# 3 Performance Objectives and Design Concepts

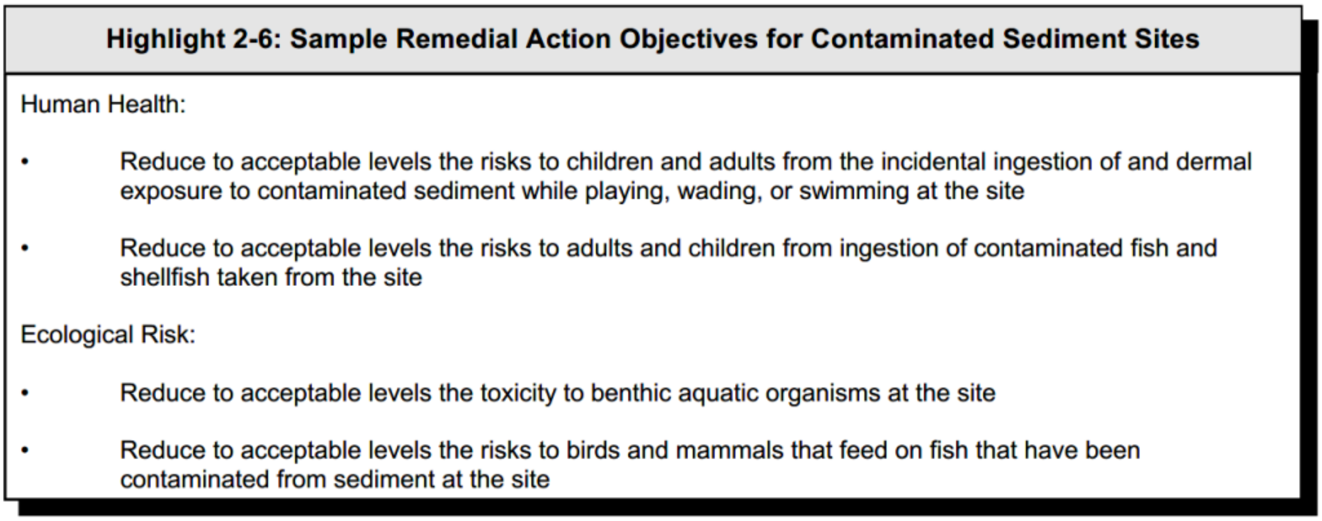
This section discusses performance objectives and cap chemical isolation design concepts, including development of design criteria to achieve the required chemical isolation based on site characteristics and other physical constraints that apply to cap design. Designing a cap to achieve its intended chemical isolation function involves an iterative approach that balances various site-specific limitations (e.g., data limitations) and constraints (e.g., limits on total cap thickness) with the achievement of chemical performance objectives. Reasonable and appropriate levels of conservatism should be incorporated into the design process to reduce the overall uncertainty that chemical isolation will be maintained throughout the intended minimum design life of the cap while balancing other considerations such as constructability, cost, and impacts on water depth and site use.

## 3.1 Chemical Isolation Performance Targets

The overall objective of any sediment remedy is to achieve the remedial action objectives (RAOs) and/or project-specific risk-reduction goals. Caps help achieve the RAOs and risk reduction goals by physically and/or chemically isolating underlying contaminated sediments. As described in Section 2.2, physical isolation occurs when the cap layer is thick enough to separate the BAZ from the contaminated sediment. Long-term physical isolation generally requires that the material placed over the contaminated sediment be physically stable and not subject to erosion. Chemical isolation occurs when the cap materials and thicknesses can retard or prevent the upward migration of COCs from underlying contaminated sediments into the BAZ via porewater over a desired minimum time period.

### 3.1.1 Remedial Action Objectives and Remedial Goals

RAOs are a general description of what remediation is expected to accomplish. The Contaminated Sediment Remediation Guidance for Hazardous Waste Sites (USEPA 2005) provides the following examples of RAOs (Figure 3-1).



**Highlight 2-6: Sample Remedial Action Objectives for Contaminated Sediment Sites**

Human Health:

- Reduce to acceptable levels the risks to children and adults from the incidental ingestion of and dermal exposure to contaminated sediment while playing, wading, or swimming at the site
- Reduce to acceptable levels the risks to adults and children from ingestion of contaminated fish and shellfish taken from the site

Ecological Risk:

- Reduce to acceptable levels the toxicity to benthic aquatic organisms at the site
- Reduce to acceptable levels the risks to birds and mammals that feed on fish that have been contaminated from sediment at the site

**Figure 3-1. Example remedial action objectives.**

*Source: USEPA (2005).*

RAOs are designed to achieve risk-reduction goals by preventing exposure of receptors, both human and ecological, to unacceptable levels of COCs by specific pathways. Unacceptable levels of COCs are those that exceed the safe or acceptable levels, which are defined by site-specific risk pathways.

Remedial Goals (RGs) are protective concentrations of COCs in specific site media, which may include sediment and porewater, surface water, fish, and other aquatic organisms. RGs may vary spatially throughout the site due to differences in site use, receptors, and risk pathways. Background concentrations are considered in the development of RGs and during the long-term monitoring program to evaluate progress toward achieving RAOs (USEPA 2002b, 2005).

It is important to understand the role of RGs during the design and long-term monitoring project phases. At many capping sites, capping is combined with other remedial technologies to achieve RAOs. It is common for capping to be used to achieve immediate risk-reduction goals in capped areas while natural recovery processes work toward achieving long-term RAOs in areas surrounding the cap. Natural recovery of concentrations that develop on top of a cap as a result of ongoing external sources or redistribution onto the cap from uncapped areas may also be required to ultimately achieve the lowest risk-reduction goals. At more complex sediment sites using multiple remediation technologies, iterations of remediation and monitoring may be used to evaluate progress toward meeting RGs and achieving RAOs sitewide (USEPA 2022). Where RAOs are based on reducing contamination in surface sediment, sediment RGs are developed to evaluate achievement of RAOs. For receptor-based RAOs, RGs for surface water, porewater, and biota may be developed in addition to sediment RGs.

### 3.1.2 Chemical Isolation Performance Targets

It is important to understand how capping and other elements of the selected remedy contribute to achieving RAOs. When developing a remedial design, specific performance targets should be developed for each remedial technology, including for capping. For example, while dredging may seek to achieve a target post-dredging sediment concentration, capping may seek to limit post-remedy porewater COC concentrations below a particular concentration at a specified depth or zone. Although sediment-based RGs are generally used when determining the limits and extents of a cap (i.e., sediments with concentrations above the RG may be capped), porewater-based performance targets are more useful for informing chemical isolation design. Performance targets are numerical criteria (e.g., porewater concentration) applied to a specific depth position within the cap profile that can be used to evaluate long-term chemical isolation (see Section 3.2.1 for more details).

Porewater-based performance targets are useful for chemical isolation design because long-term contaminant transport processes through the cap (see Section 3.3.1) primarily relate to porewater. During design, these processes can be modeled using site-specific information to determine chemical isolation design requirements such that long-term flux of COCs does not affect the continued achievement of RAOs. For sites that have developed porewater-based RGs to support RAOs, those RGs should be used as chemical isolation performance targets. For sites with sediment-based RGs, this guidance recommends developing corresponding porewater concentrations as performance targets. Porewater-based performance targets pose other advantages in cap design because the bioavailability of contaminants from the bulk capping media differs from the site sediment due to differences in the media such as the grain size, fraction organic carbon, the nature of the carbon, presences of oxides and ligands, cationic exchange capacity, and other factors, as discussed below. Specific advantages of porewater-based performance targets compared to bulk-sediment-based RGs, include the following:

- The bioavailability of organic COCs in cap material may differ from the bioavailability in existing surface sediment when their organic content and the nature of their organic carbon differ.
- Differences in geochemistry between capping media and sediment can affect the availability of inorganic COCs.
- The sand content of caps (many caps use sand to construct the initial habitat layer) has lower ability to sorb contaminants; consequently, the sediment-to-water flux of contaminants may be higher than for sediment even if the bulk concentration is the same.
- Bulk contaminant concentrations in sorptive cap amendments, which act as a sink for contaminants, may actually be higher than RGs but still effectively control porewater concentrations and achieve desired risk reductions and/or sediment-to-water flux reductions.

For situations where deposition of new sediment layers over a cap occurs, sediments in the BAZ may have characteristics similar to pre-cap surface sediments. The use of a porewater target may simplify the design by reducing uncertainty about the nature and quality of sediment deposition on the cap. The corresponding porewater concentration for a sediment-based RG can be calculated by selecting appropriate and representative values for existing sediment characteristics (density and fraction organic carbon) and sediment-porewater partition coefficients determined for the site (see Equation 5-1).

The conversions between sediment RGs and porewater performance targets rely on equilibrium partitioning equations (discussed in Section 5.5.3.2) and site-specific organic carbon content (for organic contaminants), which requires the use of sediment-porewater partition coefficients (organic carbon–porewater partition coefficient [$K_{OC}$] for organic contaminants and adsorption-desorption distribution coefficient [$K_d$] for inorganic contaminants). Organic carbon in sediments can include a variety of diagenic, petrogenic, and pyrogenic forms that can have different $K_{OC}$ values, resulting in potentially substantial differences in partitioning across various sediment types (Cornelissen et al. 2005; Hawthorne, Grabanski, and Miller 2006; Hawthorne et al. 2011; Jonker et al. 2003). $K_d$ values for inorganic contaminants can similarly vary over a wide range depending on the chemical properties of the contaminants. Additionally, experiments and experience suggest that freely dissolved concentrations in porewater are a better indicator of toxicity and bioavailability than bulk sediment concentrations (Adams, Kimerle, and Mosher 1985; Di Toro et al. 1991; Kraaij et al. 2002; Mayer et al. 2014; Burkhard, Mount, and Burgess 2017). There are several effective methods for accurately measuring freely dissolved concentrations in porewater, including recently improved passive sampling techniques.

