

ENCYCLOPEDIA OF

ENVIRONMENTAL

ANALYSIS

— AND —

REMEDIATION

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Editor

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SEDIMENTS, MANAGEMENT AND REMEDIATION OF CONTAMINATION

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From the American industrial revolution (circa 1830) to the present, waste products from mines, factories, and municipalities have been discharged and spilled into the nations waterways as point-source pollution. These discharges have been supplemented by nonpoint discharges of fertilizer, pesticides, and other products that runoff from rural areas. Much of these pollutants become adsorbed to the surface of fine-grained particles which settle and form a contaminated sediment at the bottom of the waterway. Contaminated sediments may be subsequently buried by clean sediments, remobilized by erosion or disturbance, and resuspended by dredging. These contaminated sediments were long considered benign until research in the 1960s and 1970s revealed that some chemicals in sediments were bioavailable and could bioaccumulate up the food chain.

The federal/state regulations and criteria which affect the excavation, treatment, and disposal of contaminated sediments and dredged materials are continuously changing to incorporate the results of new research data and experiences. Prior to the 1960s, dredged materials were not considered to be problematic, thus disposal alternatives were typically evaluated

on the basis of economics or lowest cost rather than environmental impact. This generally meant open water disposal of harbor and channel sediments, and land (or wetland) disposal of river sediments. During the mid- to late 1960s, questions were raised about the effects of dredging on water quality. In 1971 the U.S. Environmental Protection Agency (EPA) issued the report "Criteria for Determining Acceptability of Dredge Spoil Disposal to the National Waters" as the first effort to identify and classify contaminated sediments in the nations waterways for purposes of controlling dredging and disposal operations. The major concern at that time was to limit nutrient loadings such as nitrogen and phosphorous. Thus, sediment quality criteria (SQC) were established from limited scientific data to define the type and quantity of pollutants associated with dredged material. Sediments that failed these criteria were considered unsuitable for open water disposal and required placement in a confined disposal facility (CDF). Since that time the EPA criteria for classifying contaminated sediments has expanded to include numerous heavy metals and PCBs with the sediment quality criteria undergoing frequent updating. Although the development of these criteria was expected to have a positive effect on human health and well being, they have significantly slowed the process and increased the cost of dredging clean sediments from the nations waterways.

It is obvious from the nature of the problem that the process of remediating a site with contaminated sediments is very difficult, complex, and multidisciplinary in nature and that existing regulations, in many respects, often complicate the problem. Although regulations specify the criteria for defining a hazardous material, it is not clear how to sample and test a submerged site to define the spatial extent of pollutants, how to select and operate the appropriate dredge, how to treat or contain and isolate the contaminated sediments, and finally how to monitor and verify that target levels have been attained. There have been a small number of contaminated sediment remediations and demonstrations to date, however, this field is still in its infancy and is likely to increase in importance in the future.

In 1992, U.S. Congress passed the Water Resources Development Act which requires EPA, in consultation with the National Oceanic and Atmospheric Administration and the U.S. Army Corps of Engineers, to conduct a national survey of data regarding sediment quality in the United States. The goals of the National Soil Inventory (NSI) are to assess the national extent and severity of sediment contamination, to identify areas in need of further assessment and to identify high risk areas for appropriate remedial action. The NSI is to be updated every two years with the first report to congress in summer 1995. The effort to date (1) is based on over 3.4 million records from water body segments around the country including sediment chemistry and biological sample measurements of tissue residue, toxicity, benthic abundance, and histopathology. These preliminary analyses have identified over 1700 water body segments as potential areas of concern with many additional areas likely to be added in the future. The first step in remediating these areas must be to identify and control the source followed by a concerted effort to clean the contaminated sediments.

A listing of industries associated with particular sediment contaminants is presented on Table 1. Such contamination is typically historical and much of it predates regulatory control.

