Depending on the nature of each contaminant of concern, contaminants can be released to the water column by dissociation from particles / organic matter and/or by volatilization during the capping process. Capping material should be gently placed by a spreader or other equipment to minimize the release of contaminants. Silt curtains can be used to minimize the spread of contaminants resulting from the cap-laying activity.

6.4.5 Stresses Exerted on Cap

See Section 5.4 for information on assessing stresses. A thin-layer cap should be designed to withstand these stresses so that it is not eroded away. In cases where a navigational channel occurs in close proximity to a thin-layer cap, the characteristics of the channel and vessel traffic (i.e., channel width, depth; vessel turning radius and propeller wash) can have an effect on the force exerted on the capping material. A guidance document that covers these variables is available from Transport Canada (2009). It was used for the Peninsula Harbour Thin-Layer Capping Project in Marathon, Ontario.

6.4.6 In-Water and Shoreline Infrastructure and Debris

If the project design calls for the removal of debris, then a description of debris removal methods, a turbidity control plan, the location of on-site temporary storage of debris if required, and an off-site disposal site should be stated in the design. If the design calls for the structures/debris to remain, then a description of how the cap will be laid around the structures/debris should be specified in the design.

6.4.7 Staging/Laydown Area

Detailed information on transportation routes to the staging/laydown area and detailed procedures for staging and loading trucks/barges at borrow pits, unloading, and inspecting/maintaining proposed access ways should be included in the design. The staging/laydown area must comply with all provincial regulations and best management practices associated with sediment runoff controls and must be put back to its original condition at the completion of the project to the satisfaction of the government agencies.

6.4.8 Transport of Capping Material and Staging Area

The sand supply source with its daily and total supply capacity for the project must be described. If the supply is short of 100% of total demand, then an alternate source should be identified.

6.4.9 Construction, Equipment and TLC Placement

The design must include the following:

- Placement technique (e.g., diffuser, bucket, belt with spraying system),
- Minimum, maximum, and average acceptable cap thickness,
- Mode of sand delivery from the stock piled area to the capping barge(s),
- Positioning methods — Methods used to locate and control the capping position must include a range of electronic positioning systems. The horizontal accuracy of the capping position should be provided (e.g., +/- 1 metre). Real-time kinematic GPS, or equivalent, should be used. Accuracy of water depth should also be provided (e.g. +/- 0.1 metre),
- Intended lift thicknesses (cap thickness with one pass),
- Overlap between successive placements to ensure consistent coverage,
- Coverage at the edge of the area of contaminated sediment,
- Production rates, and
- Horizontal area covered.

Further discussion on equipment and techniques for the transportation and placement of capping material is included in Section 5.4.5.

6.4.10 Construction Monitoring

The goal of construction monitoring is to assess compliance with design and performance standards (i.e., to determine if a cap is placed properly, with regard to area coverage and cap thickness), and to determine possible impacts to water quality and downstream areas.

Test plot(s) could be included in the design so that various placement methods can be tested to identify production rates and monitor the effectiveness of various placement methods across a range of site conditions. Coring and SPI cameras can be used to measure cap thickness and the cap intermixing zone.

Water quality measurements should be conducted to measure the release of any contaminants during various placement methods. Sand placement volumes should be monitored to allow for estimation of the area capped and cap thickness.

Components to assess are as follows:

- Cap material quality and quantity,
- Cap thickness,
- Areal extent of cap coverage, and
- Water quality (sediment and contaminant resuspension).

Methods for assessing may include the following:

- Sediment coring,
- Visual observations (e.g., diver observations),
- SPI camera, and
- Water Quality Monitoring:
  - Contaminant resuspension monitoring, and
  - Turbidity monitoring (surrogate for TSS monitoring).

Water Quality Monitoring and Controls During Construction

The main concerns for TLC projects are TSS that result from the release of fines in the capping material and the resuspension of the contaminated sediment due to the capping material falling on top of the contaminated sediment. Real-time monitoring (turbidity) and the collection of grab samples for laboratory analysis of TSS and chemical concentrations should be stipulated in the design.

Water quality performance criteria and a water quality monitoring program (i.e., parameters to measure, sample collection methods, sampling frequency, sampling locations, and contaminant analytical methods) should be included, with a figure indicating sampling stations.

Water samples should be collected for measurements of contaminant resuspension, and the water sample collection method should be described. All measurements and samples are to be logged with station ID, date, time, position, depth, status of capping operation, meteorological observations, and any other pertinent observations.

Monitoring should be performed in distinct periods and include parameters of concern specific to the project (an example follows):

- **Baseline -** prior to intensive in-water work (e.g., **real-time:** turbidity, specific conductance, dissolved oxygen; **samples**: suspended solids, COCs),

- **Initial Intensive -** during operation start-up / initial production (e.g., **real-time:** turbidity, temperature, specific conductance, dissolved oxygen; **samples**: suspended solids, COCs),
- **Standard -** during a specified minimum number of days per week (**real-time:** turbidity, temperature, specific conductance, dissolved oxygen; **samples**: suspended solids if turbidity exceedance is observed), and
- **Conditional -** if there is a major change to the operation, a procedural change, or visual impact to water quality is noted (case specific)

Methods to minimize turbidity and contaminant release during capping must be included in the design. Turbidity curtains are normally used to control fines and contaminant release during TLC but are subject to feasibility limitations (e.g., depth and currents)

The compliance boundary must be determined with government agencies, and it is used to assess if all parameters are meeting the water quality criteria. Some distance from the point of operation or the capping materials release point, or a distance to land outside of the control barrier can be used as a compliance boundary.

Warning and work stoppage criteria must also be specified, and contractor actions based on monitoring results must be included in the design.

Cap Construction Controls (Thickness and Coverage)

To monitor the effectiveness of capping, a cap thickness and coverage monitoring program must be included, with a figure showing coring locations and acceptable criteria. Measures to control sand placement (to ensure final cap thickness and area coverage) and equipment and methods required to verify cap thickness should be included. Verification methods can include:

- Measurement by Weight: Weigh scales for commodities must be certified in accordance with applicable provincial laws and regulations. Certification should be made within a period of not more than one year prior to date of use. For shipments from off-site facilities and locations, trucks should be weighed at the receiving facility,
- Measurement by Volume: Volumes measured as in-place volumes can be determined by measuring the weight of sand placed and converting weight to volume per specified method in the design, and
- Measurement by Area: The area of cap placement should be measured by square dimension (using length and width) or radius, and verified by the on-site oversight representative. Procedures for measurement should be described in the design.

6.5 Long-Term Monitoring and Maintenance

In addition to construction monitoring, long-term monitoring should be conducted to assess the impact of the project on the environment, and the impact of the environment on the project, to assess short- and long-term effectiveness of the TLC in achieving management goals (i.e., long-term performance monitoring).

6.5.1 Long-Term Performance Monitoring

The goal of performance monitoring (physical, chemical, and biological) is to determine if TLC is performing as intended, and to determine if the contaminant concentrations and corresponding risks are reduced to acceptable levels. A long-term performance monitoring plan, including monitoring components, frequencies, and duration, must be specified in the design. The existence of adequate baseline data (to compare with future monitoring data) should be assessed, and if it does not exist, then additional data should be collected prior to TLC implementation.

Physical and Chemical Monitoring

The physical integrity of caps should be monitored over time to ensure the cap is not eroding away. Thin-layer-capped area coverage, upon initial application, can be assessed by taking cores or sediment profiles of transects over the capped area. The video images can also be used in areas where visible differences between the cap and the surrounding sediment outside the cap are present. When using visual equipment, one must ensure that the equipment has the resolution to clearly see the cap.

The thickness of the accumulated sediment on top of the cap can be measured to determine deposition rate. Deposition rates can be estimated by using:

- An in-place ruler to measure the deposited sediment,
- Sediment traps to quantity incoming sediment, and
- Historical bathymetric differences (precision may be an issue).

With contaminant sources controlled prior to TLC, any newly deposited material will provide additional effectiveness for the thin-layer cap. Depositional rate and chemical concentrations in the cap can be used to assist with modelling of future contaminant concentration in the thin-layer cap in order to assess if the TLC will still meet the clean-up level in the future. The newly deposited material can also be analyzed to assess the quality of sediment coming into the TLC area.

Physical monitoring should occur as per the long-term monitoring plan, and after any significant storm event beyond a certain threshold that is established in the design assumptions.

The monitoring of TLC can involve the monitoring of the surface sediment (i.e., newly deposited material plus cap material) and comparing it with clean-up levels. For additional information on chemical monitoring, see Section 5.5.2.

Biological Monitoring

Submerged aquatic vegetation can be mapped before construction of the thin-layer cap and then assessed post-cap to evaluate vegetation recolonization. Surface sediment can be collected and toxicity tests can be conducted to assess changes. Benthic invertebrates on top of the cap can also be collected to assess benthic invertebrate recolonization and structure. If a sufficient number of benthic invertebrates can be collected, they can be analyzed for COCs. The sampling plan for benthic invertebrate tissue study should specify whether gut clearing is required or not. Tissues of fish and organisms at higher trophic levels can also be sampled for bioaccumulation of contaminants, and compared with baseline data to assess changes post-TLC.

6.5.2 Adaptive Management

The purpose of adaptive management is to identify and outline contingency measures that will be taken in case the long-term monitoring data indicate that capping is ineffective in reducing risk as projected. Adaptive management should include the following:

- Measures to implement as needed (e.g., additional source control, additional administrative control, placement of additional clean sediment to exposed areas if required),
- Time frame to meet the objective,

- Parties responsible for funding and implementing, and
- Monitoring of measures implemented.

6.6 Challenges and Uncertainties

The largest uncertainty associated with TLC is the cap performance. Cap performance will be dependent on the quality of the material that will be deposited on the cap from surrounding areas, and the action of waves and currents, which may move capping material off the site. If these challenges prevent the project from successfully meeting its goals, then the adaptive management plan should be implemented.

7. *In situ* Management Techniques

It is the intention of the authors that this section be read in conjunction with the discussion of site characterization and long-term monitoring included in Section 2 and 9. It is noted that the subheadings are the same in this section, but this section includes specific information on site characterization and long-term monitoring pertinent to *in situ* management techniques.

7.1 Introduction

In situ remedies are sediment management techniques that are applied directly to the contaminated sediment in place without any removal from the waterbody or any addition of overlying cap material. As a result, they are generally limited to the following:

- Physically binding the contaminants and sediment as a whole,
- Chemically binding the contaminants, and
- Altering the geochemistry of the immediate environment to prevent or control certain reactions.

While this area is an emerging science, these techniques can be grouped into two general categories: *in situ* solidification/stabilization (ISS) and *in situ* amendment addition. Other *in situ* techniques, such as phytoremediation, have been employed to a very limited extent (tidal marshes); however, they will not be discussed in this section.

ISS involves two processes. Solidification refers to the process that physically changes the sediment into a solid continuous material. Stabilization refers to the accompanying chemical reactions that chemically bind the contaminants within the material, limiting their availability. Optimally, both solidification and stabilization are achieved together, but they can occur independently of each other.

ISS techniques use a physical binding substance, often Portland cement and often in combination with other constituents such as fly ash. These are mixed into the sediment, resulting in a solid material that cannot be penetrated by benthos or aquatic plants, or displaced by currents. The additives (i.e., the binding substances) can be mixed into the sediment by means of augers, requiring many partially overlapping columns, or by other mechanical means. In select cases, this technique can utilize standard construction equipment such as excavators to mix in the binding agents, if the work can be conducted in the dry by isolating and de-watering the area.

In situ amendment additions generally consist of mixing amendments into the upper layers of contaminated sediment, spreading amendments on top of contaminated sediment, or premixing amendments with sand and then spreading the mixture over contaminated sediment. It should be noted that premixing amendments with sand and then spreading the mixture over contaminated sediment is a form of enhanced isolation/thin-layer capping, and since these techniques have their own sections, they will not be specifically discussed in this section.

Most amendments act to adsorb contaminants, rendering them unavailable to receptors.

The most common amendment is granular activated carbon (GAC). Other common amendments include organo-modified clays and biochars. There are several manufactured amendments on the market under various trade names. These still use the common amendments, but often have the amendment contained within a delivery capsule that helps with placement. A common problem with amendments used in sediment management is their density, meaning they do not settle at the same rate as materials they are mixed with. Delivery capsules such as encasing the GAC within an external clay shell aim to solve this problem.

Amendments can also be added to alter the geochemistry of the system. As an example, nitrate can be added to prevent or reduce the production of methylmercury in the water column. Mercury is a unique contaminant, in that the greatest impacts in terms of toxicity and biomagnification stem from the conversion of inorganic mercury into organic methylmercury. Methylmercury is taken in by benthic invertebrates, and its concentration increases further up the food web, which can impact human health through fish consumption. An enhanced supply of nitrate to the water column can prevent the development of anaerobic conditions in sediment, which in turn results in lower methylmercury production (Matthews et al. 2013). Other amendments that have been used to reduce or suppress the methylation of mercury include iron oxide, iron sulfides, zero-valent iron, molybdate, and manganese oxides. The sulfate-reduction process drives the methylation of mercury; therefore, an alternation of the redox profile to drive sulfate reduction deeper into the sediment helps reduce methylmercury distribution into the ecosystem.

Phosphate additives can reduce the bioavailability of metals through adsorption, ion exchange, isomorphic substitution, and precipitation (USEPA 2013). The most common phosphate mineral utilized is apatite. USEPA (2013) indicates that this mineral is advantageous, as it yields stable end products, can be easily placed on contaminated sediment, can be mixed with other additives, is readily available, and is non-toxic. The most important limitation for phosphate additives is the potential for the release of soluble phosphate, which can increase eutrophication, a problem existing in many waterbodies. In addition, phosphate addition has only been tested at the pilot scale to date.

7.2 Goals and Objectives

The goal of *in situ* management techniques is to manage contaminated sediment in place without the need to remove anything from the waterbody. This reduces risks in terms of resuspension and transport of contaminated sediment and also removes the need for disposal (and in some cases de-watering) of the contaminated sediment.

7.3 Characterization of Site

It is imperative that any ISS or amendment addition technique be accompanied by a detailed understanding of the physical characteristics of the site.

7.3.1 Sediment

Geotechnical

If the physical mixing of amendments into the sediment is contemplated, then the geotechnical characteristics should have been sufficiently assessed to allow for selection of appropriate equipment. The geotechnical characteristics of the sediment could affect the penetration of the amendments into the sediment and the effective distribution/mixing within the sediment.

ISS of contaminated sediment induces loads on the underlying sediment. Provision for the vertical migration of porewater, induced by the weight of the solidified and relatively impermeable sediment, must be made, as well as consideration of gas ebullition.

ISS techniques require detailed knowledge of the sediment lithology, and therefore, adequate particle-size analysis to accompany core logs is essential.

If contaminated sediment from another area is being dredged and placed with subsequent plans for stabilization, consolidation of this sediment must be taken into account when working the geometry of the management area. This requires site-specific consolidation testing.

Contaminants of Concern

For ISS, it is important to understand the chemical loading and composition of the sediment, as they will be mixed with a binding agent and sometimes an amendment. This type of management should always undergo bench-scale and often pilot-scale testing to determine the correct mixtures and whether or not the resulting chemical concentrations in leachates are acceptable. Resuspension of contaminants from *in situ* mixing and transport away from the site must be considered in the design.

The amending of contaminated sediment requires a full understanding of the contaminant loading in order to help determine the type of amendment and the concentration of amendment that will be mixed into the contaminated sediment. This also requires bench-scale testing and modelling in order to understand how the contaminants behave with the amendments in the sediment being assessed.

Any altering of the site geochemistry will obviously require a detailed understanding of the concentrations of contaminants as well as other parameters in the sediment, such as organic carbon content, organic carbon supply, redox potential, and information on microbial activity.

For practical application, the variation in chemical concentrations spatially across the site will also need to be clearly delineated (along with the boundaries and depth of contamination). The volumes of amendments mixed into the sediment across the work area may need to be adjusted to ensure "hotspots" are adequately addressed. Contamination, which extends to greater depth, may factor into selecting equipment that is capable of achieving the required depth.

Geochemistry and Microbial Actions

Where an amendment is being used to alter the geochemical regime, geochemical characterization is extremely important. Under static conditions, only the upper few millimetres of sediment would be aerobic; however, bioturbation will account for aerobic conditions much further down (approximately 6 inches in fresh water and deeper in estuarine or marine sediment (Clarke et al. 2001). Beneath this are anaerobic zones, creating reducing conditions for such compounds as nitrate, iron, sulfate, and other electron acceptors.

One area where this becomes specifically important is mercury methylation. Sulfate-reducing bacteria are the principle methylators of inorganic mercury as well as (to a lesser extent) iron reducers (Matthews et al. 2013). The methylmercury is converted by anaerobic conditions, and is related to the supply of inorganic mercury, sulfate, and labile organic carbon. The redox profile, which exists within the sediment / surface water interface zone, determines the extent and depth at which sulfate reduction and the associated mercury methylation occur (see Figure 7-1).

