From Contamination to Cleanup: Exploring Effective Strategies for Sediment Remediation

By David Palmerton, PG

Sediment management plays a crucial role in restoring and preserving natural habitats. In degraded ecosystems, manipulating sediments can aid in recreating natural sediment processes, establishing suitable substrate conditions for aquatic life, and supporting the recovery of vegetation and wildlife.

In the United States, sediment management revolves around the presence of contaminated sediment. Contaminated sediment sites pose intricate technical challenges that demand significant resources to address and mitigate the associated problems effectively.

Sediment management involves deliberately regulating, manipulating, and controlling naturally existing materials such as sand, silt, and clay in various environmental settings, including rivers, lakes, reservoirs, estuaries, and coastal areas. The primary goal of sediment management is to mitigate the negative impacts of sedimentation, which can lead to the filling of reservoirs, navigation channels, and harbors, resulting in reduced capacity and functionality. Environmental engineers strive to minimize these adverse effects through effective sediment management strategies.

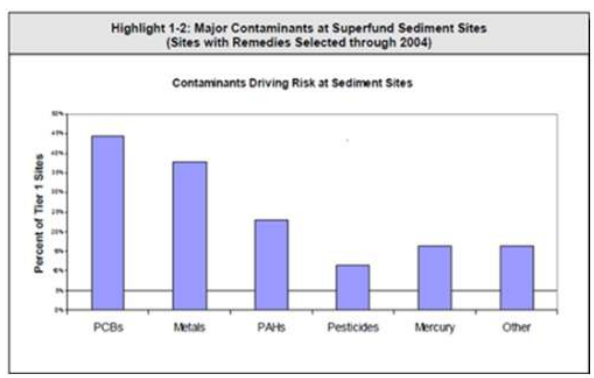
Over the past three decades, significant progress has reduced the discharge of toxic and persistent chemicals into waterways throughout the United States. However, a persistent problem remains, characterized by elevated concentrations of contaminants in the sediment found at the bottom of rivers and harbors. The situation has raised considerable concerns about its potential risks to aquatic organisms, wildlife, and humans.

This article delves into the technical challenges environmental engineers and consultants face in addressing and mitigating this issue. Furthermore, we explore strategies to optimize resources to tackle the problem at hand effectively and efficiently.

Superfund Sites

The major contaminants commonly found at Superfund sediment sites vary depending on the specific site and its history. However, several contaminants are frequently encountered in these sites. Some of the major contaminants found at Superfund sediment sites include:

- Heavy Metals
- Polychlorinated Biphenyls (PCBs)
- Polycyclic Aromatic Hydrocarbons (PAHs)
- Pesticides
- Chlorinated Solvents
- Volatile Organic Compounds (VOCs)
- Dioxins and Furans



Source: Principles for Managing Contaminated Sediment Risks at Hazardous Waste Sites, OSWER Directive 9285.6-08. 2002

It is important to note that the United States Environmental Protection Agency (EPA) classifies contaminated sediment sites based on the level of contamination and associated risks they pose. Regulatory authorities, including the EPA, may use specific assessment methods and criteria to categorize sediment sites as "high priority" or "low priority" based on factors such as the extent and severity of contamination, ecological impacts, potential human health risks, and other considerations. The EPA has identified 71 Tier 1 sites with over 10,000 cubic yards or five acres of contaminated sediment.[1] An additional 20 current or former Tier 2 sites remain, as designated by the Contaminated Sediments Technical Advisory Group (CSTAG).[2] Mega Superfund Sites, such as the Portland Harbor, the Lower Passaic River, and other similar contaminated sediment sites, have remediation costs estimated in the billions of dollars.

During the late 1990s, the EPA made a significant discovery regarding ongoing releases of sediment contaminants into surface water in numerous watersheds. Government records indicated that around 25,500 individual point source releases of 11 different sediment contaminants occurred in over 1,000 watersheds nationwide.[3] These releases stemmed from 31 distinct industrial categories. Beyond the ranking conducted by EPA, hundreds of contaminated sediment sites are spread across almost every state in the United States.