Additionally, ongoing releases from combined sewer overflows (CSOs) can be locally significant. Sediments are also contaminated by nonpoint sources such as agricultural runoff. A portion of the sediments are so highly contaminated that they require remedial action. For example, about one-half of the total amount of sediments dredged in the Great Lakes (approximately $1.5 \times 10^6 \text{ m}^3$) are sufficiently contaminated to preclude their unconfined release to the environment. In this article, such materials are referred to as problematic sediments. The management and possible remediation of these dredged materials is the focus of this article. These contaminated sediments require special consideration during dredging and disposal operations because of potentially adverse impacts on water and air quality and aquatic organisms. Sound planning and design of dredging operations and either disposal facilities or remediation processes are necessary to protect the environment, while keeping these activities economically viable. The remaining half of the sediments are generally classified as clean and suitable for unconfined/untreated disposal.

The regulatory requirements for the disposal of dredged material are determined by both the type and level of the contaminants associated with the dredged material, as well as the extent to which the contaminants could potentially be released from the sediments to proximal air, groundwater, or surface water. To date, regulatory concern with most contaminated dredged material disposal projects has been focused primarily on containment of release routes to water, but as decisions need to be made on the proper handling of some of the more contaminated materials, potential contaminant loss pathways like air emission and seepage of free oil-phase organic contamination are being examined more closely. This is reflected in Table 2, which depicts several pertinent relationships between the level of sediment contamination, the degree of contaminant partitioning to the water associated with the sediments, in conjunction with three conceptual categories under which sediment disposal can occur and the significant disposal regulations. As depicted on Table 2, these three conceptual approaches to dredged material disposal are labeled "beneficial use or open water disposal," "solids retention," and "hydraulic isolation."

Regulation of Dredging Activity

CWA-COE 404 Program. Section 404 of the Clean Water Act (CWA) regulates the disposal of dredged or fill material into navigable water by granting the U.S. Army Corps of Engineers (U.S. ACE) the authority to designate disposal areas and the authority to control their use. Navigable waters now include all waters which may be susceptible to use in interstate commerce, or the use, degradation, or destruction of which could affect interstate commerce. The CWA regulates the impact of effluent discharge and dredged material disposal activities on navigable waters. As such, the CWA typically addresses the disposal or impact of materials having a high liquid and low solid content. As an example, all states within EPA Region 5 (Great Lakes) are authorized under the CWA and have implemented water quality standards (WQS) that are as strict or stricter than those in the CWA, and these states must certify or waive WQS Certification of all proposed dredged material disposal into the US waters in order to comply with 404 permit requirements.

Table 2. CDF Design Criteria Based on Contaminant Level and Partitioning^a

		Problematic Sediments		
	Minor Partitioning	Moderate Partitioning	Extensive Partitioning	RCRA/TSCA Sediments
Minor Sediment Contamination	Minor Partitioning	Moderate Partitioning	Extensive Partitioning	RCRA/TSCA Sediments
Beneficial use or open water disposal	Solids Retention approach	Hybrid approach	Hydraulic isolation approach	Hydraulic isolation CDF MTG design
	Increasing Degree of sediment isolation	Hydraulic isolation during sediment disposal only	Increasing degree of hydraulic isolation	CWA 402 permit for a point discharge
CWA 401 certification for dredged material discharge	Filter intake CDFs CWA 401 certification for diffuse discharge or diffuse discharge	CWA 401 certification for point discharge	CWA 401 certification for point discharge	EPA minimum
	Shoreline and in-lake CDF designs	87 COE CDF Design manual		Technology guidance
		Shoreline and in-lake CDF designs	Shoreline and in-lake CDF designs	
			Upland CDF designs	
			Region 5 CDF guidance designs	
	CWA Section 404 and NEPA, EPA/COE framework			
			Increasing degree of sediment contamination	

^a Ref 3.