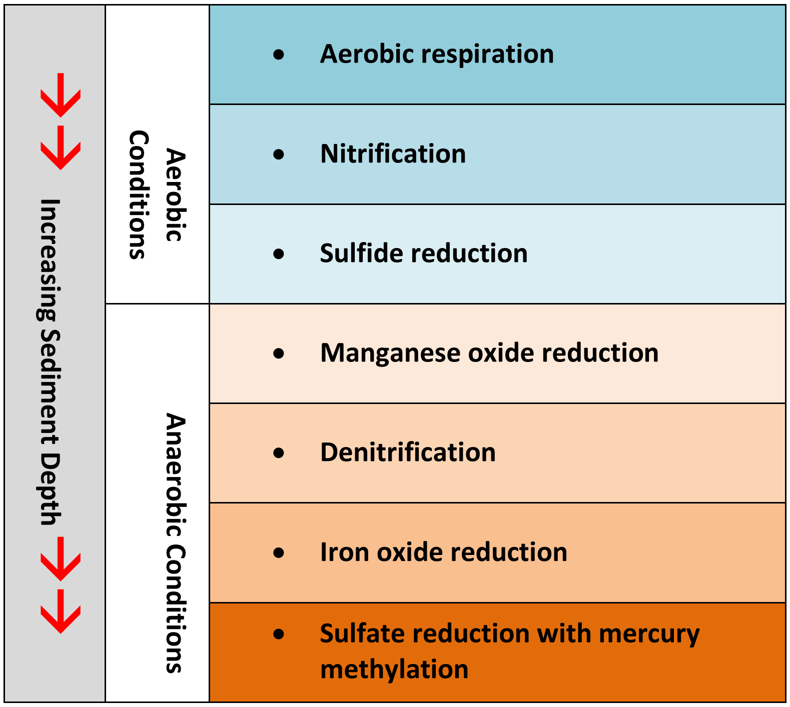

Figure 7-1: Changes in the sediment profile with depth.

Understanding the microbial species present and the varying concentrations of manganese oxides, nitrates, iron oxides, and sulfates in the anaerobic zone of the sediment helps determine the methylation potential that exists and how alteration of the geochemistry or microbial community may affect methylmercury production.

7.3.2 Surface Water

Water Depth

Water depth affects the degree to which waves or ice interact with the amended surface and the degree of scour from vessels on the amended bottom sediment. It also affects the ability to deliver amendments and effectively mix in binding agents.

Wave Energy

Wave-produced orbital motion through the water column can serve to agitate amended bottom sediment (Masselink and Hughes 2003). Waves can also serve to induce a pumping- like force in the upper few centimetres of the amended sediment (Eek et al. 2008). Waves will also affect the ability to mix binding agents into the sediment from a floating platform.

Bathymetry

Related to water depth, it is important to know the underwater topography of the area where amendments are being applied. Water depth affects the ease of delivering amendments and binding agents, equipment selection, and cost.

Current Strength and Patterns

Currents above the sediment/water interface can erode bottom particles and amendments, depending on the velocity, grain size, and lithology of the material. Currents may or may not follow the wind direction and are often complicated due to the interaction of dock walls and other underwater structures. Tidal currents are obviously more predicable in terms of direction and timing. Augering into contaminated sediment and adding binding agents generate turbidity, and as such, usually require some form of turbidity control/curtain.

Stratification

When considering geochemical alteration, the stratification of water bodies is important to understand. In addition, the waters of stratified lakes can be particularly active zones for methylmercury production if all the right components are present. When stratification results in the formation of an anaerobic hypolimnion, then sulfate reduction and the associated mercury methylation can occur in the hypolimnion waters (as well as in the sediment). Lake stratification is primarily a thermal process that can occur seasonally; however, some other factors such as differing water densities can contribute to stratification. When methylmercury is produced within the water column, the entry point into the food web is via phytoplankton, which takes up the methylmercury and are subsequently consumed by other organisms (Matthews et al. 2013).

7.3.3 Site Setting

Climate

Knowledge of the site-specific climate (e.g., temperature, precipitation, local currents, and wave climate) is important for many reasons and interrelates with a number of the other points in this section. Altering the geochemistry of the immediate environment, such as the use of nitrate to control methylmercury production, requires site-specific knowledge of the layering and yearly thermal stratification of the waterbody, as discussed in the previous section.

Waterway Usage

It is important to know the types of vessels that will be using the waterway where your amendment will be placed, as these have different drafts and create different stresses on the bottom sediment. Equipment required to place and mix in amendments will likely be deployed via barge and have to navigate amongst existing traffic.

For long-term consideration, it is also important to know if dredging for navigation purposes will ever be required in the future and to what depth it would be required. *In situ* work should not be contemplated for sediment that is likely to be removed in the future.

Debris

Debris in the vicinity of the amendment area may need to be removed prior to *in situ* treatment or it may be determined that it is best to leave it in place. Significant debris may interfere with the operation of equipment, depending on the technique used to add the amendment to the sediment. Mixing of amendment using augers, for example, would be vulnerable to debris such as metal cables. Debris could damage equipment and slow down the progress of amendment addition. Waterways commonly contain debris and the presence/absence of this should be determined well in advance.

Rate of Deposition

It is important to know the rate of deposition of sediment into the area of interest. This can be helpful in terms of establishing whether or not a habitat layer on top of the solidified sediment is necessary. The technique to assess the rate of deposition would be similar to what would be done for MNR or capping projects.

Slope Stability

When designing an *in situ* project, it is important to know the bathymetry of the area where the interaction is taking place as well as the stability of this area, if it is not flat. ISS or the mixing amendments into the existing sediment may further destabilize the area, and the risk of sloughing should be avoided.

Ecological

Some studies have shown the application of amendments at sediment sites can actually increase toxicity to some benthic invertebrates present at those locations. Some studies involving the placement of activated carbon in marine environments have shown severe impact to the benthic fauna, which increased over time and slowed down recovery up to four years post-placement. Filter and suspension feeders with higher bioturbation activity were noted to be more vulnerable (Raymond et al. 2015). That being said, Patmont et al. (2015) point out that the acceptability of a remediation option will depend on whether the benefits of the approach outweigh potential adverse environmental or ecological impacts as compared with other options. Patmont et al. (2015) discuss a 2013 review that found impacts to benthic organisms resulting from activated carbon exposure were observed in one-fifth of 82 tests. These were primarily laboratory studies. The Patmont paper also goes on to indicate that community effects have been observed less frequently in field-based activated carbon pilot demonstrations compared with laboratory tests, and often these effects diminish within one or two years following placement, especially in depositional environments where new and often cleaner sediment is being deposited. The potential effects of activated carbon on benthos can also be mitigated with the application of a habitat layer.

Prior to the application of any amendments to the sediment, the existing benthic community should be understood, along with the desired community structure post-implementation. Understanding the potential toxicity of any amendment to the existing and desired species is key to assessing the feasibility of its use.

The impacts of amendment application on aquatic species other than benthos, such as fish, crustaceans, and vegetation, should also be considered.

As a general rule of thumb for bioturbation, 0–20 cm can be considered for freshwater systems, and marine systems can extend to 50 cm and beyond (Kristensen 2005). Bioturbation should not affect amendment performance, and obviously it would not affect solidified sediment either.

7.3.4 Hydrogeological

Groundwater / Surface Water Interface

Aquatic sediment environments are often not static in the vertical dimension. Some form of flow is usually present between the porewater in the underlying sediment and the overlying surface water, and it can be upward or downward. Establishing this direction as well as quantifying the flux is important for stabilization designs, as porewater will migrate horizontally once it meets the stabilized sediment, as will gas ebullition.

Information about vertical groundwater flux is also important for amended sediment, as the flux will bring contaminants through the amendment, and for estimating such things as amendment thickness and breakthrough time when modelling.

A common and relatively simple method utilizing a seepage meter is described by Lee (1977) and has been utilized by the authors on more than one occasion. A description of this technique is provided in

Section 5.3.5. Other methods in shallow systems include the use of piezometers as well as more sophisticated seepage meters. These can also be used for testing porewater chemistry although work is on-going in this area regarding the quality of such data.

7.4 Construction

7.4.1 Amendments

Amended sediment is designed to chemically sequester contaminants from the sediment and reduce the exposure to aquatic organisms and the aquatic environment. A number of variables need careful consideration, including sediment and site characteristics, and specific engineering factors, as noted next.

Estimating Stresses Exerted on Sediment from Propellers, Waves, River Currents, and Tidal Currents

Information on common stresses placed on bottom sediment, including the means to measure these stresses and the critical shear stress for erosion, is presented in Section 5. Unstable sediment that is continually or periodically being eroded and transported off-site may not be a good candidate for *in situ* amendment addition, depending on the amendment proposed; the stability must be fully assessed ahead of time. The stability of any amendment layer or amendment-sediment mixture must be fully understood. Periodic erosion would point to a risk of exposing contaminated sediment from beneath the amended surface. This risk may require an alteration of the mixture or a deeper injection of amendments.

In cases where a navigational channel occurs in close proximity to an *in situ* application, the characteristics of the channel (i.e., width, depth, and vessel turning radius) can have an effect on the force exerted on the bottom sediment, either solidified or amended. A guidance document that covers these variables is available from Transport Canada (2009).

Contaminant Flux Modelling

Amendments must be designed to sorb, retard, and control the rate of contaminant flux through the stabilized sediment layer and from underlying contaminated sediment that may not be stabilized, such that the sediment management objectives related to chemical isolation are maintained in the long term. This aspect of design relies on contaminant flux modelling. Refer to Section 5 for further details on contaminant flux modelling.

Common Amendments

Common amendments utilized in the construction process include activated carbon, biochars, reactive core mats, and organo-modified clays. These amendments all rely on an organic fraction to adsorb contaminants, and even most native sands will have some, albeit low, organic component. The tendency for hydrophobic organic contaminants to adsorb to organic fractions is well documented in the literature (Murphy et al. 2006). Performance of the various carbon-based amendments does vary, however. Murphy et al. point out that amendments such as coke and activated carbon have demonstrated non-linear sorption isotherms and extremely high equilibrium sorption partition coefficients for PCBs. It has also been shown that PAHs and PCBs bound to coke and activated carbon are less bioavailable than when bound to organic carbon.

Absorptive capacity is dependent on the type of amendment, its surface area, and the chemical makeup of the water/ porewater that is being exposed. Absorptive capacities should be measured on a site-by-site basis using column breakthrough tests.

In general, activated carbons have the highest absorptive capacity due to their extremely high surface area of approximately 1000 m^2/g (Beckingham and Ghosh 2011); however, they are a manufactured product, and as such, come with a higher price tag. Activated carbon is integrated into a number of commercial products designed to mimic the fall velocity of common capping materials such as sand. Many of these products are designed so that the surrounding material (in which they are encased) dissolves, leaving just the activated carbon.

Biochars are generally produced from animal dung, which is thermochemically decomposed using pyrolysis to form a charred carbon product. Gomez-Eyles et al. (2013) evaluated a number of carbon sources, including activated carbons and unactivated biochars, for their ability to adsorb organic contaminants, including PAHs. The study indicated that the ability for activated carbons to adsorb organic contaminants was consistently one order of magnitude higher (and often closer to two). While biochars are less costly, significantly more mass is required to achieve the same adsorptive capacity as activated carbon. Gomez-Eyles et al. (2013) also discussed the presence of native black carbon material (e.g., soot and coke). These materials are very common in contaminated sediment and soils impacted by PAHs. The presence of the black carbon along with adsorptive attenuation effects could result in unactivated biochar amendments having little to no effect on organic contaminant bioavailability, significantly reducing the ability of the biochar to adsorb contaminants. This is an area that requires more research.

Organo-modified clays (OMCs) are clays subjected to cation exchange for organic molecules. These molecules then serve as organic sorbents. According to Reible (2014), the absorptive capacity of OMCs is less than that of activated carbons, but the potential for fouling of the OMCs is less than one-half of that for carbon. In general, activated carbons are more effective sorbents of dissolved hydrophobic organic contaminants and OMCs are more effective sorbents of NAPLs. Where NAPLs are present in part of an area to be capped, the process for potential contamination migration should be carefully considered. NAPLs may be mobilized by consolidation-induced or groundwater-induced advective forces. OMCs can also be placed into mats when space or vessel draught is an issue, as can other amendments such as activated carbon.

It has been noted by several researchers that ingestion and foraging of benthos in contaminated sediment where contaminants have been concentrated into amendments is a concern. This highlights the need to ensure that benthos do not contact the layers of the cap where treatment is occurring. One solution can be the placement of a habitat layer on top of the cap.

Delivery of amendments to the water column with the aim of altering or suppressing reactions is not well developed at this time. As a result, there is not much to report regarding design. Obviously, the key with these additions would be to ensure that the coverage of the amending agent is adequate. At a site in Onondaga Lake, New York, calcium nitrate was delivered with the goal of using nitrate to suppress methylmercury production in the hypolimnion. The calcium nitrate was delivered as a neutrally buoyant plume at the centroid of three cells, each around 2 km^2 or less.

Placement

When placing amendments, the goal is to accurately place the required material in a controlled manner, mixing it with the contaminated sediment to the degree determined in bench- or pilot-scale studies. It is also desirable to reduce or control resuspension of contaminated materials into the water column as well as the creation of excessive suspended solids from the amending materials themselves.

Where amendments are being used to manage contaminated sediment, they are typically applied using three approaches (listed next and shown in Figure 7-2):

1. Laying down the amendment in a pre-manufactured mat, where the amendment is contained between two geotextile layers.
2. Placing the amendment on top of the contaminated sediment as a new layer. The amendments are typically premixed with an inert layer but can be placed as a discrete layer. This is essentially a thin-layer cap with an amendment (see Section 6).
3. Rototilling (or mixing by other means) the amendments directly into the contaminated sediment.

Equipment

All in-water *in situ* work will require basic equipment components similar to other remedies. The bulk of the equipment and materials will be deployed at the site via barges, with the required tugboats and other support vessels. The unique equipment requirements associated with *in situ* remedies relate to the mechanism used to inject or mix amendments directly into the sediment, as shown in Figure 7-2.

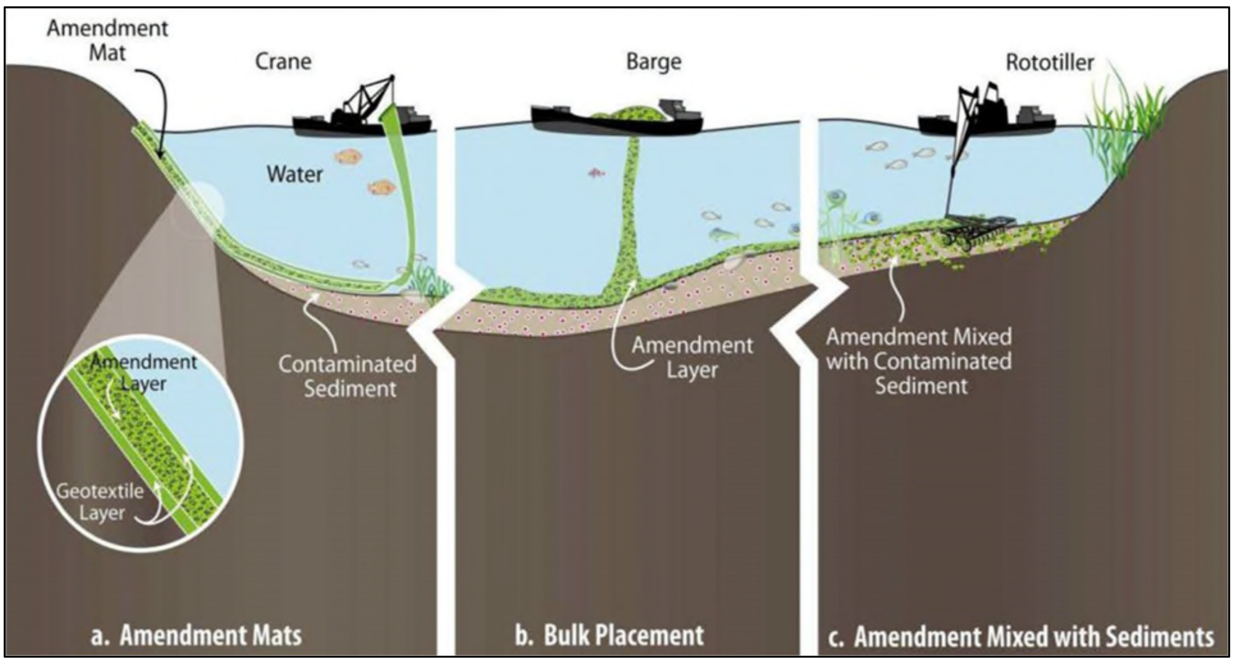

Figure 7-2: Use of amendments for in situ remediation at Superfund sediment sites (USEPA 2013).

Option 1 would require the use of a barge-mounted crane to lift, lower, and place the mat atop the contaminated area. Based upon the size and configuration of the work areas, assistance by divers is also a likely requirement for the final placement.

Option 2 is usually conducted using conventional dredging equipment such as clamshell buckets. Other systems, such as tremie tubes or spreaders similar to winter salters/sanders, can be used to disperse or “rain” the material down through the water column. Direct water-jet washing from barges and surface release from barges can also used. The delivery mechanism generally depends on the material being delivered and the type and thickness of layer being placed. With some layers, it is not desirable to have the material fall for great distances in the water column due to differential settling velocity (discussed further on). Turbidity created during placement can also be reduced by lowering the point of release, using turbidity curtains, or, in tidal areas, placing the material at slack tide.

Option 3 would require the operation of a raking device, a rototiller or an auger at the end of an articulated arm. Augers can also be extended to the water surface and operated directly from barge-mounted rigs. Auger mixing may also be conducted within enclosed caissons to ensure the desired ratios are achieved and resuspension of contaminated sediment is avoided. Given the emerging nature of this work, specialized equipment could easily be designed on a project-by-project basis to inject or mix amendments into the sediment.