### 3.1.3 Background Concentrations in Depositing Sediments

Long-term surface sediment quality will be no better than the background conditions regardless of cap chemical isolation performance. How background concentrations are considered when developing the chemical isolation design criteria is a site-specific decision. At sites where background concentrations are greater than or comparable to RGs, cap chemical isolation design criteria should focus on limiting migration of contamination from below the cap to the BAZ. Typically, background concentrations would be used to support the chemical isolation design when deposition is being considered as a process that contributes to chemical isolation.

## 3.2 Development of Chemical Isolation Design Criteria

Establishing the chemical isolation design criteria early in the design process is important because it can impact predesign data collection needs and the design approach. Design criteria are requirements that the cap design must satisfy. Chemical isolation design criteria include the chemical isolation performance targets (described in Section 3.1) and the spatial scales, locations, and depths at which the chemical isolation performance targets apply.

Appropriate spatial scales for applying chemical isolation performance targets depend on several factors, including RAOs, the nature and extent of contamination, and the applicable risk pathways and receptors. The long-term monitoring scale and scope should be understood when developing the cap design, so that design choices can be selected to satisfy expected post-remediation performance monitoring. For example, in cases where the goal of chemical isolation design is to sequester bioaccumulative contaminants, performance monitoring may entail measurement of the surface area–weighted average concentrations (SWACs) in certain size monitoring units associated with relevant risk exposure spatial scales. Corresponding design criteria may relate to average concentrations over appropriate biological exposure units or human-health exposures. In other cases, where chemical isolation is to contain contaminants that exhibit direct benthic toxicity, design criteria may relate to individual locations (i.e., a point-by-point basis). The number and location of specific monitoring locations should provide enough data to calculate statistically significant results that can be compared to RAOs.

### 3.2.1 Point of Compliance and Design Evaluation Depth

For the chemical isolation design, it is important to establish the locations (depths) within the cap profile where chemical isolation performance targets apply. These depths, and an understanding of what these depths represent, need to be established early in the design process. Points of compliance and design evaluation depths will be used to inform the modeling (discussed in Section 5) and the post-construction long-term monitoring (discussed in Section 7.2). During cap design, it is important to understand and evaluate conditions that will affect long-term remedy effectiveness. Assuming the cap remains physically stable over the course of its design life, the two factors that are most likely to affect long-term remedy effectiveness are chemical isolation performance and deposition of sediment from surrounding areas on the surface of the cap. As described in Section 7.2, the objective of remedy effectiveness monitoring is to evaluate attainment of RAOs. The point of compliance describes the depth(s) over which the RAOs apply and is typically related to the BAZ. Multiple points of compliance may be needed to address each site-specific RAO. This guidance recommends the following approach to determining the point(s) of compliance to use for developing design criteria:

- If the RGs were established to be protective of benthic organisms, the appropriate point of compliance is within or at the bottom of the BAZ. Benthic invertebrates live and feed within the BAZ and mostly occupy the top few centimeters (even if the depth of bioturbation is deeper). The point of compliance should reflect the concentrations to which benthic organisms will be exposed; conservatively this is the full thickness of the BAZ.
- If the RGs were established to be protective of ambient water quality criteria or fish at higher trophic levels representative of surface water conditions, achievement of design criteria may be measured near the cap surface or in the surface water itself.

During cap design, models are often employed to assess the chemical isolation performance of varying cap thicknesses and compositions. To support these modeling evaluations, the design must assign design evaluation depths, which are the depths within the cap where model-predicted concentrations are compared to the chemical isolation performance target concentrations (as discussed in Section 3.1.2). The design evaluation depth may represent a thickness (e.g., full BAZ thickness), or it may represent a single depth (e.g., mid-point or bottom of the BAZ). For caps where little to no long-term deposition is expected to occur, the design evaluation depth should be the same as the point of compliance. In this scenario, chemical isolation performance is synonymous with cap effectiveness, because monitoring for long-term RAO attainment will occur at a depth that directly reflects cap chemical isolation performance. Figure 3-2 illustrates an example in which the design evaluation depth is consistent with the point of compliance.

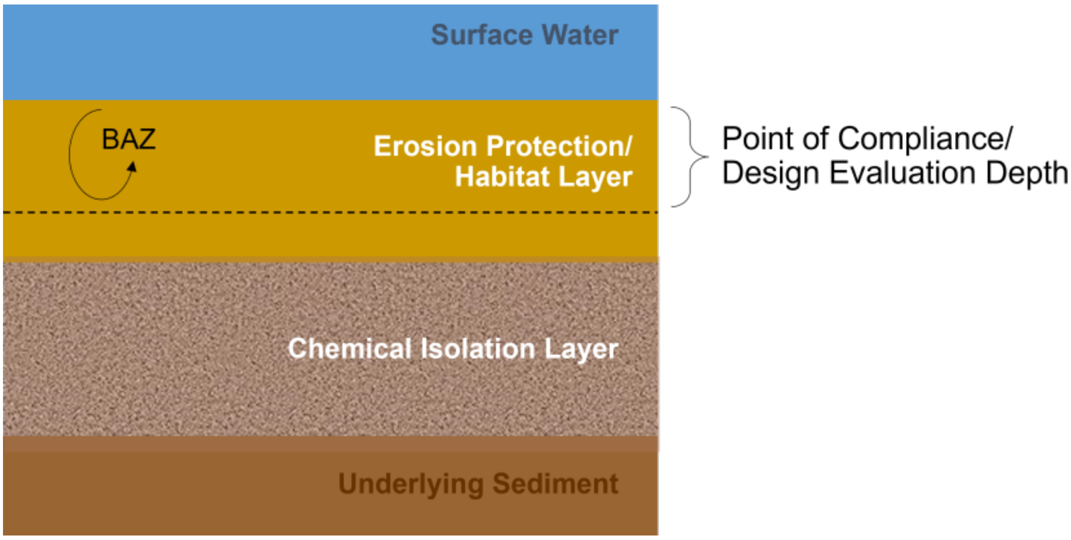


**Figure 3-2. Example cap profile with design evaluation depth same as point of compliance.**

*Source: Modified from Arcadis U.S., Inc. Used with permission.*

During the design stage, the best way to evaluate remedy effectiveness and chemical isolation performance is to use cap models that consider multiple design evaluation depths. For example, where long-term deposition is expected to occur after cap construction, it is important to understand how depositing sediment might affect long-term remedy effectiveness and chemical isolation performance. Because the point of compliance is typically related to the BAZ, long-term remedy effectiveness monitoring may involve collecting samples representative of deposited material, instead of the cap itself. The following scenarios illustrate situations where designs may consider design evaluation depths that do not coincide with the depth of compliance.

### *3.2.1.1 Deposition*

As described in Section 3.1.3, in a depositional environment, COC concentrations at the top of the cap are impacted by both the quality of depositing sediment and dissolved-phase COC transport from underlying sediment. Therefore, assessing the effectiveness of the cap can be confounded by deposition, particularly when background concentrations are elevated (acknowledging that background concentrations may change over time and be difficult to predict) or when natural recovery processes take longer periods of time to remediate contaminated sediment near the cap, but outside of the capping footprint.

- In situations where depositing sediments are likely to have COC concentrations that exceed RGs, sampling at or designing to a point of compliance that includes deposited material is not likely to be representative of chemical isolation performance. In this scenario, it is important for the design evaluation depth to ignore deposition and remain within the cap. This is illustrated by the deeper design evaluation depth (B) shown in Figure 3-3, which shows a cap profile over time as the net deposited sediment thickness increases from the left side to the right side of the schematic. Additional modeling that includes deposition and assesses COC concentrations at the point of compliance (which is equal to design evaluation depth A) may provide valuable information about possible long-term conditions and remedy outcomes. In Figure 3-3, the point of compliance rises as the BAZ transitions into the deposited sediment. This additional modeling to evaluate concentrations at the point of compliance is not intended for the design of the cap, but for informational purposes/setting expectations during post-construction monitoring.
- In situations where depositing sediments are likely to have COC concentrations below RGs, the depositing materials may contribute to additional chemical isolation performance. Additional chemical isolation performance is achieved by creating a longer attenuation distance for COC migration from below the cap to the point of compliance and by providing organic material that can provide some COC sorption capacity. Design and sampling at a design evaluation depth that includes deposited material will provide information about the combination of cap chemical isolation performance and natural recovery processes. This design evaluation depth (A) shown in Figure 3-3 is consistent with the compliance depth. In this scenario, a design evaluation depth that

ignores deposition and remains within the cap provides a more conservative chemical isolation design, as shown by the deeper design evaluation depth (B) in Figure 3-3. Each individual project should consider whether this level of conservatism is appropriate. Conversely, a design evaluation depth that considers deposition (to approximate the point of compliance) is likely to be more representative of long-term conditions.