Contaminated sediment sites exhibit a higher level of intricacy when compared to terrestrial sites. Their complexity arises from various factors, such as the dynamic characteristics of aquatic systems, the potential existence of multiple ongoing sources, and their relatively large spatial extent. Due to these complexities, conducting a comprehensive assessment of site conditions and exploring various sediment management options is imperative. This detailed evaluation is necessary to maximize the effectiveness of potential remediation strategies and minimize risks associated with the contaminated sediment sites.

Several contaminated sediment sites have been studied for more than 30 years. For example, EPA declared the Allied Paper, Inc./Portage Creek/Kalamazoo River in southwestern Michigan a Superfund Site in 1990. In 1991 fieldwork began on the Outboard Marine Corp. Superfund Site in Waukegan, Illinois. And the Wyckoff-Eagle Harbor Superfund Site began fieldwork in 1993. These sites are still undergoing cleanup today.

Significant Technical Documents

A concise overview of significant technical documents related to contaminated sediments is below.

Contaminated Marine Sediments-Assessment and Remediation

In the late 1980s, the EPA launched efforts to evaluate the extent and severity of sediment contamination in the United States. In 1989, the National Research Council conducted a study titled "Contaminated Marine Sediments-Assessment and Remediation." This study emphasized the potential far-reaching health and ecological consequences of contaminated sediments. The report examined the scale and importance of contaminated marine sediments, existing cleanup and remediation practices, and management strategies. It concluded that regular reviews of site assessment procedures and cleanup technologies were crucial. It said

[1] https://19january2017snapshot.epa.gov/superfund/superfund-contaminated-sediments-list-sediments-sites_.html

[2] https://www.epa.gov/superfund/large-sediment-sites-tiers-1-2

[3] The National Sediment Contaminant Point Source Inventory: Analysis of Facility Release Data. 1996. Office of Water, Office of Science and Technology, United States Environmental Protection Agency.

management decisions should consider a comprehensive assessment of risks, costs, and environmental and public health benefits.

Water Resources Development Act

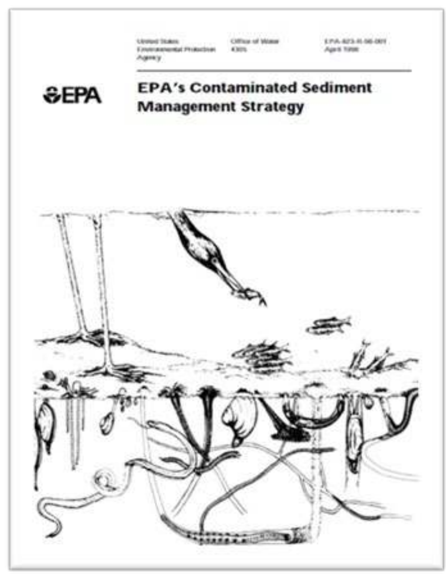
By September 1992, the EPA organized a series of forums focused on contaminated sediment and developed a management strategy. In October 1992, the U.S. Congress passed the Water Resources Development Act (P.L. 102-580), which mandated the creation of an inventory of contaminated sediment sites.

Contaminated Sediments in Ports and Waterways: Cleanup Strategies and Technologies

The National Research Council (NRC) published a document in 1992 titled "Contaminated Sediments in Ports and Waterways: Cleanup Strategies and Technologies," followed shortly by the EPA's National Sediment Inventory and then the Contaminated Sediment Management Strategy guidance in 1998. These documents marked the first comprehensive examination of the contaminated sediment issue and aimed to streamline decision-making processes.

EPA's Contaminated Sediment Management Strategy
Assessment and Remediation of Contaminated Sediments (ARCS) Program

In April 1998, the EPA introduced "EPA's Contaminated Sediment Management Strategy,"[4] followed in September 1998 by the "Assessment and Remediation of Contaminated Sediments (ARCS) Program,"[5] a pivotal publication offering technical guidance on subaqueous, in-situ capping as a remediation method for polluted sediments. Within this framework, the decision-making process for remediating contaminated sediments in waterways and identifying suitable remediation technologies follow a systematic approach guided by the expertise of the three ARCS technical work groups.