Use of Straight Amendments vs. Pre-formulated Products

There are several products on the market that encase activated carbon in pre-formulated aggregate grains. In some of these, the delivery aggregate dissolves in water over time, leaving the amendment present as a flexible medium. These delivery mechanisms are usually designed to increase the fall velocity of the activated carbon so that the delivery and placement is even when it is placed with sands and other materials. All the commonly used amendments (i.e., activated carbons, biochars) and other lesser-used products, such as compost, mulch, and other organic sources, are less dense than sands. When being mixed with sands for use as an amendment, this difference in fall velocity must be accounted for, as it can result in uneven delivery and placement, which in turn can decrease the effectiveness of the cap. Presoaking activated carbon for at least eight hours will increase its density and its fall velocity to a certain degree.

Erosion Control and Habitat Layers

Before amendment placement is completed, the erosive forces (discussed under site Section 7.3) need to be understood so that the need and type of armouring can be determined. An armour layer would protect the newly mixed sediment/amendment, the amendment layer, or mats from potential scour or damage. Armouring approaches would be similar to those employed for isolation caps.

Smaller grain sizes can be placed on top of the armouring layer to encourage the rehabitation of the area; however, these habitat layers are exposed to erosive forces. Armoured caps generally attract greater diversity of macroinvertebrates than straight sand caps (Palermo et al. 1998). The recolonization occurs as the interstitial voids of the armouring are filled with new sediment.

Concerns Associated with Resuspension

As with all contaminated sediment projects, the potential for resuspension of contaminated sediment is a concern, and one that should be minimized as much as possible. Resuspension concerns vary, depending on the grain size and the density of the contaminated sediment. Resuspension issues with *in situ* remediation would centre primarily on activities that involve the disturbance or agitation of the sediment. The potential resuspension of sediment during mixing of amendment into the sediment (through actions such as raking, tilling, or auguring) needs to be assessed in the design. The application of an amendment layer carries lesser risk of resuspension, but the potential still exists, depending on the nature of the placement technique. Mitigation and monitoring programs for resuspension need to be developed according to potential risk.

7.4.2 *In situ* Solidification/Stabilization

There is no set design for ISS relative to the ability to solidify and stabilize contaminated sediment. ISS design will be dependent on the sediment grain size and lithology as well as the type of contaminants present and their concentration. ISS has been applied at a number of small pilot-study sites, most commonly utilizing Portland cement; however, site-specific bench-scale testing is required to assess the solidification properties as well as the ability for the process to bind the contaminants. This is usually assessed using a leachate test on the solidified material. Many of the same factors noted for amendments need to be considered for ISS; additional factors (noted next) should also be assessed.

Estimating Bulking Factors

Bulking occurs with ISS due to the addition of treatment reagents, and can be estimated by following ASTM standards for apparent specific gravity and bulk density of waste. The addition of cement often results in small reductions in volume. Bulking factors may be a concern if ISS is conducted on sediment within a contained area or if maintaining water depths is a concern.

It should be noted that even after the initial bulking, solidified sediment can still undergo consolidation after the initial mixing process is completed. This consolidation may occur over a longer time, but eventually it may counteract some of the bulking effect.

Assessing the Permeability of Solidified Sediment

Knowledge of the permeability of the solidified sediment can also be important for the overall sediment management plan and conceptual site model. When combined with the groundwater/porewater flow, considering the permeability of the solidified and stabilized sediment will help determine if ISS is an applicable approach. Contaminants in the dissolved phase within upwelling water could pass through the permeable solidified mass and still have environmental impacts on surface water and biota. This is a particularly relevant issue if solidification/stabilization is only conducted on surface sediment and untreated contaminated sediment remains below this layer.

Construction Equipment

At the time of writing, the authors are only aware of ISS being used in water with augering, where the solidifying agents are mixed into the contaminated sediment in augered columns. At the Sydney tar ponds in Sydney, Nova Scotia, excavators were used to mix solidifying agents; however, this was conducted in the dry by diverting a creek around the contaminated sediment (see Figure 7-3).

Figure 7-3: Solidifying sediment in the dry at the Sydney tar ponds (courtesy of Sydney Tar Ponds Agency).

Habitat Layers

If ecological recolonization of an ISS area is a project goal, the placement of smaller grain sizes on top of the solidified surface can serve to encourage the rehabitation of the area.

7.4.3 Construction Monitoring

As with all construction projects, monitoring must be conducted during construction to determine whether ISS or amendment addition meets placement specifications and does not result in excess resuspension or turbidity in the water column. In the case of ISS, mixing into the sediment should not cause the release of any free product. Containment can be used or mixing can be conducted in the dry to prevent the release.

7.5 Long-Term Monitoring and Maintenance

7.5.1 Physical Monitoring

The physical integrity of ISS should be monitored over time to ensure that the solidified sediment is still intact and to determine if new clean sediment is accumulating overtop to provide a new substrate.

Amended sediment should undergo physical monitoring periodically and after any significant storm event that goes beyond a threshold of intensity established in the design assumptions (causing the erosion of the amended layer). Accumulating sediment on top of the amended sediment should also be measured to determine its chemical composition.

7.5.2 Chemical Monitoring

The monitoring of amended sediment usually involves the assessment of porewater within the sediment as well as any resultant flux over time. This is to verify that the modelling was reasonably accurate and breakthrough at an unacceptable level is not occurring. Monitoring should be targeted at least yearly and can be tapered off over time to less frequent intervals as confidence in the amended sediment is gained. Conventional methods for collecting porewater samples for chemical analysis are complicated, expensive, and not always representative of the intended pore-water location or depth interval. More recently developed passive sampling techniques provide a simple, reliable and representative approach to accurately measure concentrations of HOCs in sediment porewater. Further detail on passive sampling can be found in Section 5.

7.5.3 Administrative Controls

Administrative controls are often part of a sediment management project. If possible, having vessels avoid amended areas will help prevent physical disturbance of amendment layers or areas with amendment mixed only to a certain depth. They should be marked on nautical charts and maps, and perhaps marker buoys deployed, so that their presence is well known.

7.5.4 Adaptive Management

The purpose of adaptive management is to identify and outline contingency measures that will be taken in case the long-term monitoring data indicate that capping is ineffective in reducing risk as projected. The adaptive management plan should include the following:

- Measures to implement as needed (e.g., additional administrative controls or placement of additional clean sediment to exposed areas;
- Time frame for Implementation;
- Party responsible for funding and implementing; and
- Monitoring of measures implemented.

7.6 Challenges and Uncertainties

A significant uncertainty associated with amendment addition is the effectiveness of the mixing or delivery method for the additives to achieve adequate coverage and integrity of the treated area and layer thickness. Another uncertainty is whether the modelling of the amendment's performance can accurately represent reality in the field.

With the aim of altering or suppressing reactions, the geochemical microbial environment is also very complex, but should become better developed over time as this technique is applied and refined.

A significant uncertainty with ISS is the long-term stability (chemically and physically) of the mixture and the resulting impacts on permeability of the solidified sediment which all affects contaminant breakthrough.

Many uncertainties will be resolved and associated challenges understood both during and after project implementation. If these challenges prevent the project from successfully meeting its goals, then the adaptive management plan should be implemented.

8. Monitored Natural Recovery

It is the intention of the authors that this section be read in conjunction with the discussion of site characterization and long-term monitoring included in Section 2 and 9. It is noted that the subheadings are the same in this section, but this section includes specific information on site characterization and long-term monitoring pertinent to monitored natural recovery.

8.1 Introduction

Monitored natural recovery (MNR) is a sediment management option that uses ongoing natural biological, chemical, and physical processes to reduce risk. It relies on naturally occurring processes like biodegradation, sorption, and/or burial by natural sedimentation processes to reduce mobility and/or toxicity of contaminants. Recovery must be demonstrated through long-term monitoring. MNR is not a “do nothing” approach; it requires extensive monitoring.

The Technical Resource Document on Monitored Natural Recovery, published by the USEPA (2014), and Magar et al. (2009) provide a good overview of these naturally occurring recovery processes. These documents include the lines of evidence used to support MNR, the role of conceptual site models in site characterization, and the process of evaluating sediment management alternatives; sedimentation and contaminant isolation; and the fate and processes of contaminants in sediment. Guidance is also provided on long-term monitoring and site forecasting with predictive models. The cost of implementing MNR is relatively low and it is non-invasive, but it requires extensive site characterization, modelling, and long-term monitoring.

Extensive long-term monitoring is required to demonstrate that risk is actually being reduced. A long-term monitoring plan, an administrative controls plan, and an adaptive management plan (in case MNR is not effective in reducing risk) must be included as part of the MNR design.

8.2 Goals and Objectives

The goal of MNR is to use ongoing natural processes to reduce risk to acceptable levels (background levels or reference conditions) within a reasonable time frame.

8.3 Characteristics of Site and Eligibility for MNR

A proper design for a MNR project requires extensive site characterization to ensure an observed reduction in exposure and risk that can be expected to continue into the future. MNR requires monitoring, and possibly adaptive management, to ensure it is working. MNR is effective in waterbodies that are relatively deep and slow moving, and it can be used at sites where (USEPA 2005):

- Risk is low to moderate,
- Anticipated land and waterway uses or new structures are not incompatible with natural recovery,
- Sources of contamination have been controlled and are no longer contributing to the site,
- Natural recovery processes have a reasonable degree of certainty to continue at rates that will contain, destroy, or reduce the bioavailability or toxicity of contaminants within an acceptable time frame,

- Sedimentation rates exceed rates of erosion,
- Expected human exposure is low and/or reasonably controlled by administrative controls,
- Sensitive, unique environments could be irreversibly damaged by capping or dredging,
- The sediment bed is reasonably stable and likely to remain so,
- Sediment is resistant to resuspension (e.g., cohesive or non-erosive sediment),
- Contaminant concentrations in biota and the biologically active zone of sediment are moving toward risk-based goals,
- Contaminants readily biodegrade or transform to lower-toxicity forms,
- Contaminant concentrations are low and cover diffuse areas,
- Contaminants have low ability to bioaccumulate, and
- The harm to the ecological community due to sediment disturbance outweighs the risk reduction of active clean-up.

8.3.1 Modelling

A conceptual site model will contain information about source control and site-specific processes, including the ongoing fate and transport processes. Using the sources, pathways, and relationships presented in the conceptual site model, a quantitative mathematical model that captures the response of the system (past, present, and future) to natural processes should be developed. The predictions made using modelling should be field-validated with monitoring data. Readers are referred to Mager et al. (2009) and USEPA (2014) for guidance on how to use numerical models to evaluate MNR.

8.4 Long-Term Monitoring and Maintenance

Long-term monitoring (LTM) for MNR identifies recovery trends and verifies attainment of project objectives and goals. Source control monitoring should also be part of the LTM plan, as recovery can be halted or reversed if source control is insufficient. The key objective for LTM is to determine progress toward attainment of clean-up levels.

The LTM plan should also accommodate for disruptive events like storms and climate change. Monitoring will be required to assess whether buried contaminated sediment has been disturbed or transported, the spatial extent of the contaminant release and the degree of increased exposure. When assessing increased exposure, the length of time organisms may be exposed to higher levels of contaminant concentrations should be included.

To assess the effectiveness of MNR, the following trends (i.e., lines of evidence) could be used for LTM (USEPA 2005):

- Long-term decreasing trend of COCs in the water column,
- Long-term decreasing trend of surface sediment contaminant concentrations or sediment toxicity or contaminant mass within the sediment,
- Sediment core data demonstrating a decreasing trend in historical contaminant concentration through time, and
- Long-term decreasing trend of contaminant levels in invertebrates and/or higher-trophic-level biota.

Existence of adequate baseline data to compare with future monitoring data should be assessed, and if it does not exist or is insufficient, then additional data should be collected.

At sites where surface sediment chemical concentrations are at or below clean-up levels, but deeper sediment concentrations exceed clean-up levels, monitoring may focus on maintaining the status quo.

A sampling and analysis plan to support the LTM plan must be included in the engineering design report.

The LTM plan should be flexible to accommodate the trends data as they become available. As an example, if three consecutive monitoring results over a specified time frame indicate declining trends, the monitoring frequency can be adjusted to allow longer periods between monitoring. If data indicate that chemical levels are not declining, then investigative work should be undertaken to find out why the system is not recovering, and the MNR plan and LTM plan should be adjusted accordingly. The potential for major storm events and the associated monitoring plan should also be included in the LTM plan. Finally, the LTM plan should state when LTM is no longer required. Detailed guidance on designing an LTM plan is available in many documents (FCSAP: LTM Planning Guidance 2013, USEPA 2005, USEPA 2005a).

8.4.1 Administrative Controls

Contaminated sediment remains in place during MNR; therefore, as with capping and *in situ* projects, administrative controls are an important design consideration. These controls are an administrative tool that establishes administrative procedures/approaches to ensure contaminated sediment is not disturbed, exposed, or re-suspended. For MNR, any activities that would interfere with or counteract the natural recovery process need to be restricted. This could include restrictions on in-water developments, site alterations, recreational activities that involve dredging, filling/covering, piling, or scouring and have the potential to disturb, expose, or resuspend the contaminated sediment. No-anchor zones, reduction in vessel speed, no-fishing zones, and fish advisories are examples of administrative controls that apply to sites with MNR.

8.4.2 Adaptive Management

The purpose of adaptive management is to identify and outline contingency measures that will be taken in case the long-term monitoring data indicate that MNR is ineffective in reducing risk as projected. The adaptive management plan should include the following:

- Measures to implement as needed (additional source control, additional administrative control, or a total re-evaluation that could involve a different approach for all or part of the project, e.g., a placement of a thin layer of clean sediment (TLC) to enhance natural recovery, or an active cleanup (dredging and/or capping)),
- Time frame for decision to intervene (when do you implement adaptive measures),
- Parties responsible for funding and implementing, and
- Monitoring of measures implemented.

8.5 Challenges and Uncertainties

Challenges and uncertainties include lack of complete understanding of highly complex aquatic systems, climate change, and surrounding land use changes (potential sources of contaminants), and these will affect MNR. If these challenges prevent the project from successfully meeting its goals, then the adaptive management plan should be implemented.

9. Monitoring

All sediment management options, with the exception of monitored natural recovery, involve in-water work, and thus the potential to have adverse impacts on the aquatic ecosystem. These impacts generally occur through the creation and migration of suspended contaminated sediment and dissolved contaminants. The increase in suspended solids and dissolved contaminants could have acute and chronic ecological impacts (e.g., plugging of fish gills, change in fish behaviour, habitat alteration, and reproductive changes) (Birtwell et al. 2008, Wilbur and Clark 2001). As a result, it is imperative that any sediment management project have a water quality monitoring program to ensure that potential impacts to the aquatic ecosystem are mitigated. The most common form of monitoring is TSS in the water column as a direct measure of the potential for impacts from in-water work. Since TSS cannot currently be measured in real time, turbidity is commonly used as a surrogate. This requires developing a site-specific relationship between the TSS and turbidity for the site of interest. Most jurisdictions have turbidity/TSS guidelines for the physical impacts caused by suspended sediment. Turbidity, in cases of re-suspended contaminated sediments, can also serve as an indicator for contaminants in the water column.

9.1 Construction Monitoring and Verification

Construction monitoring and verification is conducted to assess if the project is meeting design specifications and if the design is achieving project objectives and performance criteria.

The results of construction monitoring trigger specific actions during the project implementation. Exceedances can result in the modification of work activities or even temporarily shutting down work activities. Verification samples which exceed clean up levels will trigger additional actions required to meet the clean-up levels.

9.2 Long-Term Monitoring

LTM identifies recovery trends over time. LTM should be conducted to assess short- and long-term effectiveness of the risk management activities in achieving management objectives and goals. LTM can include physical, chemical, and/or biological monitoring, which is used to document that the project is achieving long-term objectives and ecosystem recovery.

Once LTM determines that the contaminated sediment does not pose an unacceptable human or ecological risk in the foreseeable future, such that further management action is not required, then LTM can be re-evaluated. The re-evaluation can result in a reduction in frequency and intensity, and potentially the termination of some components of LTM. The reassessment should also include the local conditions, particularly pointing to the vulnerability of the site to flooding and risks due to climate change. The LTM plan must include objectives, tools/methods, and exit criteria, and should be reviewed and accepted by relevant agencies. LTM planning guidance is available from many sources (FCSAP 2013 and USEPA 2005a).

10. Concluding Remarks

The information presented in this document provides the reader with the foundation on which the majority of sediment management projects are based upon and outlines the key factors that should be considered in the design of contaminated sediment management projects.

Management strategies for sediment sites will invariably involve blended remedies on a more frequent basis to address the numerous chemical, physical, biological, and socio-economic aspects. Some sites may also need to be completed as a series of smaller projects over a longer time to overcome challenges that might delay a larger project (regulatory approval, multiple partners, agreements, access, funding or conflicting schedules).

Technology and sediment management techniques will of course continue to develop over time providing further options for consideration. So too will our understanding of the challenges posed by climate change and the requirement needed to make *in situ* management resilient to the impacts of changing conditions. The need for sustainable projects in the future will also drive greater emphasis on the beneficial re-use of contaminated sediments wherever possible. Ultimately, though the topics covered in this document will still represent key components to most sediment management design work. The document will serve as a useful resource for project managers who are asked to manage, review, or provide advice on the development of a sediment management design for a particular site.