In approving a discharge site for a 404 permit, the ACE applies guidelines developed jointly by ACE and EPA in a Memorandum or Agreement (4) as codified in 40 CFR Part 230. These guidelines require that dredged or fill material should not be discharged into an aquatic ecosystem unless it can be demonstrated that the discharge will not have an unacceptable impact either individually or in combination with other activities that could affect the ecosystem. A primary emphasis of this review is the ability of the disposal operation to be carried out to satisfy the four requirements found in Section 230.10. These requirements are as follows. 230.10 (a): The discharge site must represent the least damaging, practical alternative; 230.10 (b): Requires compliance with established legal standards (eg, State Water Quality Certification); 230.10 (c): No significant degradation of the aquatic ecosystem; and 230.10 (d): All practical means must be made to minimize or mitigate adverse environmental impact. The concept of a "mixing zone" in the vicinity of the point of discharge is introduced in 404(b)(1) guidelines presented in 40 CFR 230 and may also appear in state water quality regulations. This concept allows contaminant concentrations to exceed state WQS only within a predefined mixing zone that is immediately adjacent to the point of discharge or dredging activity. The mixing zone analysis is being eliminated by many States in favor of WQS limits based on biological concentrating contaminants (BCC).

CWA-EPA 404 Program Review. Under CWA 404(c), the EPA Administrator is given authority to veto a Section 404 permit issued by U.S. ACE if the administrator determines the discharge of dredged or fill materials into the specified disposal area will have an unacceptable effect on municipal water supplies, shellfish beds, fishery areas, wildlife, or recreational areas. EPA has promulgated regulations that define the environmental restrictions associated with these disposal areas (40 CFR Part 231).

CWA-State 401 Program Review. As stated above, Section 401 of the CWA provides that an application for a 404 permit must include a certification from the state in which the discharge originates that the discharge will comply with the following sections of the CWA:

- 301:Effluent Limitations
- 302:Water Quality Related Effluent Limitations
- 303:Water Quality Standards and Implementation Plan
- 306:National Standards of Performance
- 307:Toxic and Pretreatment Effluent Standards

Primary emphasis in this review is maintenance of state WQS beyond the mixing zone at the point of discharge. The State must establish procedures for public notice for all applications for 401 Certification. A 404 permit cannot be granted, and a USACE maintenance project cannot proceed if certification is denied by the State.

CWA-State 402 Program Review. The continuing discharge of rainwater and/or seepage from a confined disposal facility (CDF) is also subject to control under the CWA. Such discharges may be required to adhere to discharge limitations, based on State 401 WQS Certification and authority. Some confusion has occurred in the past because regulations under Section 402, the National Pollutant Discharge Elimination System (NPDES) program also seem to be appropriate. EPA

Great Lakes Region 5 has expressed interest in using Section 402 to regulate certain types of discharges from CDFs, such as rainwater, that are not specifically exempted from Section 404. However, Section 402 has never been used for this purpose, and Section 401 has equivalent power. A state may, when appropriate, issue a 401 Certification letter that could be virtually indistinguishable in content from a typical NPDES permit. However, because most CDF releases, which are usually diffuse and intermittent, do not usually violate state WQS outside of an approved mixing zone, state 401 Certifications may range from simple waiver letters to permit-like letters requiring specific pollution monitoring and limits, groundwater monitoring requirements, fish migration timing restrictions, and even plan modifications that may or may not be acceptable to the ACE or the permittee. Any project consisting of problematic sediments or dredged materials is likely to require considerable effort coordinating for an acceptable 401 Certification from the State.

Marine Protection Research and Sanctuaries Act (MPRSA). Section 102 of MPRSA requires EPA, in consultation with ACE, to develop environmental criteria for all ocean disposal. Section 103 of MPRSA provides that U.S. ACE must specifically authorize all ocean disposal of dredged materials.