EPA
EPA's Contaminated Sediment Management Strategy

Sediment Management Work Group

Formed in 1998, the Sediment Management Work Group (SMWG) is the first private group of industry and government parties. SMWG manages contaminated sediments using science and risk-based evaluation of contaminated sediment management options. The group aims to advance scientifically sound approaches to improve sediment risk assessment, collect and share information to enhance and evaluate remedial technologies and alternatives while promoting risk-based and cost-effective sediment management decisions. This group greatly encourages the use of monitored natural recovery.

[4] USEPA, EPA's Contaminated Sediment Management Strategy. EPA-823-R98-001. 1998
[5] https://semspub.epa.gov/work/HQ/189670.pdf

A Risk Management Strategy for PCB-Contaminated Sediments

On March 26, 2001, the NRC published a report entitled "A Risk Management Strategy for PCB-Contaminated Sediments."[6] This book provided a risk-based framework for developing and implementing strategies to manage PCB-contaminated sediments applicable to PCB sites and other contaminated sediment sites around the country.

In 2002, EPA rolled out 11 principles for managing contaminated sediments for the Superfund and RCRA Solid Waste programs that are still relied upon today.[7]

- Control sources early.
- Involve the community early and often.
- Coordinate with states, local governments, tribes, and natural resource trustees.
- Develop and refine a conceptual site model that considers sediment stability.
- Use an iterative approach in a risk-based framework.
- Carefully evaluate the assumptions and uncertainties associated with site characterization data and site models.
- Select site-specific, project-specific, and sediment-specific risk-management approaches to achieve risk-based goals.
- Ensure that sediment cleanup levels tie to risk-management goals.
- Maximize the effectiveness of institutional controls and recognize their limitations.
- Design remedies to minimize short-term risks while achieving long-term protection.
- Monitor during and after sediment remediation to assess and document remedy effectiveness.

Updated Report on the Incidence and Severity of Sediment Contamination in Surface Waters of the United States

In 2004, the EPA released the "Updated Report on the Incidence and Severity of Sediment Contamination in Surface Waters of the United States: National Sediment Quality Survey,"[8] identifying areas where contaminated sediment was present at potentially harmful levels.

Contaminated Sediment Remediation Guidance for Hazardous Waste Sites

In December 2005, the EPA published "Contaminated Sediment Remediation Guidance for Hazardous Waste Sites," one of the latest documents to provide contaminated sediment remediation guidance. This document outlines the entire process from remedial investigation and risk assessment, feasibility studies, remedy selection considerations, remedial action, and long-term monitoring.

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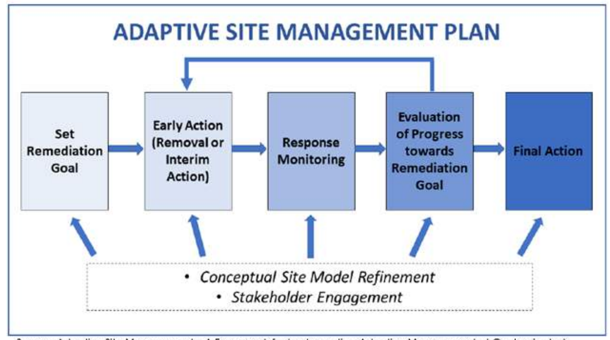
[6] https://nap.nationalacademies.org/catalog/10041/a-risk-management-strategy-for-pcb-contaminated-sediments#:~:text=A%20Risk%2DManagement%20Strategy%20for%20PCB%2DContaminated%20Sediments%20emphasizes%20the,%2C%20cultural%2C%20and%20economic%20impacts

[7] Principles for Managing Contaminated Sediment Risks at Hazardous Waste Sites, OSWER Directive 9285.6-08. 2002.

[8] https://archive.epa.gov/water/archive/polwaste/web/pdf/nsqs2ed-complete-2.pdf

Adaptive Site Management – A Framework for Implementing Adaptive Management at Contaminated Sediment Superfund Sites

Most recently, in 2022, EPA developed "Adaptive Site Management – A Framework for Implementing Adaptive Management at Contaminated Sediment Superfund Sites." This document sets up a framework for implementing adaptive site management within Superfund by performing early or interim actions followed by a final action guided by an adaptive site management plan.