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12. List of Acronyms

CAD:	contained aquatic disposal
CDF:	confined disposal facility
COC:	contaminant of concern
CUL:	clean-up level
CSM:	conceptual site model
DMU:	dredge management unit
DRET:	dredging elutriate test
DTPA:	diethylenetriamine-pentaacetic acid
ECF:	engineered containment facility
FCSAP:	Federal Contaminated Sites Action Plan
GAC:	granular activated carbon
GLAOC:	Great Lakes Areas of Concern
HOC:	hydrophobic organic compound
ISS:	*In situ* solidification/stabilization
ITRC:	Interstate Technology and Regulatory Council
LTCST:	long tube column settling test
LTM:	long-term monitoring
MNR:	monitored natural recovery
NAPL:	non-aqueous phase liquid
PAH:	Polycyclic aromatic hydrocarbon
PCB:	polychlorinated biphenyl
PCOC:	potential contaminant of concern
PUP:	plant uptake program

SARA:	Species at Risk Act
SBLT:	sequential batch leachate test
SMO:	sediment management option
SMU:	sediment management units
SWAC:	spatially weighted average concentration
TCLP:	toxicity characteristic leaching procedure
TLC:	thin-layer capping
TLCLT:	thin-layer column leaching test
TSS:	total suspended solids
USACE:	United States Army Corps of Engineers
US EPA:	United States Environmental Protection Agency
VFC:	volatile flux chamber test

13. List of Key Terms

Advection:	The transportation of dissolved contaminants due to fluid movement (e.g., upwelling groundwater).
Aerobic:	In the presence of oxygen.
Anaerobic:	In the absence of oxygen.
Bioaccumulation:	The accumulation of a contaminant in an organism. This occurs when the uptake is faster than the organism can metabolize and excrete the contaminant, or where the organism lacks the ability to metabolize.
Bioturbation:	The burrowing of aquatic invertebrates into sediment.
Blended Remedies:	Combining two or more different sediment management techniques to suit the specific site conditions, budget, and/or management objectives in the best manner.
Booster Pumps:	When hydraulic dredges are required to transport the dredged slurry long distances, booster pumps are required to keep the slurry moving and prevent the solids from settling out and clogging the line.
Conceptual Site Model (CSM):	Presents a comprehensive and concise understanding of the site conditions, including the contaminant source, contaminants of concern, pathways, and receptors.
Contaminants of Concern (COCs):	The contaminants at a site that are deemed to require management. In the preliminary stages of site assessment, contaminants are identified as those that exceed applicable guidelines. This list is often reduced through risk assessment and occasionally, for some contaminants, where background levels are naturally elevated (metals).
Diffusion:	The migration of a substance due to random molecular motion from high to low concentration.
Dike:	Another word for a berm placed into water.
Dredge Management Unit:	A defined volume of sediment for a dredging project that is based on a specific area and depth. These prisms are defined by previous sampling and investigative work. Dredge management units vary in size and shape due to the varying depth of contamination and/or other considerations such as response to toxicity testing.
Dredge Prism:	A three-dimensional defined area of sediment destined for removal.

Dredging Elutriate Test (DRET):	A test whereby sediment samples are mixed with site water in a laboratory to create elutriate mixes simulating the mixing that would occur at the head of a hydraulic dredge. The chemistry of the elutriate is then measured and used in models to predict the fate and transport of chemicals of concern. Toxicity tests can also be performed on the elutriates.
Freeboard:	The distance between the water surface and the top of a barrier keeping water out (i.e., the distance remaining before water overtops a dike/berm or other impermeable wall or structure).
Hydraulic Dredging:	Dredging where the substrate to be dredged is removed by suction as a slurry (i.e., sediment and water) and pumped in a pipeline. The solids content is usually 10 to 15%. Hydraulic dredges usually have some form of cutter head which serves to bite into and agitate the sediment prior to the suction pump removing the generated slurry.
Hydraulic Head:	A measurement of the total fluid energy; used in hydrogeology and other water sciences to estimate groundwater flow and direction.
Hydrophilic:	Contaminants that are more strongly bound (through ionic or hydrogen bonds) to water molecules than sediment particles and organic fractions.
Hydrophobic:	Contaminants that are more strongly bound to the fine-grained sediment particles and organic fractions.
Hypolimnion:	The dense bottom layer of water in a stratified lake, positioned below the thermocline. This layer is coldest in the summer and warmest in the winter (upper layers are frozen from the surface to a certain point determined by recent temperatures).
In situ:	In the context of sediment remediation, this refers to remediation that is conducted in place, with no physical removal of contaminants.
Leachate:	The movement of water through contaminated soils and sediment (groundwater, rainwater) can cause a portion of the contaminants to be removed and subsequently transported. This process is largely dependent on the type of contaminant (hydrophobic vs. hydrophilic) and the pH of the water.
Magnetometer:	In the context of sediment remediation, a geophysical device that is usually towed behind a vessel to measure magnetic anomalies. A magnetometer is useful for locating debris that contains metallic components.

Non-Aqueous Phase Liquid (NAPL):	A liquid that will not dissolve in water, and as such, remains as a distinct and separate phase. This liquid can be either dense (DNAPL) or light (LNAPL). Chlorinated solvents are DNAPLs and petroleum hydrocarbons, such as diesel fuel, are LNAPLs.
Octonal-Water Coefficient (K_{ow}):	The ratio of a chemical's concentration in the octanol phase to its concentration in the aqueous phase of a two-phase octanol/water system. K_{ow} = concentration in octanol phase / concentration in aqueous phase. It is used to identify the preference phase for contaminants: organic (e.g., fish tissue) vs. water.
Oxidation:	Where a chemical species loses electrons and thus becomes oxidized.
Phytoplankon:	Microalgae that utilize light from the sun and nutrients from the water to produce their own energy; an important source of food for aquatic ecosystems.
Porewater:	The water that resides in the interstitial spaces between sediment particles. This is particularly important for contaminants, as the toxicity of sediment has been linked mostly to contaminants in the porewater phase.
Reduction:	Where a chemical species acquires electrons and thus becomes reduced.
Risk Assessment:	In the context of contaminated sites, the process by which the risks of chemical stressors to receptors at a particular site or area are evaluated. In general, this involves estimating doses of contaminants and comparing these to toxicologically derived limits.
Sediment Management Options (SMOs):	An examination of potential remediation options for a site, with the end result being the identification of a preferred option.
Sorbents:	In the context of sediment remediation, usually materials that adsorb contaminants onto their surface. Activated carbon is a very effective sorbent for many contaminants due to the high surface area created during the activation process.
Sub-Bottom Profiler:	An echo sounder that uses lower frequencies to penetrate to various depths of the sediment/water interface before reflecting, to provide information about stratigraphic layering and sediment type.
Surface-Weighted Average Concentration (SWAC):	A technique whereby the amount of surface area for each unique value is factored into the calculation of an average value so that larger areas are given more influence in the overall average. A geographic information system (GIS) is often utilized, as it can perform spatial interpolations (e.g., using Thiessen polygons).

Total Suspended Solids (TSS):	Particles such as mineral grains and/or organic debris suspended in the water column. At certain levels, these are detrimental to aquatic life. Sediment remediation techniques involving physical contact with the sediment introduce suspended solids into the water column, and as such, limits and monitoring are required, and sometimes mitigation.
Turbidity:	The measurement of light penetration through the water. A correlation between turbidity and total suspended solids can be established, and can therefore be used as a surrogate for monitoring plumes from dredging operations. Turbidity can be measured in real time, and therefore carries the advantage of measurements in real time.

Appendix A: Canadian Guidance on Sediment Management Strategies

- Canada-Ontario Decision-Making Framework for Assessment of Great Lakes Contaminated Sediment
  http://publications.gc.ca/collections/collection_2010/ec/En164-14-2007-eng.pdf

- Framework for Addressing and Managing Aquatic Contaminated Sites under the Federal Contaminated Sites Action Plan (FCSAP)
  http://www.dfo-mpo.gc.ca/pnw-ppe/fcsap-pascf/docs/pdf/fcsap-pascf-eng.pdf

- Aquatic Site Classification System (FCSAP)
  https://www.canada.ca/en/environment-climate-change/services/federal-contaminated-sites/publications.html

- Long-Term Monitoring Planning Guidance (FCSAP)
  https://www.canada.ca/en/environment-climate-change/services/federal-contaminated-sites/long-term-monitoring.html. For full document, contact: FCSAP.PASCF@ec.gc.ca

- Guidance for Assessing and Managing Aquatic Contaminated Sites in Working Harbours (FCSAP) Version 1.0, June 2019
  available by request at: ec.pascf-fcsap.ec@canada.ca;

- Guide to Monitored Natural Recovery (MNR) in Aquatic Sediment for Federal Contaminated Sites (FCSAP)
  Currently draft

- Sediment Remediation Conceptual Cost Estimation Tool (FCSAP)
  available by request at: ec.pascf-fcsap.ec@canada.ca;

- Supplementary Guidance for Assessing Risk to Higher-Level Receptors (FCSAP)
  available by request at: ec.pascf-fcsap.ec@canada.ca;

- Disposal at Sea Technical Guidance: Chemical Characterization of Dredged Material Proposed for Disposal at Sea
  Contact: Environment and Climate Change Canada, Disposal at Sea Program

- Canadian Sediment Guidelines for the Protection of Aquatic Life (CCME)
  http://www.ccme.ca/en/resources/canadian_environmental_quality_guidelines/index.html

- Guidance on Human Health Risk Assessment of Contaminated Sediments: Direct Contact Pathway (DRAFT)
  http://www.hc-sc.gc.ca/ewh-semt/pubs/contamsite/sediment-sediment/index-eng.php

- Ontario: Guideline for Identifying, Assessing, and Managing Contaminated Sediment in Ontario: An Integrated Approach
  https://www.ontario.ca/document/guidelines-identifying-assessing-and-managing-contaminated-sediments-ontario-integrated-approach

- A Guidance Manual to Support the Assessment of Contaminated Sediments in Freshwater, Estuarine, and Marine Ecosystems
  Volume I – An Ecosystem-Based Framework for Assessing and Managing Contaminated Sediments
  http://www2.gov.bc.ca/assets/gov/environment/air-land-water/site-remediation/docs/requests-for-comments-archive/guidance_manual_volumei.pdf

- British Columbia: Guidance Manual to Support the Assessment of Contaminated Sediments in Freshwater, Estuarine, and Marine Ecosystems in British Columbia
  Volume II – Design and Implementation of Sediment Quality Investigations
  http://www2.gov.bc.ca/assets/gov/environment/air-land-water/site-remediation/docs/requests-for-comments-archive/guidance_manua_volumeii.pdf

- A Guidance Manual to Support the Assessment of Contaminated Sediments in Freshwater, Estuarine, and Marine Ecosystems
  Volume III – Interpretation of the Results of Sediment Quality Investigations
  http://www2.gov.bc.ca/assets/gov/environment/air-land-water/site-remediation/docs/requests-for-comments-archive/guidance_manual_volumeiii.pdf

- British Columbia: Guidance Manual to Support the Assessment of Contaminated Sediments in Freshwater, Estuarine, and Marine Ecosystems in British Columbia
  Volume IV - Supplemental Guidance on the Design and Implementation of Detailed Site Investigations in Marine and Estuarine Ecosystems
  http://www2.gov.bc.ca/assets/gov/environment/air-land-water/site-remediation/docs/technical-guidance/x19_v4.pdf

- Criteria for the Assessment of Sediment Quality in Quebec and Application Frameworks: Prevention, Dredging, and Remediation
  http://planstlaurent.qc.ca/fileadmin/publications/diverses/Qualite_criteres_sediments_e.pdf

- Quebec Ecological Risk Assessment of Open-Water Sediment Disposal to Support the Management of Freshwater Dredging Projects
  http://planstlaurent.qc.ca/fileadmin/site_documents/documents/guide_ecotoxicologique_ang.pdf

- Quebec Guide for the Development of Environmental Monitoring and Surveillance Programs for Dredging and Sediment Management Projects http://planstlaurent.qc.ca/fileadmin/site_documents/documents/Usages/Guide_PSSE_final_anglaisMM1.pdf

Appendix B: Case Studies

Case Study 1: Blended Remedy, The Northern Wood Preservers Alternative Remediation Concept (NOWPARC), Thunder Bay, Ontario, Canada

Sediment contamination around the Northern Wood Preservers Inc. (NWP) site contributed to the identification of Thunder Bay as an Area of Concern under the 1987 Great Lakes Water Quality Agreement between Canada and United States . The contaminated sediment contained polycyclic aromatic hydrocarbons (PAHs), chlorophenols, dioxins and furans as a result of wood preserving activities over 50 years at the site. In order to remove Thunder Bay Harbour from the AOCs list, remediation of contaminated sediment at the NWP site was required.

NWP, Abitibi-Consolidated Inc., Canadian National Railway Co., Environment Canada and the Ontario Ministry of the Environment worked together on the Northern Wood Preservers Alternative Remediation Concept (NOWPARC) to remediate the area around the NWP site in Thunder Bay Harbour (Golder, 2005).

A Steering Committee composed of senior representatives from each of the participating organizations directed the project starting 1997. An Implementation Committee composed of technical specialists from a subset of the participating organizations and project management consultants advised the Steering Committee.

The selected remedy is a blended remedy of dredging, treatment, isolation, containment, and monitored natural recovery. The total cost of the project was $20 million (M).

Location

The Northern Wood Preservers' (NWP) site is located in the Thunder Bay Harbour in northern Ontario. The Northern Wood Preservers wood processing and treatment facility is located on largely reclaimed land on the west side of Thunder Bay Harbour in Thunder Bay, Ontario.

Figure CS1-1: Location map for Northern Wood Preservers, Thunder Bay, Ontario Canada (courtesy of ECCC).

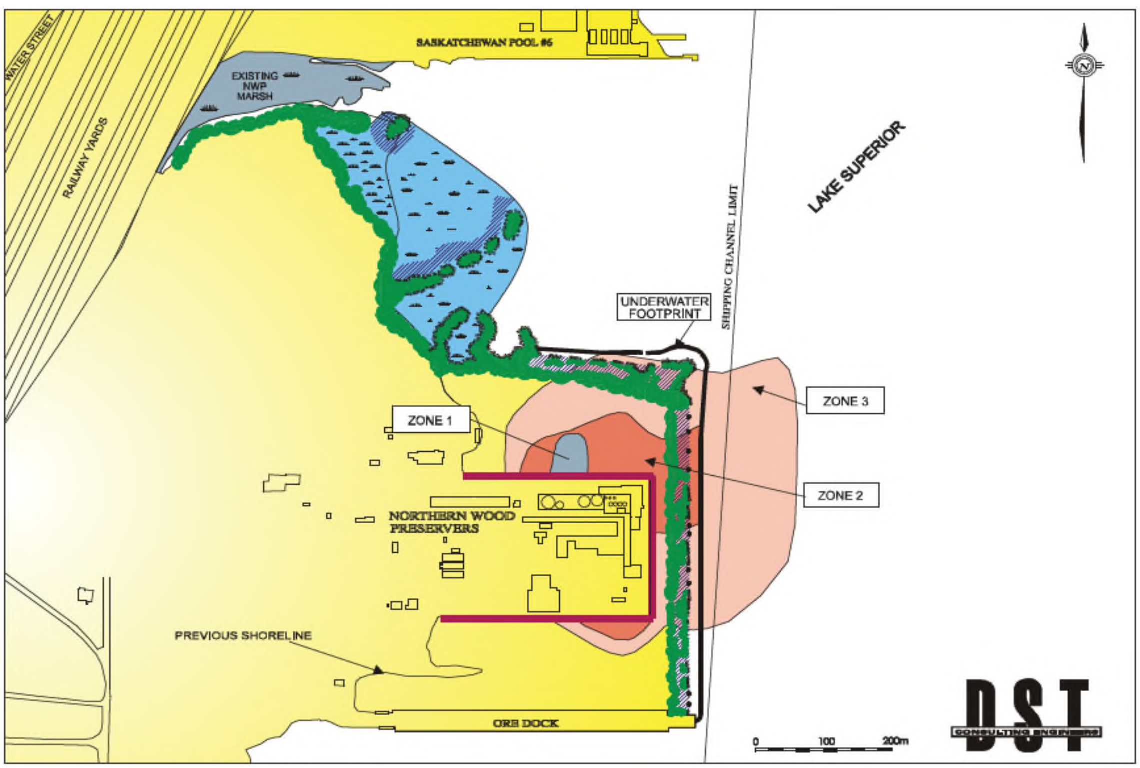
Contaminants of Concern

Site studies and surveys identified elevated levels of creosote contaminated sediment, containing polycyclic aromatic hydrocarbons, chlorophenols, dioxins and furans at the NWP site. These contaminants affected the harbour water quality, biological community structures and sediment quality.

Risk Characterization

The site assessment based on chemistry and biological effects indicated the following four zones at NWP (MOE 1998):

1. Zone 1: An area containing a creosote pool.
2. Zone 2: An area of acute toxicity (PAHs greater than 150 parts per million [ppm]) that needed to be removed and treated.
3. Zone 3A: An area of chronic toxicity (PAHs between 30 ppm and 150 ppm) that needed to be isolated.
4. Zone 3B: An area of chronic toxicity (PAHs between 30 ppm and 150 ppm), however 80% of area is less than 50 ppm TPAHs thus was identified for Monitored Natural Recovery (MNR).



NOWPARC sediment contamination zones

Figure CS1-2: Contamination zones. Source : NOWPARC Brochure(Governments of Canada and Ontario)

Source of Contamination

The NWP site was contaminated as a result of wood preserving operations which took place at the site over a 50 year period.