National Environmental Policy Act (NEPA). Dredged material disposal activities must comply with applicable NEPA requirements regarding identification and evaluation of alternatives associated with the dredging project. Sections 102(2) and 102(2)(E) of NEPA require the examination of reasonable alternatives to the actions proposed by the lead federal agency. All alternatives, even those discarded, must be analyzed in an environmental assessment (EA) or environmental impact statement (EIS) (qv). For federal dredging projects, the ACE is responsible under NEPA for developing alternatives for the discharge of dredged material. The U.S. ACE is also responsible for preparing NEPA documents for Section 404 permit decisions. NEPA does not define performance objectives, but does require the process evaluation procedure.

Contaminated Sediments

Regulation of Contaminated Dredged Materials. For the purposes of this document, dredged materials are considered contaminated when the ambient or leachable concentration of metals or organic compounds exceed federal RCRA or TSCA regulatory limits or when contamination exists in high enough concentrations and are sufficiently available to affect human and/or ecosystem health. Contaminated dredged material may threaten human health by direct exposure or when contaminated water or organisms are consumed. Consequently, an acceptable disposal option for such sediments will entail some form of isolation from the ambient environment. Contaminants in sediments can be from point sources (municipal or industrial effluent), nonpoint sources (eg agricultural runoff or airborne sources), and from other sources such as spills or leaks.

RCRA and TSCA regulations provide for the land disposal of contaminated materials in cells that hydraulically isolate the waste material from proximal ground and surface waters. Wastes placed within such landfill cells must not contain free liquids as defined by the paint filter test (EPA Method 9095).

RCRA and TSCA land disposal regulations are therefore directed at wastes that are very high in solids and have little or no free liquids. Conversely, CWA regulations are directed at the disposal of waters containing very small concentrations of suspended solids and partitioned contaminants. With large portions of both water and solids, environmentally acceptable disposal options for dredged sediments combine aspects common to both of these regulatory perspectives.

In general, the potential for sediments to hold or bind contaminants increases with increasing percentages of fine-grained sediments (silts and clays) and organic carbon content. Fine-grained sediments have a high surface area per unit mass and significant ionic forces that attract and retain many classes of contaminants. The presence of organic matter increases the affinity of sediments for metals and organic contaminants.

Sediment pH and oxidation/reduction status also affect the mobility and biological availability of contaminants. Strongly acidic (low pH) sediments slow microbial activity and increase the soluble level of toxic metals. Weakly acidic to slightly alkaline sediments result in less mobile metals. The oxidation/reduction potential of a sediment, as measured by the redox potential of the sediment, has a major effect on the capture or release of metals by a sediment. Frequently, the sediment contaminants are chemically stable under the geochemical conditions existing within the *in situ* sediments. However, changes in the pH or redox potential of a sediment during dredging, remediation or disposal will substantially affect contaminant mobilization. This influences the partitioning of the contaminant between the sediment solids and the pore water. EPA is currently updating equilibrium sediment quality criteria (SQC) that normalize nonionic organic contaminants to organic carbon and metal contaminants to acid volatile sulfide (AVS). The role of long-term equilibrium contaminant partitioning is reflected in the regulatory scheme shown on Table 2. Contaminant mobilization mechanisms in dredged materials, SQC, and remediation of contaminated materials are discussed in greater detail in a later section.

Problematic Sediments. In this article, problematic dredged materials are defined as materials which are sufficiently contaminated to preclude their unconfined release to the environment, eg open water disposal or beneficial reuse. Problematic dredged material are commonly the result of nonpoint source releases and spills or point-source releases which occurred prior to the effective date of the CWA as well as most other environmental regulations. Because the unrestricted release of problematic dredged materials to the environment is unacceptable, the Adequate Environmental Performance and Protection (AEPP) disposal criteria for these materials will require containment to some extent. The extent of containment required is dependent on the nature, concentration, and partitioning potential of the specific contaminants. Provided an acceptable level of suspended solids is achieved in the effluent, the AEPP criteria for the disposal of sediments associated with low levels of tightly sorbed contamination may require only physical isolation of the dredged material. AEPP criteria for the disposal of sediments with higher levels of contaminants that partition to the aqueous phase at concentrations of concern will generally require hydraulic isolation of the dredged material as well as any derived effluent. These two approaches to the disposal of dredged materials have been labeled the "sediment retention approach" and the "hy-

