

# Evaluating *the Effectiveness of* Contaminated-Sediment DREDGING



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**As the science of environmental dredging and sediment management changes, adaptive management strategies can help long-term remediation projects keep pace.**

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**W**ater bodies fed by current or former industrial, agricultural, or mining areas frequently contain contaminated sediments, and throughout the U.S., miles of riverbeds and vast areas of harbors, lakes, and estuaries are affected (1, 2). Contaminants in sediments can have direct toxic effects on organisms and can accumulate in organisms consumed by humans. The presence of sediment contamination also limits the productive use of a water body and its associated economic benefits (e.g., Ref. 3). The Hudson River in New York State is probably the best-known example of a large river system with widespread sediment contamination. The proposed cleanup addresses the upper 40 miles of river where 2.65 million cubic yards are slated to be removed (4). Cleanup has yet to begin, although dredging of 265,000 cubic yards

from 94 acres is planned for the first year of dredging (5). The Hudson River is just one of many large river systems undergoing investigation or remediation. Other large rivers include the lower Passaic River in New Jersey, the Kalamazoo and Tittabawassee rivers in Michigan, the Lower Fox River in Wisconsin, the upper Columbia River and Duwamish River in Washington State, and the Housatonic River in Massachusetts and Connecticut.

The U.S. EPA is charged with protecting public health and the environment. Superfund is one of the primary authorities used by EPA to identify contaminated sites and ensure their cleanup. After EPA places a contaminated site on the National Priorities List (ostensibly designating a Superfund site), the pathway toward cleanup typically requires describing the magnitude, extent, and distribution of contaminants; estimating the risk to environmental receptors or human health; and determining risk-based cleanup concentrations of contaminants. EPA compares a number of remedial options on the basis of multiple criteria before selecting a remediation to implement. A detailed remedial plan is then selected in the Record of Decision.

Determining how to remediate contaminated sediments is a complex and often controversial undertaking. There are several options for dealing with the risk posed by contaminated sediments. These include monitoring to establish that natural processes are reducing chemical exposures and concentrations in sediments, isolating the contaminated sediments in situ by capping them, adding amendments (e.g., organic carbon) to decrease contaminant bioavailability, or removing the contaminated sediments by dredging or by draining and excavating (6). The decision of whether to remove contaminated sediments is particularly controversial. Superfund operates under a "polluter pays" principle, and of the above options, dredging is typically the most complex and expensive to implement. As such, it is rarely a desirable option for responsible parties at a contaminated site. There are also questions regarding the efficacy of the approach and the degree to which dredging results in reduced risk to human health and the environment (e.g., Refs. 7-9). Dredging removes large amounts of contaminated sediments from the aquatic environment; however, this is not always accompanied by a corresponding reduction in risk.

### **The NRC review of dredging effectiveness**

In 2006, Congress directed EPA to ask the National Research Council (NRC) to conduct an independent review of the effectiveness of dredging at Superfund megasites. Megasites are the most expensive, and typically the largest, of the Superfund sites and are defined as those with remediation costs exceeding or expected to exceed \$50 million. The NRC convened a panel of 14 experts to evaluate the degree to which

dredging results in anticipated risk-reduction benefits in the expected time frame. The committee was asked to consider aspects of dredging such as the short- and long-term changes in contaminant transport and in ecological effects. The committee was also charged with evaluating monitoring strategies and whether those strategies are sufficient to inform assessments of effectiveness. Overall, the committee was charged to develop recommendations to facilitate decision-making that is scientifically based and timely for megasites but not to recommend particular remedial strategies at specific sites.

The NRC report (10) was published in late 2007. This article summarizes many of the issues discussed in the report along with several of the report's findings and recommendations; however, only the report itself fully represents the committee's consensus conclusions and recommendations. The NRC report contains much greater detail on particular sediment dredging projects than can be relayed in this format; readers are referred to the full NRC report for additional detail.

### **Challenges in the effective remediation of sediments**

Selecting and implementing a remedial option to manage the risk of contaminated sediments are challenging for a number of reasons.

