Deciding About Sediment Remediation

A step-by-step guide to making the decisions

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Introduction

Sediment remediation has come to the Great Lakes Basin. In the basin there are 43 Areas of Concern (AOCs) where contaminated sediments have contributed to serious environmental degradation (Figure 1). In the 12 years prior to 1999, 17 AOCs had 31 sediment remediation projects completed or underway at a cost of $600 million (Zarull 1999). Most of these projects were the result of regulatory actions in which a specified mass of contaminated sediment had to be removed. For up-to-date information about specific AOCs, see the "sources of information" section.

This booklet is written for persons planning resolution of sediment remediation (clean-up) issues. This audience includes people who are not technically trained, as well as scientists and engineers. These are people who make, or influence, decisions to cover, or clean up contaminated sediments, or to let natural recovery occur. The information in this booklet will be helpful wherever sediment remediation is being considered.

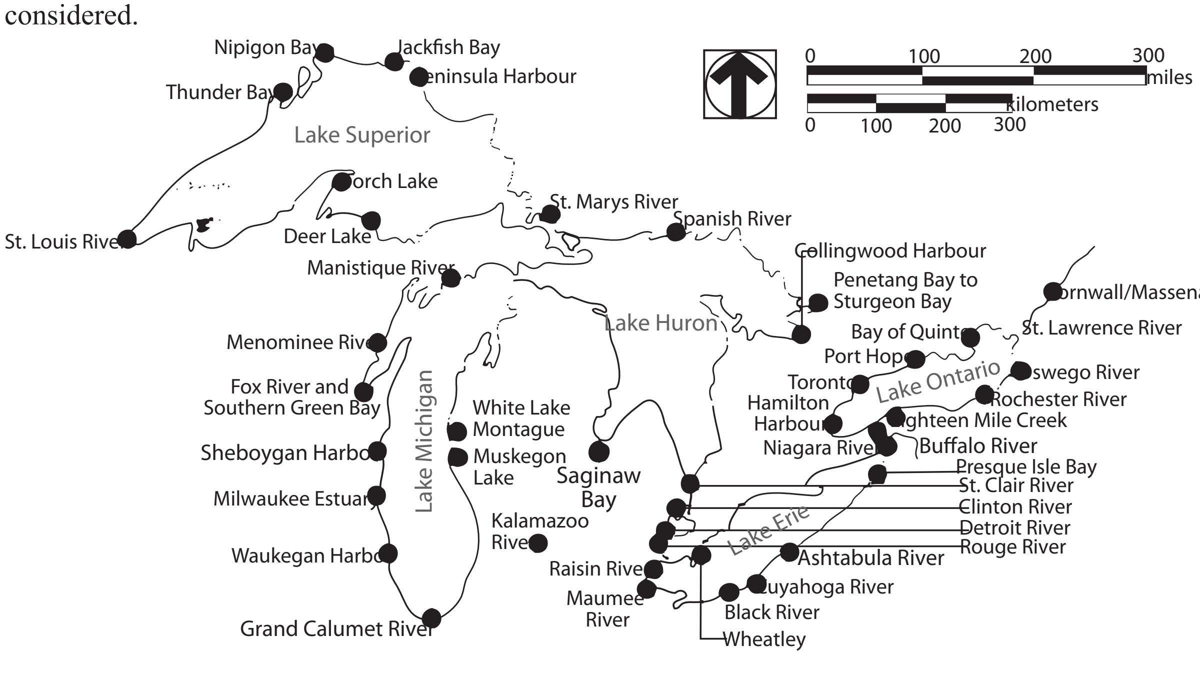

Figure 1. Great Lakes Areas of Concern. Source: USEPA 1994d.

This booklet moves step by step through a sequence of decisions needed to determine whether or not, and how, to clean up contaminated sediments in particular areas. The sequence combines risk management and sediment management. The Sources of Information section near the end of the booklet lists many of the other information resources needed to make these decisions.

Disclaimer

This booklet does not describe work needed to do environmental impact studies or natural resource damage assessments, nor does it describe work needed to satisfy regulatory requirements. The booklet does not address health and safety risks and precautions with respect to any mentioned materials, conditions, procedures, technologies, or equipment. An earlier draft of this booklet was peer-reviewed and the information provided is believed to be reliable and accurate. However, this booklet is provided without express or implied warranties of any kind, including (but not limited to) warranties of accuracy, completeness, or latest state-of-the-art of the information in the booklet. The booklet is not an exhaustive treatment of the subject. There is no explicit or implied endorsement or recommendation of companies, products, or processes mentioned in the booklet.

Much of the booklet summarizes work done by faculty, staff, and students at the University of Wisconsin (Madison and Green Bay), the University of Windsor (Ontario), and the University of Minnesota (Duluth) on a joint project in 1995-1997. Their task was to create a decision framework to help resolve the issue of whether or not to clean up contaminated sediment deposits in Great Lakes AOC. Funding of that project came from the Great Lakes Protection Fund (GLPF AOC594-1905), the United States Environmental Protection Agency's (USEPA) Great Lakes National Program Office (GLNPO GL985062-01-0) and the University of Wisconsin Sea Grant Institute (federal grant NA46RG0481). In the booklet, this work is called the GLPF project, in recognition of the project's major funding source. The GLPF project complemented other work done in GLNPO's Assessment and Remediation of Contaminated Sediments (ARCS) program.

What is a "Contaminated Sediment?"

A National Research Council (NRC) committee defined contaminated sediment as "a sediment containing chemical concentrations that pose a known or suspected threat to the environment or human health" (NRC 1989). A more recent NRC committee pointed out that there is no universally accepted definition of "contaminated" sediment (NRC 1997, USEPA 1994b). The latter committee assumed that various regulatory agencies (local to international) use both qualitative and quantitative definitions of "contaminated" sediments and also use methods that allow them to know when contamination exists and is (or is not) significant.

Toxic sediments is the term of choice in this booklet for several reasons: (a) almost all sediments are contaminated to some extent by diffuse sources of pollution, including widespread atmospheric deposition of pollutants, (b) only *toxic* sediments seem to justify the high costs of remediation, and (c) *toxic* is a shorter term than *contaminated* for sediments of concern. In this term of choice, *toxic* fits the NRC (1989) definition of "chemical concentrations that pose a known or suspected threat to the environment or human health" sufficient to justify consideration of remediation.

What is a Decision Framework?

A decision framework is a series of logical steps used in exploring remediation options before committing to any particular option, or set of options. Such a framework is very important in management of toxic sediments, before, during, and after remediation actions are taken. An example of such a decision framework, developed on the GLPF project, was described by Harris (1997). These frameworks are expressions of a systems engineering approach that is essential in planning the complex technological process of sediment remediation (NRC 1997, USEPA 1994b). A decision tree is a visual representation of a decision framework (Figure 2).

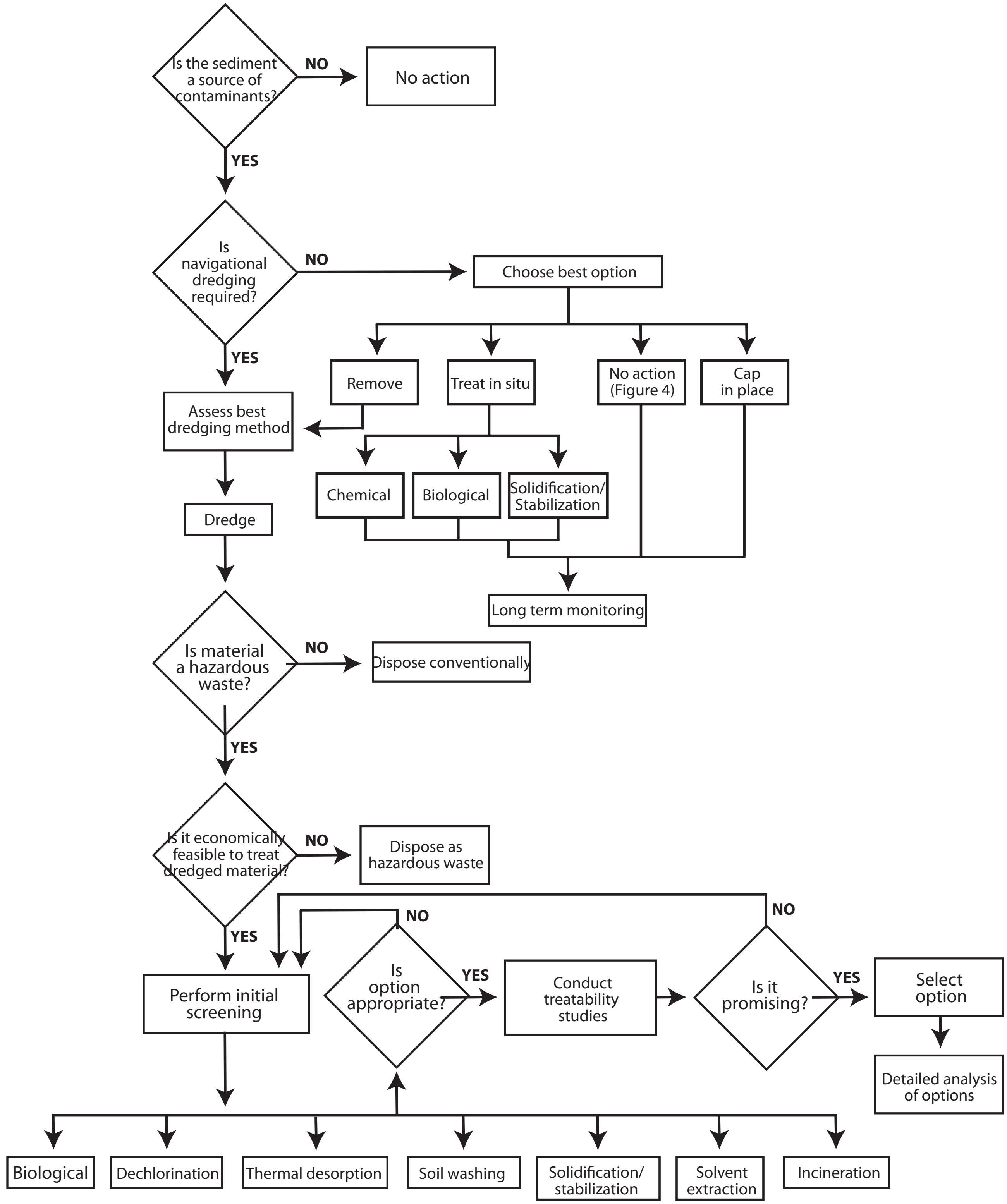

Figure 2. Applicable remedial options. Source: USEPA 1993.

Logical Steps

In this booklet, a simple, linear form of a decision framework is used to communicate the step-by-step process of resolving sediment clean-up issues. This framework is modified from that used in Selecting Remediation Techniques for Contaminated Sediment (USEPA 1993) and consists of the following steps:

1. Monitoring. Periodic sampling and testing of sediments, fish, and other aquatic organisms leads to the discovery of a sediment contamination problem. Discovery of the problem leads to assessment. Monitoring also plays a role in evaluating the adequacy of Steps 3 through 7.
2. Assessment. Assessment is evaluation of the significance of the sediment problem. If the sediment problem is not significant, "no action" is a logical next step. If the sediment problem is significant, some form of remedial action is a logical next step. Assessment reappears in Step 5 of this simple decision sequence if "remedial action" is required.
3. No Action. Factors leading toward a "no action" decision include evidence of: (a) biodegradation of the contaminants in the sediment and/or (b) clean, natural sediment depositing permanently and quickly over the toxic sediment.
4. Prevention. The first remedial action toward cleanup is prevention of additional contamination of sediments. Prevention actions may be taken at local, and more distant, sources of contamination.
5. Remediation (including Treatment). Remediation is the improvement of the environment where the toxic sediments are located. Remediation requires a new, detailed site investigation and reassessment in order to learn exactly how much toxic sediment needs to be remediated and precisely where it is. Remediation includes: (a) capping a toxic sediment deposit with an adequate, clean cover layer, (b) removal of toxic sediment, and (c) treatment. Treatment includes any processing to alter sediment in, or removed from, a water body. Treatment can include: (a) treatment of sediments in place and/or (b) volume reduction (soil washing or size classification) to economize on the mass of sediment that requires additional processing. Treatment can also include dewatering of removed sediment for processing or for ultimate disposal.
6. Disposal. Disposal is the final step in this simple framework, and it is usually the most controversial step in remediation. There may be a dozen possible disposal options. However, regulations, economics, and circumstances may severely limit the choices to those that are often quite unpopular.
7. Reuse (The editor's added step not shown in Figure 2). Reuse of the products from toxic sediment treatment. Candidates for beneficial reuse of material include the clean fractions of sediment separated from toxic sediment fractions as well as the nontoxic products of treatment processes.

Steps to Manage Risk

Risk management is a necessary element in resolving toxic sediment issues. Risk management requires considering problems *and* opportunities. Problems associated with toxic sediments are highly visible because they drive remediation investigations. Sediment remediation decision steps should not be limited to assessing the problems. If a problem is an economically depressed fishery because of toxic sediment contamination and published advisories warning against consumption, opportunities include economic recovery and economic expansion as a result of cleaning up the contamination and abolishing the cautionary advisories. "Benefits" are another term for opportunities. Opportunities associated with remediation are less visible, in part, because of little experience with the long-term consequences of sediment remediation.

Risk management is gaining awareness and importance in coping with toxic sediments.

> "A framework [is] necessary to provide a consistent structure to assess the risks from PCB contamination and the risks associated with the various technologies and options that might be used to clean up a site. The framework should be risk-based and applicable to a variety of sites, where risks can range from obvious and short term to less evident and decades long…. Any decision regarding the specific choice of a risk management strategy for a contaminated sediment site must be based on careful consideration of the advantages and disadvantages of available options and a balancing of the various risks, costs, and benefits associated with each option." (NRC Committee on Remediation of PCB-Contaminated Sediments. NRC 2001, p. 53)

Risk management is a systematic process with the purpose of minimizing the adverse consequences of risk. One of the risks to any organization that discharges waste into receiving waters is a responsibility for outcomes traceable to toxic byproducts contained in the waste. In such organizations, risk management begins with toxicity screening of components used in manufacturing and processing, followed by source controls within the plant and actions to reduce or eliminate future liability for toxic waste that was discharged to receiving waters prior to the elimination of toxic sources.

Risk management is vital to a diligent evaluation of alternatives in coping with a toxic sediment situation, to the selection and implementation of a "solution," and the evaluation of the success of the solution to the problem. Almost all risk management processes contain generic steps as listed by Leuck (2001). Risk managers may use different terms and procedures in their work. The general steps of risk management can be translated into a toxic sediment context as follows:

1. Specify the problems that toxic sediments at a site have caused for the environment, people, organizations and communities and identify the opportunities presented if the toxic sediments are cleaned up.
2. Identify and assess the environmental pathways that expose people and the environment to toxics in sediments located at a site. Identify and assess the exposure to environmental and financial risk of organizations and communities where the toxic sediments are located.
3. Examine and propose alternative ways to eliminate or limit the exposures of the environment, people, organizations, and communities to toxic sediments at a site.
4. Evaluate potential environmental, social, and economic effects of remediation options.
5. Compare alternative sediment remediation plans.
6. Select and implement plan(s).

7. Monitor the effectiveness of implemented plan(s).

8. Change implemented plan(s) as needed to keep risk within preselected limits. The results of monitoring must be used to manage risks associated with toxic sediments, products, and byproducts of remediation actions.

Risk management needs to be integrated within any decision framework used to resolve issues of toxic sediments. The risk management approach to a toxic sediment problem reappears in following sections of this booklet to demonstrate the need in each aspect of remediation.

The risk management process requires the repeated involvement of all "interested" and "affected" parties at every step throughout the cycle (NRC 2001). This circular framework is shown in Figure 3 and illustrates several very important points. First, risk management does not end when a particular sediment clean-up project is completed, unless the toxic compounds in the sediment are rendered harmless. Second, involvement of all interested and affected parties throughout the remediation decision-making process is probably critical to public acceptance of a remediation project.

Risk management practices can also be borrowed from other efforts to cope with uncertainty in the geologic environment (ASCE 1996) and in the management of projects (The Institution of Civil Engineers 1998). See the "Sources of Information" section at the back of this handbook.

Figure 3. A risk management process cycle. Source: NRC 2001

Implicit Goals

Several goals in any effort to clean up toxic sediments are commonly assumed and unstated (such as "effective remediation"), or are believed to be unrealistic and, therefore, are not stated (such as "cost-effective remediation").

1. <u>Effective Remediation</u>. Effective remediation is an obvious, implicit goal of any effort to resolve toxic sediment problems. This goal is important because of the presumably high stakes in either not doing remediation or doing effective

remediation. Ineffective remediation is a waste of time and funds. The importance of effective remediation justifies substantial efforts to be made in "monitoring," "mass balance modeling," and "assessment."

2. Cost-Effective Remediation. Cost-effective remediation is a not-so-obvious, implicit goal of steps to undertake remediation. This goal becomes attainable as published (or personal) experience with remediation provides information on economies of scale and optimization of remediation activities and processes. The concept of "economy" was a stranger to soil and sediment remediation, and early remediation projects were marked by huge cost overruns (Keillor 1993).

Monitoring

Monitoring is essential to any sediment remediation project carried out with diligence. Monitoring has at least three basic, ongoing purposes:

- » To provide an early indication of environmental problems
- » To evaluate the effectiveness of management actions
- » To guard against adverse effects from products of remediation

Monitoring is important in evaluating the effectiveness of any steps taken to manage contaminated sediments. Each remediation option has a set of monitoring requirements;
some may be so substantial as to alter the selection of a remediation option.

Monitoring is an essential ongoing activity to watch over the selected disposition of toxic sediments. This activity may be monitoring the continuing integrity of confined sediment disposal sites, the continuing integrity of toxic sediment deposits capped in place, or the progress of natural recovery in toxic sediment deposits.

Great Lakes states and the Province of Ontario have historically relied on monitoring of the Great Lakes ecosystem to provide an early warning of environmental degradation and adverse health effects. The International Joint Commission's designation of Great Lakes AOC was based on monitoring observations of environmental degradation and human health risks that are significant enough to justify taking action. In many AOCs, these risks are associated with toxic sediments.

Federal, provincial, state, and tribal government agencies have responsibilities for monitoring contaminants in water bodies in North America, including contaminants in organisms and in sediments. These agencies have worked out monitoring strategies, sampling techniques, and testing methods that are beyond the scope of this booklet.

Assessing the Problems and Opportunities

An important step in dealing with a potential contaminated sediment problem is to assess the magnitude and significance of the problems and opportunities. Assessment of contaminated sediment problems and opportunities quickly becomes complex. Opportunities are defined and identified in the section on risk management. Assessment questions about problems include:

- » How contaminated are the sediments?
- » What are the areas and volumes of toxic sediments?
- » Are the toxic sediment deposits stable?
- » What are the likely fate and effects of these toxic sediments on the aquatic ecosystem?
- » What is the likelihood of the toxic sediments being resuspended and transported?
- » What are the likely benefits of sediment cleanup?
- » When can the benefits be realized?
- » What is the likely cost of sediment cleanup?
- » Who is going to pay for the cleanup?

The ARCS *Assessment Guidance Document* (USEPA 1994a) was intended for use in the earliest stages of assessing the scope or magnitude of a toxic sediment problem. That report guides the user through the methods used in sediment sampling, sediment toxicity testing, and quality assurance testing. It also describes the assessment of benthic community structure, and surveying for fish tumors. The report shows the process of sediment classification (or ranking) for severity of toxicity, based on sampling, surveying, and testing results.

Assessment begins with an evaluation of the significance of particular toxic sediments and whether or not any actions need to be taken. Assessment becomes an aspect of risk management and a partner to monitoring on an ongoing basis after a sediment remediation decision is taken because of the inherent risks to human and ecosystem health from toxic sediments.

Sediment Characterization

Adequate sediment characterization is vital in making sound decisions about sediment cleanup. Inadequate sediment characterization translates into faulty cleanup plans and wasted expenditures. Adequate characterization should be sought for the sake of effectiveness and economy. Characterization of sediments includes the following evaluations:

- » Identification of physical and chemical properties.
- » Identification of the toxicity of the sediments to aquatic organisms and humans.
- » Determination of toxic sediment mobility.
- » Determination of dredgeability.
- » Determination of the treatability of the sediments, both in situ (in place) and ex situ (removed).

1. <u>Initial Sediment Characterization</u>. Initial characterization needs to be sufficient to determine the significance of a contaminated sediment problem and to decide if “no action,” “pollution prevention,” or “remediation” steps are to be taken. The thoroughness of sediment characterization should match the thoroughness of the site investigation.
2. <u>Detailed Sediment Characterization</u>. Detailed sediment characterization is a needed complement to precision site investigation for “remediation” options. Detailed

characterization may also be needed to estimate the risks of choosing the "no action." The costs of detailed analysis may be justified by the savings from avoiding the unnecessary remediation of clean sediments.

Sometimes visual or inexpensive tests can be used to identify toxic chemicals and boundaries of toxic sediment deposits. In assessing sediment contamination in Hamilton Harbor, Ontario, successful surrogate tests for polyaromatic hydrocarbons (PAHs) helped keep the cost of analyzing 800 samples down to $30 per sample (Murphy 1994). That average cost per sample was a fraction of the sample analysis costs cited by others, including:

a) $500 - $1,500 per sample for in-house testing in a federal lab (Murphy 1994)
b)$800 per sample costs for chemical testing of Geulhaven sediments in the Netherlands (van Oostrum 1992)
c)$1,944 - $7,080 per sample testing costs for a small set of 25 sediment samples (Ross 1993)

Site Investigations

If some actions are considered where toxic sediments are found, there is a need for follow-up investigation(s).