draulic isolation approach," respectively. As discussed below, the disposal of sufficiently contaminated problematic dredged material can be regulated by the Resource Conservation and Recovery Act, Subtitle C (RCRA-C) and/or Toxic Substances Control Act (TSCA). AEPP criteria for the disposal of such highly contaminated materials which meet the regulatory requirements for land disposal will require a hydraulic isolation design based on RCRA-C Minimum Technical Guidance (MTG).

TSCA Sediments. Enacted in 1976 by U.S. Congress in response to the discovery that DDT and other pesticides were impacting waterfowl and that polychlorinated biphenyl (PCBs) were present in large numbers of birds and fish, TSCA required EPA to test certain existing chemicals to determine if they posed an unacceptable human health or environmental risk. While the 29 sections of TSCA cover a wide range of considerations, TSCA has become fundamentally associated with the control of PCBs at concentrations equal to or greater than 50 ppm. The use, control, and disposal of PCBs under TSCA are covered in 40 CFR Part 761, as issued in 1982. Subpart D specifies that, in general, PCBs at concentrations equal to or greater than 50 ppm must be disposed of in an incinerator. However, 40 CFR Part 761.60 (a)(2) also allows PCBs at concentrations less than 500 ppm to be disposed of in a chemical waste landfill as defined in 761.75. TSCA specifically addresses dredged sediments contaminated with PCB concentrations equal or exceeding 50 ppm in 761.60(a)(5). This section provides three methods of PCB contaminated sediment or sludge disposal: (1) incineration, (2) placement in a TSCA chemical waste landfill, and (3) using a disposal method approved by the Regional Administrator. Application for the (3) must demonstrate that disposal in an incinerator or chemical landfill is not reasonable and appropriate, and that the alternative disposal method will provide adequate protection to health and the environment. TSCA also allows for the temporary storage of wastes containing PCBs at concentrations equal to or greater than 50 ppm for a time period not to exceed one year in an approved storage facility.

A chemical waste landfill under 40 CFR Part 761.75 (TSCA) must satisfy well-defined technical liner requirements. These technical liner requirements are based on hydraulic isolation of the PCB contaminated material and include the following:

1. As a minimum, the landfill must have 4 feet of *in situ* natural soils or 3 feet of compacted soils having a hydraulic conductivity equal to or less than 1×10^{-7} cm/s. A synthetic membrane liner must be used when, in the judgment of the Regional Administrator, the hydrogeologic or geologic conditions at the site require it to achieve an equivalence to these criteria.
2. The landfill design must include a leachate collection/monitoring system.
3. The bottom of the liner system must be at least 50 feet from the historic high water table. Floodplains, shorelands, and groundwater recharge areas shall be avoided.
4. The landfill must be protected from the 100 year flood.
5. The landfill site must have low to moderate relief to minimize long-term erosion.

6. The landfill must be equipped with a monitoring system that allows both ground and surface water to be monitored.

These regulatory requirements, although not consistent in minor design details with those required by RCRA-C for a hazardous waste landfill, are consistent with the full containment concepts of RCRA. The TSCA chemical landfill requires a greater thickness of vertical buffer between the liner and seasonal high groundwater table. From a dredged material disposal perspective, the 50 feet above the historic high water table requirement would virtually eliminate all CDFs for TSCA waste in the United States if not for alternative (3) eg, disposal method approved by the Regional Administrator. The conceptual basis for the TSCA regulations is the hydraulic isolation of the waste from surface and groundwaters. This is identical to the conceptual basis for RCRA-C and RCRA-D regulations.