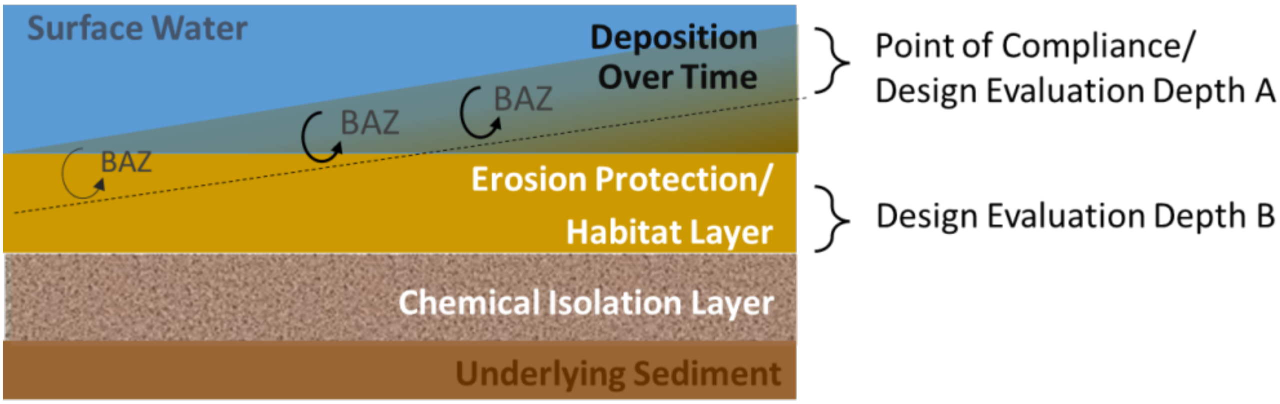


**Figure 3-3. Example design evaluation depths for a cap profile with deposition.**

*Source: Modified from Arcadis U.S., Inc. Used with permission.*

### *3.2.1.2 Presence of Larger Armor*

Larger armor may not provide attenuation of COCs moving through the cap, and the large pore spaces at the surface may be more representative of surface water concentrations. For that reason, it is generally inappropriate to evaluate the effectiveness of the cap at the surface of the cap if the surface of the cap is composed of large armor (left side of schematic in Figure 3-4). If infilling of the void space occurs due to deposition, as illustrated by the addition of material over time (left to right in Figure 3-4), additional attenuation may occur and bioturbators may colonize the portion of the armor that is filled in. As described in the section above on deposition, depending on the quality of the depositing sediment (i.e., COC concentration) the infilled portion of the armor stone could be an appropriate location within the cap to compare concentrations to the RGs.

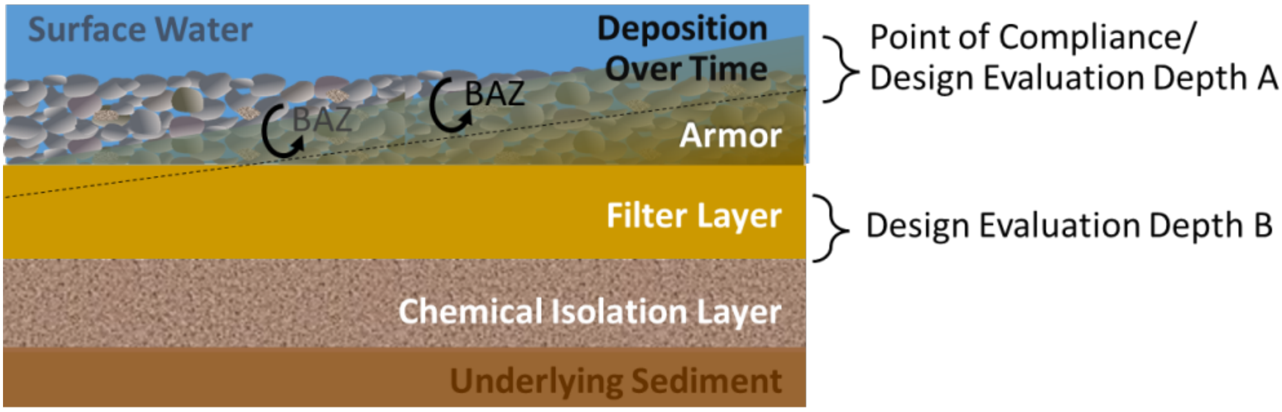


**Figure 3-4. Example design evaluation depths for a cap profile with armor stone.**

*Source: Modified from Arcadis U.S., Inc. Used with permission.*

Deposition of sediments with COC concentrations less than the RG may provide additional attenuation and, therefore, a design evaluation depth (A) that is consistent with the compliance depth, as shown in Figure 3-4, may be appropriate. Evaluations at design evaluation depth (A) also provide information about remedy performance because it accounts for the COC concentration input from transport from the underlying sediments through the cap as well as input from deposition.

In situations where depositing sediments are likely to have COC concentrations that are elevated or exceed RGs, sampling at or designing to a point of compliance that includes deposited material is not likely to be representative of chemical isolation performance. In this scenario, it is important for the design evaluation depth to ignore deposition and remain within the cap, shown by the design evaluation depth (B) in Figure 3-4. That said, sampling beneath the armor stone may be difficult during post-construction monitoring (unless monitoring ports are placed during construction). In such cases, it may be important to evaluate the concentrations within the depositing material filling the interstitial spaces of the large armor stone, as shown by the design evaluation depth (A). Understanding the likely COC concentrations in this material is helpful for setting expectations during monitoring.

As discussed previously, each individual project should consider the appropriate level of conservatism and whether the goal of the design is remedy performance (which accounts for the combined effect of COC transport through the cap from beneath the cap and from sediments depositing on top of the cap) or cap performance (which considers the COC transport from beneath the cap).

### 3.2.2 Design Life Objectives

Caps are designed to provide effective long-term risk reduction. During the design process, a “design life,” or a minimum period over which the cap is designed to meet the design criteria for all COCs and RAOs, must be established. This does not mean that the cap will not provide risk reduction after its design life is exceeded. Actual cap performance life may be longer than its design life due to conservatism in the design process. A typical design life that is widely accepted for caps is 100 years. Shorter timeframes may be considered under certain circumstances and have been used in caps that have been constructed. Appropriate cap design lives should be determined on a project-by-project basis.

***Breakthrough***

*The word “breakthrough” has been used inconsistently in cap design. In some cases, the word breakthrough is used to describe the point in time when concentrations of COCs at the top of the cap are detectable. More commonly, the word breakthrough is used to describe the time when the concentrations of COCs at the design evaluation depth exceed performance target concentrations. To avoid ambiguity, the design criteria should be described explicitly (i.e., a specific COC concentration [e.g., performance target] or flux measured at a defined depth [e.g., design evaluation depth or point of compliance] at a specific future point in time [e.g., 100 years]).*

### 3.2.3 Conservatism in Cap Design

Cap designs should incorporate reasonable and appropriate levels of conservatism to reduce the overall uncertainty about whether the cap will achieve the performance objectives over the desired design life. A cap designer should understand how to best balance conservatism with practical considerations throughout the cap design and construction phases to achieve this objective. It is important to understand what level of conservatism is included in the design. The effects of the conservative choices applied in cap design must be quantified and compared to choices that may be more practical and/or representative of actual conditions (i.e., those that may be used in lieu of the conservative choice). Making conservative assumptions for every design assumption may result in construction impracticability concerns and add unnecessary costs. The most significant conservatism is typically incorporated into design and construction as follows:

- Selection of design criteria (e.g., conservativism built into risk assessments, the selection of RGs, and the development of chemical isolation performance targets).
- Selection of input parameter values used in model evaluations. Inputs with the largest influence on model results include groundwater seepage rates, contaminant concentrations in porewater, partitioning characteristics, and ongoing deposition onto the cap. Conservativism in modeling is discussed in Section 5.
- Material type, thickness, and placement tolerances (e.g., minimum thickness, minimum amendment dose that must be placed to meet the cap performance goals). Construction considerations are discussed in Section 6.
- Material overplacement during construction (e.g., a contractor may place more cap material and amendment than specified to ensure the cap meets the design specifications). Construction considerations are discussed in Section 6.

## 3.3 Chemical Isolation Design Concepts

This section summarizes the basis of cap chemical isolation design. This includes an explanation of the processes that control the fate and transport of chemicals and how these processes affect the design of the cap. Strategies to achieve effective cap chemical isolation are also discussed.

### 3.3.1 Contaminant Transport Mechanisms through Caps

The design of a cap to chemically isolate underlying sediment contamination relies on an understanding of contaminant fate and transport processes and methods to attenuate the transport of those contaminants. Key processes that control the transport of the chemical include advection, dispersion, diffusion, bioturbation, gas ebullition, and partitioning. Table 3-1 in Section 3.4 provides information on how these processes are assessed, Section 4 discusses data needs, and Figure 3-5 illustrates these processes.