***Difficulties in site characterization and in estimating the effects of remediation.*** Documenting the amount of contaminated sediments at a site is difficult because typically the thickness and horizontal distribution of contamination are uneven and sediment sampling techniques might not present a full picture of existing contamination. Encountering debris, rocks and boulders, hardpan, and obstacles such as piers and pilings creates operational difficulties when characterization and removal of contaminated sediment deposits are attempted. Site conditions greatly influence potential negative effects from dredging. These effects can involve contaminant releases from disturbed sediments into the overlying water, resuspension and transport of contaminated sediments during operations, and residual contaminated sediments that remain following operations (11). Successful sediment remediation is possible; however, the difficulties of accurate site characterization, possible adverse effects from dredging, and the remediation technologies' inherent limitations need to be recognized during remedy selection and explicitly considered in expectations of risk reduction.

***Difficulties in predicting the future transport and effects of contaminated sediment.*** An important consideration in determining the appropriateness of removing contaminated sediments is the extent to which the sediments are likely to be transported in the future. The dynamic nature of aquatic environments, especially over long peri-

ods (tens to hundreds of years), complicates considerations of whether a sediment deposit is stable (i.e., unlikely to be eroded and transported by river channel migration, floods, storms, or other severe events). Many contaminants of concern in sediments are legacy contaminants (e.g., PCBs, DDT, or dioxins and furans) released to the environment decades ago, and they can be buried beneath layers of less contaminated sediments (12, 13). Contaminants buried below the biologically active zone—the upper layers of sediment where organisms live or interact—are neither accessible nor available to sediment- and water-dwelling organisms. Disrupting sediment beds to remove contaminated sediments can expose aquatic receptors to otherwise inaccessible contaminants. If exposure and transport of buried contaminants during severe events are likely to increase risk, the removal (even with associated negative consequences) can effectively reduce risk.



Large pieces of trash, such as this junked automobile, hamper dredging operations.

**Difficulties in measuring the effect of a remediation.** In large areas where entire river basins or harbors are contaminated, measurable changes in environmental conditions, such as contaminant concentrations in water and fish or transport of contaminants, might not occur after remediation of an isolated area. Other ongoing sources of contaminants, including urban runoff and unremediated sediments, might be contributing to adverse effects and thus hamper the ability to achieve and demonstrate remedial effectiveness. Similarly, ongoing declines in environmental contaminants at the basin-wide level (e.g., natural burial processes reducing exposure to fish or reductions in point sources) can lead to the interpretation that cleanups are having a beneficial effect even when those contaminant declines are unrelated to the remediation. Hence, there is a great need for developing an understanding of contaminant source areas, the spatial and temporal dynamics of contaminants, and the pathways that link them to biota. This understanding is generally referred to as the conceptual site model (6, 14), which is often supported by more specific hydrodynamic, sediment transport, and contaminant mass balance models. Monitoring the effectiveness of the remedy makes it possible to test and refine the conceptual site model.

## Evaluating the effectiveness of dredging

Agreeing with recent guidance and reports on sediment remediation, the NRC committee emphasizes that remediation decision-making should be conducted on the basis of risk reduction (6, 9, 15, 16). Optimally, remediation is effective when risk—as measured through a combination of measures such as contaminant concentration, bioavailability, bioaccumulation, toxicity, and population effects—declines at or faster than the predicted rate over the spatial area encompassed by those predictions and when this decline would be greater than risk reduction occurring through natural processes, such as burial or degradation.

The committee evaluated the experiences at 26 dredging projects to determine what can and cannot be achieved with dredging. These sites ranged widely in geographic and physical environment, the volume of sediments removed, and the projects' cleanup levels (e.g., a specified contaminant concentration in sediment) and long-term remedial objectives (e.g., to reduce risk to acceptable levels). Extensive detail, including site characteristics and a summary of the extent to which the dredging projects achieved their specified cleanup levels following implementation and their long-term objectives, is provided in the report and its appendixes (10).

Many sites possessed data on cleanup levels measured shortly after implementation. However, at several sites cleanup levels were based simply on mass or volume of sediment removed and hence not directly related to risk. The committee's analysis indicates that dredging can be effective for removal of mass (e.g., dredging to a specified depth), but mass removal alone may not achieve risk-based goals. At sites where data on attaining contaminant-specific cleanup levels existed, there were systematic difficulties in achieving those levels. The analysis of pre-dredging and post-dredging contaminant concentrations in surface sediments indicates a wide range of outcomes: some sites showed increases, some showed no changes, and some showed decreases in contaminant concentrations (although cleanup levels may not have been reached). The most difficulties were associated with sites that contained significant debris, an inability to over-dredge into clean material, or other site conditions that hindered dredging. Capping to cover surface sediments or backfilling to dilute them with clean material after dredging was often necessary to achieve cleanup levels.