RCRA Subtitle C Sediments. As promulgated in 1976 and amended by Hazardous and Solid Waste Amendments (HSWA) in 1984, RCRA-C is a national regulatory mechanism that controls the treatment, storage, and disposal of hazardous waste as defined under 40 CFR 261 and thereby minimizes the present and future threat to human health and the environment. 40 CFR 261 specifies that a waste is hazardous if it is not excluded from regulation as a hazardous waste and it meets any of the following criteria: (1) is named as a hazardous waste and is included in one of three lists under 40 CFR 261, (2) exhibits a hazardous waste characteristic, (3) results from the mixture of a waste with listed hazardous waste, (4) is derived from a listed hazardous waste or exhibits a hazardous waste characteristic, and (5) is an environmental media which contains a listed hazardous waste. The first list under 40 CFR 261 contains hazardous wastes from nonspecific sources (eg, spent halogenated solvents, such as perchloroethylene). The second list identifies hazardous wastes which commonly result from manufacturing or industrial processes (eg, bottom sediment sludge from the treatment of wastewater by wood preservers). The third list contains commercial chemical products or chemical manufacturing intermediates which, when discarded, must be treated as hazardous waste. If a waste is not listed as hazardous, it is still covered by RCRA if it exhibits one of four hazardous waste characteristics: ignitability, corrosivity, reactivity, or toxicity. For example, under the definition provided for toxicity, a solid waste is hazardous if the extract obtained from the sample using the Toxic Characteristic Leaching Procedure (TCLP) test contains a hazardous constituent at or above the regulatory threshold provided for that constituent. To date, most RCRA-C sediment characterization efforts in the Great Lakes area (EPA Region 5) have focused on toxicity as defined by the TCLP test.

Of major potential significance to the disposal of contaminated dredged materials is the land disposal ban enacted by HSWA. These regulatory requirements mandate that hazardous wastes or Subtitle C media must be properly and adequately treated prior to land disposal. Such treatment would include destruction of organic constituents and/or solidification of the metal constituents in the waste such that it will pass a TCLP test. In 1986, EPA banned the land disposal of untreated hazardous waste containing dioxin and solvents (see DIOXIN EMISSIONS INVENTORY). Next, in 1987, EPA banned the disposal of certain untreated hazardous wastes that had

previously been banned by California. Third, EPA published a ranking of all other hazardous wastes based on their hazard or volume. From 1988 to 1990 EPA enacted a ban on the land disposal of these wastes without treatment. By banning the direct land disposal of such hazardous wastes, Congress sought to reduce the rate of hazardous waste production and the long-term risks associated with hazardous waste disposal.

The treatment requirements under RCRA-C for contaminated environmental media such as sediment, depend on the type of RCRA-C contaminant associated with the sediment. Conceptually, sediments can be contaminated with one or more listed hazardous waste or can exhibit one or more hazardous waste characteristics. In practice however, the identification of sediments which require compliance with the RCRA-C regulations for listed waste has been rare. This is due to the RCRA-C exclusions under 40 CFR 261.4(a) for hazardous waste mixed with domestic sewage and waste released from industrial point-source discharges subject to Section 402 of the CWA. An overview of the treatment and disposal regulations for sediments requiring compliance with RCRA-C is provided below.

The treatment and disposal of sediments contaminated with a listed hazardous waste can be handled in one of two ways. Where feasible, such sediments can be treated to the extent that the sediments no longer contain the listed waste. The threshold levels for this determination are provided by the EPA Region in which the activities occur. Treatment procedures which reduce the listed RCRA-C wastes from the sediment to concentrations below these thresholds render the sediments nonhazardous. Subsequent disposal of the sediments is then not regulated under RCRA-C. In contrast, if the treated sediments still contain listed hazardous wastes, but meet the treatment standards provided under 40 CFR 268, the disposal of the sediments would continue to be regulated under RCRA-C. Consequently, such treated sediments would need to be dewatered until the sediments pass the paint filter test and subsequently placed in a RCRA-C disposal facility.