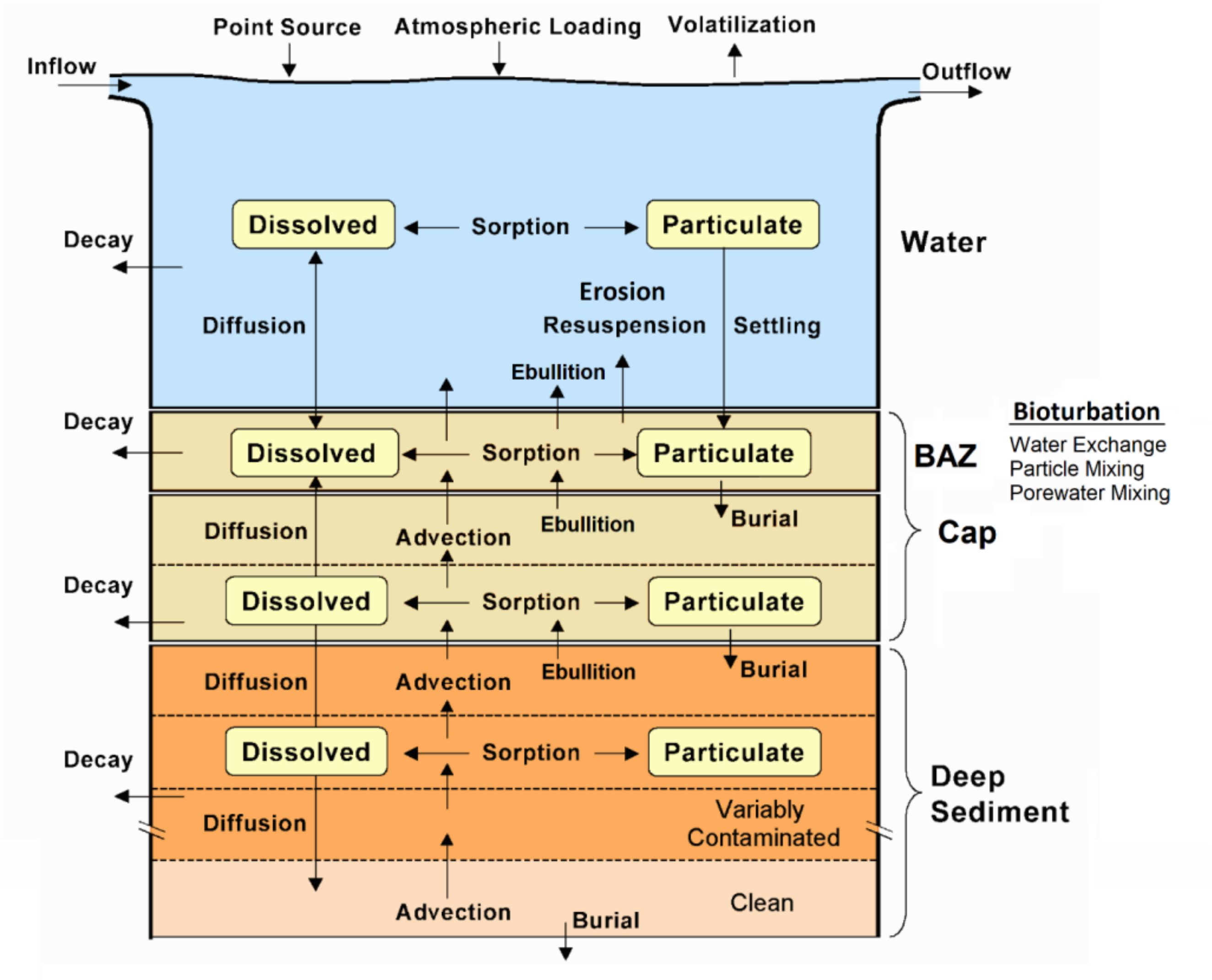


**Figure 3-5. Contaminant fate and transport mechanisms.**

*Source: Modified from C.E. Ruiz et al. (2007). Used with permission.*

Advection refers to contaminant transport due to groundwater seepage. Seepage can be upward (from sediments to the surface water) or downward (from surface water into the sediments). These rates depend on the hydraulic gradients and hydraulic conductivity of the sediments where a cap is placed. For example, clay sediments are less permeable (have a lower hydraulic conductivity) than sand or gravel sediments, so clay sediments would have a lower seepage rate for a given hydraulic gradient or pressure head. Similarly, lower-permeability cap materials may also affect seepage rates. Seepage rates may vary seasonally due to changes in the groundwater table and surface water elevations affecting the hydraulic gradient. Seepage rates that change on shorter timescales of hours or days could be caused by tidal swings, or even changes in surface water depths due to water level regulation/management. Reversals in groundwater flow direction due to these short-term changes in tidal swings could also result in increased dispersion. Dispersion acts to spread transport of contaminants and also to dilute concentrations due to mixing. Also contributing to the seepage rates is consolidation-induced porewater expulsion. The weight of a cap puts force on the underlying sediments, resulting in a reduction in sediment pore space (consolidation). The porewater present in the pore space is expelled during consolidation, and some of it is expected to move upward into the cap. This adds to the seepage during the time consolidation is occurring. Depending on the characteristics of the sediment, consolidation could last months to years after construction of the cap. In sediments that are dredged prior to placing a cap, consolidation may be limited or not occur at all if the buoyant weight of the cap is equal to or less than the buoyant weight of the dredged sediments.

Diffusion is the transport of a chemical across a concentration gradient (the chemical moves from higher concentration to lower concentration). Therefore, even with no groundwater flow, chemical transport into the cap is still possible. Understanding whether advection or diffusion controls the transport is helpful when selecting the best cap design. In a diffusion-dominated system (a system with little to no advection), the cap design may consist of a thicker cap, which provides more attenuation distance to meet the design criteria. In an advection-dominated system, increasing the thickness of the cap may not have much impact on controlling contaminant transport, and an amendment may need to be added.

Bioturbation is the mixing of sediments or cap material caused by the movement of benthic organisms and the organisms that prey on them. Bioturbation affects both the porewater and solid particles in a cap or sediment. In addition to sediment mixing, bioirrigation occurs when benthic organisms flush their burrows with overlying water, enhancing the exchange of dissolved substances between the porewater and overlying surface water. The depth to which benthic organisms mix the sediments or exchange water is a factor in the design of a cap. In general, the thickness of the cap should be equal to or greater than the depth of bioturbation to effectively isolate the contaminated sediments. This consideration differs from how technologies such as in situ treatment or enhanced natural recovery are implemented, where mixing with underlying sediments is an expected outcome.

Partitioning is also an important consideration in cap design. Chemicals that partition more strongly to solids will move slower than chemicals that partition less strongly. For example, dioxins and furans are known to bind strongly to organic carbon in sediment and capping media; in comparison, benzene or naphthalene bind less strongly and are more mobile. From a chemical mobility standpoint, a cap designed to address benzene or naphthalene must be more robust than a cap designed to address dioxin and furans.

A final key transport mechanism that should be considered when designing a cap is gas ebullition. Ebullition is the process by which biogenic gases produced from the biodegradation of organic matter by microorganisms in the sediment migrate through the upper sediment, capping media, and overlying water column to the air/water interface. Ebullition may be an important transport mechanism for nonaqueous-phase liquids (NAPLs) and may also enhance transport of other contaminants from the sediment to the surface water column at sites with high gas ebullition rates. Viana and Rockne (2021) summarize the fundamentals of ebullition-facilitated NAPL and contaminant transport. The occurrence of ebullition-facilitated transport of NAPL and other contaminants must be understood during the cap design stage so that components of the cap can be designed to handle such transport (e.g., use of organophilic clays to absorb NAPL).

With transport mechanisms in mind, the thickness and composition (materials and amendments, if necessary) of the cap needed to meet cap design criteria can be identified. Amendments may be added to the cap if there are constraints on thickness or if increasing thickness alone is not sufficient to meet the design criteria. This minimum cap thickness and amendment dose, if necessary, are estimated primarily through contaminant fate and transport modeling, discussed in Section 5.

### 3.3.2 Amendment Addition

Amendments may be added to a cap in a discrete layer (loose or confined in a mat), mixed with other cap materials in a bulk layer, or added directly to sediments in the case of in situ treatment. The type of amendment selected for a cap depends on the particular contaminants or contaminant group being addressed and may involve the use of a combination of amendments. Appendix B provides additional information about capping amendments. In addition to the characteristics of the amendment used to enhance the protectiveness of the cap, cost and availability of the amendment are important to consider. The design dosage should be based on the chemical isolation modeling results (see Section 5) and may be informed by the results of bench-scale treatability studies (see Case Study No. 1 in Appendix A) or recommendations in the literature. It is critically important that material characteristics of amendments (e.g., granular activated carbon [GAC] vs. powdered activated carbon [PAC] particle sizes) are understood and incorporated into the modeling effort. Both the quantity of an amendment and the capacity of the amendment to retard COC migration through the cap can be affected by the amendment's physical and chemical characteristics. When considering amendments to enhance chemical isolation/attenuation, it is often necessary to collect data that will support the modeling and design activity. The efficacy of the amendment type and quantity should be evaluated through modeling (discussed in Section 5).

If amendment will be present in the BAZ, it is important to consider the potential for short-term impacts from the amendment dose to the benthic community. For example, there is general consensus in the literature that the addition of activated carbon at doses in the range typically applied to sediments (5% by dry weight or less) has little or no effect on the survival of benthic organisms (Cho et al. 2007; Kirtay et al. 2017; Kupryianchyk et al. 2011; Luthy et al. 2009; McLeod et al. 2007; McLeod, Luoma, and Luthy 2008; C. Menzie et al. 2016; Millward et al. 2005; Werner, Higgins, and Luthy 2005; Zimmerman et al. 2005; Zimmerman et al. 2004; Sun and Ghosh 2007; Tomaszewski, Werner, and Luthy 2007). Some studies have found no significant effect to communities in terms of species diversity and abundance for activated carbon doses up to 10% (Kupryianchyk et al. 2012). Where deposition of clean sediment over the cap surface occurs, deposited materials may also provide or enhance the habitat quality on top of the cap and reduce potential ecological exposure to amendments in the BAZ.

## 3.4 Site Characteristics for Chemical Isolation Design

Site characteristics are critical when designing a cap to achieve chemical isolation, and designs must be site specific. The 2014 Contaminated Sediments Remediation guidance document (ITRC 2014) presents a series of steps as elements of a remedy evaluation framework. The first step identified in the guidance is to review the physical, sediment, contaminant, land, and waterway characteristics. Table 3-1 summarizes the characteristics identified in the 2014 Contaminated Sediments Remediation guidance document (ITRC 2014) that relate to designing a cap to achieve chemical isolation. A significant portion of the required information may be available from remedial investigation and feasibility study reports. Other information may need to be obtained through predesign investigations.