Source: Adaptive Site Management – A Framework for Implementing Adaptive Management at Contaminated Sediment Superfund Sites. U.S. Environmental Protection Agency (EPA) June 2022

Large and intricate contaminated sediment sites often encounter lengthy remediation timeframes, multiple interconnected sources of contamination, widespread impact on human and ecological receptors, and uncertainty regarding the timing and extent of the effects of sediment remediation on reducing risks to receptors. Characterizing sediment beds is challenging due to their heterogeneous conditions and ongoing transport processes. Conducting remediation in underwater environments is particularly difficult and susceptible to recontamination. These challenges make developing and selecting a final protective remedy in a Record of Decision (ROD) before commencing any remediation efforts difficult.

A combination of remediation and monitoring iterations to assess progress toward achieving Remedial Action Objectives (RAOs) and remediation goals are applied in adaptive site management. It helps address uncertainties, make informed decisions about the need for additional remediation, and determine the appropriate timing for such actions to achieve RAOs. This approach can effectively facilitate progress at Superfund sites. This management approach relies on monitoring and reevaluating to improve site understanding and track progress toward goals continually.

Principles for Evaluating Remedial Options for Contaminated Sediment Sites

Developing a precise conceptual site model is crucial when dealing with sediment sites. This model should effectively identify the sources of contamination, the mechanisms of transport, the pathways of exposure, and the receptors at different levels of the food chain.

It is of utmost importance to base the remedial action objectives, remediation goals, and cleanup levels on site-specific data that are clearly defined.

RAOs typically derive from the conceptual site model. We can develop site-specific remediation goals with an improved understanding of site conditions, representing remediation goals as a range of values within acceptable risk levels. The remediation goals incorporate the development of human health and ecological remediation goals too.

As part of the remedial investigation process at many sediment sites, conducting a site-specific assessment is vital to determine whether contaminated sediment (surface and subsurface) or contaminants alone are moving. This assessment should consider the scales and rates at which such movement may occur, as it can significantly impact their contribution to the overall risk.

Identifying suitable areas for monitored natural recovery (MNR), in-situ caps, or near-water confined disposal facilities (CDFs) relies on accurately evaluating sediment mobility and the fate and transport of contaminants. Using numerical models can be beneficial in predicting future conditions at a site, providing valuable insights for decision-making.

We apply the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) selection criteria during the feasibility study phase. We evaluate major alternatives such as dredging and excavation, in-situ capping, in-situ treatment, and MNR. The project manager makes a site-specific decision regarding the number and type of remedial alternatives to develop. Combining a variety of approaches offers the most promising alternatives.

The NCP requires considering the no-action alternative at every site. The no-action or no-further-action alternatives typically do not include any treatment, engineering controls, or institutional controls but may involve monitoring.

The NCP establishes a framework of nine criteria for evaluating remedies.

- Overall Protection of Human Health and the Environment
- Compliance with Applicable or Relevant and Appropriate Requirements (ARARs)
- Long-Term Effectiveness and Permanence
- Reduction of Toxicity, Mobility, and Volume Through Treatment
- Short-Term Effectiveness
- Implementability
- Cost
- State (Or Support Agency) Acceptance
- Community Acceptance

Furthermore, during the feasibility study phase, it is necessary to consider Applicable or Relevant and Appropriate Requirements (ARARs). These requirements could include the Clean Water Act, Resource Conservation Recovery Act, Rivers and Harbors Act, Toxic Substances Control Act, State Water Quality Standards, State Hazardous Waste Regulations, State Solid Waste Regulations, National Pollutant Discharge Elimination System (NPDES) Permit Regulations, or other applicable regulations.

Additionally, you should consider the National Historic Preservation Act, National Environmental Policy Act, and Executive Orders as other important considerations.

Remediation Strategies

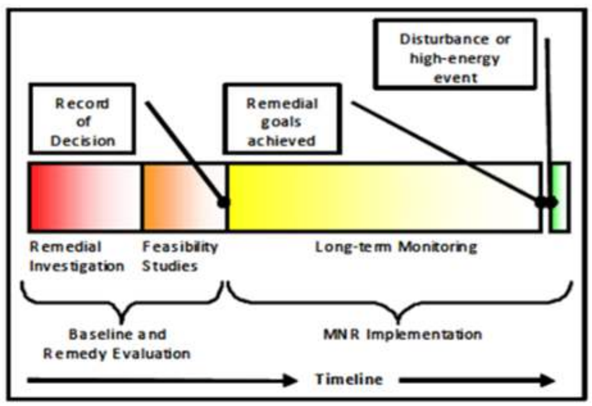
When addressing and mitigating contamination in contaminated sediments, stakeholders must consider several remediation strategies. The selection of a specific strategy depends on various factors, including the nature and extent of contamination, the characteristics of the sediment site, local regulations, and stakeholder considerations.