1. Preliminary Site Investigation. A preliminary site investigation needs to be adequate to determine the significance of a contaminated sediment problem and to decide if "no action," "pollution prevention," and/or "remediation" options are to be taken. The thoroughness of preliminary site investigation should match the requirements for any mass balance modeling and simulation done to determine a future course of action for dealing with a toxic sediment site.
2. Precision Site Investigation. From the early days of sediment remediation, the inadequacies of site investigations translated into unnecessary extra costs, and the need for adequate site investigations was recognized.

> "All borings are very expensive, but those which cost the most are those which were not done!" -Ottmann and Lahuec (1972), cited by Herbich (1992).
>
> "Soil surveys and especially sample analysis for contracts in polluted sediments should be very intensive in view of the often erratic distribution of the pollutants. For normal dredging contracts, soil survey and testing takes less than one percent of the dredging cost. For contracts in heavily polluted material these costs might be well above 10 to 30 percent of the dredging cost." - Volbeda and Bonte (1990).

The second statement, from authors with the Dutch dredging firm, HAM bv, was based on experience in removing toxic sediments from the Geulhaven Basin in Rotterdam Harbor. This project (done in 1989) was one of the first sediment remediation projects in Europe. At that time, it was considered too expensive to spend more than $50,000 (U.S. dollars) on site investigations before dredging while budgeting and spending $5 million on dredging (van Oostrum 1992).

Sediment remediation by removal, treatment, and disposal is so expensive that it warrants detailed location of toxic sediments within sediment deposits, followed by precision removal of the toxic sediments.

Precision in site investigation is an exercise in remediation economy. The goal is to find all of the sediments that may need remediation and only remove the toxic sediments. Typically, information about the spatial variability of the contaminant concentrations and the sediment depth of contamination has to be collected at discrete points across the toxic sediment area with sediment cores. Over-depth dredging (excavating below and beyond the toxic sediment/clean sediment boundaries) is done to compensate for ignorance about the location of toxic sediments between the cores and errors in locating the dredge equipment on the toxic sediment deposit.

Ideally, remote sensing with a sub-bottom profiler could locate the targeted sediment deposit in three seamless dimensions. Unfortunately, at many sites the presence of gases within the sediments and the lack of a distinguishing acoustic signature hinders this gathering of continuous information along discrete transects.

Precision location and removal of toxic sediments is possible with accuracies of a few inches (few centimeters). Precision in survey and removal of sediments depends upon precision navigation. Trials conducted on Lake Ketelmeer, The Netherlands, indicated that the relative accuracy of the differential global positioning system (DGPS) used for mapping was 0.6 inches (1.5 centimeters) standard deviation in horizontal directions and plus or minus two inches (five centimeters) in the vertical direction (Arts et al. 1995). In these tests, a digital terrain model (DTM) was created to locate the boundary between the toxic sediments and the underlying clean sediments. This DTM had a standard deviation of about three inches (eight centimeters). When dredges were tested in the Ketelmeer, their depth measurement accuracy was less than one inch (two centimeters) and their steering accuracy was 0.4 inches (one centimeter). During full-scale remediation, contaminated sediments were located with an accuracy of four inches (10 centimeters) and all dredges were able to get within two inches (five centimeters) of the DTM boundary surface (Berg 2002).

Somewhere between the extremes of high sample number/high-cost site investigation and the costly, unnecessary removal, handling, and disposal of clean sediments that results from inadequate site investigation is a cost-effective optimum investigation. The key to determining the optimum level of investigation is to learn something about the spatial variability of the toxic sediments at a site.

Optimization of a site investigation can produce sizeable cost savings for expensive remediation efforts. For example, a simple exercise with Wisconsin Sea Grant's REMSIM site investigation module indicated that on a hypothetical remediation project with 93,300 cubic yards (78,000 square meters of toxic sediments averaging one meter thickness) to be removed, the project cost savings from optimized sediment investigation are likely to be 10 to 18 percent of non-optimized project costs as unit remediation costs increase from $19, to $77, to $154 per cubic yard ($25, $100, to $200 per cubic meter). Appropriate optimized core spacings are 48, 31, 24 yards (44 meters, 28 meters, and 22 meters), for those unit costs, respectively. The assumed base case site investigation has a more typical core spacing of 110 yards (100 meters).

Economical, but precise, site investigations will have several features:

» Use of inexpensive surrogates for expensive laboratory analysis wherever possible. After suitable testing and verification, visual inspection or simpler analysis (such as testing for organics) can reliably identify the location of targeted toxic chemicals in the sediments. Murphy (1994) developed some inexpensive analytical tests for toxic sediments in Hamilton Harbour, Ontario.

» Use of geostatistics to make an economical selection of coring sites to allow accurate interpolation of the contaminated sediment/clean sediment boundary location between coring sites. The appropriate choices of geostatistical methods depend upon understanding local sedimentation processes. The selection of sampling sites is based on a predetermined level of accuracy or certainty needed in locating the targeted sediments.

» Development of a pair of digital terrain models (DTMs) of the surface of the contaminated sediment layer and the surface of the interface between the contaminated sediment layer and the underlying clean sediment or substrate. In some cases, the contaminated sediment may form an isolated patch or set of patches within a sediment layer. These DTMs represent the location of targeted sediments within a predetermined level of confidence.

Risk Management

Risk management involves risk assessment and controlling identified risks in a way that ideally minimizes problems and maximizes opportunities.

1. <u>Specify Problems and Opportunities.</u> Risk assessment is an early step in evaluating the problems and opportunities of sediment cleanup. Problems associated with continued environmental exposure to toxic sediments have been well-documented. There is a large and growing body of literature about the toxic effects of contaminants on people and other living organisms exposed to contaminants found in sediments

   Less understood are the problems and opportunities for firms and communities that are attributable to the presence of toxic sediments: "toxic economics."

   The economic problems include:

   » Added health costs for people exposed to toxic chemicals
   » Loss in value of degraded parts of the environment
   » Depressed value of real estate
   » Barriers to development of property
   » Suppression of recreational business activity due to the proximity of sediments believed to be toxic
   » Economic effects of sediment cleanup on the parties who pay for cleanup

   Risk management requires identification of opportunities as well as problems associated with the long-term presence of toxic sediments. Opportunities are the "good things," the benefits that can come from cleaning up toxic sediments. They are the consequences of relief from the problems—the mirror image of problems.

Opportunities include:

- » Economic benefits for firms and consultants participating in planning and carrying out remediation activities
- » Improved environmental and human health
- » Freedom from future financial liability for sediment cleanup
- » Increased value of real estate and removal of barriers to sale of properties
- » Removal of barriers to development and redevelopment
- » Expansion of recreational activity

Generators of waste that cause toxic sediments are sometimes identified as *principal responsible parties* (PRPs). They may be firms, other organizations, or governments. There are opportunities as well as problems for PRPs who have toxic sediments to be managed.

2. Identify and Assess Exposures. The ARCS Risk Assessment and Modeling Overview Document (USEPA 1993) is a tool for early use in assessing the significance of a toxic sediment problem and for an assessment needed to look at risk to humans and other organisms by examining dose/exposure/effects from toxic sediments.

   The ARCS document does not deal with the probabilities of exposures from: (1) toxic sediment re-suspension, transport and re-deposition, (2) contaminant release during toxic sediment processing, (3) inadequacies in sediment processing, and (4) failures of containment structures. These risks involve the probabilistic nature of physical processes, machines, and constructed structures designed to withstand adverse natural processes. These risks are dealt with in the fields of reliability engineering, coastal engineering, and geotechnical engineering.

3. <u>Formulate Alternative Plans for Remediation</u>. The formulation of alternative plans for sediment cleanup requires an engineering feasibility and risk management study. Construction and maintenance requirements should be evaluated. Risks and challenges should be identified in each plan and used to anticipate governmental and public acceptability.

4. <u>Evaluate Potential Effects of Remediation</u>. One tool to use in gaining this understanding is mass balance modeling.

   Mass balance modeling of the fate and transport of toxic sediments in the lower Fox River and Green Bay of Wisconsin helped show some of the consequences of sediment contamination in the Fox River. This modeling was used with other models that estimated the movement of toxic substances through the aquatic food web. This combination of models was also used to estimate the potential effects of sediment cleanup on the concentrations of contaminants in fish eaten by humans over the decades following sediment cleanup.

5. <u>Compare Alternative Plans</u>. This step is also implicit under "choose best option" in Figure 2. The comparison of alternative plans (or options) includes (but is not limited to):

- Costs
- Site requirements
- Time required to remediate
- Length of time before results can be seen
- Examples of successful experience with alternative technology
- Regulatory requirements and their likely effects on remediation productivity in each plan
- Construction and maintenance challenges and requirements
- Probabilities of success in achieving clean-up goals
- Requirements for short-term and long-term monitoring and other risk management needs
- Timing and implementation of each option
- Acceptability of each option to client, community and regulators

NRC 2001 contains a whole chapter on involving interested and affected parties in considering sediment remediation from the beginning of the planning process, which is crucial to improving chances for acceptance of the selected plan.

6. Select and Implement Plan(s). As part of the assessment process, the step of "select and implement plan(s)" should be followed in a hypothetical, "what if?" sense for risk management purposes. All of the actions in Figure 2 need to be conceptually followed to the end before a plan, or plans, are selected.

   Promising treatment options and conventional and hazardous waste disposal have different monitoring considerations for the purposes of risk management. For example, some treatment options result in toxic byproducts. Other treatment options may have harmless byproducts.

   The selection step is the last step in the planning process, but deciding how and when to implement the plan is essential in adequately comparing alternative plans. An appropriate risk management strategy will make plan selection subject to review and alteration if new information about the site, new and successfully tested technology, etc., give sufficient cause for modification or cancellation of the selected plan (NRC 2001).

7. Monitor. Adequate consideration of short-term and long-term monitoring requirements is an essential part of assessing remediation alternatives. This step also becomes part of a cleanup implementation and risk management plan. Monitoring is probably the most neglected and often overlooked step in the plan-design-build sequence. Monitoring is an essential ongoing activity in sediment remediation because remediation is driven by the presence of long-lived, slow-to-degrade toxic chemicals in sediments.

   Risk management of remediated sediments doesn't end when cleanup is done, unless the contaminants have been altered to nontoxic forms. The active lives of many persistent toxic chemicals are probably at least as long as the life of the society in which the toxic chemicals were produced. The monitoring of persistent toxic byproducts of sediment remediation projects may consume funds in perpetuity.

8. Managing Risk in an Investment Life Cycle. Risk management of toxic sediments is commonly viewed within a narrow "problem" focus at a particular site. It is better to conduct such risk management within the broader context of an investment life cycle at the site. Equipment, plants, and firms have life cycles (generally in this order of longevity from least to greatest), as do living organisms. Sediment contamination occurs over the lifetimes of equipment and plants. The consequences of contamination and remediation extend over the lifetimes of firms, and beyond. One systematic approach to risk management over investment life cycles is *Risk Analysis and Management for Projects, or* RAMP (The Institution of Civil Engineers 1998).

A Useful Role for Simulation

Simulation (or modeling) is the practice of working through a process on paper, on a computer, or in the laboratory in order to maximize productivity, carefully allocate resources, and minimize mistakes before developing the process in real life.

Simulation has been used in planning manufacturing processes for nearly 40 years and in environmental work for about 30 years. Bioenergetics modeling has been used in Great Lakes fisheries management and in modeling the fate of contaminants moving through the aquatic food web for approximately 20-30 years. Computer and physical scaled models are widely used in coastal engineering for simulating the movement of sediments by water waves and currents.

Surprisingly, a role for process simulation has apparently not been recognized in planning for sediment remediation (USEPA 1994a; NRC 1997; NRC 2001, Apitz et al. 2005). Simulation (or modeling) is widely used to describe the movement and fate of toxic sediments and the migration of toxics and groundwater through the soils surrounding landfills and confined disposal facilities. Simulation has apparently not been used in North America to optimize the capacities of dredges, barges, tugboats, and cranes, nor to model sediment treatment processes for planning and optimization of costs.

Here are at least nine possible uses for simulation in resolving a toxic sediment problem:

1. The environmental significance of particular toxic sediments deposits: the re-suspension, transport, fate, and effects of particular masses of toxics in sediments
2. Some anticipated quantitative environmental improvements from cleanup (with time frame)
3. The likely environmental significance of particular remediation efforts
4. The likelihood of breaching protective caps over contaminated sediments during extreme storms and floods
5. The likelihood and time scale of contaminant migration to groundwater from sediment deposits and from confinement facilities
6. Cost-optimizing site investigations
7. The most productive and cost-effective mix of equipment capabilities in remediation activities

8. Estimations of the consequences in cost and productivity attributable to regulatory restrictions
9. Estimations of the likelihood of inadvertently generating hazardous waste during remediation

The first four needs in the previous simulation list can be met by using simulation tools for modeling contaminant transport fate and effects of toxics in an aquatic ecosystem of concern.

The Value of Mass Balance Modeling

> "A mass balance model is simply an accounting of the accumulation over a specified time interval of one or more materials within a specified control volume in terms of all significant inputs to, outputs from, and transformations (production and decay) within the control volume." - DePinto (1994)

Mass balance modeling of contaminants in a river reach or in a harbor is like financial bookkeeping: it accounts for all inputs (receipts), outputs (disbursements), accumulations (savings), and losses in that area while keeping the equivalent of account balances. Mass balance models account for contaminant movement between the atmosphere, water column, sediments, and biological organisms. Mass balance modeling is used with sediment transport models, bioaccumulation models, and other models to estimate where the toxics go and the risks that they pose to the environment. The uptake of toxics from sediments to fish consumed by people is part of this accounting effort.

A mass balance model is an essential predictive tool that allows planners to estimate the significance and consequence of a toxic sediment problem and proposed remediation actions. Such a model can aid decision makers in allocating scarce financial resources to remediation projects that appear to be the most beneficial to an ecosystem. The modeling effort is used to help answer the following questions:

» How much difference is it likely to make in a particular aquatic system if the toxic sediments are cleaned up?

» How much of the toxic sediments need to be cleaned up to make a significant improvement?

» How long after sediment cleanup is done will the results and benefits appear?

In the debate over remediation of toxic sediments in the lower Fox River of Wisconsin, a key question was whether or not extreme flood events on the river and extreme storm surges sweeping up the river from Green Bay have sufficient power to resuspend toxic sediment deposits in the river and carry them to the bay. If the answer is "yes," toxic river sediments provide a continuing source of PCBs and other contaminants to Green Bay and the rest of Lake Michigan. If the answer is "no," then natural recovery is a prospect if clean sediments rapidly cover toxic sediments as upstream pollution sources within the river are quickly eliminated. The same key question concerns the possible capping of toxic river sediments. Will clean stable caps over toxic sediment deposits be stable under all foreseeable river flow conditions and during all storm surges over the future range of Green Bay water levels?

The role of mass balance models was described in a report to the Great Lakes Water Quality Board (IJC 1988) and summarized by Dantas, Henshaw, and McCorquodale (2000) in the following way. Mass balance models:

- Assist in quantifying unknown, poorly quantified, or hard-to-quantify sources.
- Identify the significant contaminant transport and transformation processes controlling the concentration of contaminant(s) in various environmental compartments.
- Determine the mix of load reduction effort most responsive to the Great Lakes ecosystem or most cost-effective source reduction strategy.
- Predict the effect of a particular remediation strategy in terms of the decrease in concentration of a target pollutant(s) in sediment, water, fish, and birds, and estimate the time required to get the effect.

One problem with mass balance studies is that the benefits of sediment cleanup are likely to extend beyond the geographical range of the studies. In planning their economic benefits study, GLPF project economists quickly discovered that many of the people who would benefit from a Fox River sediment cleanup in Wisconsin fished in Lake Michigan as well as in Green Bay and the Fox River. The benefits of Fox River sediment cleanup are likely to extend to the broader, more distant Lake Michigan. The economists lacked information on how much sediment cleanup in the Fox River would reduce PCB loadings from Green Bay to Lake Michigan and reduce PCB concentrations in Lake Michigan fish. They had to limit their survey questions to the value of lowered contaminants in fish taken from the Fox River and Green Bay.

1. What's Needed to do Mass Balance Modeling? The USEPA is a good source for models. The agency has some water quality simulation models. Mass balance modelers in the Great Lakes Basin have used the IPX (In-Place Pollutant Export) model, a modification of EPA's WASP4 model. The IPX model was specifically designed for sediment applications (Velleux et al. 1996). It is a two-dimensional model that simulates depth-averaged water column concentrations. The Green Bay Mass Balance Study used a combination of nutrient and toxicant models (including IPX), integrated with a bioaccumulation mode. Mass balance modeling is unsuitable for novice users and requires skilled modelers. Here are minimum data requirements for mass balance modeling in a river:

Minimum Data Requirements for Mass Balance Modeling in a River (Dantas, Henshaw, and McCorquodale 1997)

Hydraulic Data

- Map of river geometry
- River hydrograph
- Upstream and downstream water elevation
- Bed slope
- River cross-sections
- Outfall locations, flows, chloride and total dissolved solids (TDS) concentrations
- Water column chloride and TDS concentration
- Water column temperature measurements
- Rainfall hydrograph

Sediment Data

- » Grain size distribution
- » Spatial variation in grain size distribution
- » Resuspension parameters (age, critical shear stress required to resuspend sediment)
- » River suspended solids (SS) concentrations over the year
- » Turbidity and SS relationship in river
- » Sediment deposition in traps (calibration)
- » Net sediment deposition at selected points (calibration)

Contaminant Data

- » Concentration in sediment, including spatial variation (horizontal and vertical)
- » Concentration in water
- » Concentration in water column of suspended sediment
- » Total organic carbon (TOC) and dissolved organic carbon (DOC) in water

Bioaccumulation Data

- » Measure of bioconcentration factors and food chain bioaccumulation factors for all trophic levels
- » Aquatic animal concentration data

2. A Two- or Three-Dimensional Mass Balance Model? The choice is a trade-off between effort and accuracy. Three-dimensional (3-D) models simulate water and sediment movement in both vertical and horizontal directions and require a lot more costly data collection and input than do two-dimensional models. In most riverine and harbor situations, a 2-D model can adequately simulate the physical situations.

3. What Does Mass Balance Modeling Cost? Mass balance model studies can be done at a modest cost compared with the total cost of sediment cleanup in a water body. The cost of sample collection and site characterization usually accounts for the bulk of the modeling cost. Use of applicable historical field data can dramatically reduce overall costs. Here are three examples of model studies showing that mass balance modeling costs are in the neighborhood of one million dollars.

   The pioneering lower Fox River/Green Bay Mass Balance Study began in 1989, took five years to complete and cost $12 million (DePinto 1994). This was an exceptionally large study. About 80 percent of the costs ($9.6 million) were for extensive data collection and analysis. Data interpretation, model development and model running accounted for an additional 10 percent ($1.2 million) of the costs. The total study costs were much more than an order of magnitude lower than expected sediment remediation costs of $369 million or more (WDNR 2001a).

The much less expensive Buffalo River Mass Balance Study used some of the information developed during the Fox River/Green Bay Mass Balance Study to predict the transport and fate of PCBs, PAHs, and metals in the Buffalo River, New York, that were being transported into Lake Erie. Much less data needed to be collected from the Buffalo River than from the Fox River and Green Bay. The Buffalo River Mass Balance Study cost about $1.2 million (including roughly one million dollars for data collection, reduction and analysis), according to DePinto (1997).

A less expensive mass balance study was done in the St. Clair River. Only graduate students from the University of Windsor were paid directly to work on the project. An estimated $60,000 (U.S. 1997 dollars) was spent for modeling and supportive studies plus $700,000 spent over two to three years to collect field data. If indirect costs are considered, the modeling effort probably cost $100,000 with a total study cost of $800,000 (McCorquodale 1997; Johnson 1997).

Benefits of Remediation

Identifying the benefits of sediment remediation and doing a cost-benefit analysis of remediation are key parts of toxic sediment management (NRC 1997). It is challenging, but important, to attempt to identify benefits of a contemplated project. Some benefits are not recognized or can not be quantified before a project starts. Economic and environmental benefits may become apparent and quantifiable only after the project is completed. Nevertheless, the remediation project may have great value over time.

A. Economic Benefits

A two-stage approach was suggested in the booklet Estimating Economic Benefits of Cleaning Up Contaminated Sediments in Great Lakes Areas of Concern (Stoll et al. 2002). In the first stage, a simple scoping study is done. It is based on easily acquired data and available studies done elsewhere. This may be all that is necessary to make a reasonably good judgment about whether economic benefits are likely to exceed expected costs or vice versa.

If a simple study is not adequate, a deeper investigation of economic benefits and costs is needed. Contingent valuation appears to be the most promising way to investigate the perceived benefits of cleaning up toxic sediments. This method relies on a survey of informed people to determine their willingness to pay for remediation that will accomplish certain specific goals (such as removal of advisories warning against consuming fish from the area). Contingent valuation is the only method of estimating total values (including nonuse values) that has gained substantial acceptance among economists.