However, it became clear that detailed evaluations of long-term risk reduction had generally not taken place. For example, at some dredging sites, only the volume of sediment or the depth of dredging was monitored to establish the success of the operation. At others, no biologic indicators such as toxicity or bioaccumulation of contaminants were evaluated. In general, the committee could not establish whether dredging alone is capable of long-term risk reduction, because monitoring at most sites did not include all the measures necessary to evaluate risk over time, dredging may have occurred in concert with other remedies or natural processes

that affect risk, or insufficient time had passed to evaluate long-term risk reduction.

On the basis of existing data, the committee was able to draw several conclusions regarding the short-term effects of dredging. Particularly useful in this regard were some heavily monitored pilot studies (e.g., the 2005 pilot study conducted on the Grasse River in New York State). Monitoring data show that dredging can have short-term adverse effects, including increased contaminant concentrations in the water, increased contaminant concentrations in the tissues of caged fish adjacent to the dredging activity, and short-term increases in tissue contaminant concentrations in other resident biota. However, monitoring for those effects was not conducted at many sites.

Overall, the committee concluded that dredging is one of the few options available for the remediation of contaminated sediment and that it should be considered, including in combination with other options, to manage the risks that the contaminated sediments pose. The need to remove contaminated sediments can be particularly acute at sites where navigational channels need to be maintained or where buried contaminated sediment deposits are likely to be subjected to erosion and transport from high flows or changes in hydrologic conditions. But the negative consequences of dredging and the potential for ineffective application, especially where site conditions may complicate or hinder dredging, need to be considered in selecting the most appropriate remedy for the site.

### **The necessity of monitoring**

Tremendous amounts of effort and resources go into establishing which remedial actions will take place at a site, yet measures to establish whether the remediation achieved its intended effect are often neglected. Current monitoring techniques are generally adequate for describing risk. However, they have not been adequately applied at many Superfund sites to describe whether long-term risk-reduction objectives have been achieved. Environmental monitoring is the only way to evaluate the success of a remedy in reducing risk and is therefore an essential part of the remedy—it is not an extra, “add-on” activity.

Unfortunately, parties responsible for managing the site may perceive several reasons to select suboptimal monitoring plans. Monitoring decisions may be influenced by financial, jurisdictional, or political interests. Cleanup negotiations between regulators and responsible parties can be contentious, and agreements on the scope of cleanups often result from a long and difficult process. The scope of post-remedial monitoring may be established during those negotiations. Parties have few incentives to establish whether a chosen remedial action had its intended effect. When regulators and responsible parties perceive that they might have something to lose and nothing to gain in a robust post-remediation monitoring program, the result can be limited post-remediation confirmation sampling, or none at all.

The NRC report emphasizes two requirements for effective monitoring. First, the remedy requires characterization of pre-remedial trends for comparison to post-remediation trends; the time span of pre- and post-remedial sampling needs to be sufficient to capture the timescale of recovery processes. Second, proper reference sites and conditions should be specified and monitored; this is necessary to estimate changes due to the remediation instead of processes occurring throughout the basin. These monitoring activities require consistent sampling over time (same location, sample, or organism characteristics, time of year, and method), sufficient sample sizes, and measurements of properties directly linked to the desired risk reduction. Otherwise, if the monitoring program is unable to link the remedial activity to the desired end state (i.e., linking exposures to effects at the site), that monitoring is not useful to the site's decision makers (box on next page). Ultimately, a site's remedial action objectives and conceptual site model should be the basis for determining the most appropriate indicators to measure success.

The report emphasizes that EPA needs to do a better job in establishing whether a remedy has been effective in reducing risk. This need includes ensuring that monitoring is being conducted and that the monitoring is capable of determining whether remedial goals have been achieved. These monitoring data should be compiled electronically and made publicly available so that evaluations of remedial efficacy can be verified independently.