- Monitored Natural Recovery (MNR) is a risk management approach used in sediment remediation. It relies on natural processes to reduce the risk associated with contaminated sediment. These natural processes include burial by cleaner sediments, transformation or degradation of contaminants, and physical processes such as dispersion or dilution. Over time, these processes can reduce contaminants' toxicity, mobility, and bioavailability.

The key aspect of MNR is monitoring. It is essential to track the recovery progress to ensure that the natural processes effectively reduce risk. Monitoring protocols typically involve sampling and analysis of sediment, water, and sometimes biota to evaluate the concentration and distribution of contaminants and the ecological and human health risks associated with the site.

While MNR is often cost-effective, it is unsuitable for all sites or contaminants. Its appropriateness depends on various site-specific factors, including the nature and extent of contamination, sediment transport and deposition rates, ecological and human health risks, and stakeholder acceptance.

A technical guide titled "Monitored Natural Recovery at Contaminated Sediment Sites" describes the evaluation and implementation of monitored natural recovery (MNR) at contaminated sediment sites.[9]



Source: Figure 4-1 MNR timeline for a contaminated sediment site. Monitored Natural Recovery at Contaminated Sediment Sites. May 2009

- In Enhanced MNR (EMNR), various materials or amendments can be applied to the contaminated sediment to enhance the natural recovery processes. These materials serve different purposes and can target specific contaminants or environmental conditions.

  EMNR commonly utilizes materials such as activated carbon, clay minerals, zeolites, or activated alumina as amendments to reduce the bioavailability and mobility of contaminants. Oxygen-Releasing Amendments, Nutrient Amendments, pH Adjustments, and Biostimulation/Bioaugmentation (for example, introducing microbial populations or specific microorganisms) are also useful.

  EMNR aims to optimize the conditions for natural recovery processes to occur more efficiently and rapidly. The selection of materials or amendments depends on the presence of contaminants, site characteristics, and the desired remediation goals.

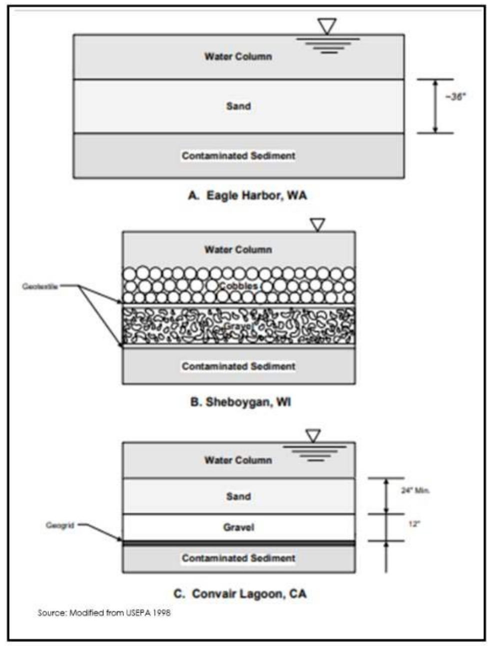
- In-Situ Capping is another technique used for the remediation of contaminated sediment sites. The method involves placing a layer or cap of clean material directly over contaminated sediments. The cap isolates the contaminated sediments from the overlying water column and biota, thus preventing the

[9] https://clu-in.org/download/contaminantfocus/sediments/ER-0622-MNR-FR.pdf

release of contaminants. The cap can also stabilize the sediments, reducing the likelihood of resuspension of the contaminated sediments.

The selection of cap material for capping can vary, encompassing options such as sand, gravel, or manufactured materials like geotextiles. The choice of cap material depends on site-specific conditions and the type of contamination present. In certain instances, "active" caps are employed, incorporating materials capable of adsorbing or degrading contaminants, further diminishing the potential for contaminant release.