**Table 3-1. Summary of site characteristics that inform cap chemical isolation design**

| Characteristic | Considerations for the Chemical Isolation Design |
|---|---|
| **Physical Characteristics** | |
| Erosion Potential | Defines erosion protection (e.g., cap armor) requirements. Typically evaluated through modeling (e.g., flood event simulation for rare storm events) or calculations (e.g., ship propellor scour) for reasonable extreme conditions. Does not affect chemical isolation if the cap is physically stable, although it may impact long-term deposition and bioturbation. |
| Sediment Deposition | Important factor in predicting long-term remedy effectiveness and in evaluating the role of top-down recontamination from sources outside of capped areas. Evaluated by various methodologies including sediment trap sampling, geochronology cores, repeated bathymetric surveys, historical documents, or modeling. Sediment Profile Imaging (SPI) may be useful when evaluating the deposition of distinct layers if conducted after large events and before the signatures of the deposited layers are lost to bioturbation or other processes. |
| Hydrodynamics and Bed Shear Stresses | Important to selection of cap media and/or construction methods. May govern limits on top-of-cap elevation needed to provide required maintenance dredging elevations or to preserve hydraulic capacity in rivers to prevent increased flooding. May govern the interim stability during cap installation. Expected flow velocities from currents, tidal processes, marine navigation, wind waves, outfall discharges, and other factors may be important in determining bottom shear stresses that impact a cap during construction or over the long term. Typical long-term average bottom velocities are also needed in cap design modeling, as they govern mass transfer from the sediment to overlying surface water across the sediment–water interface. Assess using velocimeters, acoustic Doppler current profile, modeling, or other means. |
| Water Depth and Site Bathymetry | May be important to determine acceptable top-of-cap elevation and thus may determine either cap thickness or pre-dredging requirements: The selection of cap surface materials for shallow areas that are periodically exposed has specific design requirements related to habitat, wetting and drying processes, solar radiation, and (potentially) aesthetic considerations. Deep water areas can present constructability challenges, making it difficult to accurately control placement location and thickness of placed materials. Monitoring may also be more difficult. These could impact choice of design and/or material selection. Water depth does not directly impact chemical isolation but may affect the influence of other factors such as wave impacts, gas ebullition, groundwater seepage rates, etc. |

| | |
|---|---|
| In-Water and Shoreline Infrastructure | Locations of underwater utility crossings may limit cap extent and/or require specific types of cap designs over such structures. Other types of structures may pose limitations on construction methods and thus also dictate the use of certain capping materials or construction approaches. Overhead clearance is important to consider when selecting the cap construction method and may also influence cap design choices. |
| Presence of Debris | Removal of debris present at the site should be considered prior to the cap installation. Debris present at the site may not provide a smooth surface on which to install the cap. This may adversely affect the chemical isolation of contaminants or result in localized erosion. Alternatively, the cap may be placed over the debris to avoid the cost of removal and disturbance of the underlying sediment. Such cases may require a thicker overall cap and thus could impact the cap design. |
| Slope and Slope Stability | Areas of steep slopes (typically slopes steeper than 3H:1V) will require special consideration due to the potential for caps to slide downslope and amendments to separate from capping media. Available cap type options for steep slopes can impact the cap design. |
| Groundwater / Surface Water Interaction | Groundwater seepage through sediments is one of the most important factors influencing cap design. Areas with higher seepage rates have advection-dominated COC flux processes, and areas with lower seepage rates have diffusion-dominated flux processes. Some areas may have downward groundwater flow where surface water flows into the sediment. Spatial variation in groundwater / surface water exchange is important to evaluate. This can be assessed using differential piezometers, seepage meters, and other methods. Caution is required when interpreting seepage meter data due to the potential impact of hyporheic flows and equipment-related influences, which may produce biased results. |
| Ebullition | Ebullition is the release of gaseous bubbles from sediment that are the result of bacterial decomposition of organic matter. The buoyancy of these bubbles through the sediments creates a transport mechanism that can facilitate movement of chemicals; this is called ebullition-facilitated transport. Whether ebullition is present can be assessed by observing the water surface during warm weather for evidence of bubbling, examining gaseous voids in sediment cores, and other techniques. For some sites, depending on the lability of the organic matter that is decomposing, cap placement can reduce ebullition by insulating the sediment and lowering the seasonal maximum sediment temperatures (e.g., Huls and Costello 2005) and consolidating the sediment. Cap material selection and construction methods can be affected by ebullition because gas buildup beneath a cap must be avoided. |
| Hydrostatic Uplift | Hydrostatic uplift of the cap or underlying sediment, typically by gas ebullition, has the potential to fracture the uppermost layer of sediment or cap and disturb the cap by creating a preferential pathway through that material. For geosynthetic membranes, hydrostatic uplift or gas ebullition can cause shifting and movement of the material. This is related to the hydrodynamic and physical setting of the site as well as the geotechnical properties of the sediment. Selection of cap materials should consider this potential process. Geotextile materials or soil/granular materials that have higher permeability will generally allow water and gas to pass through. Caps may have the ability to self-heal to some extent if uplift incidents occur, especially if the impacts are on a small scale and do not disrupt their overall characteristics (thickness, uniformity, and composition) to any great extent. |

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| Benthic Community Structure and Bioturbation | Bioturbation occurs within the BAZ. Mixing by organisms feeding in and utilizing this layer reduces vertical concentration gradients of contamination. In freshwater, bioturbation depths of 5 to 10 cm are commonly observed, and deeper bioturbation can occur in salt water where deep bioturbators may be present (Boudreau 1998; Zimmerman et al. 2005; USEPA 2005, 2015b; Clarke et al. 2001; Teal et al. 2008; D.D. Reible and Lampert 2014) Depending on the depth, density of bioturbation, and the presence of deep bioturbators, a detailed evaluation during cap design may be needed, and BAZ thickness is an important parameter. BAZ thickness can be assessed using SPI cameras, inspection of sediment cores, micro-profiling of redox values, or other indicators. Mixing rates are typically sourced from literature. A goal of capping is to separate contamination from the BAZ, so CIL bioturbation could compromise the cap by creating a direct migration pathway to the surface. A habitat layer or other cap layers above the CIL need to be of an appropriate material type and thickness to prevent bioturbation of the CIL. Dissolved oxygen levels and the availability of natural organic matter (NOM) that is a food source for benthos can influence the presence and activity of the benthic and aquatic organisms that may repopulate the remedy area following capping. Changes in dissolved oxygen levels can increase or decrease bioturbation. Capping media are often coarse grained and low in NOM content, but this evolves as deposition fills the pores in the BAZ, adding NOM. |
| Wetland | Where caps must be constructed in wetlands, the wetland habitat will typically be altered and may need to be reconstructed. The type of wetland and the associated habitat layer requirements can play an important role in cap design. Vegetation may affect the translocation of capped contaminants to the surface and impact the thickness of the cap needed to provide physical isolation. |
| **Sediment Characteristics** | |
| Sediment and Porewater Geochemistry, Including Organic Carbon | Geochemistry is important in cap design. The most important aspects are sediment organic carbon content, organic carbon type (for sites that may contain a high proportion of black carbon types), and DOC concentrations; for inorganic chemicals, pH and cation/anion chemistry may be important. Underlying contaminated sediment geochemistry can be assessed in the laboratory from bulk sediment samples. |
| Geotechnical Properties / Bearing Capacity | The geotechnical properties and stability of the sediments in areas to be capped may require specific materials that the sediment can support and may determine cap installation equipment and procedures. Assess through geotechnical analysis of sediment core samples and/or sediment probing field observations. Sediments with low bearing capacity may require the placement of a base layer to consolidate the surficial sediment before placement of the CIL to prevent intermixing with the sediment. Sediment with low bearing capacity may also be subject to consolidation after cap placement such that the surface bathymetry of the cap varies from construction due to consolidation instead of erosion. Understanding this is important to avoid erroneous conclusions about loss of cap thickness and integrity later. |
| Grain-Size Distribution | Grain size is important when modeling chemical mobility in the sediments below the cap and is an important parameter to evaluate spatially. The variability and representative values must be determined and used as inputs to models used for cap design. It is measured in the laboratory on samples from sediment cores. |
| Presence of Fluid Mud or Fluff Layer | The degree to which the surface sediments are consolidated may impact the extent to which sediments initially mix with cap material upon placement. The thickness of the soft surficial sediment layer dictates the need for placement of a base layer prior to placement of the CIL. Conditions can be assessed in the field through direct examination of the bed surface, collection of core samples that can be finely segmented, and other techniques. Immediately after dredging, a layer of unconsolidated “fluff” may remain and should be considered during cap design, if the cap is intended to be installed before this layer consolidates. |
| Sediment Consolidation—Deep Sediment (Porewater Expulsion) | If sediment consolidation occurs due to the weight of the cap materials, porewater is expressed into the cap, delivering an initial chemical load into the cap. Consolidation may be limited (or not occur at all) if dredging occurs prior to capping. Assess porewater expulsion through consolidation testing on sediment cores and modeling. |

| **Contaminant Characteristics** | |
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| Horizontal and Vertical Distribution of Sediment Contamination | Determination of the nature and extent of contamination is fundamental to cap design. Importantly, the depth interval below the bottom of the cap must be adequately characterized. If dredging is to be conducted prior to capping, this may require sediment core sectioning specific to these depths. A 2-foot or greater interval below the cap should be characterized. A sufficient number of samples should be obtained to define the range of COC concentrations within an area or subarea to be capped. The horizontal extents of contamination above values to be capped should be established by a sample network suitable for defining the boundaries of the contamination. |
| Sediment-Porewater Chemical Concentrations | Sediment-porewater concentrations will depend on site-specific levels of contaminants in sediment, the organic carbon content of the sediment, and DOC concentrations in porewater, as well as the site-specific COC partition coefficients and seepage rates through the sediment. At a particular point in the sediment column, porewater concentrations may be affected by partitioning from sediment contaminants in immediate contact with the porewater or may reflect transport of contaminated groundwater or porewater from a more distance source or reflect a combination of the two. Porewater concentrations are more difficult and expensive to characterize than sediment concentrations, and a more limited set of values will typically be available. Porewater can be measured in situ using passive sampling media of various types or ex situ by extracting porewater from sediment samples or by using passive samplers in the laboratories. If porewater concentrations are to be measured for cap design (instead of estimating them by partitioning calculations from sediment), they should be measured in the depth interval of sediments below the bottom of the cap. In this case, it is advisable to also collect bulk sediment concentrations colocated with porewater samples. |
| Partition Coefficients | Sediment-porewater and cap material–porewater partition coefficient values are required for each chemical evaluated in the cap design. Literature values are often available, but care is required when selecting the appropriate values for the site. Site-specific studies may also be conducted to derive partition coefficients. These studies can be complex and challenging to conduct accurately, and a sufficient level of expertise and experience is required to derive representative values. Values may be developed using porewater concentrations and the associated sediment concentration under equilibrium conditions. |
| Source Identification and Control | Cap design should consider the schedule and sequencing of upland and in-water source control (e.g., placement of a cap as an immediate response action before source control versus isolation of a residual plume prior to cap installation). |
| Presence of Source Material (such as NAPL) | The presence of NAPL and/or sheen needs to be investigated and carefully evaluated. Due to the fate and transport of these types of contaminants and the potential for ebullition, different approaches may be required under federal, state, or local regulations, and additional considerations will need to be incorporated into the cap design process. If the sediments contain NAPL, the approximate amount of NAPL, the type of NAPL, the mobility of the NAPL, and the potential for NAPL to supply contaminants to the dissolved phase are all important considerations. Specific NAPL characteristics related to cap chemical isolation design are discussed in more detail in Section 3.4.3. |
| Background | The role of background concentrations (refer to Section 2.2 of the 2014 Contaminated Sediments Remediation guidance document [ITRC 2014] for additional details) and evaluation of the site as a component of the surrounding region should be considered when developing the CSM. This should include the definition and status of background concentrations of various media (e.g., sediment, surface water, suspended solids, porewater, biota) in the region, history of the region, and determination of the appropriate statistical/spatial analysis. Whereas the status of background sediment concentrations is useful to understand the site within its region, consideration of long-term anthropogenic effects on the region may also warrant consideration. Speculative impacts to background concentrations should not be relied on for design. ASTM E3242 and E3344 are useful refences for background evaluation. |