The Stoll booklet describes methods for comparing the estimated costs of sediment cleanup with the perceived economic benefits and gives an example of sediment cleanup in the lower Fox River, using an estimated cost of $700 million. At the time of the survey, estimates of sediment remediation costs in the lower Fox River ranged from $700 million to $1 billion. More recently, the U.S. Environmental Protection Agency and Wisconsin Department of Natural Resources' proposed remedial action plan for the lower Fox River is estimated to cost $369 million over 5-7 years, including a 20 percent contingency (WDNR).

The costs given in Table 1 assume that $700 million in remediation costs are incurred and paid for over five years in the following sequence: $200 million (Year 1), $150 million (Year 2), $150 million (Year 3), $150 million (Year 4), $50 million (Year 5).

Table 1. Example of Remediation Cost Distribution for Sediment Cleanup in Lower Fox River

Item	Row Number	Brown County	Fox-Wolf River Basin Counties	State of Wisconsin
Population (1990)	1	194,594	1,050,312	5,032,089
Persons per Household (1990)	2	2.61	2.61	2.61
Number of Households (1990)	3	74,557	402,418	1,928,003
Total Remediation Cost ($millions)*	4	633.6	633.6	633.6
Per-Household Remediation Cost ($)	5	8,499	1,575	329
Per-Household Remediation Cost Averaged Over 5 years ($)	6	2,242	415	87
Per-Household Remediation Cost Averaged Over 30 years ($)	7	902	167	35

*The $663.6 million invested when studies are completed and a plan is selected (Row 4) will earn four percent interest and pay out $700 million in costs over the five years of remediation.

A low discount rate of four percent used in Table 1 is one of three discount rates used in the Stoll booklet and selected here because of low interest rates common at the time that this booklet was written.

The Stoll booklet also describes results from a contingent valuation survey of 1,500 Wisconsin residents to learn how much they value cleanup of toxic sediments in the lower Fox River. Results from 530 respondents showed that the perceived benefits for sediment cleanup generally ranged between $100 to $300 per household, annually. These estimates are an expression of survey respondents' "willingness to pay" to achieve the desired cleanup goals. The estimates vary depending upon the models and assumptions used. The survey's author suggested that $222 per household per year was an appropriate value to use, based on survey results.

Compare the estimated per-household cost of sediment cleanup averaged over 30 years (like a home mortgage) on Row 7 in Table 1 with a perceived $222 per household per year benefit from achieving 100% of the "desired state" in the Fox River/Green Bay Area of Concern (AOC). The perceived benefit of $222 per household per year exceeds the estimated annual cost of $167 distributed among the households in the Fox-Wolf Basin counties and far exceeds the $35 per household per year annual cost distributed across the state of Wisconsin.

The contingent valuation survey results showed that Wisconsin residents value sediment cleanup. The perceived benefits appear likely to outweigh the estimated costs, depending upon how the costs and benefits are distributed. The survey tested the extent to which respondents were informed about the toxic sediment issue—an important factor in validating the survey. The survey designers did not test the respondents' willingness to pay higher taxes or forego other purchases and expenditures in favor of remediation.

There are other economic issues that need to be addressed in considering sediment remediation projects. These issues include:

- Who should pay for sediment cleanup?
- Will there be plant closings and loss of jobs if private parties pay the cleanup costs?
- What will the impact on costs of special requirements placed on remediation contractors by regulatory agencies be?
- How will imprecise location and inadequate remediation of sediments affect costs?
- What will the economic costs of long-term monitoring and risk management in perpetuity be?

The best strategy for economic analysis in Wisconsin's lower Fox River may not be the best strategy in other Great Lakes AOCs. Where a scoping study shows that recreational use, real estate development, commercial shipping, and other well-defined benefits are likely to predominate, a method or combination of methods in addition to contingent valuation can be applied where technically feasible.

B. Environmental Benefits

Environmental benefits to humans, wildlife, plant communities, aquatic habitat, etc., are some of the hardest benefits to identify, measure, and quantify. One helpful reference on this subject is a booklet titled *Economic Valuation of Natural Resources* (Lipton et al. 1995). The booklet's authors describe environmental valuation, economic tools for use in making coastal management decisions, methods for measuring values of market and non-market goods and services, benefit transfer, and the challenge of reconciling differences between theory and application. The booklet contains eight case studies. Unfortunately, none of the case studies involved sediment remediation.

Some sense of the environmental benefits of sediment remediation can be gained from looking at reports on the Natural Resource Damage Assessment Web page of the U.S. Fish and Wildlife Service. For example, one of the reports provides an estimate of damages to the recreational fishing industry in Green Bay from fish consumption warning advisories issued largely because of contamination originating in the lower Fox River of Wisconsin.

C. Who Benefits from, and Who Pays for, Sediment Remediation?

Estimated economic and environmental benefits are specific benefits. Some of those benefits are easier to identify and quantify than others and are particularly relevant to the question of who should pay the bills for toxic sediment remediation.

There are a number of strikingly different rationales that serve the individual purposes of the various parties proposing and opposing sediment cleanup that are used in the debate over what to do about the problems and opportunities of toxic sediments. The following examples of such rationales are intended to demonstrate their diversity, not their adequacy in court. The labels are arbitrary choices. These brief descriptions do not do justice to the potential persuasiveness of each rationale.

1. <u>Principal Responsible Parties (PRPs)</u>. Under this rationale, the organizations to whom the toxic chemicals in the sediments can be convincingly traced are responsible

for paying the costs incurred in cleaning up the contaminated sediments. This is a common approach used by state and federal governments. A variation on this rationale is to assess PRPs for natural resources damage and use the funds for a combination of sediment cleanup and habitat restoration or re-creation. PRPs may include local, state, and federal governments as well as private firms and other organizations.

Opponents of this rationale are likely to claim that the financial burden on a PRP or group of PRPs will have grave, adverse consequences to stockholders, employees, and the communities in which the PRPs are located. Necessary profits will be lost, stock value will drop, jobs will be lost, and plants may close or move out of the state (or out of the country). Such claims are made as job losses and transfer of work to other countries (for a variety of reasons) are a growing political issue in the United States.

2. Complicit Parties. The organizations that discharged the toxic chemicals into the environment and the organizations who permitted the discharges share responsibility for paying the costs of cleaning up the contaminated sediments. This rationale is often used as a counter-argument against the PRP rationale. This rationale has a cost-distributing advantage for organizations that might otherwise be tagged as PRPs. The rationale is strengthened if the discharging organizations have a verifiable record of always discharging legally within the permitted parameters, or if regulatory agencies were lax in monitoring such discharges. If the discharging organizations were lax in rigorous, documented maintenance of permitting conditions, the rationale is weakened.
3. Beneficiaries Pay. The organization(s) that stand(s) to benefit the most for cleanup, pay for cleanup. This is a rationale used to negotiate a sediment cleanup agreement with individual organizations to whom sediment contamination is traceable—organizations that are also PRPs. This arrangement can be attractive to a firm or to a municipal operator of a sewage treatment plant when cleanup of a particular site can free the polluting organization from future liability for the costs of remediation on that site or on other portions of the polluted waterway. The liability is lifted, making a firm more attractive on the stock market and more saleable. An added attraction of this rationale is that the organization that pays may also have control of the remediation process and the cost control measures of process selection, contractor selection, optimization, and efficiency.
4. Society Pays. Under this rationale, sediment remediation costs are paid for with government funds because the pollution was permitted by government or is a consequence of inputs from an urban society that are not traceable to particular organizations. Society benefits broadly from a healthier environment, improved recreational opportunities, etc. This rationale is a variation of the "beneficiaries pay" rationale and seems appropriate to situations in which sediment contamination is caused by a broad range of pollutants lacking one or more dominant pollutants traceable to discrete sources and organizations. An example is airborne pollution from distant sources.

The contingent valuation survey results showing a "willingness to pay" mentioned in the previous section on economic benefits of remediation provided one indication of perceived societal economic benefits of sediment cleanup. Contingent valuation is a method for estimating the broad range of economic benefits of sediment cleanup, but its use does not imply who should pay.

5. Paying over the Lifetime of Perceived Benefits. The costs of sediment remediation can be very high. One way of coping with the cost is to pay over at least part of the expected period that benefits will be enjoyed. Such a plan can soften the economic impacts of the costs, while adding to the cost because of the time value of money.

Economists Bishop and Stoll demonstrated that the estimated costs of proposed sediment cleanup in the lower Fox River of Wisconsin compare favorably with the perceived economic benefits of cleanup when the costs are distributed over 5- and 30-year periods over a population of households beyond those of the counties adjoining the Fox River (Stoll et al. 2002).

No Action

This sediment remediation option is often characterized by its title; it gets the least consideration of all remediation options. "*No action*" is often replaced by the term *"natural recovery."* Credible predictions of natural recovery require:

- Knowledge about aging and degradation of contaminants under the known anoxic or oxic conditions in the contaminated sediment bed
- Evidence that in-place contaminants are becoming less toxic or less available to organisms
- Credible prediction of source reduction or pollution prevention
- Information about sedimentation sources and processes
- Modeling of sediment transport, deposition, and resuspension at the toxic sediment site(s)

USEPA (1993) provided a decision flow chart for determining when "no action" is and is not appropriate (Figure 4). In Figure 4, the three findings leading to an appropriate "no action" decision are: (a) biodegradation of contaminants of concern, (b) an adequate build-up of sufficiently clean sediments over the toxic sediments, and (c) a location where the clean and toxic sediments will not be disturbed. The four findings in Figure 4 that lead to rejecting a "no action" decision are: (a) dredging needs to be done for other reasons, (b) a natural, cleaner sediment cover is not depositing over the toxic sediments (or not depositing fast enough), (c) there is no significant biodegradation of contaminants of concern in the toxic sediment deposit, and (d) the toxic sediment deposit is accessible to disturbance.

The decision question at the bottom of Figure 4 is: "Is cover build-up physically accessible?" This question should be restated as: "Is it likely that the built up cover can be disturbed by natural or human causes?" This flow chart needs a risk assessment step that considers the risk of resuspension and transport of the toxic sediments by storm and flood events and by vessel movement and prop wash. If "no action" is selected, it should be selected after a risk management study is completed.

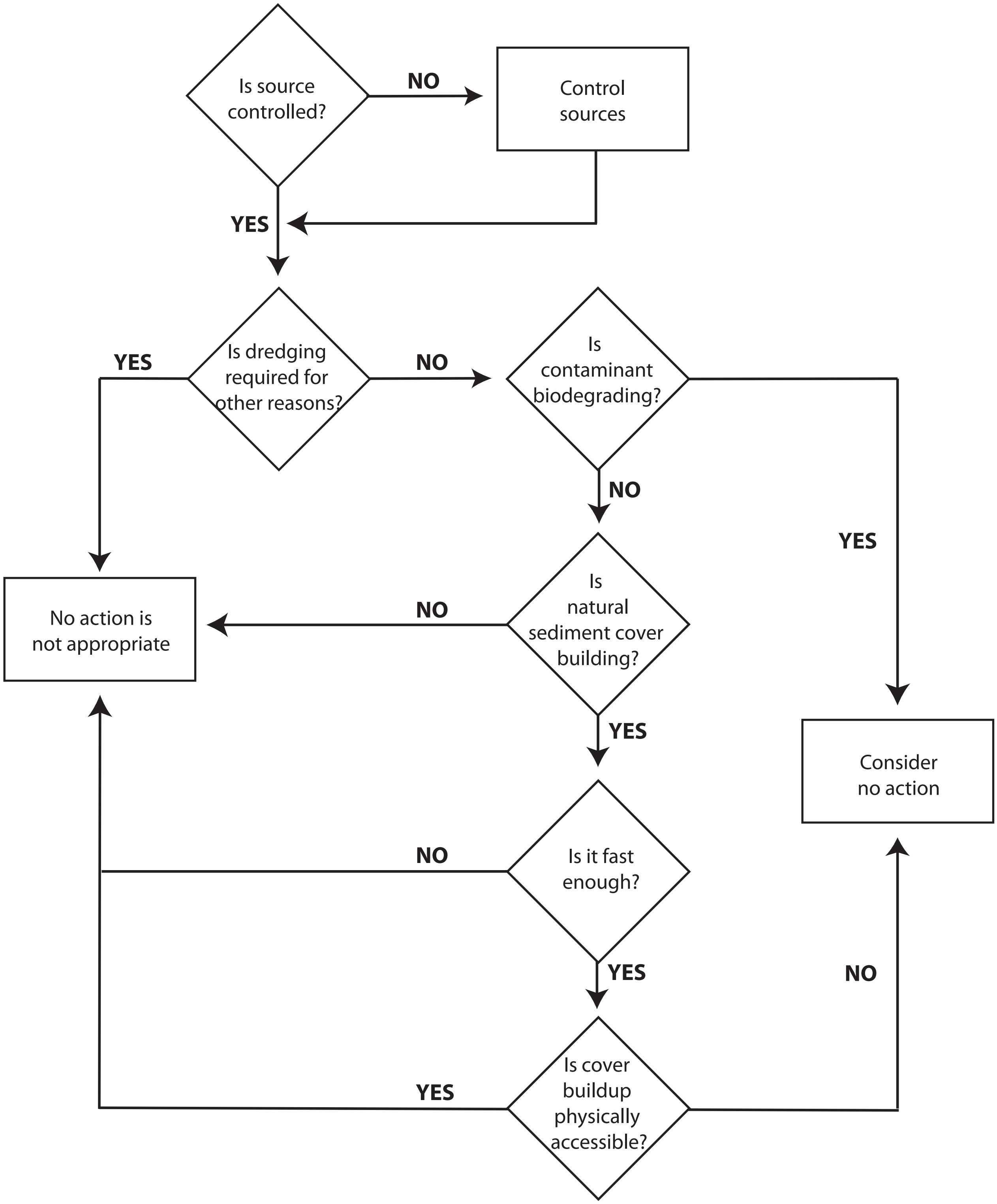

Figure 4.Flow chart for screening no action. Source: USEPA 1993.

Risk Management for the "No Action" Option

A critical risk management issue is the exposure to risk from making a "no action" decision. Some *probabilistic thinking* needs to be done to weigh the probabilities that boating activity or storm events will significantly disturb or scatter the toxic sediments before: (a) formation of an adequate, stable deposit of cleaner sediments over the toxic sediments or (b) sufficient biodegradation of toxics in the sediments occurs. *Probabilistic thinking* is the use of probabilistic methods supplemented with professional judgment to cover gaps in probabilistic knowledge.

Risk management requires selection of an appropriate spatial reference for "no action." If an extreme flood event removes most toxic sediments from a managed deposit, the value of this "cleansing" action at the deposit site is offset by the re-deposition of the toxic sediments at other unknown, probably unmanaged, sites. A narrow focus restricted to the fate and management of toxic sediments on a site is inadequate to risk management. "Dilution as the solution to pollution" is not widely recognized as an acceptable sediment remediation option.

Risk management for a "no action" option also requires selection of an appropriate time period after which the formerly toxic sediment deposit will no longer be of concern. Where persistent chemicals such as PCBs and PAHs are in toxic sediment deposits, the biodegradation rate is so low that the time scale for risk management is somewhere between "the foreseeable future" and "in perpetuity."

In the Lake Ketelmeer sediment remediation project, the Dutch designed a storage depot (confined disposal facility) using a probabilistic geotechnical analysis (Roukema et al. 1998). They picked a solution with a low risk: contaminants from the disposal site, migrating through groundwater, are not expected to surface in nearby farmland for 5,000 years (Laboyrie and Flach 2002). An alternative solution was rejected, in part, because contaminants would likely surface in 500 to 1,000 years.

Many of the physical, hydraulic processes that can impact toxic sediment deposits in Great Lakes AOCs are much more dynamic than the slow, steady movement of groundwater. There is a lot of inherent uncertainty in estimating the magnitudes and probabilities of 100- or 500-year flood and storm wave/surge events in the Great Lakes given comparatively short records (less than 100 years) and the prospects of significant climate changes over the next 20 to 100 years. The uncertainties about the stability of stable, clean sediment caps deposited over toxic sediment deposits are similarly large.

Risk management for the "no action" option may require monitoring in perpetuity (where persistent toxics are present) and will require a response plan in case natural, cleaner sediment deposition is not as rapid as anticipated, or in case the toxic sediments in the deposit of concern become exposed, resuspended, and transported downstream. Monitoring, planning, and taking alternate response measures are steps in risk management. The costs of monitoring in perpetuity and the future cost of taking corrective actions need to be considered in contemplating a "no action" option.

The significance of the "no action" option is affected by the expected consequences of future pollution prevention efforts, and any expected inadequacies of pollution prevention.

Pollution Prevention

Elimination of contributing sources of contamination is often cited as a prerequisite for cleanup of toxic sediment deposits. The Port of Rotterdam in the Netherlands invests some of its funds in the reduction of pollutant inputs to the Rhine River upstream of the port at significant point sources as part of the port's program to cope with toxic sediments while dredging to maintain adequate navigation depths (Vellinga 1995).

Elimination of sources of additional contamination at managed toxic sediment sites is compromised by changes in pollution enforcement resulting from changes in governments, and by the continued atmospheric inputs of contaminants from distant sources outside of the state, region, and continent.

Often, the halting of continued inputs and prevention of new inputs of contaminants to sediments at a site is beyond the control of the party carrying out sediment cleanup. In the fall of 2000, the James River Paper Company hired a contractor to carry out a comprehensive cleanup of a large toxic sediment deposit adjacent to the company's plant on Wisconsin's lower Fox River (Fort James 2001). As soon as the targeted toxic sediments had been removed, a clean sand layer was spread over the cleansed river bed. This sand layer (if it remains in place) is a recognizable boundary providing evidence of the cleanup in case new deposits of toxic sediments develop on the site in the future. This strategy is one way that a firm can try to reduce its liability for future contamination of an adjoining riverbed or lakebed without waiting for pollution source control by others.

A risk management analysis of any remediation option should include an evaluation of the effect that Pollution Prevention may have on that option. For example, pollution prevention actions that reduce inputs of toxic sediments to harbors that need periodic maintenance dredging have the potential to significantly expand the flexibility of sediment disposal and sediment reuse options for future dredged material.

Exploring Remediation Alternatives

Remediation of toxic sediments can be done in place (in situ) or after removal.

Remediation in Place

1. Capping. One method of remediation is to place a cap of clean sediment over contaminated sediment (Palermo 1998). Variations of this method include:

   - *In-Situ Capping* (ISC). This is controlled, accurate placement of clean sediment on top of undisturbed toxic sediments in a water body.
   - *Level Bottom Capping* (LBC). This is placement of dredged contaminated material onto the undisturbed bottom of a water body in a mounded configuration, and the controlled, accurate placement of a clean sediment cap over the mound.
   - C*onfined Aquatic Disposal* (CAD). This is aquatic disposal of relocated toxic sediments in a dredged pit on the bottom of a water body with lateral confinement and controlled, accurate placement of a clean sediment cap on top

of the relocated sediments.

» *Structural Isolation.* Isolation of a contaminated sediment deposit by relocation of a portion of the waterway passing over the deposit, followed by capping the deposit and filling over it. This can be done, in part, by using ISC, LBC, or CAD.

The goal of an ISC project is containment that is long enough for natural degradation to render the contaminant harmless or to reduce the contaminant flux sufficiently to be protective of ecological and human health (USEPA 1996).

Capping advantages include:

» Elimination of the need for (and costs of) removal, transport, treatment, and disposal at a new storage site
» Possibly reduce the potential for sediment and contaminant losses to the water column if toxic sediments remain in place (Zeman and Patterson 1996a)
» Maintaining the existing geochemical conditions in the sediment, thereby minimizing release of contaminants to surface water and air (Averett 1990)
» Significant short-term experience (several decades) with capped sediment deposits at multiple sites in estuarine and ocean waters

The disadvantages of capping deposits of toxic sediments in place include:

» Lack of long-term (more than 30 years) experience with capped deposits in estuarine and ocean waters
» Lack of experience with capped deposits of toxic sediments in fresh water
» Long-term migration of persistent toxic substances through toxic sediments and cap materials into the water column and into the ground water
» Lack of long-term experience with cap integrity including during extreme storm and flood events.

The other capping options mentioned above are more complex and add more steps and costs to remediation than does ISC. These options need to be considered if the toxic sediments are in the wrong place (i.e., navigation channels) and need to be relocated or if a portion of the waterway where the toxic sediments are sited can be relocated.

Level bottom capping (LBC) is depositing dredged material on the bottom of a water body and covering it with a cap of clean cover material. An example of LBC is the disposition of sediments in Port Stanley, Ontario (Riggs 1996). Contaminated inner harbor sediments were dredged and redeposited at another site. Then clean outer harbor sediments were dredged and placed over the deposit of contaminated sediment as a protective cap. Confined aquatic disposal (CAD) is the placement of dredged material in a dredged pit, followed by capping with clean dredged sediment. This method has been used in Antwerp, Belgium.

Some information needed in selecting a capping site:

- » The physical and hydraulic conditions at the site. Capping is not recommended at sites where the capping process will produce a nonaquatic site. Site hydraulics include water depth, currents, waves, ice movement, ice jams, storm surges, flood flows, and associated weather conditions. These conditions can significantly influence (or destroy) the stability of the toxic sediments and cap.
- » The existing and future use of the waterway. Capping is not recommended in harbor areas where maintenance dredging occurs.
- » Groundwater conditions. A site should not be selected where contaminants are likely to move from the sediments into the adjoining soils. A site should not be selected where upward groundwater seepage is evident.
- » The areal extent and thickness of the contaminated sediment deposit. These need to be defined to guide the placement of the capping deposit.
- » Physical characteristics of the contaminated sediment.