### **Improving decision-making**

A major challenge to decision-makers is the uncertainty about whether, and how well, a remedy will work. Pilot testing and associated environmental monitoring are used to test the performance of a technology or approach, to understand the factors affecting its performance, and to provide information on how, if necessary, the remedy should be adapted to achieve desired goals. In this way, the information from pilot tests and monitoring becomes a key component of the remedy selection, design, and implementation process. The use of a formal, structured process of selecting a management action, monitoring the ability of that action to achieve specified objectives, and applying lessons from that process to optimize a management action is generally referred to as adaptive management (e.g., Refs. 15 and 17-21).

Adaptive management is not the typical process used in Superfund site decision-making. The current Superfund approach typically establishes a single path to remediation in the Record of Decision on the basis of predictions of a remedy's ability to achieve remedial goals. At large, complex sediment sites, which may take years or even decades to remediate, the current Superfund process is not realistic, because of the inherent uncertainties in understanding site conditions and predicting the effects of remediation. At these sites, changes will be needed whether in response to new knowledge about site conditions, to changes in site conditions, or to ad-

vances in remediation technology. Regulators and others will need to be able to adapt continually to evolving conditions and environmental responses that cannot be foreseen at the time of remedy selection. Instituting an adaptive management process from the outset recognizes the uncertainty inherent in predicting remedial results and allows adaptation of the remedy on the basis of site experience to optimize progress toward attaining remedial goals. In this way, adaptive management does not postpone action but rather supports action in the face of limited scientific knowledge and the complexities and unpredictable behavior of large ecosystems (20).

## Use of appropriate indicators to measure remedial effectiveness

Contaminant concentrations in captured fish are sometimes used to indicate the effect of a remediation. The selected fish species and age class are critical. Migratory fish or fish that have a wide home range and spend a small amount of time in areas to be remediated cannot be expected to indicate the full effect of remediation, because contaminant concentrations in these fish represent exposure over their entire range, not just over the remediated area. Because people often target these larger, highly mobile fish while fishing, they are useful indicators of contaminant exposures via consumption. However, in the described scenario, contaminant concentrations in fish are less relevant to the question of whether a remediation was effective in reducing risk. Fish species that have a small home range, benthic macroinvertebrates, caged organisms, or in situ samplers, such as semipermeable-membrane devices, would better indicate the effect of the remediation. It is possible to link the exposure of wide-ranging fish to the remediated area through modeling, but predictions of contaminant concentrations in fish tissue are more uncertain than measurement of contaminant concentrations in fish of known, small ranges.

In selecting a remedy at a site and in evaluating the effectiveness of that remedy, the full range of positive and negative effects associated with a remedy need to be considered to quantify the net risk reduction associated with a remedial option (6, 22). Effects include possible increases in risk to the spectrum of human and environmental receptors that might be caused by remedy implementation and the treatment, storage, transport, and disposal of dredged sediment as well as risk reduction from removal of contaminated sediments from aquatic systems. To compare the potential effects of remedial options as accurately as possible, the uncertainty about the estimates of responses to remediation should be recognized and quantified to the extent warranted to optimize decision-making.

However, establishing a transparent, objective, and reproducible system for conducting such comparisons and evaluations is not straightforward. Some potential effects and their uncertainty will remain difficult to quantify and compare accurately (e.g., the impact of a large dredging project on quality-of-life issues, such as noise or light pollution, or potential psychological consequences from not implementing a removal remedy, if community members perceive that an unmitigated threat to

human health exists in their environment). Other "implementation risks" to worker and community health and safety can presumably be estimated, such as equipment failures and accident rates associated with an active remediation, but are given little consideration in EPA's feasibility studies at Superfund sites (22). Establishing which potential risks and effects should be considered in a net risk-reduction framework and how to enumerate and compare them remains a challenge for EPA to address.

The science of environmental dredging and sediment management is continually changing. New information is being gathered, research to determine the effects and effectiveness of dredging is being conducted, and technologies and performance continue to evolve and improve. That process will continue for the foreseeable future. In many ways, we are at the beginning, not the end, of the learning curve of implementing efficient and effective remediation of contaminated sediments. Sustained effort from practitioners and greater attention from policy makers will be required to advance the field, not only to improve sediment management but also ultimately to reduce risks and restore contaminated waterways to beneficial use.

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