For sites where removal of contaminated sediments is not easy or cost-effective or where removal may pose additional risks, consider In-Situ Capping. However, successful implementation requires careful planning, design, and long-term monitoring to ensure the cap remains intact and effective over time. It is also important to consider potential ecological impacts, such as disruption to benthic habitats.



- Dredging and excavation are physical methods of remediating contaminated sediment sites. They involve the removal of contaminated sediments from the site for treatment, disposal, or containment elsewhere. These techniques are often useful when the concentration of contaminants in the sediment is high or if the contaminants pose a significant risk to human health or the environment.

  Dredging is useful for submerged sediments in rivers, lakes, or harbors. Specialized equipment scoops or suctions the contaminated sediment from the water body. Careful dredging techniques minimize the spread of contaminants during the process. Then, transporting dredged sediment to a treatment or disposal site.

  For sediments in dry areas or areas that can be temporarily drained or diverted, excavation is suitable. Traditional earth-moving equipment like backhoes physically digs up and removes the contaminated sediment.

  After dredging or excavation, the contaminated sediment often needs to be treated to stabilize or destroy the contaminants. Treatment can involve techniques like solidification/stabilization, thermal treatment, or bioremediation.

  The dredged or excavated area may also need remediation afterward. Remediation could involve filling the area with clean material and restoring the natural habitat.

  While dredging and excavation can effectively remove contaminants, they are invasive techniques that disturb the environment and the existing habitat. They require a suitable location for disposing or treating the contaminated sediments, and the process can be costly and time-consuming. Therefore, these methods are suitable when other remediation options are not suitable or effective.

- In-situ treatment of contaminated sediments involves applying remedial techniques directly at the contamination site without removing the sediments. This approach is less disruptive and more cost-effective than ex-situ methods like dredging or excavation.

  In-situ bioremediation, in-situ chemical oxidation (ISCO), and electrokinetic remediation have been explored and tested for sediment remediation. Although their use is less widespread than other techniques like dredging, excavation, or in-situ capping, we've permitted their use with many local agencies.

  In-situ bioremediation microorganisms are useful to break down contaminants. Bioremediation involves the injection of nutrients or other amendments to stimulate native microbial populations or, in some cases, the addition of specific bacteria that can degrade the contaminants. In-situ bioremediation has demonstrated its potential for sediment remediation, particularly for organic contaminants like petroleum hydrocarbons or certain types of pesticides. However, applying this method in an aquatic environment can be more challenging due to water flow, temperature, and oxygen levels, which can affect microbial activity.

  In-situ chemical oxidation involves the injection of chemical oxidants into the sediment to break down contaminants. Chemical oxidation can be effective for organic contaminants like certain petroleum hydrocarbons or chlorinated solvents. In-situ chemical oxidation use for sediment remediation has been more limited, but studies and trials have shown its potential. The effectiveness of in-situ chemical oxidation for sediments can depend on the type of oxidant used, the nature of the contaminants, and the characteristics of the sediment.

  Electrokinetic remediation is a relatively newer and less established research or pilot-scale technique. The method shows promise for certain types of contaminants and conditions, but its use has challenges and limitations. For example, applying it in heterogeneous sediments can be more difficult and requires significant energy. This method uses a low-intensity electric field to move charged particles, including certain types of contaminants, in the sediment. The method is valuable for moving contaminants toward treatment zones within the sediment.

  While these techniques have potential, more research and field testing is needed to understand their effectiveness and feasibility for different types of sediment sites.

Guiding the Decision-Making

After assessing all remedial alternatives, risk factors guide the decision-making process. This process will aid in selecting an appropriate remedial action or a combination of actions that can effectively mitigate risks posed to human health and ecological receptors.

The achievement and long-term maintenance of predefined chemical or biological cleanup levels typically characterize a truly effective sediment remedy. All relevant risks should be mitigated to acceptable levels, considering the intended future uses of the water body and the objectives outlined in the ROD. However, due to substantial residual contamination post-remediation at some sites, or the inability to completely control all contamination sources to the water body, achieving sediment or biota levels that allow for unrestricted exposure and use may take years, if not decades. Therefore, evaluating several intermediate measures of remedy effectiveness at most sites is often suitable alongside the primary metric of long-term risk reduction.