The following is a list of other considerations that should be investigated before a potential capping site can be selected (Palermo 1991b):

- » Potential changes in circulation patterns or erosion patterns related to refraction of waves around the disposal mound
- » Normal level and fluctuations in background turbidity
- » Potential for recolonization of the site by benthic organisms
- » Previous disposal operations
- » Nearby obstructions or structures that restrict the use of large equipment at the site
- » Ability to monitor the disposal site adequately for management decisions
- » Technical capability to implement management options should they appear desirable
- » Public and regulatory acceptability for use of the site
- » Other site uses and potential conflicts with other activities

2. <u>Treatment in Place</u>. Sediment treatment in place is a form of *in situ* sediment conditioning. Nutrients may be added to the sediment to enhance, or speed up biodegradation of toxics in the sediment. Chemicals may be added to assist in transforming toxic chemicals in the sediments to innocuous or less-toxic forms. Sediment treatment, or conditioning, has the best potential for working in protected deposits that are not subject to ice scour or resuspension from wind waves, currents, boat wake, and prop wash.

   An innovative technology was developed at the National Water Research Institute (NWRI) in Burlington, Ontario, Canada, that illustrates some of the requirements and challenges of cleaning up toxic sediments in place. The NWRI process uses biostimulation—introducing an oxidizing agent into the sediment that stimulates the activity of indigenous aerobic bacteria to degrade certain organic contaminants. Nutrients can also be added, as needed, to stimulate the bacterial activity. A pilot-scale demonstration was done at the Dofasco Slip in Hamilton Harbour from the summer of 1992 to the fall of 1993. The treatment was applied to about one hectare (about 2.5 acres) of sediments that were severely contaminated with PAHs. Over two shipping seasons, 48 percent of the PAHs were degraded (Wardlaw 1994, Murphy et al. 1995). Adequate treatment of a site like the Dofasco Slip would require multiple treatments over three years.

Successful in situ treatments, according to Murphy et al. (1995) need:

» Complete and thorough injection of the biostimulant
» A dose adequate to penetrate completely through the contaminated sediment layer and adequate to compensate for the waste byproducts of anaerobic bacteria in deep sediments
» Sites relatively free of sediment mixing and resuspension
» Multiple treatments over multiple years

These authors estimated that full-scale treatment-in-place could be done at just 20 percent of the cost of dredging and dredged material storage in a confined disposal facility.

3. Risk Management with Remediation in Place. Risk management issues with capping include:

» Capping is relatively new and the long-term effectiveness and integrity of a cap is unknown
» Toxic chemicals are left in the sediment intact
» There is a risk of cap erosion and contaminated sediment resuspension by boat wake, prop wash, flood currents, storm surge, and wind waves
» Contaminants may migrate through the cap and surrounding soil into surface water and groundwater
» Thorough monitoring of the integrity of the cap and contaminant migration are required *in perpetuity* for persistent toxic sediments with sufficient frequency and coverage to take prompt corrective action
» Inadequate monitoring and lack of corrective action can lead to a return to a preremediation condition

The costs of monitoring in perpetuity are easily overlooked or underestimated in evaluating costs of capping. Risk management of a capping project requires an open-ended commitment of funds and other resources on a very long time scale that is not common to local governments who often become the "local sponsors" or parties responsible for maintenance of such facilities. Governments may not be willing, or able, to sustain such a commitment to risk management. Many of the probabilities of events that jeopardize the integrity of a cap are the same as those that jeopardize a "no action" option.

Risk management for capped aquatic storage of toxic sediments occurs in a challenging environment of potentially destructive hydrodynamic forces from moving vessels, floods and storm surges.

There is a short history of projects in which there was controlled, open-water placement of clean material directly on top of toxic sediments. For example, Aziz et al. (2001) reported on 11 years of monitoring dredged toxic sediment that was placed in an underwater pit in the Duwamish, Washington, waterway, one of the early toxic sediment capping projects. The U.S. Army Corps of Engineers (USACE) and the USEPA are principal sources of information on capping projects that have had nine to 17 years of monitoring. A short history and a small number of adequately monitored projects lead to a small database and inadequate information about the statistical probabilities of cap failures. Risk managers must resort to "probabilistic thinking" in assessing the risks of capping.

Treatment of toxic sediments in place has some of the same risk management issues as "no action" and "capping." The issues include:

» The risks of boating activity and storms disturbing a toxic sediment deposit during treatment

» Treatment may not be adequate and may leave significant residuals of toxic sediments

Sediment Removal

A direct way of dealing with toxic sediments is to remove them from the waters in which they are creating an environmental problem (PIANC 1996). This removal can either be done by dredging or by removing the overlying water and excavating the exposed sediments. The most common method of removing toxic sediments from a water body is dredging. A less-common method is dry removal ("removal in the dry").

1. Environmental Dredging. *Environmental dredging* usually means the application of modern dredging techniques to remove toxic sediments. Environmental dredging dates from the mid-1980s as a purpose-driven adaptation of the centuries-old practice of dredging for navigation. Contractors have gained experience, new advances in dredging equipment have been developed and tested, and projects have been completed. Innovations include (a) increased precision in locating and removing sediments, and (b) less turbidity during dredging. Environmental dredging can be done with both mechanical and hydraulic dredges. Mechanical dredging is shown in Figure 5.

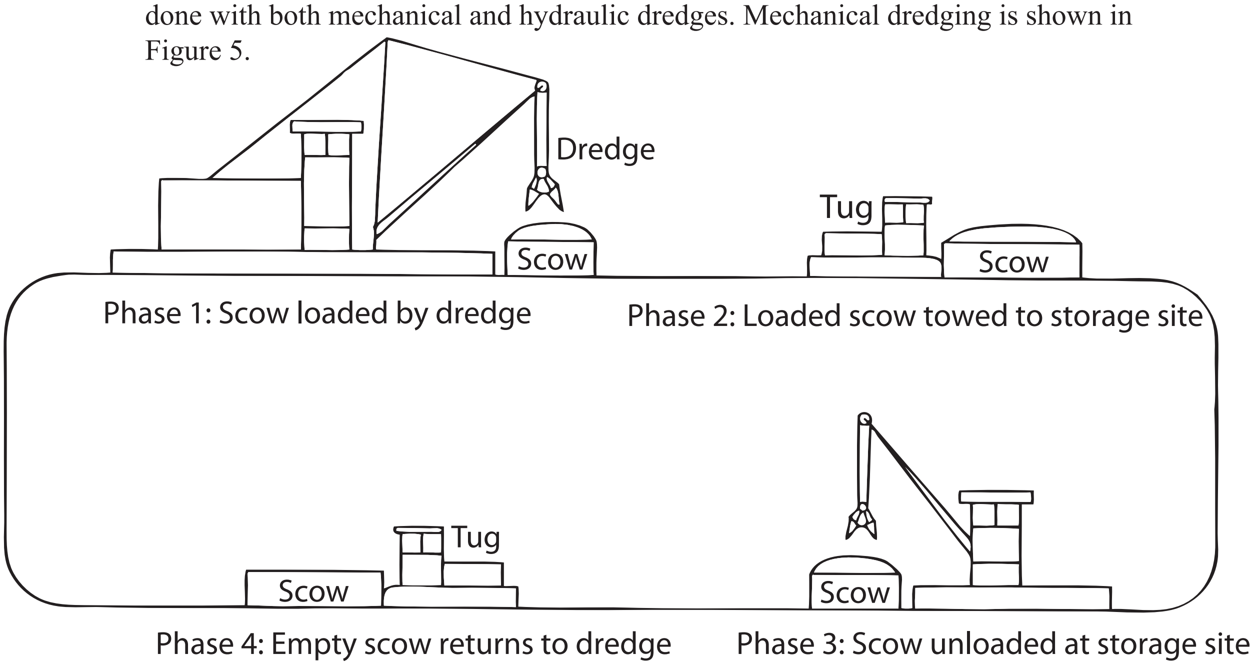

Figure 5. Mechanical dredging cycle. Source: Blazquez et al. 2000.

2. Productivity in Dredging. The productivity of a hydraulic or mechanical dredge is usually stated in terms of cubic meters or cubic yards per hour or per day. Productivity in an environmental dredging project is a function of:

» The presence of debris
» The size of the dredge pipe (or bucket)
» The pumping rate (or bucket cycle time)
» The efficiency of dredge performance
» The "dredgeability" of the sediment
» The effective working time in a 24-hour day and a seven-day week
» Disparity between the productivity of the dredge and the productivity of the other equipment in the steps of sediment removal, processing and disposal
» Constraints on productivity placed by regulatory agencies in an effort to reduce adverse environmental impacts

A sediment remediation dredging project in the lower Fox River of Wisconsin late in the summer and fall of 2001 was done with a hydraulic dredge (horizontal auger type) operating 24 hours per day. The dredge removed 50,316 cubic yards (38,703 cubic meters) of sediment. The average daily dredging rate was 833 cubic yards (541 cubic meters) per day, and the highest rate was 1,599 cubic yards (1,230 cubic meters) per day. The dredged slurry had an average solids content of 8.4 percent (range of 3.5 to 14.4 percent). The sediments were mainly soft organic silt ranging in thickness from 1 to 16 feet overlaying firmer native clay (Fort James et al. 2001).

Often there is a large disparity in productivity of a dredge and productivity of other equipment used in a dredging operation. Simulation can be useful in examining and reducing this disparity by better matching of available equipment.

Mechanical and hydraulic dredging costs and performance (production rate) can be modeled as part of the simulation of sediment remediation (Henshaw et al. 1999; Blazquez et al. 2000, 2001). The simulation of dredging and disposal activities helps evaluate the consequences to productivity and cost from various combinations of available equipment in a dredging system.

Dredgeability of Sediment

Herbich (1992) provided a brief discussion and a few references on this subject. Certain geotechnical properties are used to evaluate the dredgeability of a sediment:

» Consistency and compactness measured as in situ shear strength
» Grain size distribution
» Angularity of coarse grains
» Plasticity of fine-grained sediments
» Organic content
» Presence of debris, shells, or other non-soil materials

The USACE has a Dredging Research Program that has produced more than one Dredging Research Technical Notes on the subject of dredgeability and developed a knowledge-based expert system computer program titled "Geotechnical Factors in Dredgeability" (DREDGABL).

Effective Working Time

This is the percentage of a 24-hour day and a seven-day work week that a dredge is actively working. Dredging contractors try to maximize the effective working time because they get paid for cubic yards or cubic meters of sediment removed. The larger the percentage of effective working time, the lower the costs per unit volume of material dredged.

Effective working time can be reduced by a number of factors that include:

» The presence of debris
» Downtime for maintenance and repair
» Vessel traffic in the dredging area
» Regulatory agency constraints
» Pauses to check for adequacy of sediment removal
» Pauses to relocate silt curtains/screens
» Environmental windows to avoid disrupting fish spawning activities
» Storms, floating ice and other weather factors
» Other elements in the remediation system unable to match the dredge production rate

On typical navigation dredging projects, effective working time typically ranges from 10 percent (severe winter conditions) to 60 percent (typical of spring and fall operations) to 80 percent (ideal summer conditions) in the Great Lakes region (Blazquez et al. 2001). On environmental dredging projects, these percentages are likely to be significantly lower because of restrictions placed on operating conditions for reasons of risk management.

3. <u>Dry Removal.</u> One sediment remediation option is removing the sediment "in the dry" by removing the water overlying the sediment. Dry removal involves cordoning off a targeted toxic sediment deposit, removing the water, and excavating the toxic sediments on the exposed bed of the water body. This is accomplished by creating a dam or cofferdam around the deposit to isolate the water above the sediment. The isolated water is pumped out, and the toxic sediment is removed from the site with conventional excavating equipment.

4. <u>Risk Management in Sediment Removal</u>. There is risk involved in removing toxic sediments. There is a possibility of short-term exposure and contaminant release during dredging and transport of the material from the water and through treatment processes. There is a risk of airborne re-suspension of fine toxic sediments from a dewatered sediment deposit. There is a shift in the long-term risk of exposure from the insecure, dynamic, hydraulic environment of the water body to the more secure environment of a landfill. There is also a risk of exposure from residual contaminants

left behind in un-dredged sediments when a removal project is completed.

Management of risk in dredging means minimizing dredged material losses and contaminant release during dredging and processing. Risk management means maximizing the removal of targeted sediment and not leaving behind significant deposits with high concentrations exposed and available for re-suspension and update by aquatic organisms.

Environmental dredging stresses minimum release of contaminants and minimum loss of dredged material over productivity. Kuo et al. (1991) reported less than one percent loss of dredged material when clamshell dredges were used. Van Oostrum and Vroege (1994) reported that dredged material losses on various projects ranged from near zero to five percent.

Sediment and contaminant losses during dredging can be significantly reduced (Barnard 1978; Brahme 1983; Raymond 1983; Kaneko et al. 1984; Buchberger 1993). These losses can be reduced at the bucket or hydraulic dredge head through design. These losses can be confined to a small area around an operating dredge with silt screens or silt curtains. Silt screens are made of geotextile fabrics and allow water to flow through while retaining some or all of the solids. Silt curtains are made of fabrics that do not allow water to flow through, retaining all of the solids. Silt screens and silt curtains have a demonstrated ability to reduce turbidity by as much as 80-90 percent under good conditions with little current (Zappi and Hayes 1991). Where there are substantial tidal currents or stream flow, screens and curtains may create unacceptable re-suspension of sediment.

A modest mass balance accounting exercise is valuable in estimating losses of contaminants during a sediment remediation project. Such an exercise is different from the mass balance modeling described elsewhere in this booklet.

Table 2 shows the estimated losses of PCBs from dredging and other steps in a pilot remediation project at Sediment Management Unit (SMU) 56/57 in 1999 on the Fox River (Wisconsin) in comparison to the annual transport of PCBs past the site from the river to Green Bay. The estimated transport of PCBs downstream during dredging was about two percent of the PCBs removed from the sediments by dredging, based on deposit and process mass balance monitoring. Sediment exposed to, or suspended in, the water column during dredging was believed to have increased both the dissolved concentration of PCBs in the water column and increased the PCB concentrations on suspended particles (Steur 2000). The PCB loss at SMU 56/57 was a considerable improvement over losses during the first Fox River pilot dredging project at SMU N the year before when an estimated 13 percent of the PCBs removed were lost during a one month monitoring period (FRRAT 2000). The monitored period of dredging at SMU N took place in December when ice formed and became a problem. Silt curtains were used, occasionally disturbed by passing vessels, occasionally damaged and repaired.

In contrast to results at SMUs N and 56/57, Henshaw (1997) estimated much better results during environmental dredging in the St. Clair River near Sarnia, Ontario. In 1997, about 170 cubic meters of sediments contaminated by a chlorinated organic compound were removed by a mechanical dredge with a cable arm bucket. He concluded that 0.001 to 0.05 percent of the contaminant removed by dredging was lost to the water column during dredging. He estimated that 1.5 percent of the contaminant would have been lost using navigational dredging methods.

Table 2. Estimated removal and losses of PCBs [1] during the SMU 56/57 pilot dredging project in 1999, lower Fox River, Wisconsin. From Steuer (2000).

Process	Volume in cubic yards (cubic meters)	PCB mass in pounds (kilograms, kg)	Percent of PCBs in dredged mass
Total in SMU 56/57 deposit	80,000 (61,538)	4,600 - 6,600 (2,090 - 3,000)	
Total removed from SMU 56/57	31,500 (24,112)	1476 (671)	100
Transport downstream during dredging		32 (14.5)	2
Dewatered sediment transported to landfill		1440 (654)	97.5
Volatilized to the atmosphere		5.7 (2.6)	0.4
Processing effluent returned to the river		Less than 0.4 (less than 0.2)	Less than 0.1
Annual load from the river to Green Bay		410 (186)	

1. Specifically: Aroclor 1242

Risk management in dry removal is similar in some ways to the situation in a remediation project for toxic soils on land. Airborne re-suspension and transport of toxics from exposed surfaces must be controlled as well as vehicle tracking and leakage of toxic sediments transported off-site. The dewatered, exposed toxic sediment deposit must be protected from flooding and washing of sediments back into the water body. Water pumped from the dewatering site may need to be treated to remove contaminants.

Sediment Treatment after Removal

In this booklet, "treatment after sediment removal" means any conditioning of the sediment to render it suitable for disposal or reuse. Sediment treatment can be as simple as volume reduction for further treatment, reuse or disposal. The following descriptions are a sample of the broad range of treatment methods available.

1. Volume Reduction. Volume reduction includes both dewatering and size separation processes. Getting rid of excess water is the first step in volume reduction for direct disposal of sediments in a landfill or for treatment processes that use heat or solvents. The cost of heating water in contaminated sediments is a major cost in thermal treatment processes and the need can be minimized through dewatering.

   a. Dewatering – Dewatering can be as simple as discharging slurry from the pipeline of a hydraulic dredge into a geotextile bag where the water leaks from the bag, leaving a "sausage" of dewatered sediment to be hauled away (IDR 2002). At some sites, sediments can be removed from a waterway with a mechanical dredge at close to in situ densities (typically 40 to 60 percent solids) and hauled to landfills "as is." Such sediments may not need to be processed for further dewatering. Landfills typically accept soil that is at least 50 percent solids.

Dredged sediments may require additional, mechanical dewatering. In 2000, hydraulically dredged sediments from the lower Fox River's Deposit 56/57 were mechanically dewatered with filter presses to a minimum of 50 percent solids for placement in the Fort James' company landfill (Fort James et al. 2001). Additional dewatering may be needed. Hazardous waste landfills require at least 80 percent solids content, and dredged material for construction fill must be 88 to 90 percent solids (Das 1994). Dewatering to 80 percent solids content is considered optimum before using thermal desorption processes (Eykholt and Vaidya 1997).

b. Size Separation (Classification) – Physical separation techniques are widely used in the mining industry to recover valuable minerals. These techniques can be useful in some situations to clean sediment fractions from toxic sediment fractions. Physical separation methods improve remediation economy by reducing the volume of contaminated material and concentrating the contaminants that need treatment. These techniques include gravity separation, soil washing, magnetic separation, and froth flotation.

Size separation using gravity and differences in particle density may be as simple as discharging dredged material with high water content and allowing the discharge to carry smaller, lighter particles farther from the discharge point than the larger, denser particles are carried. This simple method is used at the Erie Pier confined disposal facility in Duluth Harbor and at the Slufter confined disposal facility in the Port of Rotterdam, The Netherlands. Gravity also separates particles by density in the conical hydrocyclones used in the soil-washing process.

Soil washing is a volume-reduction process in which water in sediments is useful as a carrier. This process is useful for separating soils or sediments that contain at least 50 percent sand and gravel and less than 20 percent solid organic material (Anderson 1993). Contaminants are often associated with the organic fraction and the fine fraction of the sediment. The reduction process involves:

» Removal of oversized material
» Sediment washing with water to separate and segregate size fractions and contaminants
» Recovering separate coarse and fine solid fractions

The recovered and separated fractions can be disposed of or reused depending upon their contaminant concentrations, water content, and physical characteristics.

During the USEPA ARCS demonstration program, the Dutch Bergmann soil-washing process was used to process PCB-contaminated sediments dredged from the Saginaw River in Michigan (USEPA 1994e). About 80 percent of the solids contained in the material fed to the soil washing equipment was recovered as a washed sand product. The remainder of the material recovered was oversize material, fine particulates, and particulate organics. The PCB concentrations in the washed sand were reduced 82 percent from the PCB concentrations in the toxic sediment fed to the process.

During the GLPF project, pilot studies were done using Great Lakes sediments, and the data was used to construct a mathematical model of cost and performance of soil washing. This model is part of the REMSIM software. Proper grain size and contaminant characterization are essential to the success of soil washing.

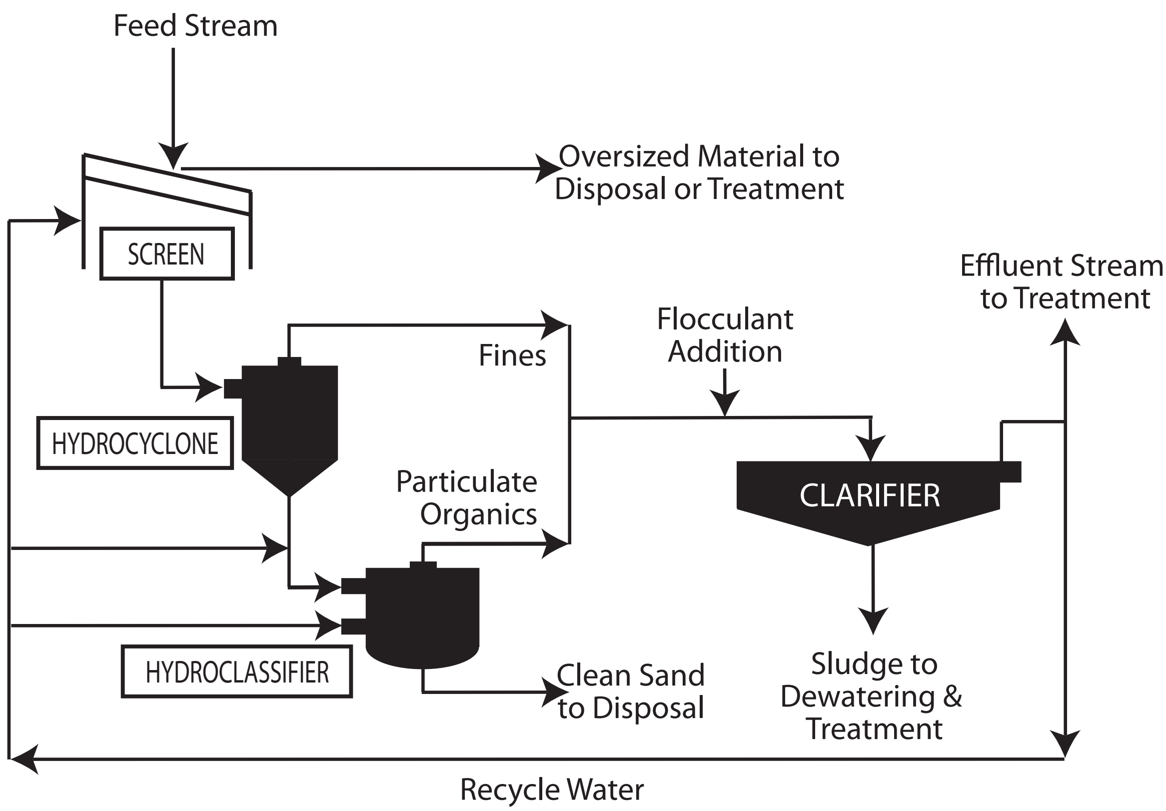

Figure 6. Volume reduction. Source: Witt 1996.