Clean-up Goals

Total PAH sediment removal criterion was 150 ppm based on acute sediment toxicity.

Site-specific clean up criteria were developed for three zones extending around the NWP site based on biological effects assessment completed in 1995 (sediment toxicity and benthic community assessment). Zone 1 and 2 were identified for removal and treatment whereas Zone 3A was identified for containment and Zone 3B for MNR. A total of 60,000 m3 of contaminated sediment required management.

Remedy Selected

The selected remedies to manage the 60,000 m3 of contaminated sediment was a combination of dredging, treatment, isolation, containment, and monitored natural recovery.

The following remedies were implemented in the three management zones. (EC et al., 1996):

- **Zones 1 and 2 Remove and Treat:** Approximately 11,000 cubic metres (m3) of highly contaminated sediment was dredged and treated to meet the 1991 Canadian Council of Ministers of the Environment (CCME) Industrial/Commercial Criteria for Soil,
- **Zone 3A Contain and Cap:** Approximately 21,000 m3 of contaminated sediment (PAHs between 30 ppm and 150 ppm) were contained inside the rockfill containment berm (RCB) that was built, and capped with clean fill to isolate this sediment from the aquatic environment, and
- **Zone 3B Monitored Natural Recovery:** Approximately 28,000 m3 of marginally contaminated sediment outside the RCB were left to recover naturally. Nearly 80 percent of this area contained was below 50 ppm total PAHs, and Beak Consultants conducted predictive modelling that indicated that PAH concentrations would continue to decrease as the PAHs decayed. The majority of this marginally contaminated sediment also is located in the shipping channel.

The main activities in the remediation of the NWP site are outlined as follows.

Rockfill Containment Berm

The rockfill containment berm (RCB) was designed to contain the area around the NWP site. Construction of the RCB began in August 1997 and was completed in December 1997. Approximately 260,000 tonnes of shale and 22,000 t of rip-rap (armour stone) were used to construct the 850 metre (m) long berm. Within the RCB, 21,000 m3 of marginally contaminated sediment (that having chronic toxicity) were contained and capped with approximately 800,000 tonnes of clean fill.

Figure CS1-3: Construction of the rock-filled containment berm (RCB) (courtesy of ECCC).

Environmental Dredging

During the fall of 1997, approximately 3,200 m3 of contaminated sediment (acute toxicity) were removed using a Cable Arm Clamshell Environmental bucket to prepare the lake bottom for construction of the berm. In August 1998, the remaining 7,800 m3 of contaminated sediment within the RCB were removed and placed in dewatering cells prior to treatment.

The dredged sediment removed in 1997 to allow Construction of the rockfill berm was temporarily stored in a partially laid up self-unloading bulk carrier (decommissioned lake freighter) moored adjacent to the project site. The dredged sediment was hydraulically pumped from the dredge scows into the storage vessel. In 1998, pumper trucks were used to remove the sediments from the lake freighter and deposit the sediment in a (Engineered Bioremediation Cell (EBC) within the RCB. In 1998, the mechanically dredged sediment was placed in scows then double handled into 500 m3 dewatering cells. The dewatered sediment was then mixed with DARAMEND® organic amendment and placed on the EBC. Sediment porewater from the dewatering cell and effluent from the EBC underdrainage system were pumped to a retention pond. The retention pond effluent was treated by an on site mobile wastewater treatment plant and discharged with the confines of the RCB.

Figure CS1-4: (left)Dredging contaminated sediment using a Cable Arm clamshell environmental bucket and placement on a scow and (right) an overview of sediment handling, dewatering and the temporary storage area (courtesy of ECCC).

Sediment Treatment (Bioremediation/Thermal treatment)

Bioremediation was chosen as the initial sediment-treatment method. Due to the higher-than-anticipated contaminant concentrations, site-specific remediation criteria were not met over the period from September 1998 to February 2000.

Adaptive Management

Enhanced bioremediation bench-scale laboratory testing confirmed that an alternative treatment technology would have to be used. In the summer of 2001, approximately 17,000 tonnes of contaminated sediment were loaded into fully lined rail cars and transported to a thermal treatment facility in British Columbia.

Figure CS1-5: Thermal treatment facility (courtesy of ECCC).

Contaminant Isolation Structures (Clay Isolation/ Waterloo Sheet Pile Wall)

As part of a technology demonstration, a 600 m long clay isolation barrier was constructed adjacent to the NWP pier to prevent the movement of contaminants into the harbour. The barrier, completed in August 2000, contained approximately 114,000 tonnes of clay.

Adaptive Management

Tests indicated that the clay isolation barrier provided good containment but did not consistently meet the design requirements for permeability. A Waterloo Barrier®, a steel sheet pile wall, was installed in October 2001 as a contingency measure to ensure containment of the on-site contaminants. Constructed of approximately 6,000 square metres (m2) of sheet piling, the barrier was placed along a 660 m section around the NWP pier.

Figure CS1-6: Installation of Waterloo Sheet Pile Wall Barrier®(courtesy of ECCC).

Stormwater and Groundwater Control and Treatment

A groundwater treatment plant was required to treat contaminated groundwater that builds up behind the clay isolation barrier and the steel pile wall barrier. Groundwater levels under the NWP site will be maintained slightly below the level of the lake. A granular activated carbon (GAC) treatment plant was constructed in 2001 to treat the collected groundwater and the effluent that the ongoing NWP operations generated.

Modifications were made at the industrial site to improve the management and diversion of stormwater. A collection system was installed along the groundwater collection trench.

Fish Habitat Enhancements

A fish habitat enhancement study was developed to assess and track fish community around the NWP property. The study compared pre and post remediation conditions and also compared to other sites within Thunder Bay Harbour.

The project design included the replacement of approximately 150,000 m2 of fish habitat was lost due to dredging and infilling operations. As part of the compensation required by the Department of Fisheries and Oceans to address loss of fish habitat, approximately 48,000 m2 of new or altered aquatic habitat were created in two areas. Reclamation of lost wetland habitat in the Northern Marsh was completed in 1999. Engineered habitat enhancements along the berm were completed in 2002. A planting plan for the greenspace was implemented in June 2003.

Figure CS1-7: Overview of fish habitat enhancement features (courtesy of ECCC).

Environmental Monitoring

Water Quality Monitoring - undertaken during berm construction, site isolation, fill placement and sediment removal to confirm that the measures implemented are protective of the environment as well as provide data towards the evaluation of the innovative removal technology employed.

Replacement Fish Habitat Monitoring was conducted to measure the success of fish habitat creation and remediation activities, a replacement fish habitat monitoring was conducted. In order to achieve a no net loss of fish habitat, the berm and shoreline received treatments to enhance their suitability as habitat for fish and other fauna. The creation and enhancement of fish habitat in intercostal and marsh areas of the project were assessed for effectiveness. The 2004 and 2006 study results suggested that the fish habitat around the restored areas of NWP is similar to that of other sites within the Thunder Bay Harbour. Given that remedial actions were not concluded until 2003, any responses by the fish community around the NWP property are likely ongoing and will require future sampling to document (Parker et al., 2008).

Terrestrial Environment Monitoring was conducted to document impacts on wildlife during construction, and to assess the use of the upland areas of the berm and vegetated visual barrier by wildlife.

Ground Water Monitoring was conducted to measure contaminant levels and their changes in ground water over the long term and to measure rates of ground water flow.

Sediment and Biological Monitoring was conducted under the Long Term Monitoring plan (see below).

Figure CS1-8: Sediment sampling (courtesy of ECCC).

Long-term Monitoring

In 1999, a post-construction monitoring was carried out to establish baseline harbour conditions. The results of this survey was used to track natural recovery of the sediment in Zone 3B, located outside of the RCB.

Monitoring consisted of chemical analysis of sediment for PAH compounds, and a suite of biological tests including biomonitoring of mussels for PAHs, assessing the benthic community and performing laboratory bioassay tests of sediment. Fifteen sites, located at 50 m and 100 m from the RCB, were sampled.

A follow-up surveys were completed in 2004, 2009, and in 2014 to measure natural recovery in the harbour area outside of the RCB (MECP 2020). The 2014 data indicated that contamination persist at select sampling sites around the NWP site, specifically sites located in the northeast corner of the rockfill berm, and half way down the east side of the berm from the northeast corner (DRAFT MECP 2020). Samples were again taken in 2020 to assess recovery of these areas and results are still being analyzed and assessed.

Public Consultation and Environmental Assessment

The project was assessed under the Canadian Environmental Assessment Act (CEAA) of 1992 as a Comprehensive Study. The CEAA identified responsibilities for projects involving the Government of Canada as well as the procedures they must follow to assess any significant adverse effects they may cause.

Environment Canada was the lead Responsible Authority (RA) under the 1992 Act and thus responsible for carrying out the overall assessment because it contributed federal funds to the project. Other RAs included the Fisheries Habitat and Management Branch of DFO, due to Fisheries Act triggers under CEAA (1992) and the Canadian Coast Guard, which was also part of DFO, due to Navigable Water Protection Act triggers under CEAA (1992). A comprehensive study was required for this project since it involved the construction of a temporary facility for the treatment of material that could be classified as hazardous waste.

Project Duration

The project began in 1997 and was completed in 2004.

Operation Summary

During this project, 11,000 m3 of highly contaminated sediment were removed, treated and reused; 21,000 m3 of contaminated sediment were contained, 28,000 m3 of sediments were left for monitored natural recovery; and 5 ha of fish habitat were created.

Figure CS1-9: NWP site before and after remediation (courtesy of ECCC).

Costs

The project, initially budgeted at $9.3 M was completed at a cost of $ 20 M.

Activity	Original Budget ($000s)	Final Budget ($000s)	Variation	Original Distribution	Final Cost (%)
Berm construction	1,950	2,200	250	22	11
Dredging	730	1,100	370	8	6
Treatment	2,300	4,300	2,000	26	23
Isolation	500	3,600	3,100	6	19
Containment	1,450	2,000	550	17	10
Habitat creation	250	390	140	3	2
Groundwater treatment	650	1,170	520	8	6
Stormwater management	150	335	185	2	2
Environmental/ construction monitoring	200	730	530	2	4
Long-term monitoring	250	400	150	3	2
Project management	300	2,800	2,500	3	15
Contingencies and insurance	570	975	405		
Total	**9,300**	**20,000**	**10,700**	**100**	**100**

Lessons Learned

1. Conduct Pilot Scale Tests prior to awarding construction contracts thus providing more flexibility to adapt to unforeseen circumstances.
2. Creosote pool should have been handled separately from the contaminated sediment.
3. Conduct comprehensive chemical and geotechnical characterization of site conditions
4. When assessing Sediment Management Options do not restrict the selection based on a pre-determined budget.

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Golder Associates Ltd., June 2005. Project Completion Report - Northern Wood Preservers Alternative Remediation Project (NOWPARC) Project, Northern Wood Preservers Site, Thunder Bay Ontario. Submitted to the NOWPARC Steering Committee.

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Parker, S., Addison, P.A, MacIntosh, K.J., and Garach, G.R. 2008. Northern Wood Preservers Alternative Remediation Concept (NOWPARC). Fish community comparison between nearshore remediation areas of the Northern Wood Preservers facility and four nearshore areas within Thunder Bay Harbour in 2004 and 2006. Ontario Ministry of Natural Resources, Upper Great Lakes Management Unit, Lake Superior, Thunder Bay, Ontario, Canada, and Government of Canada, Fisheries and Oceans Canada, Thunder Bay, Ontario, Canada Report.

Case Study 2: Thin Layer Capping (TLC) at Peninsula Harbour (Jellicoe Cove), Ontario, Canada

Peninsula Harbour is one of 43 Areas of Concern (AOCs), identified under the 1987 Great Lakes Water Quality Agreement between Canada and the United States. Peninsula Harbour was designated an AOC because a review of available data indicated that water quality and environmental health were severely degraded. Further monitoring showed high levels of contaminants in fish and sediment, loss of fish habitat, and degraded fish and benthic communities (worms and insects that live on the lake floor). The contaminated sediment in Jellicoe Cove, Peninsula Harbour (PH) was capped with thin layer of clean sand in 2012. This was the first thin layer capping (TLC) project in Canada to manage contaminated sediment.

Location

Peninsula Harbour is located on the north shore of Lake Superior near the town of Marathon, Ontario (Figure CS2-1). At Peninsula Harbour, the sediment and invertebrate tissue concentrations of mercury were found to be the highest in Jellicoe Cove. The only waterways that enter into Jellicoe Cove are two small creeks, Shack Creek and an unnamed creek north of Shack Creek. Within Jellicoe Cove, the area requiring management was delineated based on risk.

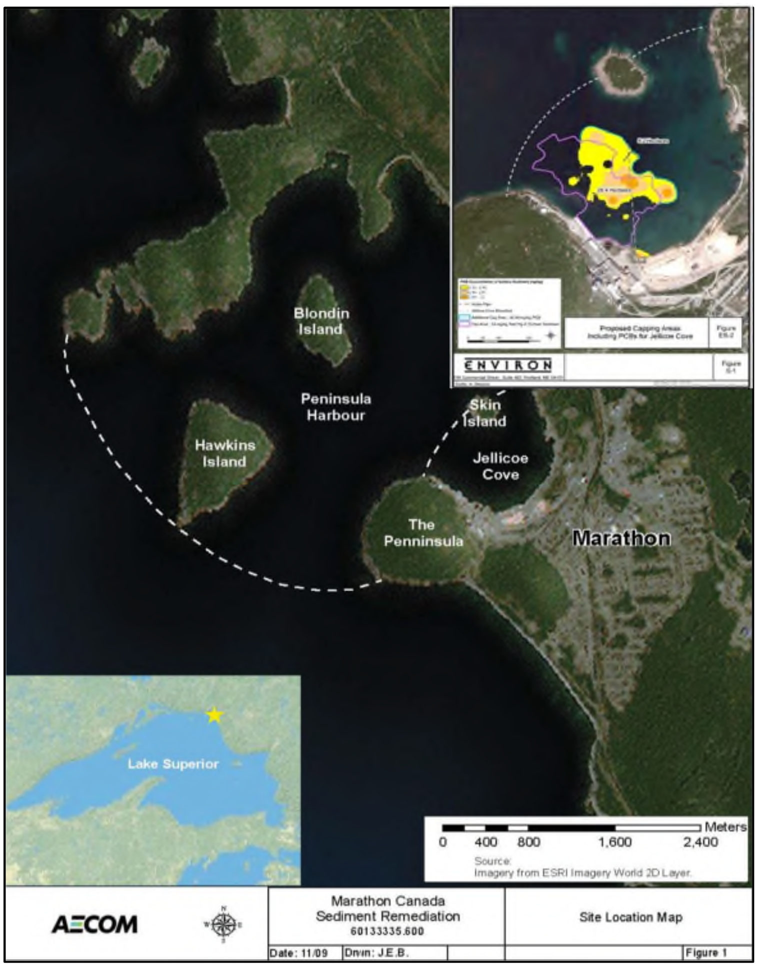

Figure CS2-1: Jellicoe Cove, Peninsula Harbour, Ontario, Canada (courtesy of AECOM).

Site Characterization

The sediment management area is approximately 250,000 square metres (m^2) or 25 hectares (ha). Water depth in the management area ranged from 4 to 20 m. Due to the remoteness of the location, equipment and some capping material (coarse sand) were transported from distant locations (at additional cost and time).

Contaminants of Concern

Contaminants of concern are mercury and PCBs. Total mercury concentrations in the surficial sediment range from 0.04 to 19.50 µg/g, exceeding the Severe Effect Level (SEL) (Ontario Sediment Quality Guideline) where the sediment is likely to affect the health of sediment-dwelling organisms. The average mercury concentration at the surface was 7 ppm, which was 3.5 times higher than the SEL. PCB concentration in sediment up to 1,058 ng/g has been found in Jellicoe cove (Hayton, 2005).

Source of Contamination

The contamination of sediments at PH is due to historical pulp mill and chlor-alkali plant activities. The mill ceased its operation in 2009.

Risk Characterization

An ecological risk assessment (ERA) and a screening level human health risk assessment (HHRA) were conducted. The results of the risk assessment indicated that:

- Invertebrates living in sediment are not likely to be harmed by mercury or PCBs,
- Reproduction in fish may be reduced by mercury and PCBs,
- Birds are not likely to be harmed by mercury or PCBs in the fish they eat,
- Some mink young may be harmed by PCBs in the fish they eat. Current levels of mercury are not likely to harm mink, and
- Fishermen’s families may be at risk from PCBs in fish from the AOC. Current levels of mercury are not likely to harm fishermen or their families.

Clean-up Criterion

The clean-up criterion for PH is 3 mg/kg total mercury. Managing areas that exceed 3 mg/kg mercury will reduce the risk from both mercury and PCBs to acceptable levels, as PCB-contaminated areas are co-located with mercury contaminated areas > 3mg/kg.

Remedy selected

Thin layer capping was selected as the preferred option to manage the contaminated sediments in PH by Risk Managers at ECCC and MOECC, upon reviewing comments from the stakeholders and the PH Technical Committee. Thin layer capping at Jellicoe Cove will reduce the spread of contaminated sediment from Jellicoe Cove to the rest of Peninsula Harbour.

Monitored natural recovery, isolation caping, thin layer capping, and dredging sediment management options (or a combination of these options) were considered. Thin layer capping was selected as the preferred option, based on input received from local stakeholders, the Indigenous community, and the public. The following criteria were used in selecting the final sediment management option:

- Ability to achieve sediment management goals with defined targets,
- Technical feasibility (reliability, scheduling, and construction/operation requirements),
- Community preference,
- Environmental impacts, human health implications, and ability to control residual contamination,
- Requirements for chemical, physical and biological monitoring,
- Compliance with regulatory requirements, and
- Overall project costs.