| Climate Change | |
|---|---|
| Climate change | Climate change considerations are typically considered in a resilience evaluation of the design, which may be done through a sensitivity analysis. Once the design is developed, reasonable future climate impact scenarios for the site should be selected and the resilience of the design examined for those scenarios. For example, if total precipitation may be lower in the watershed, reduced groundwater discharge may be examined in a sensitivity analysis. This is discussed further in Section 3.6. Sources of climate change predictions are frequently changing and being updated and should be consulted through appropriate government agencies depending on the location of the site. Potential impacts include increases or decreases in water levels, precipitation, or sea levels. The magnitude and direction of change must be considered on a site-specific basis. Some areas are predicted to be more drought-prone, while others may be wetter. |

Acronyms and Abbreviations:
ASTM = ASTM International
BAZ = biologically active zone
CIL = chemical isolation layer
cm = centimeter
COC = contaminant of concern
CSM = conceptual site model
DOC = dissolved organic carbon
ITRC = Interstate Technology and Regulatory Council
NAPL = nonaqueous-phase liquid
NOM = natural organic matter
SPI = sediment profile imaging

### 3.4.1 Classes of Contaminants of Concern and Chemical Mobility

The nature of the COCs that are the focus of risk reduction can have a large impact on chemical isolation and on setting performance targets. COCs that strongly partition to organic carbon or oxides that are often present in capping media are more easily controlled and can be isolated using thinner caps. COCs that poorly partition to capping media may require amendments (or greater amounts of amendments) or thicker caps to achieve chemical isolation. Many hydrophobic organic compounds, such as polychlorinated biphenyls (PCB), dichlorodiphenyltrichloroethane (DDT), and dioxin, and high molecular weight polycyclic aromatic hydrocarbons (PAH) are strongly partitioned to organic carbon in sediments and cap materials, resulting in lower porewater concentrations and slower dissolved-phase mobility.

By comparison, many low molecular weight organic compounds tend to be less hydrophobic and more mobile in the environment. Mobility and bioavailability of many inorganic contaminants (such as mercury, arsenic, and others) increase in the absence of acid volatile sulfides and present challenges for chemical isolation. Acid volatile sulfides are sulfides in sediment that are soluble in cold acid and are reported as the most active part of the total sulfur in aquatic sediments. It is a key partitioning phase controlling the activities of divalent cationic heavy metals in sediment. Furthermore, redox conditions can change the fate and transport of a contaminant and determine whether some contaminants, like arsenic and manganese, are released from the aquifer rocks and sediments into the groundwater. Understanding whether groundwater/porewater is oxidized (oxic) or reduced (anoxic) can have implications on the groundwater/porewater quality and the transport of contaminants through or into the designed cap (United State Geological Survey [USGS] (2019)). The determination of the redox conditions for some contaminants is crucial to determining contaminant levels, bioavailability, and how to mitigate the potential migration to the cap.

### 3.4.2 Site Heterogeneity

Site heterogeneity includes many factors that impact risk and cap design. Elements of heterogeneity that may be important are differences in the COCs present, COC concentrations, sediment grain size, erosion/deposition rates, sediment–water exchange or seepage rates, organic carbon content of the sediments, sediment geotechnical properties, and others. Heterogeneity represents a component of uncertainty in cap design due to the need to choose representative design inputs for areas with heterogeneous characteristics. It is often managed through delineation of subareas within the capping footprint with similar characteristics. Within subareas, heterogeneity (which represents a form of uncertainty in choosing representative values for cap design) may be addressed by choosing representative average values (e.g., for contaminant concentrations, grain size, seepage rates, or any other input characteristic required) or by assigning more conservative values (e.g., 95% upper confidence limit [UCL] or 95th percentile values) for certain parameters. The choice of how to assign representative values, and for what parameters, to address heterogeneity first requires an understanding of both the heterogeneity and the parameters that are most important to cap design. This may require preliminary sensitivity modeling.

Performance targets generally do not differ among subareas with broadly similar characteristics as a consequence of heterogeneity unless there are significant differences in required cap thicknesses and amendments. If a particularly thick cap is required in a subarea, the selected design evaluation depth (e.g., distance above the top of the CIL or distance relative to the BAZ) may differ from other subareas that have thinner caps. Among portions of a site that are broadly dissimilar, and for which different protective concentrations have been calculated through risk assessments (for example, receptors may be different), there may be differences in chemical isolation design performance targets.

## 3.4.3 NAPL Considerations

Where NAPL is present in the sediment, additional characterization is warranted to evaluate whether and where it may impact the chemical isolation design. NAPL may be immobile and strongly retained in sediments, particularly when emplaced as oil particle aggregates. Emplacement as oil particle aggregates (Fitzpatrick et al. 2015) differs from NAPL emplacement into terrestrial soils by gravity drainage with contiguous pore saturation. Capping NAPL requires careful consideration if NAPL exhibits mobility because it may be difficult to contain.

NAPL mobility and its ability to migrate must be evaluated and quantified (ASTM International’s [ASTM] Standard E3282; ASTM 2022) to determine the magnitude of NAPL that may impact a cap. Site geometry relative to NAPL layers may be of particular importance. For example, the thicknesses of the layers containing NAPL and the intersection of these layers with the sediment–water interface and sediment bed slope in these areas are factors that may need to be understood for an effective remedial design, which could favor NAPL removal in addition to or in lieu of capping. A three-dimensional understanding of NAPL source material and how it is expressed on the sediment bed may be important for cap design. Contamination in the form of NAPL, or dissolved from NAPL, has the potential to move from the sediment to the sediment–water interface via the following transport mechanisms:

- migration of NAPL by advection, gravitational forces, or bioturbation
- ebullition-facilitated transport of NAPL and sheens
- consolidation-induced transport of NAPL
- advective migration and diffusion of dissolved-phase contaminants within the sediment porewater that have dissolved from NAPL

NAPL mobility must be evaluated and its residual saturation must be quantified to identify the NAPL mass that has the potential to move into the cap over its design life (e.g., 100 years). The cap can then be designed to sequester the NAPL that may be transported into the cap to prevent migration of NAPL into the BAZ. Surface surveys for visual observations of sheens or diver surveys for observations of gas releases provide a screening-level evaluation of ebullition-facilitated NAPL transport. The chemical isolation design should consider ebullition-facilitated NAPL transport, buoyancy, and erosion/scour. Control of ebullition-facilitated NAPL transport should consider the proper venting of the gas as well as sequestration, biodegradation, or NAPL removal. Releases due to buoyancy effects (i.e., light nonaqueous-phase liquid [LNAPL]) should consider the geometry of the cap because the LNAPL will rise upward along the slope of the cap. Isolating contaminants from mobilization due to erosion and scour must consider the durability of the cap as it relates to current and future hydraulic conditions. Cap amendments (e.g., organophilic clay) are typically needed to address NAPL transport and prevent sheens in the surface water above the cap. These amendments are typically placed in a layer referred to as an “NAPL sorption layer.” Similarly, where dissolved-phase contaminants are diffusing from NAPL, amendments (e.g., activated carbon) are used above the NAPL sorption layer to achieve long-term chemical isolation.

### *3.4.3.1 Gas Ebullition*

Ebullition may be an important transport mechanism of NAPLs and other contaminants from the sediment to the surface water column in some sites. Viana and Rockne (2021) summarize fundamentals of ebullition-facilitated NAPL and contaminant transport, and Viana and Rockne (2022) summarize approaches to measure and assess ebullition-facilitated NAPL and contaminant transport in sediment. ASTM Standard E3300-21 (ASTM 2021) provides guidance for evaluating ebullition and associated NAPL and contaminant transport in sediments. Ebullition creates preferential flow paths through the sediment and cap, reducing the contact with much of the capping media placed to adsorb and sequester contaminants.

#### *3.4.3.2 NAPL Stability Assessment*

The potential for upward movement of NAPL into the CIL should be evaluated to determine whether NAPL in sediments can move via NAPL body-scale migration, or if it is only mobile at the pore-scale. NAPL movement depends on the NAPL type and properties (i.e., density, viscosity, NAPL–water interfacial tension, pore fluid saturation, relative permeability, and wettability) and site conditions (i.e., hydraulic conductivity, vertical hydraulic gradient, and sediment porosity). Empirical field observations of NAPL morphology, NAPL distribution relative to geologic units, and NAPL (or staining) vertical distribution and continuity in cores may also be used as a line of evidence to evaluate NAPL movement. Typically, a tiered and weight-of-evidence evaluation of NAPL movement is conducted to evaluate the need for an NAPL sorption isolation layer. The ASTM Standard E3282-21a (ASTM 2022) may be used to inform this evaluation.

#### *3.4.3.3 Sediment Consolidation Beneath the Cap*

NAPL could potentially move due to post-capping sediment consolidation. The added weight of a cap placed on sediment effectively squeezes fluid out of the underlying sediment as the sediment pore space (i.e., porosity) decreases, increasing the NAPL saturation in the consolidating sediment. Quantifying how much NAPL could move due to consolidation requires knowledge of the NAPL saturation, thickness of sediment being consolidated, and the decrease in pore space. In sediments, NAPL may be in the solid, aqueous, or immiscible phase. Immiscible NAPL migration requires a continuous phase for mobility.