2. Bioremediation. Bioremediation is any process that uses natural, adapted, or engineered organisms such as bacteria, fungi, and enzymes to transform toxic organic compounds into less toxic forms or into nontoxic carbon dioxide and water, or methane. Bioremediation processes typically use anaerobic and/or aerobic bacteria to metabolize toxic organic contaminants. Aerobic bacteria need a supply of oxygen to satisfy their energy needs. Anaerobic bacteria obtain their energy in the absence of oxygen.

   Bioaugmentation and *biostimulation* are important in bioremediation processes. Bioaugmentation is the addition of microorganisms that have the ability to degrade targeted organic toxic contaminants in the sediments. Biostimulation is the improvement of environmental conditions that stimulate the activity of microorganisms in degrading contaminants within soil or sediments.

Bioremediation may occur in sediments in place (in situ) as described in an earlier section, or it can take place *ex situ* where sediments are removed and treated as soil. For bioremediation to be successful, the microorganisms must be in close proximity to the contaminant, the contaminant must be biologically available, and the microorganism must have the ability to degrade the contaminant to a less harmful, or harmless state.

Even persistent toxic substances can be intentionally bio-degraded, with difficulty. Polychlorinated biphenyls (PCBs) are an example. PCBs are among the most difficult organic compounds to degrade because:

- » PCB degradation by bacteria is incidental to the preferential degradation of other compounds as an energy source
- » PCBs (particularly the highly-chlorinated forms) have low solubility and may not be biologically available to bacteria and other microorganisms

PCBs are a complex family of toxic chemicals. There are up to 209 different variations (congeners) of PCBs. The more highly-chlorinated PCBs are degraded by anaerobic bacteria. The less chlorinated PCBs are degraded by aerobic bacteria. Mixtures of PCBs can be degraded under sequential biodegradation; first with anaerobic bacteria in a process called reductive dechlorination, then by aerobic bacteria. Aerobic bacteria have been used to rapidly degrade less chlorinated PCBs to harmless compounds.

Bioremediation of PCBs is an emerging technology. The processes are limited by the percentage efficiency of the degradation and the time and effort required to achieve satisfactory remediation.

Bioremediation of metals is also an emerging technology. It has been done experimentally at the U.S. Bureau of Mines, using aerobic and anaerobic bacteria to leach manganese, cobalt, cadmium, and lead from mining ores by the production of metabolic waste acids. Appropriate bacteria can be stimulated to produce metabolic acids that will break metallic bonds to sediment particles so that the metals can be separated from the sediment particles. Watson et al. (1991) reported that a common sulfide-fixing microorganism (Disulfovibrio) was used, with iron sulfate as an energy source, to produce stringy masses of iron sulfide that strongly adsorbs organics and metals. The iron sulfide-organics-metals masses were captured and removed in a high-grade, or superconducting, magnetic separator. In this way, mercury in a sludge was reportedly reduced from one part per million to below one part per billion. The same process was claimed to be effective in removing radioactive metals from soils, sediments, and sludge.

Three Types of Bioremediation Processes

Three types of bioremediation processes are:

- » In situ bioremediation (described in "Sediment Treatment in Place")
- » Solid-phase treatment
- » Slurry-phase treatment

One form of solid-phase treatment is land farming. It is commonly used for processing bio-solids in sewage sludge and for processing contaminated soil. Contaminated material is spread on farm fields using conventional agricultural equipment. Indigenous bacteria are stimulated to degrade the targeted organics through active manipulation of environmental conditions—tilling for homogenization, aeration and the addition of nutrients and water.

Wardlaw (1994) described results of a pilot-scale, solid-phase treatment carried out by Grace Dearborn, Inc., using toxic sediments from Hamilton Harbour, Hamilton, Ontario. Sediments contaminated with polyaromatic hydrocarbons (PAHs) and metals were dredged from the harbor. A proprietary soil amendment was added, the soil was tilled weekly and water was added as needed. Over 245 days of active management, total PAHs dropped 90 percent from 1.1 milligrams per gram to 110 micrograms per gram (1,100 to 110 parts per million, ppm). The amendment improved the biodegradation. A control cell without the soil amendment had 50 percent removal of PCBs (Wardlaw 1994).

Slurry-phase treatment is an extension of the activated sludge process that has been used for a century for the treatment of municipal and industrial wastewater. A slurry (10 to 40 percent solids) of water, contaminated sediments, aerobic bacteria, air, and nutrients is contained within a rigid vessel (reactor). Mixing is provided by a mechanical mixer (like a cement mixer). Aeration may be provided naturally, or with a submerged air diffuser in the vessel. The suspended bacteria are maintained in intimate contact with the target contaminants within the aerated, aqueous mass, and degradation is accelerated by maintaining optimum control of the process environment. Following a treatment period, the slurry is dewatered and the processed solids are hauled off for further treatment or disposal. The water, with its high populations of acclimated bacteria is then recycled into the reactor. Faster biodegradation rates may be obtainable using an aerobic digestion process that operates at higher temperatures, with thermophilic (“heat-loving”) bacteria.

Pilot-scale slurry-phase treatments of harbor sediments were done in Toronto, Ontario, in 1992 by the Toronto Harbour Commissioners, and beginning in 1993 at the Wastewater Technology International Corporation’s pilot plant in Burlington, Ontario. Slurry-phase treatments may successfully biodegrade 87 to 97 percent of PAHs, perhaps higher.

Bioremediation is useful in reducing the toxic concentrations of contaminants in sediments. For low to moderately contaminated sediments in suitable locations, treatment in place may be the most viable option in terms of total project cost, but it may take years to complete the degradation process. Solid-phase treatment is likely to be faster (months to a year) but more expensive than in situ treatment. Slurry-phase treatment is likely to be the fastest and most expensive option for bioremediation.

There are risks to be managed in bioremediation. Solid-phase treatment under greenhouse cover exposes workers to airborne contaminants released from the tilled soil being treated. There are risk management issues in bioremediation. Solid-phase treatment in land farming may bring less exposure to workers, but it involves less control of the contaminants when flooding and soil erosion occur. In slurry-phase treatment, the risks of spillage, exposure of operators to toxics, and issues of decontamination and toxics containment are similar to the issues with other treatment processes done on land in some type of structure and equipment where the process is sheltered from the weather and from exposure to humans. Risk management procedures will differ widely from land farming to solid-phase treatment to slurry-phase treatment.

3. <u>Thermal Desorption.</u> Thermal desorption physically separates volatile and semivolatile organics from sediments by heating them to temperatures high enough to volatilize the contaminants. A flow diagram of a typical thermal desorption process is shown in Figure 7.

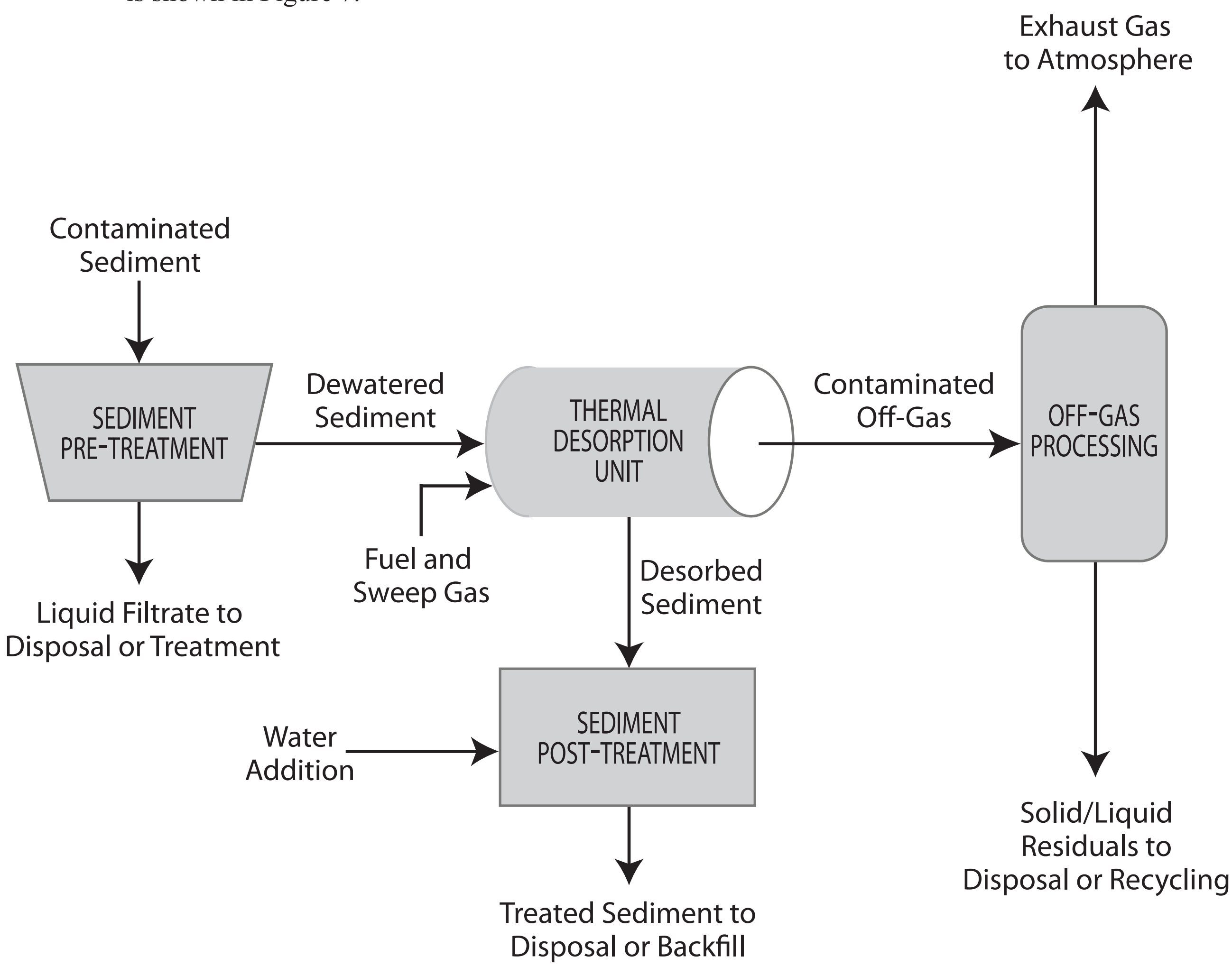

Figure 7. Typical thermal desorption process. Source: Eykholt and Vaidya 1997

Performance of a thermal desorption process is highly dependent on the boiling point of the contaminants. Coarser-grained sediments are likely to be easier to treat than finer-grained sediments. A high clay content may cause fouling or caking within the system. There are certain tradeoffs that affect cost and performance. One tradeoff with cohesive sediments is the addition of water to make material transport and mixing easier, but the additional water raises energy costs and/or decreases desorber performance.

Moisture content in the sediment is a significant factor in cost and performance of thermal desorption processes. Eykholt and Vaidya (1997) gave an example that showed a 70 percent decrease in energy required for thermal desorption when the solids content is increased from 40 to 80 percent. A high moisture content may also reduce the amount of volatilization of toxics.

If thermal desorption is going to be seriously considered as a treatment option, bench-scale treatability tests are needed for prediction of performance. If results from these tests are promising, pilot-scale tests should be run. In testing, measurements should be made of mass transfer characteristics, including the stripping factor and the number of transfer units over a range of sediment process rates and gas flow rates. Other mass transfer relationships need to be measured to identify the relationships that determine thermal desorption effectiveness for treatment of the toxic sediments to be remediated. Tests should also be run to determine the optimum amount of dewatering that should be done before desorption is done. This is important for cost reduction and process improvement.

When results from the USEPA's ARCS pilot studies of thermal desorption were examined during the GLPF project, contaminant removal efficiencies could not be correlated to performance factors such as sediment exit temperature and residence time (Eykholt and Vaidya 1997).

4. Solvent Extraction. Solvent extraction is an emerging technology in remediation. A flow diagram of the process is shown in Figure 8. Solvent extraction causes a preferential separation of a particular substance from one phase to another. Contaminants are concentrated in a relatively small volume that requires further treatment and disposal.

Commercial solvent extraction systems have been used at a number of Superfund sites and field studies. This experience shows that the method can be effective in treating sediments contaminated with organic wastes such as PCBs and PAHs. Solvent extraction of inorganic contaminants such as heavy metals had yet to be demonstrated when this booklet was written.

The effectiveness of the treatment depends on a number of factors, including: (a) an adequate number of extraction cycles and (b) the degree to which the volume of contaminated material requiring further treatment can be reduced.

If solvent extraction is going to be seriously considered as a treatment option, bench-scale treatability tests are needed for prediction of process performance. If results from these tests are promising, pilot-scale tests should be run. In testing, measurements should be made of partitioning factors over a range of feed rates and operating parameters for the characteristics of the toxic sediments to be remediated. A mathematical model of solvent extraction performance and cost could be developed, but the effort would require knowledge of the partitioning coefficients specific to a given solvent or remediation process.

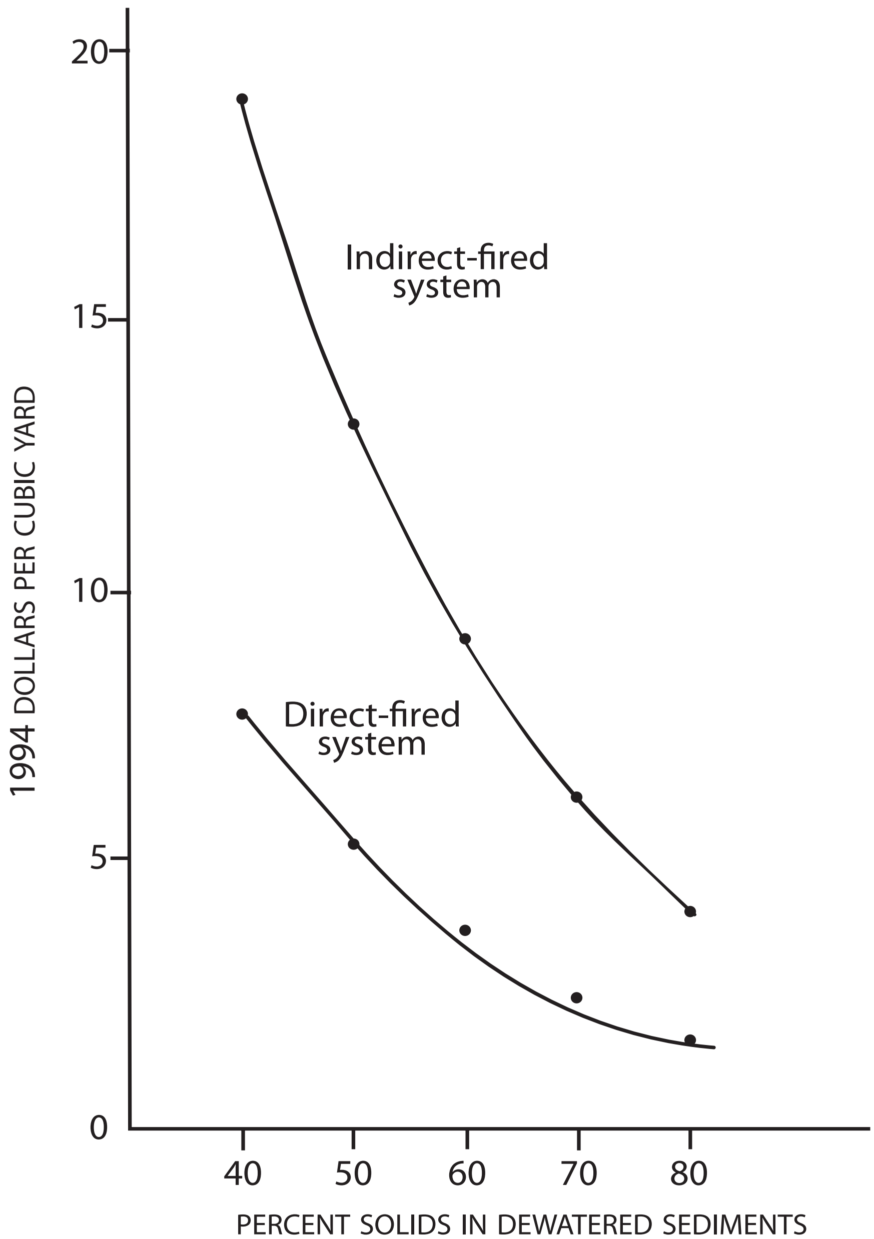

Figure 8. Flow diagram of a solvent extraction system. Source: Eykholt and Viadya 1997

5. Wastewater Treatment. Wastewater is water removed from a treatment process. Wastewater treatment options include:

   1. Routing wastewater to a sewage treatment plant (POTW)
   2. Clarification with chemical addition
   3. Filtration
   4. Clarification followed by filtration
   5. Granular activated carbon (GAC) adsorption
   6. Clarification followed by filtration and GAC adsorption

   Inputs require adequate characterization of the quantity and characteristics of the source water. Flow charts of these six treatment options are shown in Figures 9 through 14.

Wastewater treatment can be simulated. The usefulness of such simulation in planning was demonstrated in the development of a wastewater treatment model for the REMSIM software. Such simulation can be used in the feasibility planning stage to estimate cleanup performance, capital costs and operating costs for wastewater treatment. The model included mass balance analysis of water solids and contaminants plus cost analysis for each of the six treatment options listed above. The treatment options in REMSIM were appropriate for removal of particulate solids and dissolved hydrophobic organics. Outputs from the various options could be easily compared with discharge permit requirements. Well-documented and commercially available technologies were selected. Cost/capacity relationships were obtained in the spring of 1997 from equipment vendors and wastewater treatment plants around the Great Lakes.