TLC Design

The basis of the TLC design is for the capping material to mix with existing contaminated sediment. The Request for Proposals (RFP) was issued based on performance and was not prescriptive. It specified a test plot where methodologies to lay the cap were to be tested to ensure that it meets the performance criteria prior to full scale production enabling the use of new technologies/methods.

Capping Material

Clean medium and coarse sand were chosen as the capping materials. Medium sand was locally available but coarse sand was barged in from Manitoulin Island. To protect the capping material from eroding away via propeller wash and local currents in the capped area, a coarser sand and a thicker cap was designed along the existing dock.

Sand specification and testing methods were developed to assess the quality of the sand. These methods include:

- Obtaining one sample for every 5,000 m^3 of sand used (4 samples for coarse; 6 samples for medium),
- Ensuring each sample was a composite of 5 sub-samples taken throughout the stockpiled sand (done at the quarry),
- Testing the samples for specific gravity, particle size, and chemistry,
- Using medium sand with mass median diameter (D_{50}) of 0.7 to 1.8 mm, and coarse sand with D_{50} of 3.1 to 3.8 mm,
- Delivering sand to the site using trucks (from local quarry) and barges (from Manitoulin Island),
- Stockpiling sand on the dock to ensure sufficient supply, and
- Loading sand from the dock onto the supply barge using a conveyor belt.

The Cap Thickness Criteria for medium sand was 10 to 30 cm, with an average thickness of 15 cm. For coarse sand, it was 12.5 to 37.5 cm with an average thickness of 20 cm.

A thicker cap and heavier sand were used in areas of high energy (along the MPI dock).

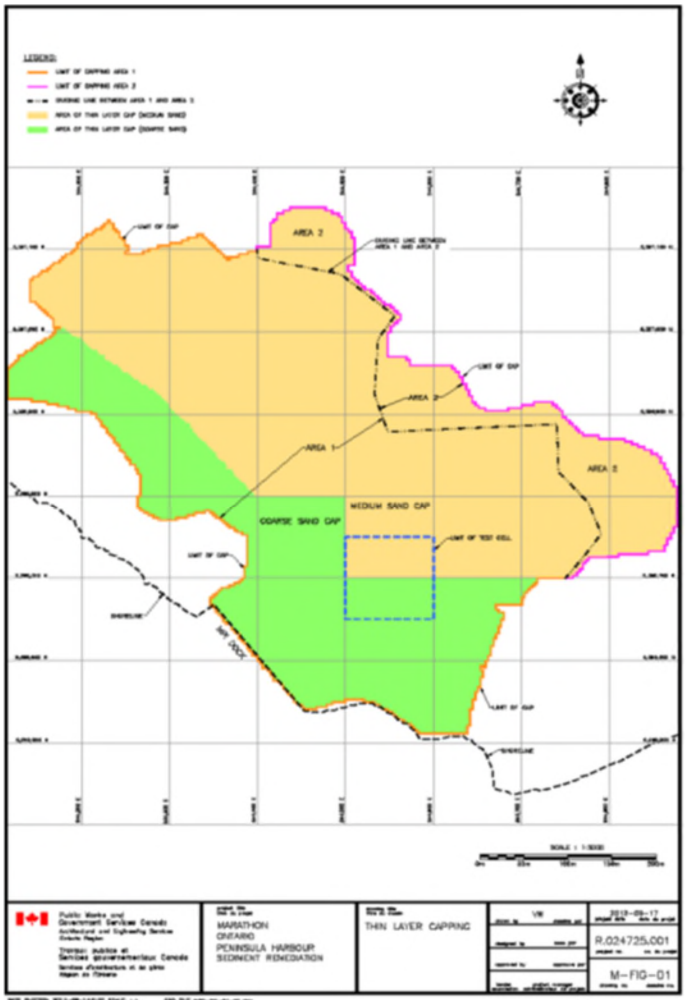

Figure CS2-2: Capped Area. (green: coarse-sized sand; beige: medium-sized sand)(courtesy of Public Services and Procurement Canada).

Environmental Mitigation and Controls

Silt curtains were used to reduce the spread of fines from the capping material and also to control the spread of any mobilized contaminated sediment from the capping activity. Silt curtains were hung from a box frame attached to the floating platform, forming a moon pool configuration.

Figure CS2-3: A floating silt curtain box around the placement cell to minimize movement of fines (courtesy of Pacific Productions).

Figure CS2-4: Silt Curtains around near-shore habitats to protect fish habitat (courtesy of ECCC).

Figure CS2-5: Silt fences around the stockpiled sand (Capping material) (courtesy of ECCC).

Capping Operation

Capping was carried out in two phases:

- **Test Phase:** the placement techniques were fine-tuned for both medium and coarse sand to optimize the placement technique while meeting the cap thickness and water quality criteria, and
- **Production Phase:** consistently using the selected methodology from the Test Phase.

Cap placement using buckets was selected by the contractor. This method met the performance criteria specified in the RFP.

An RTK-GPS integrated DREDGEPACK® positioning system was used to accurately position the bucket over the placement grid (one bucket in each grid), and carry out the following tasks:

- Controlling the sand placement rate by controlling the size of the grid. For example, each grid was set at 2.95 m x 2.95 m to achieve an average capping thickness of 20 cm,
- Recording each bucket and each grid that was completed using the DREDGEPACK® software,
- Adjusting the placement grid size periodically to account for changing water depths and dispersion rates, as determined from coring results, and
- Applying sand until the entire cell was capped, and then taking cores to verify the thickness.

Cores were taken using a cable-suspended piston coring device to ensure that cap thickness criteria were met.

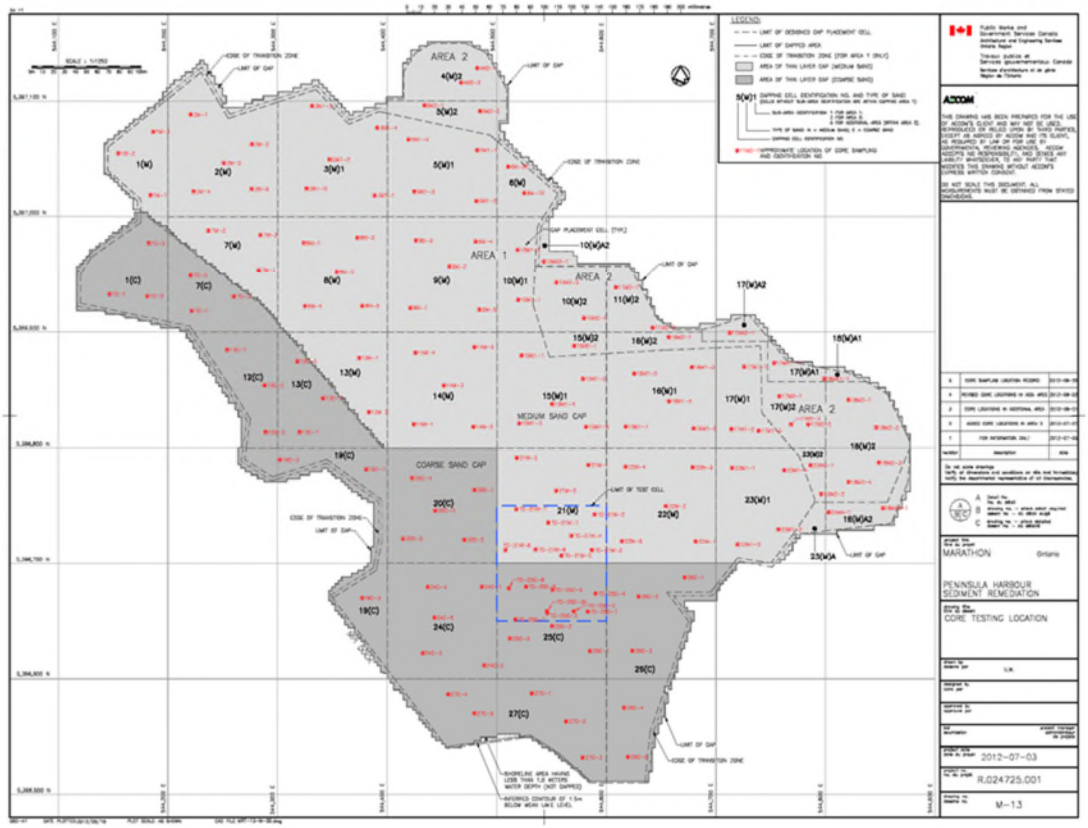

Figure CS2-6: Capped Area with core sampling locations
(dark grey: coarse-sized sand; grey: medium-sized sand)(courtesy of AECOM).

Figure CS2-7: Cap thickness verification via cores (courtesy of AECOM).

Construction Monitoring

Cap area coverage, thin layer cap thickness, and water quality were monitored during construction.

Water Quality Monitoring (WQM)

WQM was divided into 4 phases:

1. Baseline (pre cap).
2. Testing Phase (one week, intensive).

   During the testing phase, real-time measurements (turbidity, TSS, temp, specific conductance and DO) were taken at 25 m intervals up to 100 m from the capping barge. Water samples were collected for the analysis of TSS, and additional water samples were taken from the bottom (0.5 m from the bottom) for analysis of mercury and PCBs.
3. Standard (operation).

   During operation, monitoring was conducted twice per day, two time per week. Real-time measurements (turbidity, TSS, temp, specific conductance and DO) were taken at 100 m from the capping barge. Shack Creek, the control site, and one additional background location were also sampled to establish background levels.
4. Conditional/Additional monitoring.

   Additional monitoring was done when there was a major change to the operation (procedural change), or a visible plume extending 50 m or more from the capping barge was seen. Conditional monitoring was performed until it was confirmed that the operational change was meeting the turbidity criteria.

Water quality was monitored over three depths (surface, mid, and bottom), as well as sampling locations that were selected according to the location of capping operations. Turbidity, temperature, and dissolved oxygen measurements were made.

Water samples at depth were also taken to assess the release of mercury and PCBs from the contaminated sediment as a result of capping activity.

Water Quality Monitoring Criteria are summarized in Table 1.

Table B-1: Water Quality Monitoring Criteria.

Criteria	Shallow Curtain Protected Area (If Required)		Non Curtained Area	
	TSS (mg/L)	Turbidity (NTU)	TSS (mg/L)	Turbidity (NTU)
Primary Criteria - exceedance requires immediate notification of contractor and cessation of operation to evaluate cause	45	15	150	50
Measured at:	10m to the land side of the silt curtain		100 m from the capping operation	
Secondary Criteria - exceedance requires immediate notification of contractor to evaluate cause and continued monitoring; second exceedance within a one(1) hour period requires cessation of operation to evaluate cause	25	8	90	30
Measured at:	any location within 10 m to the land side of the silt curtain		100 m from the capping operation	

Notes:

- TSS is the controlling criteria; turbidity may be adjusted following review of site-specific TSS-turbidity relationship
- The background level will be determined by averaging TSS/Turbidity at all depths from the reference site
- criterion compared to water column average with depth of measurements noted below
- depth of real time and water sample collection:
  - ≤ 2 m - one measurement point at mid depth
  - > 2m and < 4m - two measurement points; 0.5 m below the surface and 0.5 m above the bottom
  - ≥ 4 m - three measurement points; 0.5 m below the surface, mid depth, and 0.5 m above the bottom

Water Quality Monitoring Summary

1. At the 100 m compliance boundary, all turbidity/TSS readings were in compliance during the standard monitoring.
2. Conditional monitoring was done 3 times during the entire capping operation. In each case, operational changes were made to reduce turbidity. Excess turbidity was caused by:
   - Propeller wash from a tug boat,
   - The turbidity curtain dragging on the lake bottom in shallow water, and
   - Capping without a full turbidity curtain

Project Duration

The project started in the summer of 2012 and was completed in August 2012.

Costs

The cost of the project was approximately $7 M dollars excluding long-term monitoring.

Capping Operation Summary

1. Capped 23 ha with medium/coarse sand.
2. Placed 36,000 tonnes of coarse sand and 49,600 tonnes of medium sand.
3. Average production was 4,635 m^2 or 1,616 tonnes per day.
4. Capping started on June 5, 2012 and ended on August 5, 2012 (48 working days with 12-hour shifts).
5. 3 hours of delay due to weather; 26 hours of delay due to mechanical problems.
6. A video of the PH Thin Layer Capping Project video was produced. https://www.youtube.com/watch?v=UZExnX5Q-70

Monitoring of the Ecosystem Recovery

A 20-year Long-Term Monitoring (LTM) plan was developed that included:

1. Re-colonization of submerged aquatic vegetation and cap movement (0, 1, 3, 5, 10 years post cap).
2. Re-colonization of the benthic community (5, 10, 15, 20 years post cap).
3. Benthic invertebrate tissue survey (Hg) (5, 10, 15, 20 years post cap).
4. Fish tissue survey (5, 10, 15, 20 years post cap).
5. Sediment Chemistry (5, 10, 15, 20 years post cap).

The results of the previous survey determine the components of the next survey. The monitoring frequency and the components of study depend on the findings of previous survey. Even though the duration of the PH LTM is assigned a 20 year time period, LTM can end earlier or later depending on the results.

In 2017, a 5-year post capping monitoring study was conducted at Peninsula Harbour, and the report will be available in 2019.

Lessons Learned

Starting construction in early spring was crucial to success of the project (3 hours of downtime due to weather).

The ability to modify the sequencing of cells being capped was valuable for maintaining productivity in light of optimizing construction activities and minimizing cap disturbance.

Case Study 3: Monitored Natural Recovery at St Lawrence River, Cornwall, Ontario, Canada

The section of the St Lawrence River at Cornwall (SLR) is one of 43 Areas of Concern (AOCs) identified under the 1987 Great Lakes Water Quality Agreement between Canada and the United States. The St. Lawrence River (Canadian section) was designated as an AOC because a review of available data indicated that water quality and environmental health were severely degraded. Cornwall, the largest urban centre in the AOC, has been a hub of industrial activity for more than 100 years. This legacy led to contamination issues in local waters affecting the aquatic environment. Sediment contamination in the St Lawrence River AOC has been studied since the mid-1970s, in an effort to understand the nature and extent of mercury contamination within the river. These efforts have resulted in the identification of three zones where sediment with elevated levels of mercury, requires management.

The SLR was the first Canadian AOC to adopt Monitored Natural Recovery (MNR) as a sediment management strategy when in 2005 the Contaminated Sediment Strategy (CSS) for the St Lawrence River (Cornwall) AOC identified MNR as the preferred sediment management option. A steering committee consisting of various government departments and a local Indigenous group was formed to oversee the progress of MNR.

Various studies have been completed from 2005 to 2015 in order to improve the understanding of the conditions at the site and assess the initial progress of MNR. In 2015 it was recognized that under MNR a formalized plan to verify successful recovery was needed. Remedial goals and a long-term monitoring plan (LTMP) was developed in 2017 to monitor the progress of MNR and eventually confirm when these targets are achieved.

Location

The SLR drains from Lake Ontario into the Gulf of St Lawrence, passing through the provinces of Ontario and Quebec along with the State of New York. The City of Cornwall, Ontario lies on the north shore of the SLR across from New York and just upstream from Quebec (Figure CS3-1). The mercury contamination of concern is located in three zones along the Cornwall shoreline.

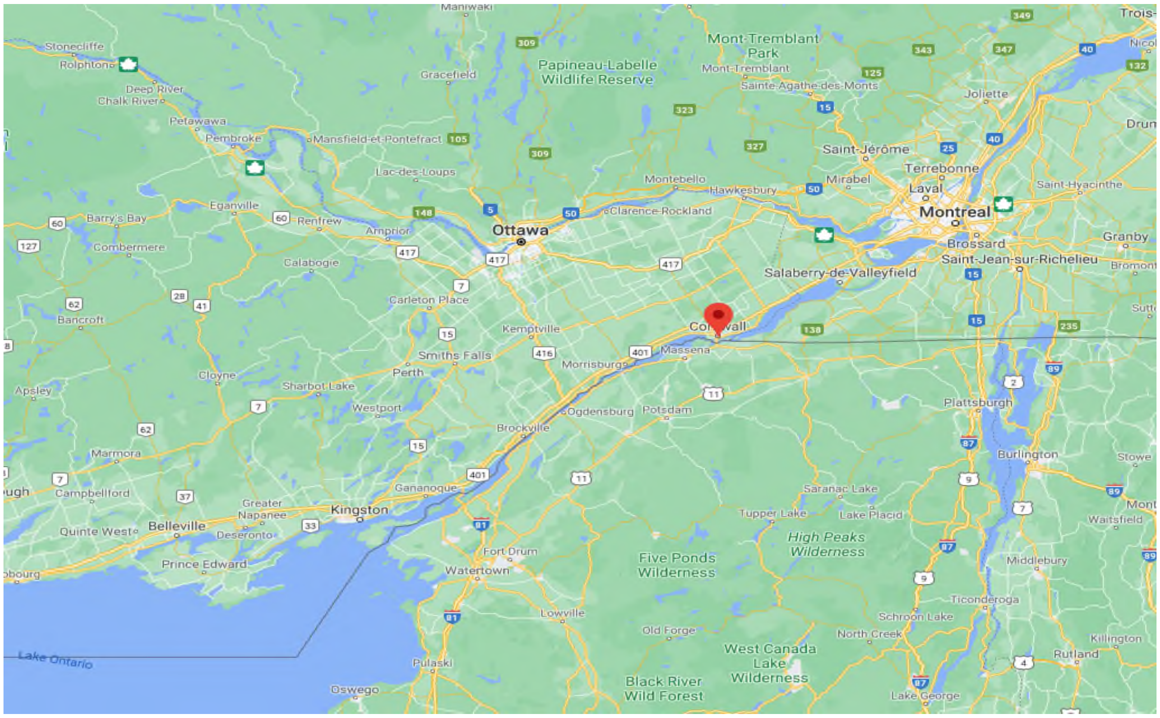

Figure CS3-1: Site Map for Cornwall.