To help ensure adequate baseline data for future comparisons with subsequent data sets, we should forecast the post-remediation monitoring requirements during the site characterization phase.

Moreover, devise monitoring plans to allow for comparison between actual results and the model predictions that underpinned the selection of the remedial approach. By the time remedial actions are in execution or a monitoring plan is written, there should be a significant amount of baseline site data gathered during the remedial investigation or site characterization phase. Examples are collecting samples to establish the type and scope of contamination, providing data to collate necessary information for risk assessment to human health and the environment, and evaluating the viability of different remedial alternatives. Contemplate the necessity for environmental monitoring and how the data will help to gauge performance relative to cleanup levels and RAOs.

The decision-making process that follows the assessment of all remedial alternatives is a critical step in sediment remediation. This process should be grounded in a thorough understanding of risk factors associated with the contaminated site. It should aim to select an appropriate remedial action or a mix of actions that effectively mitigates the risks.

Risk factors usually encompass the type, concentration, and distribution of contaminants, the characteristics of the sediment, the potential pathways of exposure to humans and ecological receptors, and the potential impacts on human health and the environment.

Once these risk factors are well understood, evaluate each remedial alternative based on its mitigation ability. The evaluation should consider several aspects, including:

- Effectiveness: How well can the remedial alternative reduce the risks to acceptable levels? It could involve considering the types of contaminants the alternative can treat, its effectiveness at reducing contaminant levels and risks, and its long-term reliability.

- Implementability: Is the remedial alternative technically feasible? Can it be implemented, given the site conditions and constraints?

- Cost: What are the remedial alternative's capital, operational, and long-term costs? Compare costs against the expected benefits or risk reduction.

- Time: How long will implementing the remedial alternative and achieving the desired risk reduction take?

- Sustainability: What are the environmental impacts of the remedial alternative itself? It could involve considering energy use, emissions, waste generation, and other factors.

In some cases, no single remedial alternative may be sufficient to mitigate the risks, and combining remedies is advantageous. For example, dredging could remove the most heavily contaminated sediments, followed by in-situ capping to isolate the remaining lower-level contamination and monitor to track the natural recovery processes.

The decision-making process aims to select a remedy or combination of remedies that best balances these considerations to achieve an effective, implementable, cost-effective, and sustainable reduction in risks to human health and the environment.

Community Acceptance

Throughout the remediation process, stakeholders should actively consider community issues to guarantee effective and inclusive decision-making and address the affected community's concerns.

Making human health and safety a primary concern is crucial. Engage with the community to comprehend health concerns and actively communicate the measures to mitigate risks throughout the remediation process. Clearly and accessibly convey information about the project, including its objectives, methodologies, and potential impacts. Additionally, offer educational resources to enhance community understanding and enable informed participation.

Identify and address any potential disruption in community resources, such as fishing areas, recreational spaces, or other natural amenities, by actively developing plans to restore or provide alternative access to these resources during and after the remediation process.

Open lines of communication should be maintained with the community, providing regular updates on the progress and outcomes of the remediation project and addressing any concerns or complaints promptly and transparently.

Engaging early, actively listening, and involving the community in decision-making can help build trust, improve outcomes, and foster a sense of shared responsibility.

Conclusion

Remediation efforts require careful planning and design to ensure their effectiveness and sustainability. Efforts include conducting comprehensive site assessments, characterizing the contamination extent and pathways, considering potential impacts on ecosystems and human health, and gaining community acceptance.

Engaging a team of qualified professionals, including environmental scientists, engineers, and remediation specialists, with expertise in contaminated sediment remediation is crucial. Their experience and knowledge contribute to effective project planning, execution, and monitoring.

Active monitoring and data collection is crucial throughout the remediation process. These activities enable evaluating the chosen strategy's effectiveness, identifying necessary adjustments, and ensuring compliance with environmental regulations. Adaptive management approaches allow modifying or refining the remediation strategy based on monitoring results and stakeholder feedback.

The utmost importance lies in choosing the appropriate remediation techniques; base the decision on site conditions, the specific contaminants present, and the desired remediation goals.

Ultimately, a multidisciplinary approach, collaboration among various stakeholders, adherence to environmental guidelines, and a commitment to long-term monitoring and management are imperative for achieving effective and sustainable sediment remediation outcomes.