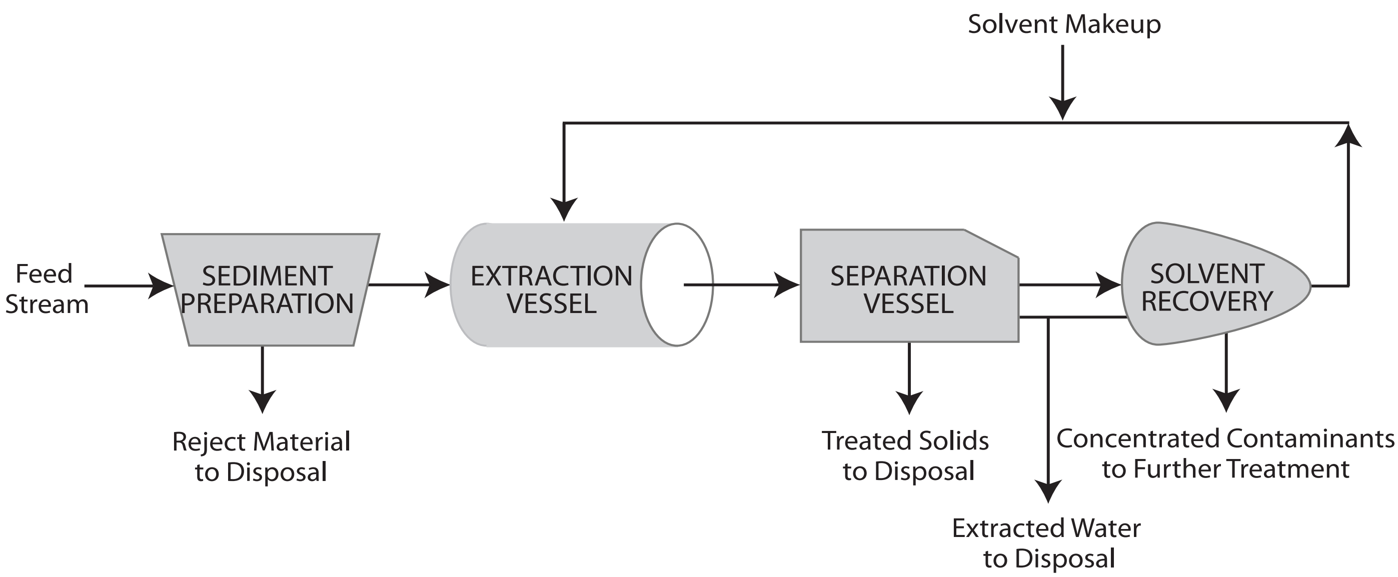

Figure 9. Flow diagram of a solvent extraction system. Source: Eykhold & Vaidya 1997

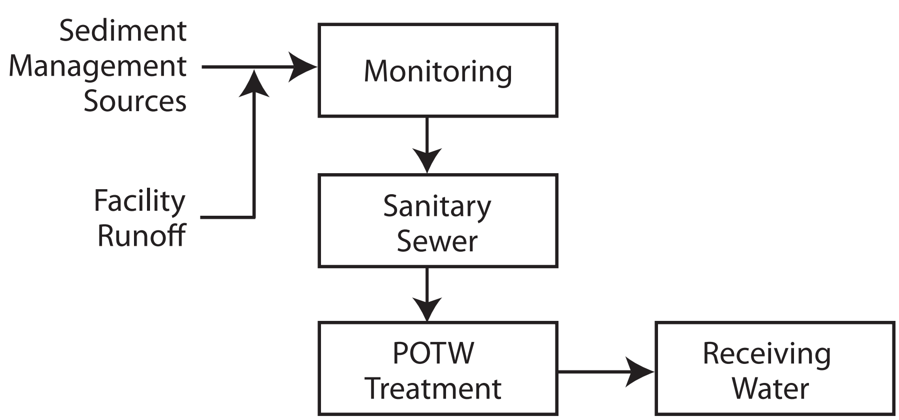

Figure 10. Flow diagram of a of POTW treatment. Source: Mumford 1997

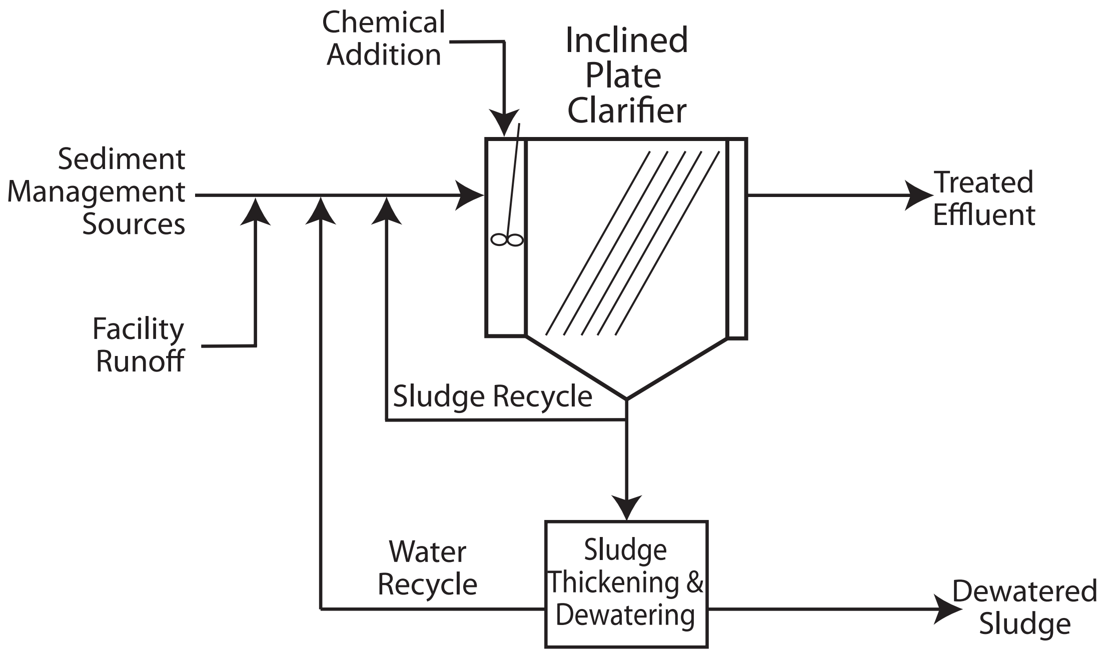

Figure 11. Flow diagram of a typical wastewater clarification process. Source: Mumford 1997

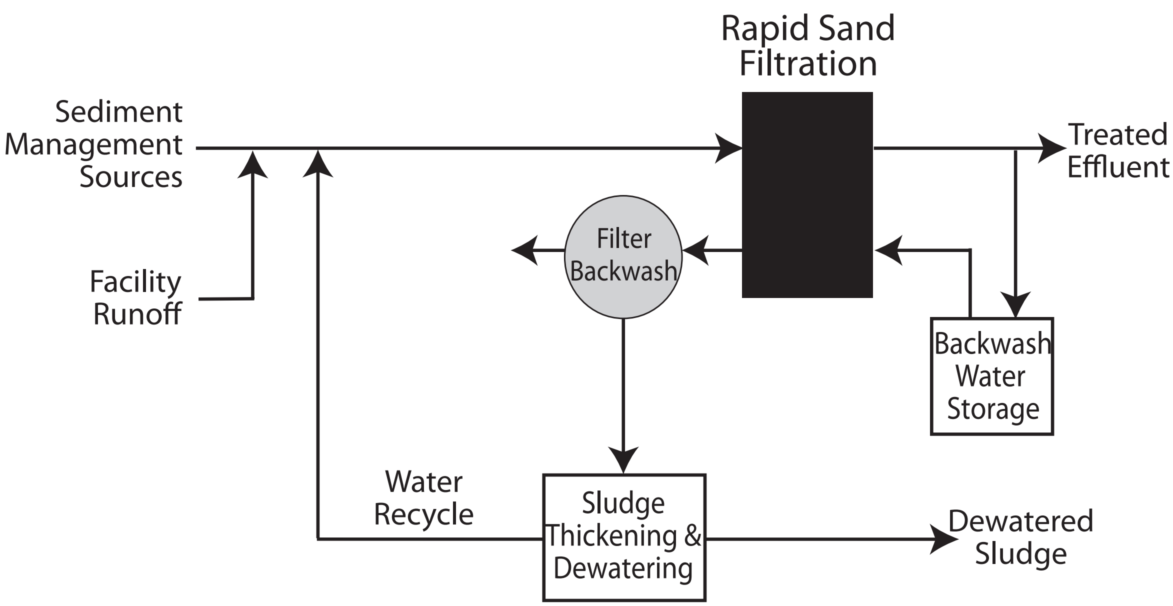

Figure 12. Flow diagram of a typical wastewater filtration process. Source: Mumford 1997

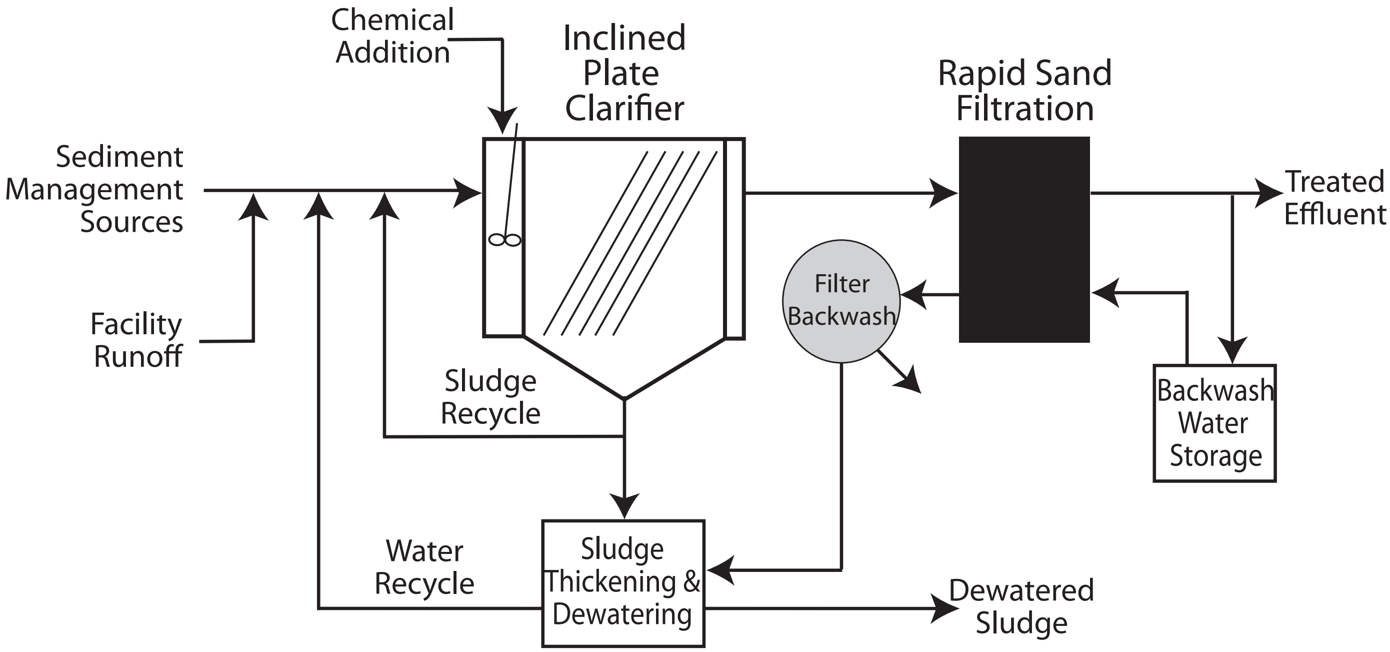

Figure 13. Flow diagram of a typical wastewater clarification and filtration process. Source: Mumford 1997

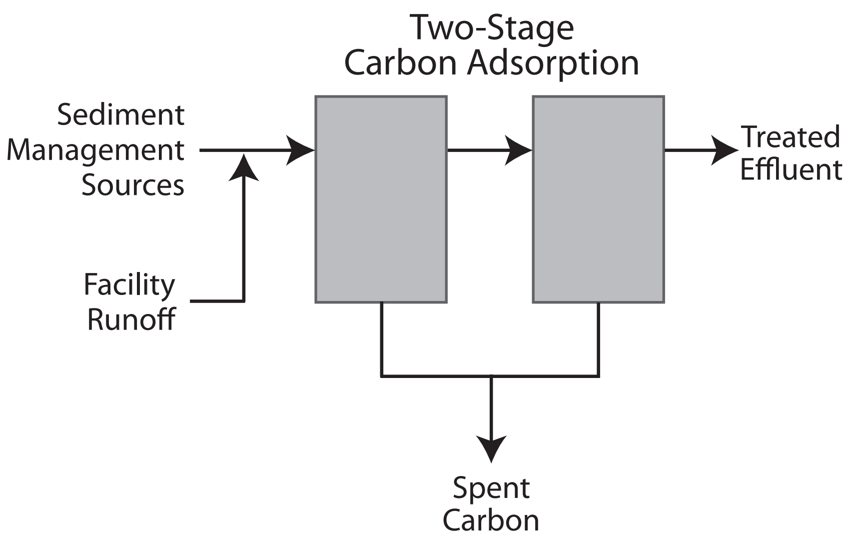

Figure 14. Flow diagram of a typical GAC adsorption process for wastewater treatment. Source: Mumford 1997

6. Risk Management in Sediment Treatment. The risk management issues for the toxic sediment treatment options mentioned in this section are similar to risk management issues common to the construction, chemical production, and wastewater treatment industries. The risks include those associated with (a) the handling and preparation of toxic sediments for treatment, (b) exposure to the treatment processes, (c) exposure to off-gases and effluents, and (d) exposure and handling of treatment products and by-products.

Reuse of Sediments

Beneficial reuse of clean dredged materials has had a long history. Beneficial reuse of contaminated sediments is more challenging because of the physical and chemical nature of the sediments. The usefulness of toxic sediments seems to be inherently a contradiction. For what good purpose can such harmful materials be used? The usefulness of toxic sediments depends on effectively separating clean sediments from toxic sediments, or rendering harmless the toxic sediments.

Confined disposal facilities (CDFs) can be "mined" for the coarser materials to be used as construction fill or aggregate, lengthening the life of the facility. After closure, the facility may have some use for wildlife habitat or recreation. Three examples of the usefulness of CDFs are:

» The Erie Pier CDF in Duluth Harbor, Minnesota. Site used for disposal of sediment from navigation dredging and for recovery of useful sand and gravel through gravity separation.

» The Slufter CDF outside of Rotterdam Harbor, the Netherlands. Site used for disposal of sediment from navigation dredging and for recovery of useful sand and gravel through gravity separation.

» The Ijsseloog CDF in Lake Ketelmeer, the Netherlands. Site used for dredged material disposal following environmental and navigation dredging and for subsequent development of recreation facilities on the site.

At the Erie Pier CDF, coarse clean sediment recovered from dredged material is sold to contractors. At the Slufter CDF, sediments enter as a slurry. Coarse sediments settle out first; fine sediments are transported to a greater distance within the water impoundment of the CDF. A small dredge periodically "mines" the coarser sediments, removing them for reuse.

Beneficial reuse options include:

» beach nourishment

» land application

» construction fill

» habitat creation

» landfill cover

1. Beneficial Open-Water Disposal. Open-water disposal is sometimes attractive for its potentially low cost and for the transformation of a "waste" into a useful material. Clean sand and gravel in dredged material are a natural resource in the wrong place. Returning these materials to the coastal sediment transport system can improve protective beaches and restore some of the sediment lost because of erosion control in watersheds, harbor deepening for navigation, and erosion control along shorelines. Deep-water disposal of clean sand and gravel can provide some "structure" to featureless beds of water bodies—new lakebed forms where fish and other aquatic organisms may colonize and congregate.

   Where open-water disposal of clean, coarse sediment is prohibited or severely restricted, it may be due to a statutory or regulatory lack of recognition of the material as a potential resource. In Wisconsin, all dredged material is by statute defined as a "solid waste," and disposal of sand and gravel has long been regulated much more stringently than is the use of sand and gravel from land sites which are not considered solid waste sites.

2. Creation or Re-Creation of Islands and Other Habitat Areas. Dredged sediments have potential use in creating or recreating barrier bars, spits, islands, marshes and other wildlife habitat. These sediments are building materials in replacing terrestrial or aquatic land forms lost to subsidence, high water levels, and erosion.

   It is technically feasible to create natural-looking habitat out of sediment; habitat that has sand and gravel beaches for shore birds and upland vegetated areas for wildlife. This is the concept used to design the re-creation of the Cat Island Chain in lower Green Bay offshore of the city of Green Bay. The original bay mouth chain of islands and barrier bars was largely destroyed by severe storms during the high water level period in the early 1970s. Restoration of the island chain is one critical element in re-establishing emergent beds of aquatic vegetation that used to draw huge flocks of waterfowl. The restored islands will provide nesting and feeding habitat for shorebirds. It has been proposed that sediment dredged from the navigation channel adjacent to the island sites be used in rebuilding the islands.

   Coastal engineering and physical modeling in wave tanks can be used to design and create stable, attractive habitat with a minimal amount of rock armoring for sediment confinement, over a selected range of water levels and storm conditions, with a large measure of confidence. Such confidence measures are essential if contaminated dredged material is to be placed on site beneath clean sediment caps and confined in ways similar to confined aquatic disposal features mentioned in the prior sections on capping and disposal. Most of the structural features need not be visible, giving the appearance of natural barrier bars, spits, islands, and beaches.

   Some of the "islands" in the Duluth-Superior Harbor, now valued for their natural resource features, are "spoil islands"—convenient deposits of dredged material created in the first half of the last century. Toronto, Canada, has used dredged material and construction rubble to create and expand a complex of harbor islands and spits for wildlife and for human recreation.

3. Beneficial Uses of Landfilling and Land Application. Landfilling costs can be reduced if some of the dredged material is separated and conditioned to make it suitable as landfill cap material. The value of this cap material can help offset some of the costs of disposal. One landfill offered a discount of $5.50 per cubic yard ($7.15/cubic meter) from the normal tipping fee if the dredged material could be used as daily cover (USACE 1994b).

   Fine dredged material is a consequence of soil loss, a serious problem in watersheds where row crops (such as corn) dominate agricultural lands, slopes are steep, and soil erosion is prevalent. Land application of fine dredged material can be a way of compensating for soil loss by returning some of the lost material to the land. The cost of land application is about one dollar per cubic yard ($1.30/cubic meter) for spreading material on fields, plus the cost of trucking (Harrington 1996). Dredged material can be used to reclaim (or decrease the depth of) gravel pits, quarries, and open pit mines and other stripped land areas that no longer have a use.

4. Reuse of Sediments in the Manufacture of Useful Products. Thompson and Francingues (2001) identified some potential beneficial reuses of toxic sediments in manufactured products that have been explored for large sediment remediation projects. Some of these examples are described in the Appendix. These projects are to develop industrial processes to create saleable products. The economic practicality of these projects depends upon:

   » a significant capital investment in advance of a remediation project
   » a commitment for a dependable supply of dredged material for years to come
   » charging a fee to receive dredged material…a fee comparable to landfill tipping fees

   Contaminated sediment that is commonly considered an undesirable, expensive waste product has the potential to be a raw material for a commercially valuable product. The cost to the sediment supplier may be considerably less than the tipping fee charges at municipal landfills, but that savings is likely to be at least partially offset by the costs of additional dewatering beyond that percentage of solids acceptable at a landfill. If the preliminary estimates for manufactured products described in the Appendix are reasonable, the tipping fees charged by plants manufacturing these products seem likely to be cheaper than tipping fees charged for use of hazardous waste disposal sites.

Risk Management in Beneficial Reuse

In the case of aquatic habitat creation, a risk of breaching a disposal site and dispersing toxic sediments contained there is one apparently unavoidable consequence of using the sediments to achieve desirable, "natural-appearing" habitat. The habitat site will probably not be constructed like the armor stone "fortresses" of conventional confined aquatic disposal sites. The risks inherent in created aquatic habitat subject to floods, strong currents, storm surges, and storm waves are quantifiable with hydraulic physical model testing and other coastal and hydrologic engineering methods. The quantified risk can often be reduced, but the reduced level of risk may be higher than is commonly accepted with confined disposal facilities and landfills. Acceptance of risk for the sake of gaining habitat may be difficult because of little precedent for such action.

Risk management issues in the use of toxic sediments to create aquatic bedforms include assessment of:

» Probabilities of breaches in contaminant barrier integrity from storm wave action
» Probability of contaminant migration into the groundwater and lake water
» Monitoring requirements in perpetuity

Risk management issues with land application include:

» Uptake of contaminants by vegetation

» Volatilization of contaminants to the atmosphere
» Possibility and prevention of groundwater contamination

Risk management issues involved in using contaminated sediments to manufacture useful products include:

» Airborne, dust, and wastewater emissions of toxics from the manufacturing process and plant
» Hazards to plant personnel during the handling and processing of toxic sediments
» Short-term and long-term leaching of toxics from the manufactured product
» Disposal of toxic scrap products and byproducts

There cannot be beneficial use of toxic sediments without acceptance of some level of risk associated with the use. However, there are also risks associated with "no action" and with every other option for cleaning up contaminated sediments.

Disposal of Toxic Sediments

Disposal of toxic sediments means finding a site that will safely contain them for a very long time. In the Netherlands, a confined aquatic disposal facility in Lake Ketelmeer was selected for the lake's remediation project. It is estimated that contaminants in the facility will not reach groundwater beneath adjoining farmland for 1,000 years, compared with 500 years for a rejected disposal alternative (Laboyrie and Flach 1998)

Disposal alternatives include:

» Municipal landfill
» Hazardous waste landfill
» Confined disposal facility
» Unrestricted open water disposal
» Level bottom capping
» Contained aquatic disposal

Answers to at least three important questions determine whether or not a given disposal option is feasible.

» Do regulations allow waste to be disposed of in the manner indicated in the option?
» What are the risk management requirements for the option?
» What are the likely disposal costs compared with costs of other options?

The same questions apply to reuse of toxic sediments and the by-products of sediment treatment.

CDFs are one means of disposal for large amounts of moderately to highly contaminated dredged material. There are decades of experience with design, operation, and maintenance of CDFs in the Great Lakes and in many other places.

Risk Management in Disposal

There is a short-term risk of exposure to persons involved in removing, handling, and disposing of toxic sediments. That risk is managed with the use of appropriate equipment and methods by experienced remediation contractors. There is a long-term risk of environmental exposure from toxic chemicals in sediments at the disposal site. Management of this long-term risk requires an open-ended commitment to monitoring by the party who accepts responsibility for receipt and storage of the materials. Disposal may involve transfer of liability for future harm.

There is a continuum of risk with the lower risks in confinement within on-land, designed landfills with conservatively safe barriers, leachate collection and treatment, and adequate caps in areas with low seismic risk. The higher risks are likely to be in semi-confined, in-water sites exposed to combinations of flood water flow, storm waves, storm surges, and storm water levels. Some of these risks were mentioned in the earlier sections on capping and habitat creation.

Risk management of toxic sediments confined on land occurs in a very different environment than does risk management of toxic sediments confined in and near large or swift bodies of water. On-land confinement structures are not exposed to the destructive hydrodynamic forces from vessels and storm surges and may not be subject to floods or land movements.

The time scale for risk management in the storage of toxic dredged material can be very long. In the Netherlands, a confined aquatic disposal facility in Lake Ketelmeer was selected for the lake's remediation project. It is estimated that PCBs, PAHs, and metals within the facility will not reach groundwater beneath adjoining farmland for 5000 years, compared with 500 to 1000 years for a rejected disposal alternative.