Contaminants of Concern

The St Lawrence River site consists of approximately 130,000 m3 of the river bottom exceeding the Province of Ontario's sediment guidelines for metals (copper, lead, zinc and mercury) as well as oils and grease in one of the zones. From an AOC perspective Mercury is the primary contaminant of concern due to the concerns with bioaccumulation and magnification.

Source of Contamination

Historical sources were industrial point sources from the late 19th century through the 20th century and include, a former chlor-alkali plant at ICI Forest Products/Cornwall Chemicals, a former paper mill, a former textile mill, and other industrial sites.

Figure CS3-2: Zones of Contamination for the St Lawrence River site (courtesy of Governments of Canada and Ontario).

Figure CS3-3: Pictures of Zone 1 (courtesy of ECCC).

Figure CS3-4: Pictures of Zone 2 (courtesy of ECCC).

Figure CS3-5: Pictures of Zone 3 (courtesy of ECCC).

Risk Characterization

The primary tool to assess Risks to benthic organisms at the sites is Environment and Climate Change Canada's Benthic Assessment of SedimenT (BeAST) methodology (Reynoldson et. al 2000). This approach involves 4 lines of evidence (sediment chemistry, sediment toxicity, benthic community structure, and bioaccumulation measurement) and includes a large number of reference sites in a continuously updated database for comparison. Sediment concentrations of mercury and methyl mercury remain elevated in comparison to reference locations. Toxicity is present to some of the organisms used in this work, however, toxicity endpoints have remained relatively stable over time. Methyl mercury concentrations in benthos are mostly stable, but with some slight increases in Zones 1 and 3. Community structure has remained relatively stable to date, generally with some small deviations from reference sites depending on the metrics examined.

The baseline mercury tissue concentrations in fish showed a large amount of variability.

The risks to human health have also been assessed for the three zones in terms of direct sediment contact during swimming and wading. Based on current uses of the area, no current human health risks were identified.

Management Criterion

The MNR goals for the site were developed and divided into primary (most important for demonstrating improvement) and secondary (provide additional information on progress towards achieving primary goals) goals as follows:

The primary goals for Zones 1-3 are as follows:

1. Concentrations of total mercury and methylmercury in nearshore and offshore surface sediment of the three zones are comparable to upstream concentrations.
2. Concentrations of total mercury in tissue of YOY or forage fish collected nearshore are comparable to upstream concentrations.
3. Concentrations of methylmercury in nearshore and offshore infaunal benthic invertebrates are comparable to upstream concentrations.
4. Concentrations of total mercury and methylmercury in catch basin sediment are comparable to reference catch basin concentrations for an assessment of ongoing sources.

Secondary goals for sediment Zones 1-3 are as follows:

1. Trends in total mercury concentrations in nearshore and offshore sediment as a function of sediment depth:
    - The goal will be considered achieved if, in one or more sampling events from the three zones, vertical core profiles show decreasing trends in total mercury concentrations with a decrease in sediment depth. Decreasing concentration trends with a decrease in sediment depth may be demonstrated based on statistical regression tests or qualitative comparisons, and
    - Such determinations will be made independently for each of the three zones. Overall conclusions will be based on the combined evidence from each independent measure.
2. Sediment integrity/stability in the three zones to assess if deeper more contaminated sediment will be exposed:

- Sediment stability will be assessed using a combination of *in situ* flume studies (portable flume deployed in the field), sediment cores (extracted from the river bottom and assessed in the laboratory flume) and underwater cameras and current meters. The potential for erosion to occur (through river flow) will be established using this data along with modeling of current flows using a hydrodynamic model. This work will lead to the establishment of a monitoring trigger (likely a threshold flow through the dam). A sediment tracer (pollucite) will be placed and baseline concentrations measured in order to facilitate this future monitoring (if required).

Remedy Selected

The review of remedial options considered the following three:

1. Monitored Natural Recovery.
2. Capping.
3. Dredging.

Each option was assessed with resect to its technical feasibility, the environmental effects that could result, social-economics and the ability to satisfy the criteria related to delisting the site as an Area of Concern.

MNR was selected since there was a low risk to biota in all three zones, naturally decreasing concentrations seemed likely, physical conditions (affecting mobility of the sediments) appeared to be stable and there would be minimal environmental risk of implementing. MNR would rely on the natural accumulation of cleaner sediments on top of the contamination. In addition, as with any *in situ* remedy, administrative controls to restrict certain activities was also required, so that the deeper more contaminated sediments were not disturbed.

Since MNR requires long term monitoring to assess the recovery of the site, a long-term monitoring plan was developed for the site.

Long Term Monitoring

The long term monitoring plan (LTMP) (every 5 years until natural recovery is verified) developed in order to verify MNR processes meet the goals is as follows:

1. Nearshore and offshore surface sediment:
   - The assessment of total mercury and methylmercury concentrations in offshore (> 3m water depth) surface sediment of zones 1-3 and reference areas. A baseline assessment of the Cornwall area was completed in 2017. The upstream reference area (Lake St. Lawrence) was sampled in 2018, and
   - Assessment of Hg and methyl Hg concentration in sediment collected from the nearshore at water depths of < 3min zones 1-3 and reference areas. A baseline assessment was completed in 2017 and 2018

2. Total mercury in tissue of YOY or forage fish:
    - Assessment of the concentrations of total mercury in tissue of YOY or forage fish collected in the nearshore portion of zones 1-3 and reference areas. A baseline assessment was completed in 2017. Methyl mercury was included in these studies to account for variability in the percentage of methyl mercury between species.
3. Benthic invertebrates:
    - Assessment of methylmercury concentrations in nearshore and offshore benthic invertebrates in zones 1-3 and upstream reference areas in Lake St. Lawrence. A baseline assessment was completed in 2017.
4. Catch Basins:
    - Assessment of the concentrations of total mercury and methylmercury in sediment accumulated in catch basins in affected zones of the sewer shed. A baseline assessment was completed in 2017.
5. Vertical Mercury Profile:
    - Assessing total mercury concentrations in nearshore and offshore sediment as a function of sediment depth. A new baseline assessment was completed in 2017.
6. Sediment integrity:
    - A sediment integrity-monitoring plan was developed by ECCC in 2018 and will be implemented in 2022. A combined strategy of *in situ* and *ex situ* flume methodologies will be used in order to determine the point at which the flow of the overlying water could potentially erode surface sediment. This information combined with the determination of the force exerted from varying flow velocities would determine if and when water velocity in the SLR poses a risk of erosion and potential re-exposure of buried mercury. The future occurrence of these conditions would then trigger additional monitoring in the locations at risk. In order to provide a robust means of monitoring these areas at risk (in the future), a sediment tracer (pollucite) will be placed and baseline concentrations measured.

Figure CS3-6: LTMP activities under MNR; surface sediment sampling (top), catch basin sampling (bottom left) and in situ flume (bottom right) (courtesy of SLRIES and governments of Canada and Ontario).

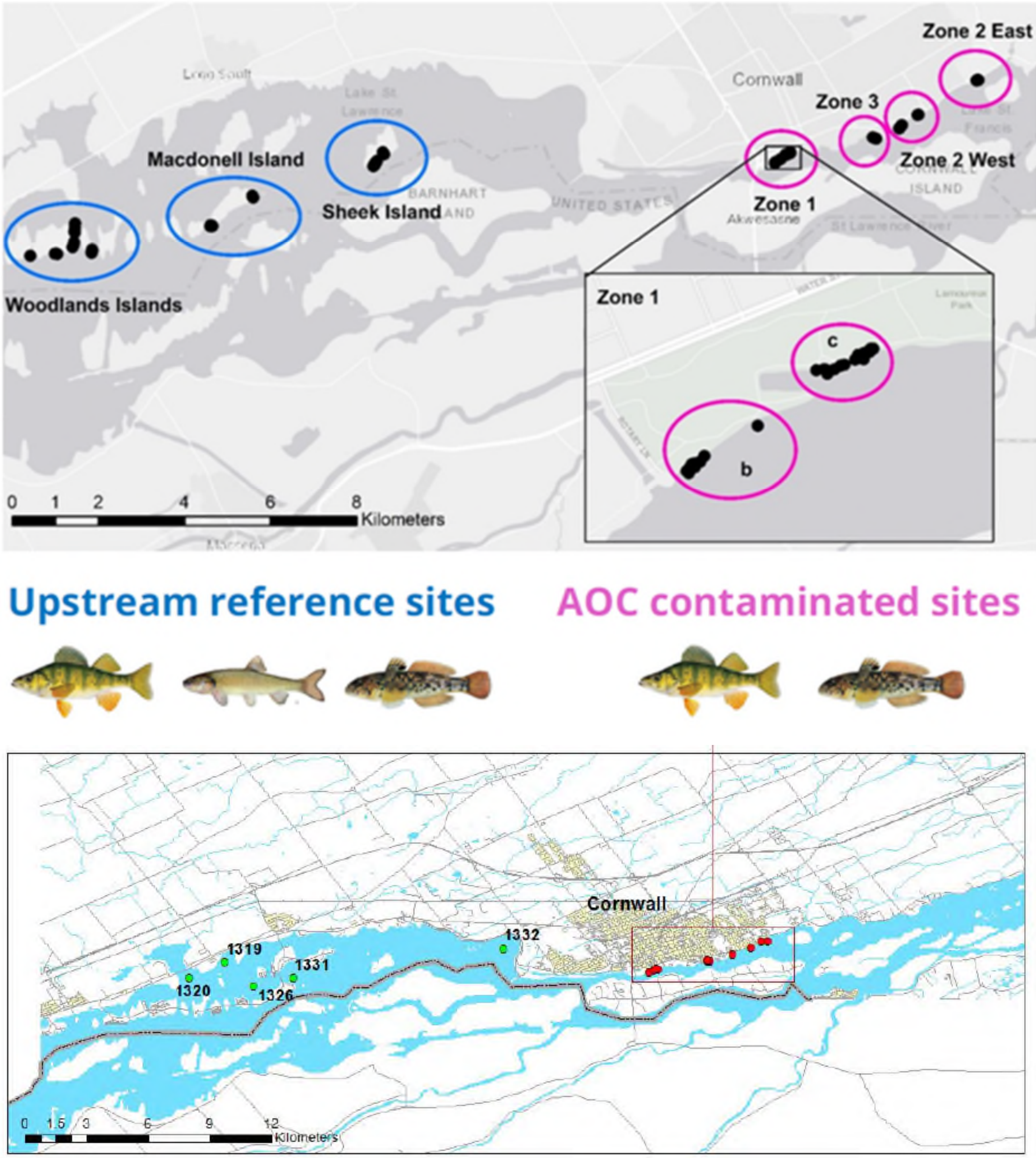

Figure CS3-7: Upstream reference sites vs. study areas for fish(top) and benthos (bottom) (courtesy of SLRIES and ECCC).

Costs

From a cost perspective the, like all MNR sites, the final cost will remain unknown until the final round of monitoring is complete and recovery is verified. The baseline sampling cost was approximately $350,000.

Each subsequent round of sampling will very in cost as the scope changes based upon the results of previous round. The spatial extent of monitoring would be reduced as recovery is confirmed in some areas. Entire components of the LTMP may also no longer be required if those recovery goals are met and verified. The number of monitoring rounds required before successful MNR is verified is also an unknown, and the potential triggering of future sediment integrity surveys (related to erosional concerns) is also unknown since it relies on weather patterns into the future.

A risk with MNR at SLR (and all MNR sites) is that if the results of the LTMP do not verify successful recovery in a reasonable time period, then the need for future adaptive management may be triggered. The need for adaptive management, the scope of what that would look like and the associated cost is also a significant unknown.

LTMP Study	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Surface Sediment						1					2					3
Fish Tissue						1					2					3
Benthos						1					2					3
Catch Basins*						1					2					3
Vertical Hg Profile						1					2					3
Sediment Integrity					If triggered											

*Catch basin sampling could be conducted between rounds if conditions within the sewer system change

Completed Baseline (year 0)
LTM preparation
LTMP rounds (if required)

References

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Case Study 4: Blended Remedy, Randle Reef, Hamilton Harbour, Ontario, Canada

Hamilton Harbour is one of 43 Areas of Concern (AOCs) identified under the 1987 Great Lakes Water Quality Agreement between Canada and the United States.

Randle Reef is a major step in the restoration of the Hamilton Harbour AOC. This project follows a shared funding model where one-third is funded by the federal government, one third is funded by the provincial government, and the final one-third is funded by local stakeholders. Accordingly, the funding partners are the Government of Canada, the Government of Ontario, and the Hamilton Oshawa Port Authority, the City of Hamilton, U.S. Steel Canada, the City of Burlington, and the Region of Halton.

Location

Randle Reef is located in Hamilton Harbour at the western end of Lake Ontario, Canada. A large commercial and residential community surrounds the harbour. The Harbour is home to the largest Canadian port on the Great Lakes, and one of the largest concentrations of heavy industry in Canada, including steel production.

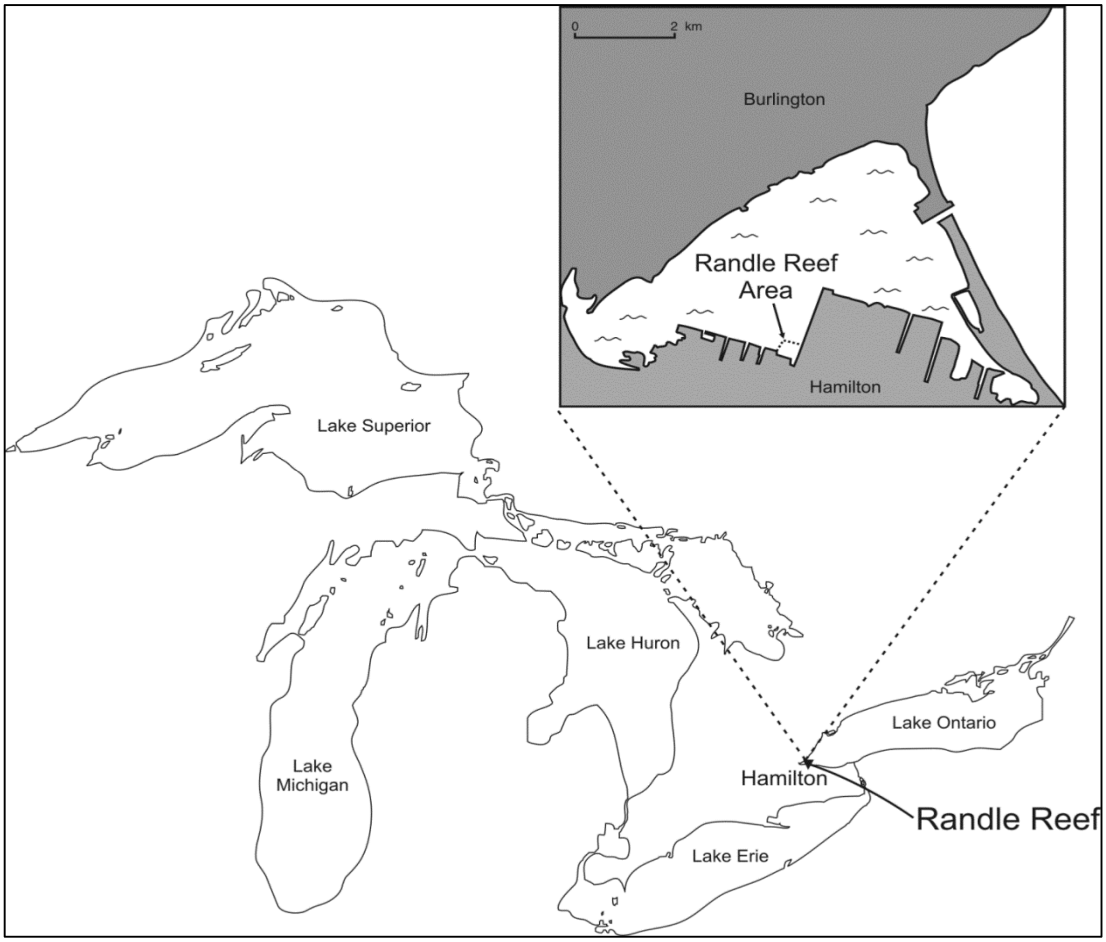

Figure CS4-1: Site Location Map for Randle Reef.

Contaminants of Concern

The Randle Reef Sediment Remediation Project work area consists of approximately 60 hectares (ha) of the harbour bottom contaminated with polycyclic aromatic hydrocarbons (PAHs) and heavy metals. Total PAH concentrations at the Randle Reef site are as high as 166,000 mg/kg with an average site concentration of 5,000 mg/kg. A number of metals including copper, cadmium, lead, nickel, manganese, iron, and zinc exceed the Province of Ontario's Severe Effect Level (SEL) guidelines for sediment. The sediment has demonstrated toxicity in most of the management areas. Through an extensive sampling program consisting of over 700 samples over several years, combined with sediment toxicity studies, it was determined that approximately 695,000 cubic metres ($m^{3)}$ of contaminated sediment required management. The depth of contamination ranges from approximately 1 to 3 m over the site.