#### *3.4.3.4 Amended Cap Layer to Address NAPL Transport*

The sum of the separate-phase (especially the immiscible phase) NAPL loads to the CIL informs the quantity of amendment in a NAPL sorption layer. Organophilic clay is commercially available, and its NAPL-absorbing properties have been proven effective in numerous capping and sediment NAPL mitigation remedies. ASTM D8106 (ASTM 2017) can be modified using site NAPL to estimate the NAPL sorption capacity of commercially available organophilic clays. It is critical to consider both the physical form of organophilic clay used and the resulting as-placed uniformity in the CIL. For example, if organophilic clay is placed as a mixture with sand, its mass per area will have greater variability compared to when it is placed using a mat-based technology. Other amendments, such as activated carbon, should be considered for use in an additional overlying layer when immiscible NAPL is primarily a source for dissolved-phase COC transport.

#### *3.4.3.5 Dissolved COCs from NAPL*

It is important to consider dissolved-phase COC transport originating from NAPL in addition to the transport of NAPL. The design of a cap to address NAPL migration will be different from the design for a cap to address migration of dissolved-phase concentrations. It can be important to empirically measure the effective solubility of NAPL in sediment sites to estimate long-term dissolved-phase COC concentrations sourced from NAPL. Note that field testing to estimate effective solubility can be complicated by inadvertently introducing NAPL into a sample intended to quantify the dissolved-phase concentration. Porous ceramic cups are a readily available material that allows for the sampling of aqueous-phase organic compound concentrations in contact with NAPL but without NAPL impacts (Gefell et al. 2018). If not empirically measured, COC concentrations in porewater where NAPL is present may be calculated assuming equilibrium with the NAPL phase using Raoult’s law.

## 3.5 Design Constraints and Optimization

Additional design criteria may need to be considered depending on the project location and setting. In some cases, these design constraints may be associated with state or federal agency permitting requirements. A top-down design approach can be a useful framework for designing caps to accommodate these additional design constraints. A top-down approach begins by establishing design criteria for the uppermost cap layer and then sequentially progressing through the design of each underlying cap layer. The top-down approach applies the following hierarchy of considerations, not all of which may apply as a design constraint for every site:

1. cap surface elevation requirements

2. habitat requirements

3. erosion protection requirements

4. chemical isolation requirements

5. NAPL control requirements

6. base layer requirements

The total cap thickness may require design optimization for each of these considerations, resulting in an iterative approach that seeks to achieve cap performance objectives in the most cost-effective manner.

## 3.5.1 Cap Surface Elevation Requirements

Cap surface elevation requirements are critical to understand early in the design process. In rivers, increasing the river-bed elevation by cap placement may cause flooding or other impacts that may need to be avoided through use of thinner cap profiles or pre-dredging all or a portion of the cap thickness before cap placement. In areas where water depths are maintained by dredging, the cap surface elevation may be required to be below the maintenance dredge depth. In marine navigation areas, the cap surface elevations will determine water depths between boat propellors and the cap, which will factor into establishing erosion protection requirements. Shallowing of areas or converting aquatic habitat to intertidal habitat may be allowed at some sites if this has a desirable ecological benefit. Capping sites in lakes or deep coastal waters may not have cap surface elevation limitations. If a cap surface elevation requirement exists, the basis for it should be stated as a design criterion.

Cap surface elevation constraints associated with flood rise impacts and navigational requirements are discussed in more detail below.

### *3.5.1.1 Flood Rise Impacts*

Caps constructed within a regulatory floodway typically require no-rise certifications consistent with the National Flood Insurance Program (NFIP) managed by the Federal Emergency Management Agency. As stated in Title 44 of the Code of Federal Regulations (CFR), Section 60.3(d)(3), NFIP regulations prohibit encroachments, such as caps, within an adopted regulatory floodway unless it can be demonstrated through hydrologic and hydraulic analyses performed in accordance with standard engineering practice that the proposed encroachment would not result in any increase in flood levels during the occurrence of 100-year floods. Flood rise analyses in support of a no-rise certification use the same hydraulic model (e.g., HEC-2 or HEC-RAS model) used to prepare the effective Flood Insurance Study report and associated NFIP map for the regulatory floodway where the cap is being constructed.

Due to such no-rise requirements, there can be limitations on cap surface elevations because the constructed caps cannot impact water surface elevations and floodway widths under the 100-year flood. In these cases, pre-dredging of sediment in advance of capping is typically required. If the caps result in an increase in water surface elevations the project will require the submittal of a letter of map revision to revise the NFIP map prior to the start of the project. Because such changes require approval by the community and/or Federal Emergency Management Agency, it is preferable to design caps that will not result in flood rise impacts to avoid the need to seek such approvals.

### *3.5.1.2 Navigational Requirements*

In waters used for navigation, there is often a minimum water depth required for vessel traffic. To find the minimum water depth required, check with the United States Army Corp of Engineers (USACE) for federal navigation channels (e.g., navigation charts) or state agencies for interstate waterways. These areas may be subject to routine or periodic maintenance dredging to maintain these minimum water depths. Cap design should consider these navigation depth requirements. In areas where navigational dredging occurs, the cap should be designed so that the cap surface elevation is less than the elevation subject to navigational dredging, including a tolerance, to avoid disturbance of the cap. This tolerance may include a buffer for over-dredging allowance and provide additional depth for material to deposit over time so that dredging can occur less frequently.

Navigational requirements may impact the cap design as follows:

- May need to dredge first to accommodate the thickness of the cap.
- May need to design the cap with thinner layers to achieve an overall cap thickness that will accommodate the required water depth. Options for thinner caps include the following:
    - A thinner CIL can be designed by incorporating amendments or adding higher amendment doses.
    - Rather than bulk sand and amendment, amendment-filled geotextiles or a thin low-permeability cap may be used.
    - Thinner armor or filter layers may be achieved by using marine armor mattresses or articulated concrete block mats.
    - A geotextile may be used instead of a filter layer to keep the CIL from piping into the armor layer. Caution should be taken when using geotextiles at shallow depths due to the potential for disruption of the cap by gas ebullition.
    - The CIL could be designed to have a certain average diameter stone and grading so that a filter layer is not needed.

In cases where ample water depth is available to place a cap without altering habitat type (e.g., converting subtidal zones to intertidal zones), influencing flooding conditions (by reducing river cross section), or impacting navigation (by reducing available depth), cap surface elevation may not be a design driver.

### 3.5.2 Habitat Requirements

Caps may be required to include a habitat layer that provides suitable habitat characteristics of the bottom substrate (Vlassopoulos et al. 2017; Yozzo, Wilber, and Will 2004; Zhang et al. 2016). This layer may provide a more suitable stone size or the addition of organic material to promote vegetation growth, fish spawning, or benthic growth and may contribute to other functions such as chemical isolation. In many cases, the need for and composition of the habitat layer is based on permit requirements. If a particular grain size or habitat substrate is required, the specific type (grain size and organic composition requirement) and thickness must be stated as design criteria together with applicable permitting requirements. Erosion protection layers (or a portion of an erosion protection layer) may also serve as a habitat layer. If an additional layer of habitat material is required, then the total cap thickness will increase.

### 3.5.3 Erosion Protection Requirements

Cap physical stability must be ensured through design for the reasonable range of anticipated erosive forces, including both natural and human-use influences. Natural events typically include flood flows and storm surges resulting from large storm events, high wind-wave events, or ice scour. In addition to naturally occurring erosion forces, areas of recreational and/or commercial power boat navigation and anchoring are important factors to consider. Where propellers can induce substantial erosive forces, this may dictate the type and size of erosion protection required and overall cap thickness. For caps with more complex site geometries, the critical forces associated with these forces will likely vary across the cap area. These may cause widespread increases in erosion potential or more variable or localized erosion potential.

When stating the erosion protection layer design criteria for each erosive force evaluated, the critical erosion condition must be identified and stated. For example, the 100-year storm event (flow, wind velocity, or coastal surge, etc.) may be a design event, pipe-full discharge may be a design event/condition for outfall scour protection, specific types of watercraft and operating conditions (speed and power) may be designated as design inputs for propeller scour protection, etc. In colder environments cap scour may be induced by the effects of ice during freeze/thaw cycles. Although this guidance does not provide details for erosion protection design, erosion protection layer requirements can be critical to the success of the sediment cap because the erosion protection layer serves to further separate underlying contamination from the BAZ and surface water. For example, if erosion protection requires an inflatable concrete mattress in a portion of the site to resist prop scour, this may produce a practically impermeable cap and alter the advective or diffusive flux-based chemical isolation design by reducing seepage rates and diffusion pathways to near zero. Site-specific considerations will influence erosion protection design and how it may impact the total cap thickness and chemical isolation design.

### 3.5.4 Chemical Isolation Layer Requirements

Establishing and optimizing design criteria for the composition and position of the CIL are important for optimizing the total cap thickness. As described in Section 3.3, cap chemical isolation can be accomplished by adding cap thickness and/or adding amendments. Increasing the cap thickness provides greater physical separation from underlying contaminated sediments and increases the attenuation distance for COC migration through the cap. Amendment addition serves to retard COC migration through the cap. CIL designs commonly evaluate several configurations of varying thicknesses and amendment doses to identify the design that best achieves the chemical isolation performance objectives and that is the most cost-effective and constructable option.

Once the cap surface elevation requirements are established and the thickness of the CIL and overlying cap layers are evaluated, the position of the CIL can be determined relative to the preexisting sediment surface. Once the elevation of the CIL is established, the depth interval of the sediment that is most representative of conditions below the cap can be determined. As noted in Table 3-1, the depth interval immediately below the CIL should be targeted to characterize COC concentrations in sediment and porewater used for chemical isolation design.