Conclusions

Seeking Effective Remediation

The initial and primary measure of the effectiveness of sediment remediation is the answer to the question: "How much of the mass of contaminants in the sediments targeted for cleanup was remediated?"

There have been some efforts to develop tools that will help achieve effective and cost-effective cleanup of contaminated sediments. In March 1996, the author visited Rijkswaterstaat offices of the Dutch government in Utrecht, the Netherlands, and tried out a computer program designed for this purpose. Running on a personal computer, this software can be used to plan an optimum sediment sampling and measurement strategy and an optimum, economical dredging strategy for cleanup of contaminated sediments to some pre-determined statistical measure of confidence. At that time the Dutch government was also working on extending this approach to other aspects of remediation beyond dredging (Gerding 1996; POSW 1995). The software was named FAST and is briefly described in Appendix A.

Mass balance modeling is recommended in an early section of this booklet as a way of understanding the probable need for, and significance of, sediment remediation. In similar fashion, mass balance modeling can help evaluate the effectiveness of remediation. The mass balance approach is based on a belief that the mass of contaminants of concern at a particular site were causing toxic effects on site or had significant potential to be re-suspended and transported to have toxic effects somewhere else. The sediment deposit mass balance approach deals with local as well as broader ecosystem concerns.

If a toxic sediment deposit is to be capped in place, the effectiveness question is: "How much of the targeted contaminant mass will be adequately covered with a cap?" The adequacy question in this context is a tough question that requires risk assessment and management to define.

If targeted toxic sediments in a sediment deposit are to be removed, there is a need for a companion process mass balance to measure how effective the remediation process is in removing, destroying, or containing contaminants and in minimizing contaminant losses during removal, treatment, and disposal.

Figure 16 combines the results of both the sediment deposit mass balance and the process mass balance done on a pilot remediation project at the SMU (Sediment Management Unit) 56/57 site in the lower Fox River, Wisconsin (WDNR 2001b). Not shown are the 357 kg (785 lbs.) of PCBs left behind and removed during a follow-up, full-scale dredging project at the same site in 2000 (Fort James 2001).

Both mass balances are accounting activities that lead to quantitative expressions of remediation effectiveness in the remediation process. In this example from the Fox River, it is assumed that contaminants are neither created nor destroyed, but simply relocated.

Sampling of contaminants in the deposit before and after dredging is the primary means of determining the mass of PCBs removed from the deposit. In the case of hydraulic dredging, monitoring of the slurry pipe flow from the dredge to the landside processing facility serves as a measure of sediments being removed from the deposit for processing. Monitoring in the river water column was done to measure losses from the deposit during dredging, silt curtain relocation, vessel traffic, and other activities. Air monitoring around the treatment site measures atmospheric losses. Monitoring of treated wastewater returned to the water body indicates the significance of another source of contaminant loss. Monitoring of contaminant mass in sediments and process wastes hauled to disposal sites indicates the percentage of contaminant mass removed from the sediment deposit and remaining within contaminant management control during remediation.

A subsequent and secondary measure of the effectiveness of sediment remediation is the answer to the question: "To what extent have the concentrations of contaminants available to aquatic organisms been reduced or increased at the remediation site?"

Answers indicate the extent to which remediation has brought reductions in bioavailable toxic contaminants at the site after remediation is done. High contaminant concentrations in a very small residual mass of sediments are likely to have much less significance in the aquatic environment than high contaminant concentrations in a large mass of residual sediments. This difference is particularly significant if there is a strong possibility that the toxic sediments on a site may be re-suspended and transported downstream in the future. The greater the percentage of contaminant mass removed, the less significant the residual concentrations become.

Assessing the risk of contaminants being "bioavailable" to aquatic organisms and people requires analysis and evaluation of both mass and contaminant concentrations. Either analysis alone is incomplete. Mass balance modeling alone may downplay the effects of residual contamination. Residual concentrations alone are ephemeral, quickly changing over time as toxic sediments move into a site, are removed by natural processes, taken up by organisms, covered by clean sediments, and moved out of a site.

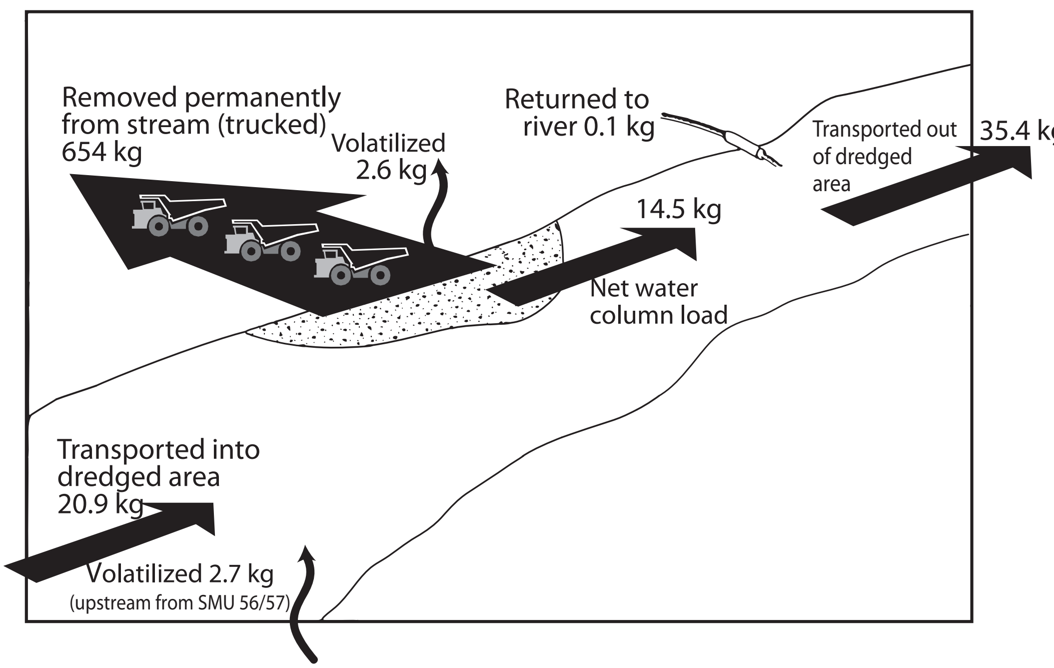

Figure 16. Pathways of PCBs at the SMU 56/57 pilot remediation site in the lower Fox River, Wisconsin, between September 1 and December 15, 1999. Source: Steur 2000.

Seeking Cost-Effective Remediation

In the early days of sediment remediation, cost-effectiveness was unknown and cost overruns were common (Keillor 1993). Is cost-effectiveness a goal worth seeking? There are some indications that cost effectiveness can be achieved with the help of state-of-the-art methods in site investigation and dredging, economy of scale, and optimum mixes of equipment with similar production rates.

As experience multiplies with large sediment remediation projects, the fruits of economy of scale and 24/7 operations will become apparent. Appendix A contains cost comparisons between a few pilot and full-scale projects on Wisconsin's Fox River. These comparisons show that the unit cost per cubic yard (meter) can be lowered.

Blazquez (1998) and Blazquez et al. (2001) showed how simulation of the dredging and disposal processes could be used to optimize the costs and productivity of those steps in sediment cleanup projects. Vaidya (1996) demonstrated that a simulation of a sediment treatment process (volume reduction) could be used to model and optimize cost and performance of the process.

Appendix A. Remediation Costs and Cost Optimization

Economy of Scale

Tables 4a and 4b demonstrate that an economy of scale can be realized when larger capacity equipment is brought in and operated 24 hours per day. The average daily production rate on the full-scale remediation project at Deposit 56/57 rose above the targeted 833 cubic yards (641 cubic meters) per day for 23 of 71 dredging days after larger equipment was brought in and used. Peak production was 1,600 cubic yards (1,230 cubic meters) per day on two days (Fort James et al. 2001). The number and capacities of filter presses used were compatible with dredging rates in order to make the overall remediation production rate satisfactory.

Table 4a. Comparison of Costs between Two Pilot Projects and a Full-Scale Sediment Cleanup Project in the Lower Fox River, Wisconsin. English units.

Parameter	Deposit N pilot project	Deposit 56/57 pilot project	Deposit 56/57 full-scale project
Period of set up of processing plant and sediment cleanup	October to December 31, 1998, and August 20 to October 14, 1999	July to late August 1999 (mob); August 30 to December 15, 1999, (dredging); December 15, 1999 to January 19, 2000 (demobilization)	July and August 2000 (mobilization), August 23 to November 8, 2000, (dredging and sand cap placement) December 15, 2000 (demobilization done)
Hours of operation	24 hours/day (1998) 10 hours/day (1999) for dewatering	24 hours/day for dewatering	24 hours/day dredging and dewatering
Daily dredging time (hrs.)	3 - 5	4.3	24
Days of dredging	104	96	71 (60 target)
Sediments removed (cubic yards)	8,175	31,346	50,316
Ave. daily dredge production rate (cubic yards/day)	79	294	709 (833 target)
Direct project cost (million dollars)	4.3[a]	11.5[b]	8.18[c]
Cost per cubic yard ($)	525	366	163
Reference	Foth and Van Dyke 2000	Montgomery Watson 2001	Fort James 2001

a. This cost included $150,000 for a public visitor area and outreach, plus $500,000 for a "redundant" plastic containment system used in the river in 1998 only. These costs were considered avoidable in a project that is not the first pilot project done in a river (Foth and Van Dyke 2000).

b. Costs included construction, dredging, treatment, disposal, operational monitoring, and construction management (Montgomery Watson 2001).

c. Included cost to place 13,500 cubic yards of cover sand over 6.5-7.4 acres at an average sand depth of 8 inches (Fort James 2001).

Table 4b. Comparison of Costs between Two Pilot Projects and a Full-Scale Sediment Cleanup Project in the Lower Fox River, Wisconsin. **Metric units.**

Parameter	Deposit N pilot project	Deposit 56/57 pilot project	Deposit 56/57 full-scale project
Period of set up of processing plant and sediment cleanup	October to December 31, 1998, and August 20 to October 14, 1999	July to late August 1999 (mob); August 30 to December 15, 1999 (dredging); December 15, 1999 to January 19, 2000 (demobilization)	July and August 2000 (mobilization), August 23 to November 8, 2000, (dredging and sand cap placement) December 15, 2000 (demobilization done)
Hours of operation	24 hours/day (1998) 10 hours/day (1999) for dewatering	24 hours/day for dewatering	24 hours/day dredging and dewatering
Daily dredging time (hrs.)	3 - 5	4.3	24
Days of dredging	104	96	71 (60 target)
Sediments removed (cubic meters)	6,288	24,112	38,705
Ave. daily dredge production rate (cubic meters/day)	61	226	545 (641 target)
Direct project cost (million dollars)	4.3d	11.5e	8.18f
Cost per cubic meter ($)	684	477	211
Reference	Foth and Van Dyke 2000	Montgomery Watson 2001	Fort James 2001

d. This cost included $150,000 for a public visitor area and outreach, plus $500,000 for a "redundant" plastic containment system used in the river in 1998 only. These costs were considered avoidable in a project that is not the first pilot project done in a river (Foth and Van Dyke 2000).

e. Costs included construction, dredging, treatment, disposal, operational monitoring, and construction management (Montgomery Watson 2001).

f. Included cost to place 10,385 cubic meters of cover sand over 2.6-3.0 hectares at an average sand depth of 10.385 cm. (Fort James 2001).

Remediation Cost-Optimization Efforts in The Netherlands

The Dutch Institute for Inland Water Management and Waste Water Treatment (RIZA) has a Development Programme for Treatment Processes (POSW) located in Lelystad, the Netherlands. POSW has had software developed to help facilitate the remediation of contaminated sediments in a cost-optimized manner at a known level of certainty.

In August 1995, The Dutch consulting firm, Aveco b.v., completed for the Dutch Ministry of Transport, Public Works and Water Management (POSW Project Office) Version 1.0 of a software program called

FAST (Aveco 1995). FAST is an acronym for "Fouten Analyse Sanerings Traject." The title can be translated as: "Error Analysis of the Remediation Path, or Phase." The software was intended to help match the accuracies of site investigation to the accuracies of dredging, leading to a "balanced removal plan with optimized total costs and results" (POSW 1995).

The POSW (1995) English language fact sheet contained an example of dredging a segment of a canal 1,100 yards (1,000 meters) long by 39 yards (35 meters) wide. The remediation target is removal of at least 80 percent of the contaminated sediment with a confidence limit of 90 percent. The FAST software was run with information from both coarse and fine grids of coring sites, 22 yards (20 meters), and 11 yards (10 meters), respectively, between coring stations. In the example, the 80 percent removal of toxic sediment at 90 percent confidence can be accomplished by removing just 4 inches (10 centimeters) of sediment, using information from the fine grid. If information is only available from the coarse grid, 8 inches (20 centimeters) of sediment must be removed to accomplish the same removal goal. The project cost using the finer grid cost $159,000 US more, but the project savings would be about $795,000 gross out of total project costs of about $6.7 million. The fine grid, with more cores, results in a net project savings of $795,000 - $159,000 = $636,000 or 9.5 percent.

POSW developed FAST with the conviction that there is an optimum to be sought in the extra effort and cost to achieve good pre-dredging site investigations and the extra effort and cost to leave no contaminated sediment behind (Gerding 1996). They believe that risk assessment with FAST "is one of the few ways to get a feeling for the results and the costs of the operations and the risks involved in the process." At that time (1996), POSW was extending the FAST approach to the treatment of dredged contaminated sediments.

A Sample of Sediment Treatment Costs

The costs of most sediment treatment processes tend to be much greater than the costs of dredging. Perceptions about these costs are confirmed, or changing, as process development and experience lead to greater efficiencies and economies of scale (Tables 5a and 5b).

Table 5a. Perceived cost per **cubic yard** ranges for various treatment methods. Costs adjusted to U.S. dollars (2000). (See Table 5b for costs in cubic meters.)

Process	Thompson & Francingues 2001 economy of scale	UWSG 1997	USEPA 1994b	Keillor 1993
Size separation and dewatering	20[a]			5 - 44
Soil washing	20[a]		38 - 90[h]	76 - 132
Biodegradation		71 - 147[g]	87 - 98[i]	39 - 181
Thermal extraction (thermal desorption)		273[e]	211[j]	40 -268
Solvent extraction		139[f]	71 - 194[k]	40 - 268
Thermal destruction	25 - 75[d]		358[l]	70 - 257
Chemical destruction				34 - 945
Solidification/Stabilization	56[b]			33 - 158
Dewater and treat at "reasonable cost"				17 - 199
Electrochemical treatment of metals and organics	33[c]			
Required tipping fee to break even in thermal destruction of toxics and production of beneficial end products	25 - 75[d]		21 - 25	

Table 5b. Perceived cost per cubic meter ranges for various treatment methods. Costs adjusted to U.S. dollars (2000).

Process	Thompson & Francingues 2001 Economy of Scale	UWSG 1997	USEPA 1994b	Keillor 1993
Size separation and dewatering	26[a]			7 - 57
Soil washing	26[a]		49 - 117[h]	99 - 172
Biodegradation		92 - 191[g]	113 - 127[i]	51 - 235
Thermal extraction (thermal desorption)		355[e]	274[j]	52 -348
Solvent extraction		181[f]	92 - 252[k]	52 - 348
Thermal destruction	33 - 98[d]		465[l]	91 - 334
Chemical destruction				44 - 1,229
Solidification/Stabilization	73[b]			43 - 205
Dewater and treat at "reasonable cost"				22 - 259
Electrochemical treatment of metals and organics	43[c]			
Required tipping fee to break even in thermal destruction of toxics and production of beneficial end products	33 - 98[d]		27 - 33	

In Tables 5a and 5b, the undated costs from Thompson and Francingues (2001) are assumed to be in year 2000 US dollars; the year in which the workshop was held and where the costs were first presented. All other costs in Tables 5a and b have been adjusted to 2000 dollars. Cost adjustments were made with Engineering News Record's Construction Cost Index. The following notes explain some of the costs in Tables 5a and b:

a. Estimated maximum operating unit cost for a facility that can process 500,000 cubic yards (384,615 cubic meters) of sediment annually.
b. Unit payment for dredging, transporting and chemical stabilization of 750,000 cubic yards (576,923 cubic meters) of dredged material to use as capping material for an old city landfill in Elizabeth, N.J.
c. Estimated unit cost to treat organics and metals in more than 100,000 cubic yards (76,923 cubic meters) of sediment.
d. $34 per cubic yard ($44/cubic meter) tipping fee required for a plant with a guaranteed sediment supply of 500,000 cubic yards per year (384,615 cubic meters), a guaranteed buyer, and stable price for 10-20 years to produce a construction-grade cement product; $25-75 per cubic yard ($33-$98/cubic meter) tipping fee required with an annual supply of 244,000 to 732,000 cubic yards (187,692 to 563,077 cubic meters) of sediment to make 20 to 60 million bricks per year; $25-29 per cubic yard ($33- $38/cubic meter) tipping fee required with an annual supply of 500,000 cubic yards (384,615 cubic meters) of sediment to make glass aggregate for tiles.
e. Total estimated cost for treatment of 100,000 yards (76,923 cubic meters) of contaminated sediment, using results from the USEPA Ashtabula River Pilot Study (USEPA 1994c).
f. Full-scale treatment of 100,000 cubic yards (76,923 cubic meters) of contaminated sediment at 80 percent on line time (effective working time), based on results from the USEPA Grand Calumet River Pilot Study (USEPA 1994d).
g. The range includes costs for solid-phase treatment of $71 per cubic yard ($92/cubic meter) for 219,780 tons (197,802 metric tons) of sediment according to Grace Dearborn (1994), costs for slurry-phase treatment of $147 per cubic yard ($191/cubic meter) at 22 to 50 tons per hour (20 to 45 metric tons/hour) according to Mourato (1993), and costs of in-situ treatment of $88 to $128 per cubic yard ($114-$166/cubic meter) according to Babin (1996).
h. The range includes costs of $38 per cubic yard ($49/cubic meter) to treat 1,170,000 cubic yards (900,000 cubic meters) at 71 cubic yards per hour (55 cubic meters/hour), $66 per cubic yard ($86/cubic meter) to treat 175,000 cubic yards (134,615 cubic meters) at 18 cubic yards (14 cubic meters) per hour, and $90 per cubic yard ($117/cubic meter) to treat 70,000 cubic yards (53,846 cubic meters) at 11 cubic yards (8 cubic meters) per hour. All

cost estimates are based on the Bergmann pilot process demonstration at Saginaw River, Michigan, during the ARCS project (USEPA 1994e).

i. The range includes a $87 per cubic yard ($113/cubic meter) cost to treat 142,857 cubic yards (109,890 cubic meters) of sediment over 10 years and $98 per cubic yard ($127/cubic meter) to treat 35,714 cubic yards (27,472 cubic meters) for five years, based on the Grace Dearborn process used at pilot scale in Burlington, Ontario, during the COSTTEP project (Grace Dearborn 1994).

j. The cost was estimated for treating 100,000 cubic yards (76,923 cubic meters) of sediment at 150 cubic yards (115 cubic meters) per day, based on the ReTec process pilot project at Ashtabula, Ohio, during the ARCS program (USEPA 1994c).

k. The cost range includes $71 per cubic yard ($92/cubic meter) to treat 695,000 cubic yards (534,615 cubic meters) at 357 cubic yards (275 cubic meters) per day, based on the CF Systems process pilot project in New Bedford Harbor, Massachusetts, and $194 per cubic yard ($252/cubic meter) to treat 71,429 cubic yards (54,945 cubic meters) at 133 cubic yards (100 cubic meters) per day, based on the B.E.S.T. process pilot project at the Calumet River, Illinois, in the ARCS program (USEPA 1994d).

l. The cost was estimated for treating 18,250 cubic yards (14,038 cubic meters) of sediment at 71 cubic yards (55 cubic meters) per day, based on the Ecologic pilot demonstration project at Burlington, Ontario, during the COSTTEP program (Eco Logic 1992).

A Reality Check on Predicted Treatment Costs

As a “reality check,” the published estimates of costs for dredging, treating, and disposing of toxic sediments need to be compared with actual costs from completed full-scale projects where prior experience, efficiencies, and economies of scale were demonstrated. The completed projects must have conditions similar to those of contemplated projects.

The following cost comparison is for hydraulic dredging, soil washing, size separation, and disposal of contaminated sediment. The project was done in 2000 to remove an estimated 50,316 cubic yards (in place) of PCB-toxic sediments from the lower Fox River adjacent to the James River Corporation’s paper plant in Green Bay. This work followed removal in 1999 of an estimated 31,346 cubic yards of sediment from the same site within an area called Sediment Management Unit 56/57 (SMU 56/57), during a pilot remediation project (WDNR Lower Fox River Web site. June 2001). The two remediation projects at SMU 56/57 removed an estimated total of 81, 662 cubic yards of sediment: more than the estimated 80,000 cubic yards of toxic sediment believed to be at this site.

The work in 2000 involved a new contractor and mobilization and demobilization of different equipment in a project that ran 24 hours a day and seven days a week to finish completion as quickly and thoroughly as possible. The 2000 project experience provides an indication of what can be expected in terms of cost and performance for future sediment remediation projects along the lower Fox River (Table 6).