Source of Contamination

The contamination of sediment at Randle Reef is the result of multiple sources over a period of more than 150 years and includes coal gasification, petroleum refining, steel making and associated coking, municipal waste, sewage effluent, and overland drainage. Many of the sources no longer exist and the application of the "polluter pay" principle was not feasible at this site. The remaining industry in the harbour is now highly regulated. There is a still a contribution from the atmosphere from industry and a major highway (Queen Elizabeth Way) that runs beside the harbour, as well as occasional bypasses of waste water. These, however, are harbour-wide impacts and have been factored into the clean-up criterion for the site (Graham et. al 2013).

Figure CS4-2: Steel making in the Hamilton Harbour in the 1950s (courtesy of the Hamilton Oshawa Port Authority).

Risk Characterization

Environment Canada's **BE**nthic **A**ssessment of **S**edimen**T** (BEAST) methodology (Reynoldson et. al 2000) was used in 2000 and 2002 to assess the quality of sediment in Hamilton Harbour and, as a follow-up, in Randle Reef more specifically. The BEAST methodology involves assessing sediment quality based on multivariate techniques using data on the physical and chemical attributes of the sediment and overlying water, benthic community structure, and the functional response of laboratory organisms in toxicity tests. Data from test sites are compared to biological criteria developed for the five Canadian / US Great Lakes. Some additional regression analysis was used as the BEAST methodology does not incorporate information on organic contaminants. Strong evidence of benthic macroinvertebrate community impairment as well as toxicity was concluded for the Randle Reef area.

Clean-Up Criterion

The clean-up criterion for Randle Reef is 100 mg/kg total PAH, based on the consideration of:

- Benthic toxicity data from another similar contaminated sediment site located in Hamilton Harbour, as well as Randle Reef itself,
- Background levels of PAHs in the Harbour (40 mg/kg),
- Uncontrollable indirect inputs of PAHs to the Harbour (e.g., vehicular emissions), and
- Other clean-up criteria for PAH-contaminated sediment sites (NOWPARC Site-Thunder Bay Canada [150 mg/kg], St. Mary's River – Sault Ste. Marie (USA) [115 mg/kg]).

The investigative studies over many years concluded that Total PAHs could be used as a surrogate for other contaminants. Thus, the metals contributing to toxicity will be addressed with the removal of the PAHs.

Selected Remedy

The selected remedy is a blended remedy that includes dredging, containment in an engineered containment facility (ECF), capping (isolation and thin layer), and monitored natural recovery.

Since 1987, Environment and Climate Change Canada (ECCC) has worked with the Ontario Ministry of Environment Conservation and Parks, the Hamilton Port Authority, representatives from local government, industry, and academia to characterize and assess the Randle Reef contaminated sediment. The selection of an ECF as the preferred remediation approach was completed by a multi-stakeholder Project Advisory Group in November 2001. The Project Advisory Group considered a number of options, including various methods of removal and disposal, removal and re-use, and *in situ* containment. The selected approach had to satisfy the *Randle Reef Sediment Remediation Project* and stakeholder objectives to:

- Maximize containment/removal of acutely toxic sediments in the Harbour,
- Ensure that the health and safety of workers and citizens are protected during all stages of the project,
- Minimize local and downwind airborne emissions during remediation process,
- Ensure safe transportation of hazardous materials through residential areas, if disposal to be located in an out-of-area site,

- Avoid high-risk alternatives that could result in technology failures, cost overruns, and protracted implementation schedules,
- Ensure no net loss of fish habitat productive capacity,
- Ensure no loss of navigation routes,
- Prevent uptake of contaminants by waterfowl,
- Provide partnership opportunities, and
- Provide a permanent solution/long-term sustainability.

Based on these objectives and analysis of the advantages and disadvantages of each of the remedies, the Project Advisory Group recommended the use of an ECF as the preferred remedy in April 2002. Specific advantages of the ECF remedy include cost-effectiveness, low technological risk, and greater opportunity for partnership resources.

ECF

The ECF is 6.2 ha in size and is situated over 140,000 m^3 of the most highly contaminated sediment. By constructing the ECF in this location, the most highly contaminated sediment will not be disturbed. In addition, approximately 445,000 m^3 of contaminated sediment surrounding the ECF will be dredged and placed inside. The ECF is constructed with double steel sheet pile walls. The outer wall is used to satisfy structural requirements while the inner wall provides environmental isolation of the sediment. The interlocks between sheet piles on the inner wall are sealed, thus creating an impermeable barrier. The contaminated sediment deposited within the ECF will be de-watered and the decant water produced by this process will be treated by an on-site water treatment system to meet provincial Ministry regulatory requirements before being discharged back into Hamilton Harbour. Once de-watering is completed, the contained sediment will be covered by a multi-layer environmental cap. Following project completion, the Hamilton Port Authority will assume ownership of the facility and be responsible for monitoring, maintaining and developing the site as a port facility.

The ECF design is based on the results of numerous studies. Extensive geotechnical investigations were completed to determine the basic structural design elements such as stability, length and thickness of sheet piles along with consolidation modelling and site hydrogeology. Additional studies used in the design include hydrodynamic studies to determine the effect the new structure would have on water flow in the harbour, bench scale effluent quality and fate, and transport modeling to determine if further water treatment would be required once the effluent exits the ECF.

The design process included a thorough options analysis that broke the project down into 6 basic project components; isolation structure; dredging design; sediment management/dewatering; containment and cover; U.S. Steel Channel and port facility. A comparison of alternative methods to achieve the goal for each component was conducted. For example, the decision to proceed with a sealed steel sheet pile wall system was a result of the evaluation of 7 options:

- Option 1 – Sheetpile Wall Systems with Sealed Interlocks,
- Option 2 – Standard Sheetpile Wall Systems,
- Option 3 – Concrete Caisson Wall,

- Option 4 – Cellular Steel Sheetpile Wall,
- Option 5 – Earthen Containment Berm,
- Option 6 – Treatment Trenches/Walls, and
- Option 7 – Hybrid Containment Structures.

Dredging

A variety of studies contributed to the dredging design. Numerous rounds of grab and core sampling that analyzed for total concentrations of PAH and metals helped determine the lateral and vertical extent of the dredging required to meet the 100 ppm total PAH sediment target. Contaminant concentrations, depths, sediment geotechnical properties, and site bathymetry information including sub-bottom profiling were gathered to determine the shape and size of dredge units and the associated dredge prisms. Sediment contaminants and their concentrations also helped identify hydraulic dredging as a preferred method based on the need to minimize potential air emissions. The air emission concern was related to high concentrations of naphthalene, which is quite volatile. De-watering during hydraulic dredging will be accomplished by settling within the ECF (polymers may be utilized if required). Excess water will be pumped through a water treatment plant (designed based upon sediment chemistry) and pumped back into the harbour.

Geotechnical information, along with assessing the structural stability of surrounding infrastructure, helped further refine the dredging area in terms of required offsets and transition slopes. The physical characterization of the sediment was also important in understanding the requirements for the transport of the sediment to the ECF via pipeline and the settling and consolidation of dredged sediment within the ECF. The rate of settling and degree of consolidation helped determine the ECF capacity.

As previously mentioned, assessing ecological risk through the completion of benthic assessment work (sediment toxicity and community structure alteration) helped prioritize the order of sediment into three categories (Priority 1, 2, and 3) to potentially be dredged. Priority 1 sediments had long been identified as severely contaminated and toxic and were to be dredged and placed in the ECF first. Priority 2 sediments are toxic with PAH concentrations >100 ppm (but lower than the Priority 1s). These will be dredged and placed in the ECF next. Priority 3 sediment have PAH concentrations >100ppm but are non-toxic. A portion of these will be dredged and placed in the ECF to fill up the remaining capacity.

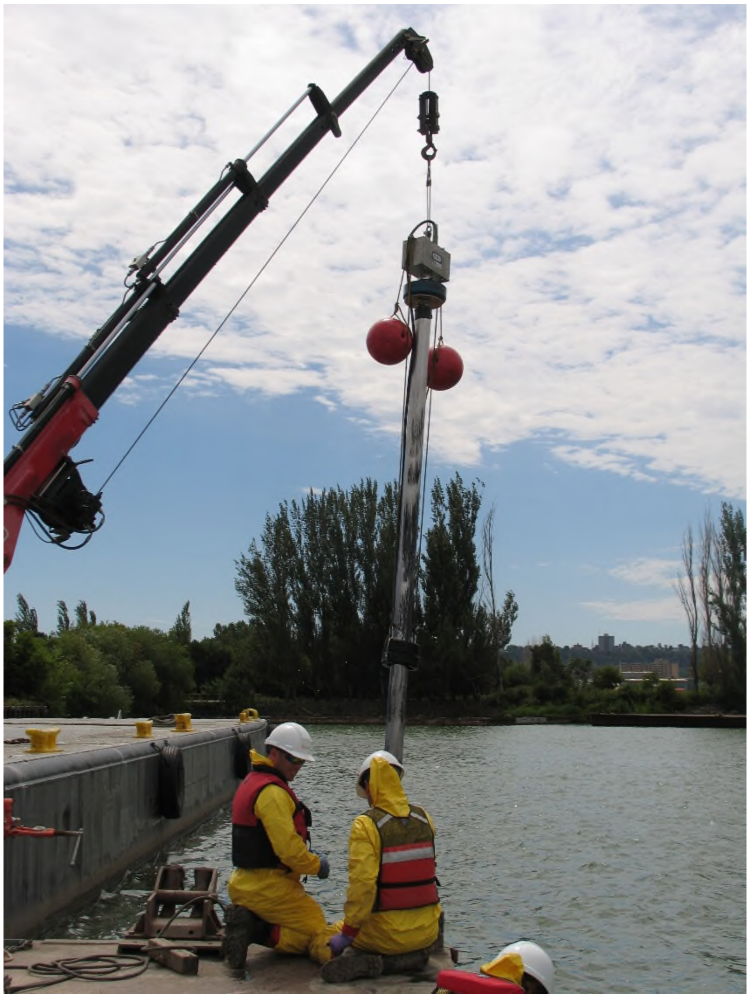

Figure CS4-3: Sediment coring at the Randle Reef site using extra-long aluminum cores tubes for deep penetration (courtesy of ECCC).

Air quality modelling was also conducted to determine the risk of airborne contaminants during ECF filling from the dredge, due to the volatile nature of naphthalene in PAHs. Air modelling indicated that naphthalene emissions from the site could pose a potential concern to off-site receptors under certain conditions. As such, the majority of dredging will be conducted hydraulically rather than mechanically to minimize exposure of the sediment to the air.

Figure CS4-4: Suma canisters used as part of the air monitoring program during the project (courtesy of ECCC).

Figure CS4-5: Mechanical dredging was used to remove contaminated sediment from between the double walls of the ECF (courtesy of Riggs Engineering).

Isolation Cap

The construction of the ECF will leave a channel between the east ECF outer wall and the Stelco property.

Figure CS4-6: The Stelco isolation cap located in the channel between Stelco and the ECF (shown in red) (courtesy of Riggs Engineering).

This channel is required due to intake and outfalls associated with existing steel-making operations. Dredging was limited in this area due to the adjacent intake, the presence of slag (which represents a challenge to hydraulic dredging) and the instability of the Stelco dock wall. As a result, the remediation consisted of placing a 65 cm thick cap consisting of sand with a minimum of 3% total organic carbon (TOC). The physical location of the intake (terminal end of the channel) limits how thick the cap can be in the area immediately adjacent to the intake; therefore, reactive core mats (RCM) with armour mats were used around the intake. The use of the RCM is advantageous as the capacity of the RCM is generally higher, per unit thickness, than a soil-based cap, thus resulting in a thinner cap able to fit below and accommodate the location of the Stelco intake pipes. Due to the higher flows in the area of the intake, the RCM were armoured to protect it from erosion. The presence of non-aqueous phase liquid (NAPL) found in some isolated locations in the channel also prompted the use of RCMs due to their ability to contain. The NAPL found was determined to be non-mobile, so the RCMS were used as a precautionary measure. The sand cap was armoured towards the channel entrance to protect it from scouring associated with adjacent vessel traffic along the Stelco dock wall. To design this isolation cap, modelling of the contaminant migration through various caps was conducted. This required information on the sediment chemistry in the area, any amendments to be considered, and groundwater upwelling rates. Seepage meters and historical information were used by ECCC to estimate groundwater upwelling rates to feed into the model. Geotechnical data as well as hydraulic information was also collected in the vicinity as well as information on future ship usage in order to ensure the adequate armouring of certain areas.

Figure CS4-7: Placement of the sand in the Stelco channel as part of the cap. (courtesy of Riggs Engineering)

Figure CS4-8: Placement of the reactive core mat (top) and Erosion control (Bottom). (courtesy of Riggs Engineering)

Thin Layer Cap

A small area of contaminated sediment (north of the ECF and adjacent to the nearby dock wall) proved to be challenging to dredge hydraulically due to the presence of slag. As a result, additional testing was undertaken, and areas of higher contamination were dredged by mechanical means and the whole area then capped with a 150 mm layer of sand that contained a total organic carbon concentration of at least 3%.

Costs

The project was estimated to cost $138.9 M and includes contingency and escalation costs due to it being an 8-year project. Other considerations included the costs of long-term monitoring and maintenance. The design was conducted in a progression of phases of increasing detail (i.e., 30%, 90%, 95%, 99%) with the costs increasing as more of the details were worked out. The project is funded by multiple partners and as such an overall budget is set. The first stage (ECF construction and dredging between the walls) was completed within budget.

Monitoring Ecosystem Recovery

To assess the effectiveness of the proposed remediation of Randle Reef beyond the typical mass contaminant removal approach, a comprehensive monitoring program has been established by Environment and Climate Change Canada. The program involves a number of studies (listed below) to be conducted before (baseline) and after remediation, with a few studies collecting data during implementation. Monitoring will continue approximately 12 years post-remediation.

List of Studies:

1. PAH concentrations and profiles in suspended sediment.
2. Characterization of sediment toxicity and benthic invertebrate communities.
3. Wild fish health endpoints.
4. Fish tumour study.
5. Surface water quality monitoring.
6. Swallow indicator study (tissue and reproductive endpoints).

Status

The project started in 2015 and as of Summer 2021, 100% of the anticipated dredged material was safely contained within the ECF. Capping of the ECF (Stage 3) is expected to start in in 2022 for total project completion in 2024.

Figure CS4-9: Aerial photo of ECF and dredging operations taken in summer 2019 (courtesy of Riggs Engineering).

Figure CS4-10: Hydraulic dredge in action at the Randle Reef site (courtesy of ECCC).

Lessons Learned to Date

Stage 1 ECF Construction Unsuccessful Tender

In February 2014, the Government of Canada initiated the public solicitation for the Stage 1 construction tender, with the result that four bid proposals were submitted, all of which were significantly above the budget estimate. The solicitation was subsequently terminated without contract award.

As the bid prices were significantly above the budget estimate for Stage 1 of the project, the Government of Canada and the other Funding Partners decided to undertake consultations with the marine construction and environmental management industries. The purpose of these industry consultations was to seek industry input and determine whether there are adjustments that could be made to the project (scope, phasing, technical design, schedule, contract terms and conditions, risk management) that would permit the project objectives to be achieved while staying within the current project budget.

After a thorough evaluation of 5 potential alternative ways to carry out the project, it was decided that only modification of the original design, in addition to alternative procurement strategies, would result in cost savings while still achieving the environmental objectives of the project. While modification of the original design resulted in decreased time and material quantities, provision of flexibility for contractors and a decrease in uncertainty also played an important role. The following major changes were made to the Stage 1 specifications to increase flexibility and decrease uncertainty:

1. As the raw steel for the steel sheet piling was a partner contribution (U.S. Steel Canada), it was decided that raw steel fabrication would be removed from the Stage 1 contract and a separate procurement process under U.S. Steel Canada’s authority would be conducted.
2. A portion of the Pier 15 wall adjacent to the site was required to be repaired as part of the project since its state of disrepair would not allow dredging in proximity to it. As the Hamilton Port Authority owns the Pier 15 wall, it was decided that this too would be removed from the Stage 1 contract and a separate procurement and project management process would be undertaken by the port authority for this portion of the work.
3. The construction sequence was amended to allow more flexibility for the contractor.
4. More lead time for mobilization prior to construction was provided.

Sealing of Inner Sheetpile Wall

The Stage 1 specifications called for the inner sheetpile wall interlocks to be sealed using bentonite. After the ECF was full, the bentonite seal was to be replaced with a cementicious grout in Stage 3. This would ensure the integrity of the seals as it was unknown how the grout would respond to flexing of the structure during ECF loading in Stage 2.

A pump-down test was specified at the end of Stage 1 to verify the integrity of the bentonite seals. The test was unsuccessful. It was subsequently determined that the subcontractor only used bench scale tests to model the behaviour of bentonite during the pump down test and that this method had never been applied on a full scale before.

In hindsight, a pilot test for the bentonite seals should have been included as part of the contract to work out any issues before full scale implementation. In addition, this incident also raises the question as to whether a pump-down test is appropriate for testing the seals. The pump-down test exerts much more force on the seals than the seals would be expected to withstand under normal working conditions. An alternative test for the seals has not yet been determined and resolution of this issue is still underway.

References

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