### 3.5.5 NAPL Control Requirements

Section 3.4.3 discusses design considerations for capping NAPL-impacted sediments. Where necessary, NAPL control is commonly accomplished by using organophilic clay, which can be constructed using bulk materials or delivered in mat-based or other proprietary delivery configurations. The appropriate construction materials and methods may depend on site geometry, NAPL characteristics, and cost. NAPL control requirements necessitate an increase in the total cap thickness.

### 3.5.6 Base Layer Requirements

The uses and functions of base layers (where used) vary from site to site, and many caps have been designed without base layers. Where base layers are incorporated into the cap design, they are generally considered sacrificial and are not assumed to contribute to chemical isolation. Their total thickness should be accounted for in the design because they increase the total cap thickness.

### 3.5.7 Cost

Cost plays an important role in the iterative nature of design; generally, the least costly option is selected from the options that equally satisfy the design requirements. The thickness of the cap components, the use and dose of amendments, and the amount of removal and disposal required to offset the cap thickness all incur costs. Cost can be used to balance design requirements for each of the factors discussed above. For example, removal and disposal costs are typically very high, relatively. Amendments can be used to reduce the thickness of the chemical isolation material and, as a result, decrease the amount of removal required.

## 3.6 Resilience and Sustainability Considerations

In addition to the cap design constraints described in Section 3.5, above, cap designs may also incorporate resilience and sustainability considerations.

### 3.6.1 Seismic Activity

Seismic considerations for cap design are important in areas that experience earthquakes. Caps are generally subject to deformation of underlying sediment during earthquakes; therefore, designing caps to resist earthquake loads is difficult and may be impracticable. In light of this, and consistent with evolving geotechnical engineering practice, seismic design for caps entails a performance evaluation and development of monitoring and maintenance elements that describe actions that would be taken after a design-level earthquake. Seismic performance evaluations include assessing the potential for liquefaction and the magnitude of liquefaction-induced settlement, as well as seismic slope stability evaluations that consider slope displacement using a Newmark-type analysis (e.g., National Academies of Sciences 2008). Liquefaction occurs when saturated cohesionless material loses its shear strength and flows like a frictional fluid (M.R. Palermo, Clausner, et al. 1998). Where designing a cap to resist earthquake loads may be impracticable, designs should assess the likelihood that underlying contaminated materials will become exposed as a result of an earthquake and include measures to monitor and repair or replace the cap where damage occurs to restore protectiveness.

### 3.6.2 Climate Change

Rising global temperatures are associated with several hydrologic impacts, including rising sea levels and changes to precipitation. Globally, the sea level has risen approximately 2 inches from 2010 to 2020. The National Oceanic and Atmospheric Administration reports that sea level rose 0.27 centimeters (cm) (about 0.11 inches) in 2022, which is consistent with the USEPA’s findings. In general, there is an increase in precipitation, most commonly from intense single-day events; however, drought has also been documented in some regions due to climate change. In the United States, for example, floods have become larger across the Northeast and Midwest, whereas in the West, southern Appalachia, and northern Michigan, floods have become smaller. Large floods are also more frequent in the Northeast, Pacific Northwest, and part of the Great Plains and less frequent in the Southwest and Rocky Mountain regions (USEPA 2022).

Although resilience to climate change and extreme weather events is not the only design criteria for caps, it is beneficial to understand how those factors may affect the cap performance. Climate change may alter sediment deposition rates and seepage rates via higher-intensity and more-frequent rain events and sea-level rise (Mauger et al. 2005). To help maintain resilience to changing climates and extreme weather events, cap designers could first conduct vulnerability assessments of their sites (ITRC 2021) and then implement adaptation measures to ensure the remedy continues to prevent human or environmental exposure to COCs (USEPA 2015a). For caps, increases in sediment erosion may signal the need to reevaluate vulnerabilities. Designers should anticipate that sites with more frequent and heavier rain events may be subject to higher erosive forces. Increased precipitation may cause higher streamflow and an increase in the surface sediments transported downgradient. Erosion of the overlaying cap layers over time could eventually expose the CIL. Sediment erosion is caused not only by storms, but also by tides and waves, flooding, ice scouring, and other physical forces that could disrupt the cap. A significant increase in sea-level rise has the potential to result in higher wave conditions in a coastal area, which could result in the need for more robust erosion protection (USACE 2011). This change in the erosion protection layer may influence the decisions about materials to use for CIL design. In addition, drought conditions may result in lower streamflow and desiccation of cap materials. Designers should assess the risk of cap material desiccation and the effect desiccation may have on chemical isolation performance.

On the other hand, increased precipitation and sea-level rise may influence the groundwater discharge to sediments, which could affect the design of the CIL. For prolonged storms, water from precipitation is more likely to increase infiltration and groundwater levels, leading to more groundwater seepage. With short but intense storms, water from precipitation is less likely to seep into the ground, recharging the groundwater. Instead, such storm events are likely to result in greater runoff to water bodies. With increased water depths, it is possible that groundwater seepage will be reduced. Likewise, in areas where droughts are more frequent, it is likely that groundwater seepage will decrease in the future. Reductions in groundwater seepage rates may extend the design lives of caps. Generally, the lower the seepage rate, the slower the rate of chemical contaminant migrations and the longer the time to exceed the design criteria. Finally, increasing salinity driven by seawater intrusion due to sea-level rise can affect the mobility of metals as a result of cation exchange, which should be considered when designing a cap to address inorganic contaminants.

For existing systems, vulnerabilities may be reevaluated periodically during the monitoring, optimization evaluations, five-year reviews, and close-out phases. Periodic reevaluations should include verifying key data; for example, evidence of increased frequency of intense inland surface water currents and tides may prompt upgrades to subaqueous capping armor, as could the changing patterns of ice versus non-ice conditions (USEPA 2015a).

### 3.6.3 Sustainability

Capping is often considered to be a more sustainable approach to remediation of contaminated sediments than dredging due to the dramatically reduced need to process and relocate contaminated sediments.

In addition to creating a resilient remedial design, the designer should also consider the environmental impacts and sustainability of the remedy. For new systems, green and sustainable remediation may be integrated into the site’s feasibility study and remedy design phases. In general, implementation of green and sustainable remediation at an early rather than later phase of the cleanup process maximizes the sustainability of the remedy. Green and sustainable remediation evaluation may lead to selection of a cap as a sustainable remedy or influence a more sustainable cap design. For example, sourcing local materials and equipment during construction phases may reduce transportation emissions.

In 2012, the USACE, U.S. Department of the Navy, and Battelle developed a tool called SiteWise™, which can assist in the calculation of certain green and sustainable remediation metrics such as greenhouse gas footprint, energy consumption, water impacts, criteria air pollutants, and worker safety for different remedial alternatives. Tools such as SiteWise™ help identify the more sustainable options among different feasible remedial alternatives that are protective of human health and the environment and in compliance with applicable or relevant and appropriate requirements. ITRC’s 2021 Sustainable Resilient Remediation guidance provides additional discussion of how to incorporate sustainability into the remedy selection and design (ITRC 2021).

## 3.7 Coordination with Construction and Monitoring Approaches

The approach and design of the cap should carefully consider the construction and monitoring methods and objectives. Sections 6 and 7 discuss construction considerations and monitoring, respectively, in more detail. It is critical that design take into consideration quality assurance and quality control (QA/QC) elements of construction, including post-construction verification that the as-placed materials meet the design criteria.

### 3.7.1 Constructability/Implementability Considerations

Early in the design phase, it is critical to evaluate the constructability or potential to successfully implement the chemical isolation function. Constructability evaluations should consider capping materials, site constraints, and installation methodology. Site conditions or regulatory restrictions (e.g., fish windows) can impact the design by limiting construction means and methods or creating schedule or material availability impacts. Where cap construction anticipates thin layers or incorporation of amendments, it is critically important that the design address tolerances for thickness, dose, and uniform mixing of amendments into the CIL. QA/QC procedures are necessary to ensure that amendments are incorporated and placed to avoid separation and ensure they are delivered in a manner that accomplishes the design. Section 6 provides more detailed guidance related to these construction considerations. Overall, the potential impact of construction-related requirements must be evaluated and addressed or incorporated into the design.

### 3.7.2 Performance Monitoring Considerations

During the design phase, monitoring considerations are crucial to successful evaluation of the performance of the chemical isolation function. Important considerations that affect cap monitoring include, but are not limited to, analytical reporting limits on chemistry samples collected from the cap (e.g., porewater), cap thickness, presence of amendments, presence of geotextile, and presence of armor that may hinder the ability to sample below the armor stone unless other methods (e.g., sampling ports) are employed. This section introduces some specific monitoring considerations for the design phase. Additional guidance on sediment and cap monitoring is provided in Section 7.

Ideally, the chemical monitoring of the cap relates directly to the design criteria. As discussed in Section 3.1, porewater is the preferred media for evaluating chemical isolation performance. Therefore, monitoring the cap performance through porewater sampling is preferred. If the criteria are on a sorbed-phase basis, then a sorbed-phase sample may also be appropriate, for apples-to-apples comparison, without the added uncertainty of having to calculate estimated concentrations through partitioning theory.

The compatibility of the CIL thickness and planned monitoring activities should be evaluated during design. If the CIL is very thin (generally less than 6 inches), it may be difficult or impractical to collect porewater samples. In addition, selection of certain materials or configurations necessary to achieve design criteria may complicate monitoring methodology. For example, in areas where large armor stone is needed, it may be difficult to collect a porewater sample within the CIL by using passive samplers or other porewater collection techniques. In this case, one alternative option for collecting porewater data in the CIL is the installation of monitoring ports, which have been installed at a number of sites, including Onondaga Lake (Parsons Engineering Science 2014) and the former Portland Gas Manufacturing site (Case Study No. 2 in Appendix A).

In addition to the design of the cap, the substance being analyzed in the porewater samples must meet the necessary reporting requirement. Laboratory method detection limits need to be below the selected criteria. For example, if a sample is nondetect, but the method detection limit is greater than the goal, it will not be clear whether the goal is met.