Direct costs provided by Fort James (2001) were divided for the comparisons in Table 6 into costs attributable to, and relatively independent from, the volume of sediment processed.
The total volume-related project costs of $6,772,800 ($134.61 per cubic yard) accounted for roughly 75 percent of the total project costs in the Fort James project and are approximately mid-range in the estimated cost range obtainable from published literature.

Table 6. Comparison of sediment treatment costs in published literature and a modest remediation project in the lower Fox River of Wisconsin. Costs are in year 2000 U.S. dollars.

Item	Fort James dredging project in 2000 (Fort James 2001)			Published costs (Table 5)
	Non-volume related costs	Volume related costs	Unit costs ($/cy)	Unit costs ($/cy)
Indirect costs				
Annual rental value of company's 27.3-acre site for remed. process	368,500			
Value of company's internal project team work	405,100			
Direct costs				
Site improvements	355,000			
Outside engineering and project management	981,100			
Operation of the company's landfill	71,100			
Dredging, dewatering, and water treatment		5,515,900	109.63	74 - 132 [c]
Loading and transport to landfill		173,000	3.44	7.38 - 14.36 [a]
Disposal tipping fee @ $21/ton in company landfill		1,083,900	21.54	18 - 34 [b]
Total Costs	2,180,800	6,772,800	134.61	99.38 - 180.36
Total Project Costs	8,953,600			

a. Remediation Guidance Document. USEPA (1994).
b. Remediation Guidance Document.
c. Keillor (1993).

Economies of Scale

There are several economies of scale that act to lower the treatment costs per cubic yard. They include:

1. Higher production rates to help distribute the costs of labor-intensive processes.
2. Higher dredging volumes to help distribute the fixed costs associated with the project.

The estimated costs for soil washing on larger projects has potential for economy of scale in reducing the volume-related unit costs. Results from the Bergmann pilot process demonstration project in the Saginaw River, Michigan, during the ARCS project were extrapolated to three possible full-scale projects (USEPA 1994b). Soil washing could be done for a) $90 per cubic yard if 70,000 cubic yards were treated at 11 cubic yards per hour, b) $66 per cubic yard if 175,000 cubic yards were treated at 18 cubic yards per hour, and c) $38 per cubic yard if 1,170,000 cubic yards were treated at 71 cubic yards per hour.

The Cost of Excess Water in Sediment to Be Treated by Thermal Desorption

In-place sediments and mechanically dredged sediments typically have a moisture content between 40 percent and 60 percent. A moisture content of 20 percent is considered optimum for thermal desorption processes (Eykholt and Vaidya 1997). These authors showed the following relationship between energy costs and percent solids in the dewatered sediment for a project to apply thermal desorption to a volume of 100,000 cubic yards (76,923 cubic meters) (Table 7). In the example, the sediment is heated from 20 degrees Celsius to 300 degrees Celsius. This is more than the heating required to boil water and remove water vapor from the system. In both systems there is a 79 percent decrease in energy required when the solids content is increased from 40 to 80 percent.

Table 7. Energy unit costs (US dollars, 1994) to desorb contaminants thermally from 100,000 cubic yards (76,923 cubic meters) of toxic sediments. Eykhold and Vaidya (1997).

Percent solids in dewatered sediments	Direct-fired system		Indirect-fired system	
	$ per cubic yard	$ per cubic meter	$ per cubic yard	$ per cubic meter
40	7.66	9.57	19.13	23.92
50	5.23	6.54	13.08	16.35
60	3.62	4.52	9.04	11.30
70	2.46	3.08	6.16	7.70
80	1.60	2.00	3.99	4.99

Relative Costs of Disposal

Costs for a number of disposal options were reported in the U.S. Environmental Protection Agency's *Remediation Guidance Document* (USEPA 1994b).

Some generalized conclusions have been made about the relative costs of disposal (Henshaw and Cervi 1997). There will be exceptions to these conclusions at some particular locations. With some of the options, the economics are a function of both the dredging method and the cost of dewatering the dredged sediment prior to disposal or reuse. The following comparable costs are only the short-term costs of transporting toxic sediments to a disposal site and securing the material on site. There are long-term costs associated with monitoring and with the possible consequences of a breach in the disposal site and any harmful environmental exposure that may result from the breach. Those long-term costs are not considered in this section.

For highly contaminated dredged sediment in the Great Lakes Basin, the costs for landfilling are generally less than the costs for confined disposal where there is less than 7,000 cubic meters (9,100 cubic yards) of mechanically dredged sediment or less than 4,000 cubic meters (5,200 cubic yards) of hydraulically dredged sediment. Landfills approved for hazardous materials are recommended for these sediments. In Wisconsin, where state landfill standards are high, the USEPA has approved licensed municipal landfills for disposal of sediments classified as hazardous waste under the Toxic Substances Control Act (TSCA).

For moderately contaminated dredged material in the Great Lakes Basin, disposal in a confined disposal facility (CDF) is generally more economical than landfilling for more than 6,000 cubic meters (7,800 cubic yards) of mechanically dredged sediment and for more than 16,000 cubic meters (21,000 cubic yards) of hydraulically dredged sediment. For lower volumes, direct municipal landfilling is generally the least expensive option. With the CDF scenario, material would be dried in the CDF, rehandled, and transported to a landfill site, where a tipping fee would be charged.

For very lightly contaminated dredged sediment in the Great Lakes Basin, open-water disposal and beach nourishment are the least costly methods of disposal, if permitted. Land application is only economical in small- to medium-sized applications.

In 1997, when GLPF project writers wrote these general conclusions about disposal options, there was little experience with level bottom capping and confined aquatic disposal, and no clear regulations had been developed for these options. At that time, it did not appear that these methods are economical for remediation projects alone. The writers thought that the economics could be favorable for a remediation project done in conjunction with a navigation dredging project so that "clean" capping material could be obtained "free." The lack of long-term experience with capping was one reason the Dutch did not seek to cap the toxic sediments in Lake Ketelmeer.

Appendix B. Reuse of Sediments in the Manufacture of Useful Products

Thompson and Francingues (2001) identified some potential beneficial reuses of toxic sediments that have been explored for large sediment remediation projects. The processes described below are dated examples of certain past efforts to manufacture useful products as reasonable alternatives to disposal. These processes may, or may not, be in use today. For described processes that are in use today, their state of development and economics may be significantly different than they were in 2000 or 2001. There are undoubtedly other processes that have been developed since this sample was put together.

No endorsement of processes and products is intended or implied here. There may be numerical errors that have propagated through the reference and into this booklet. The reader is advised to check original sources for numerical information.

The acceptability of these processes and products may vary from country to country. Concerns about environmental hazards associated with such processes should be addressed with risk analysis and risk management.

These examples of beneficial uses demonstrate that contaminated sediment that is commonly considered an undesirable, expensive waste product has the potential to be a raw material for a commercially valuable product. The cost to the sediment supplier may be considerably less than the tipping fee charges at municipal landfills, but that savings is likely to be at least partially offset by a need to increase the dewatering of the dredged material from 50% solids (acceptable at a landfill) to 80% solids (needed for thermal treatment). The tipping fees charged by plants manufacturing these products seem more likely to be cheaper than tipping fees charged for use of hazardous waste disposal sites. Substantial capital investments and a guaranteed, long-term supply of toxic sediment may be required before certain beneficial uses can be realized.

Blended (Construction-Grade) Cement.

A process was proposed by Endesco Services, Inc. Water content of dredged material is reduced using waste heat from a thermal process that creates a cement product. Bench-scale and pilot-scale projects had been evaluated using dredged material, and a demonstration plant was under construction in New Jersey in 2000 or 2001. Engineering had been completed on a module with an annual capacity of 100,000 cubic yards (77,000 cubic meters) and on a five-module production plant with an annual capacity of 500,000 cubic yards (385,000 cubic meters). For a large remediation dredging project with a production rate of 35,000 cubic yards (27,000 cubic meters) per month, a plant of this capacity would be needed. That's a plant with 25 percent of the typical capacity of a full-sized cement plant. Capital costs were estimated at $100 million. Operating costs were estimated, using a 20-year life span for the plant and use of various fuels. The tipping fee for accepted sediment, needed for profitability, ranged from $7.66 to $33.69 per cubic yard ($9.96 to $43.80 per cubic meter) (within the range of landfill tipping fees).

Building Bricks.

In 2001, Hanseaten, Stein Ziegelei GmbH of Hamburg, Germany, manufactured building bricks from contaminated dredged material. Dewatered, fine-grained sediments from the Port of Hamburg are mixed with natural clay and ground brick, dried, and pressed into bricks that are ceramicized in a kiln. Brick production was 5 million bricks per year, using 100,000 cubic yards (77,000 cubic meters) per year of heavily toxic sediments (before dewatering). The process could be scaled up to produce 20 to 60 million bricks per year, using 300,000 to 900,000 metric tons (330,000 to 1,000,000 tons) per year of dredged sediment. A capital investment of $25 to $80 million would be required, plus the costs of a facility to screen and separate the fine from the coarse dredged material. The tipping fee for accepted sediment would need to be between $20 and $60 per metric ton ($18 and $54 per ton) of sediment. [Note: for sediment at 80 percent solids, and a density of 2 tons per cubic yard, the estimated tipping fee needed would be about $36 to $108 per cubic yard.] A steady and guaranteed supply of sediment and a stable market for the bricks produced over the life of the plant are needed to make the economics work.

Glass Aggregate.

In 2001, Global Plasma Systems Corporation, in partnership with Westinghouse Plasma Corporation, was marketing Plasma Vitrification Technology. By 2001, the process had been evaluated at bench and pilot scales using dredged materials to manufacture architectural tiles, glass fiber, sandblasting grit, roadbed aggregate, or roofing granules. A preliminary design had been completed for a full-scale plant, but the technology has not been demonstrated for large dredging projects. A plant that would process 500,000 cubic yards (385,000 cubic meters) per year of sediment would produce 196,000 metric tons (218,000 tons) per year of architectural tiles. The plant would require a capital investment of $80 to $90 million. The tipping fee for accepted sediment, needed for profitability, ranged from $25 to $29 per cubic yard ($33 to $88 per cubic meter) (within the range of landfill tipping fees). As with the other proposed processes, a steady and guaranteed supply of sediment and a stable market for the glass aggregate is required over the expected life of the plant.

Lightweight Aggregate for the Construction Industry.

In 2001, Harbor Rock Holdings had a technology for producing a construction-grade lightweight aggregate, using a rotary kiln and a thermal process. Organic contaminants are thermally destroyed (greater than 99 percent efficiency), and heavy metals are immobilized. Dewatered sediments would be conditioned and extruded into pellets that are fed into the kiln for firing and thermal expansion. By 2001, the process had been evaluated on a bench scale with sediments at several sites on the East and West Coasts. The company was reportedly developing projects that can handle from 500,000 to 3,000,000 cubic yards (385,000 to 2,300,000 cubic meters) of sediment per year. No project capital and operating costs had been reported, and no required tipping fees had been estimated for profitability. The firm estimated that the national market for lightweight aggregate was about 17 million tons (15 million metric tons) per year but only 10 million tons (9 million metric tons) per year was then being produced or imported. Potential uses for the product include geotechnical fill, ready-mix or structural concrete, masonry block, specialty concrete products, and road and bridge paving.

Flowable Material for Construction Fill.

In 2001, Pohlman Materials Recovery had a technology in which chemical additives modify dredged material into a flowable construction fill product after large debris is removed. Some dewatering of the material may be required prior to blending with proprietary binders, fine aggregate, and water. Once blended, the product is transported in cement mixer trucks to the construction site for immediate use. By 2001, the process had been evaluated at pilot scales up to 30,000 cubic yards (23,000 cubic meters) for dredged sediments at two sites. By 2001, fixed and mobile production facilities had been developed with maximum outputs greater than 6,000 cubic yards (4,600 cubic meters) per day. The technology had been demonstrated for up to 10,000 tons (9,000 metric tons) of sediment but not for large dredging projects. Required tipping fees for the dredging material range from $5 to $20 per cubic yard ($7 to $26 per cubic meter). The product value depends upon demand but was estimated to range from $10 to $40 per cubic yard ($13 to $52 per cubic meter), delivered to the construction site. As with the other processes mentioned above, the economics of the process require a steady and a guaranteed supply of sediment and a market for the flowable fill product. Since only screening, dewatering, and blending are required, without thermal processing, capital costs are likely to be considerably less than for the other processes mentioned above (Thompson and Francingues 2001).

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Some Sources of Information

The following sources include Web sites, which are always subject to change in address as well as content. Use of an appropriate keyword and a Web site's search function (if available) are recommended.

The sources of information listed below are only samples of the information to be gained by using a search engine and search terms such as "remediation of contaminated sediments" or "cleanup of contaminated sediments" on the Internet. Some results are from sources that are not commonly thought of in the context of this subject. For example, such a Web search will turn up a conference on "Contaminated Sediments: Evaluation and Remediation Techniques" sponsored by the ASTM Committee D18 on Soil and Rock, May 23 – May 25, 2006. Another example: "Multicriteria Decision Analysis: A Comprehensive Decision Approach for Management of Contaminated Sediments" (Risk Analysis, Journal of the Society for Risk Analysis. Vol. 26, Issue 1, February 2006).

Benefits of Sediment Remediation

Economic benefits of sediment remediation at Waukegan, Illinois. A collaborative study by the Northeast-Midwest Institute and economists from the University of Illinois (Champaign-Urbana) and San Francisco State University, funded by the USEPA and GLNPO. The project summary report can be found at the Northeast-Midwest Institute's Web site: *www.nemw.org.* A peer-reviewed paper describing the project was published in 2004 in the Journal of Great Lakes Research. The paper by John B. Braden, Arianto A. Patunru, Sudip Chattopadhyay, and Nicole Mays was titled: "Contaminant Cleanup in the Waukegan Harbor Area of Concern: Homeowner Attitudes and Economic Benefits."

A booklet titled "Estimating Economic Benefits of Cleaning Up Contaminated Sediments in Great Lakes Areas of Concern," by John R. Stoll, Richard C. Bishop and J. Philip Keillor. 2002. The University of Wisconsin Sea Grant Institute, Madison, Wisconsin.

A handbook titled "Economic Valuation of Natural Resources, A handbook for coastal resource policymakers," by Douglas W. Lipton and Katharine F. Wellman. 1995. NOAA Coastal Ocean Program Decision Analysis Series No. 5. Coastal Ocean Office, 131 pages, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. Washington, D.C.

Guidance for Planning the Remediation of Contaminated Sediments

United States Environmental Protection Agency (USEPA). Publications and other documents are accessible from a number of USEPA Web sites. These sites include that of the Superfund Innovative Technology Evaluation (SITE) Program (*www.epa.gov/ORD/SITE/*), the Superfund Program (*www.epa.gov/superfund/resources/sediment/*), and the Great Lakes National Program Office (GLNPO, *www.epa.gov/glnpo/sediment*). Sample USEPA documents include:

> Guidance for conducting remedial investigations and feasibility studies under CERCLA. EPA/a540/G-89/004. Office of Emergency and Remedial Response, Washington, D.C. 1988.
>
> Evaluating environmental effects of dredged material management alternatives-a technical framework. EPA-842-B-92-008. U.S. Army Corps of Engineers and U.S. Environmental Protection Agency, Washington, D.C. 1992.

Selecting remediation techniques for contaminated sediment. EPA-823-B93-001. U.S. Environmental Protection Agency, Office of Water, Washington, D.C. 1993.

Remediation guidance document. Assessment and Remediation of Contaminated Sediments (ARCS) Program. EPA-905-R94-003. U.S. Environmental Protection Agency, Great Lakes National Program Office. 1994.

News about remediation processes, markets, commercialization, cleanup, demonstrations, and feasibility studies is available from USEPA's Technology Innovation Program: *http://cluin.org/produts/tins/.*

United States Army Corps of Engineers (USACE), Engineer Research and Development Center, Environmental Laboratory (EL). The EL includes a Dredging Operations Technical Support (DOTS) Program (*http://el.erdc.usace.army.mil/dots/dots.html*), and an Environmental Effects and Dredging and Disposal (E2-D2) literature database (*http://el.erdc.usace.army.mil/e2d2/main.html*).

Permanent International Association of Navigation Congresses (PIANC). Web site: *www.pianc-aipcn.org/publications/.* PIANC publishes "technical briefs" that are updates of the findings and conclusions of working groups and the organization's technical position and observations about management of contaminated dredged material around the world. Examples of useful PIANC reports include:

Handling and treatment of contaminated dredged material from port and inland waterways "CDM", Volume 1. PTC I. Report of Working Group No. 17. Supplement to Bulletin No. 89. 1996.

Environmental guidelines for aquatic, nearshore and upland confined disposal facilities for contaminated dredged material. Report of ENVICOM WG5.

National Academies Press. Web site: *www.nap.edu/.* Sample documents include:

Contaminated sediments in ports and waterways. National Research Council. 1997.

A risk-management strategy for PCB-contaminated sediments. National Research Council. 2001.

SedWeb. "A Web community for sediments research and management" sponsored by the South and Southwest Region of the Hazardous Substance Research Centers (HSRC); a five-center consortium established and supported by the U.S. Environmental Protection Agency's STAR Program. Web sites: *http://maven.gtri.gatech.edu/sediments/index.html* or *www.sediments.org.* SedWeb has a valuable page of links to other resources including: management guidance sources, federal programs, Great Lakes reports, journals, professional associations, nongovernmental organizations, libraries, remediation projects, research programs, state and local programs, magazines, and newsletters. The links to remediation projects include the major efforts to clean up PCB-contaminated sediments in the lower Fox River of Wisconsin and in the Hudson River.

The Interstate Technology and Regulatory Council, Remediation Process Optimization Team. The council is a "state-led, national coalition" of environmental regulatory agencies from 40 states and the District of Columbia, three federal agencies, tribes, and public and industry stakeholders with the mission of achieving better, more cost-effective, environmental techniques, including remediation.

Although not specifically focused on sediment remediation, their guidelines may be useful. An example: "Remediation Process Optimization: Identifying Opportunities for Enhanced and More Efficient Site Remediation" (September 2004).

Trade Magazines or Journals

Integrated Environmental Assessment and Management. A journal of the Society of Environmental Toxicology and Chemistry (SETAC). Examples of articles:

> Assessing and managing contaminated sediments: Part I, Developing an effective investigation and risk evaluation strategy. Vol. 1, No. 1. 2005. A review article.
>
> Assessing and managing contaminated sediments: Part II, Evaluating risk and monitoring sediment remedy effectiveness. Vol. 1, No. 1. 2005. A review article.
>
> Introduction to special section: finding achievable risk reduction solutions for contaminated sediments. Vol. 2, No. 1. 2006.

Terra et Aqua. A European trade journal of articles about dredging and disposal of sediments, including contaminated sediments. The journal can be accessed through the Web site of the International Association of Dredging Companies (IADC). Web site: *www.iadc-dredging.com/*.

International Dredging Review. Articles about particular dredging projects (including environmental dredging projects) and new technology. Web site: *www.dredgemag.com*.

Other Resources

Great Lakes Information Network (GLIN). From the home Web page (*www.great-lake.net*), through "Environment," then "Pollution," to "Contaminated Sediments in the Great Lakes," reaches a Web page that has information about "What's New, general resources, publications and related resources." The more direct route: *www.great-lakes.net/envt/polution/consed.html*.

The Great Lakes Commission (*www.glc.org/*). From this Web page, one can access the Web page of the Great Lakes Dredging Team, an inter-agency working group. Their Web page includes information on beneficial uses of dredged material, case studies, and contaminated sediments, as well as links to reports and to other Great Lakes organizations involved in navigational and environmental dredging.

The lower Fox River of Wisconsin. This is one of the major, long-range clean-up projects for contaminated sediments in the United States. One Web source for reports and updates is the Fox River Web site of the Wisconsin Department of Natural Resources (*http://dnr.wi.gov/org/water/wm/foxriver/index.html*). This site includes notices of meetings and proposed changes, as well as a sidebar menu that includes a link to a database of reports and documents and a link to Fox River Current (a newsletter published by the USEPA, Region 5). Another Web source for updates is that of the Fox River Watch, a project of the Clean Water Action Council of Green Bay, Wisconsin (*www.foxriverwatch.com/index.html*).

Cleanup of PCB-contaminated sediments in the Hudson River. Site development preparations for dredging are planned to begin in 2007 for portions of the river. Progress can be tracked at a number of web sites including the following web sites of principal organizations involved with the cleanup.

General Electric's Hudson River Project. *www.ge.com/en/citizenship/ehs/remedial/hudson/index.htm*

United States Environmental Protection Agency
www.epa.gov/hudson/

New York State Department of Environmental Conservation, Division of Environmental Remediation
www.dec.state.ny.us/website/der/index.html
www.dec.state.ny.us/website/der/projects/gehudsonfalls/

International experience with dredging and with sediment remediation. The International Association of Dredging Companies (IADC). Web site: *www.iadc-dredging.com/*.
The IADC and the Central Dredging Association (CEDA) have linked up to produce a series of environmental guides for dredging that have been updated and are expected to be available in June 2007. CEDA also has other publications including a newsletter; "Dredgeline". A CEDA Web site for news: *www.dredging.org/news_details.asp*. The Dutch Ministry of Transport, Public Works and Water Management (RIZA) has information on remediation and recycling of contaminated sediments under the acronym "REUSED" which stands for Remediation, Recycling and Reuse of European Sediments. Information can be obtained by beginning at the following Web site: *www.waterland.net/index.cfm/* or by using a RIZA Web site search function.