Similarly, the treatment requirements for dredged sediments which exhibit a RCRA-C hazardous waste characteristic can also be addressed through the following scenario. RCRA-C requires treatment of sediment to the standards provided in 40 CFR 268. Once adequately treated, disposal of the sediments would no longer be regulated under RCRA-C.

RCRA-C differs from TSCA in that many specific requirements for treatment, storage, or disposal (TSD) facilities are not codified. Technical requirements for TSDs have been codified in 40 CFR 264 as Minimum Technology Requirements (MTR) and are given in Minimum Technology Guidance (MTG) documents prepared by EPA. Site location requirements are codified with respect to seismic considerations and floodplains (40 CFR 264.18). RCRA does not contain site restrictions that would eliminate in-lake or near-shore TSDs or CDFs. Under Subpart N, the hazardous waste regulations simply specify a liner system designed to prevent any migration of wastes out of the landfill and a leachate collection system immediately above the liner that will prevent the leachate depth from exceeding 30 cm over the liner. These specifications form the basis for the worst-case hydraulic isolation CDF design criteria.

The groundwater protection standards of Subtitle C involve the use of EPA-approved health-based standards for evaluating compliance with approved environmental performance

standards. Such standards include the Maximum Contaminant Levels (MCL) established by the CWA. When no MCLs exist, the reference doses (RFDS) for threshold constituents, and carcinogenic potency factors (CPFs) for nonthreshold constituents are used. CPFs measure the ability of a chemical to cause cancer assuming a risk level of 10^{-6} for Class A and B carcinogens and 10^{-5} for Class C carcinogens (5).

RCRA Subtitle D Sediments. As promulgated on October 9, 1991, Subtitle D (40 CFR 258) defined minimum landfill standards for those facilities receiving MSW and for landfills codisposing sewage sludge with MSW. The codisposal regulations were copromulgated under the authority of RCRA-D and CWA. Separate regulations are being developed for sewage sludge monofills under CWA Authority. The RCRA-D regulations are the first to clearly establish performance objectives for the landfills. A default composite liner is provided in Subtitle D, however the general performance criteria for a MSW landfill requires that groundwater quality be maintained such that all constituents are at concentrations below their MCLs at a regulatory specified point of compliance adjacent to the landfill.

Remediation of Contaminated Sediments. Remediation of contaminated dredged material to remove or lower the level of contaminants may involve combining several treatment processes to achieve cleanup objectives. Treated sediments, once cleaned, can be used as beneficial fill material outside of a CDF or as designed components within the CDF. For example, cleaned fine-grained sediments could be used to line a CDF. The Assessment and Remediation of Contaminated Sediments (ARCS) program in EPA Region 5 has performed pilot- and bench-scale demonstrations of selected technologies. A full discussion of these technologies is presented in a later section. It should be noted that, at present, these technologies have not been widely implemented at full scale.

The containment of contaminated sediments in CDFs is generally viewed as the most cost-effective remediation tool. This is consistent with a parallel trend in Superfund sites where containment of the contaminated soils or wastes has been the selected alternative in a clear majority of existing Record of Decisions (RODs). This containment policy is expressed in recent revised Remedial Investigation/Feasibility Study (RI/FS) procedures for contaminated municipal solid waste landfills (6). These revised RI/FS procedures make containment of the waste the presumptive remedy. As with dredging projects, the quantities of contaminated solids and relatively low contamination levels associated with MSW landfills frequently makes current waste remediation technologies prohibitively expensive.

Confined Disposal of Problematic Sediments

Nationwide CDFs were built to dispose of clean dredged materials; within the Great Lakes Region (EPA Region 5), however, all existing CDFs were designed for the disposal of problematic dredged materials. Such facilities are designed to retain dredged solids while allowing the carrier water to be released from the containment area. The general conceptual drawing for this process is shown on Figure 1. The principal functional components of the CDF are the containment dikes that hold the dredged materials and a weir, or filter wall, or treatment system that allows the carrier water to decant from the CDF. The design of containment dikes is site-specific and must con-

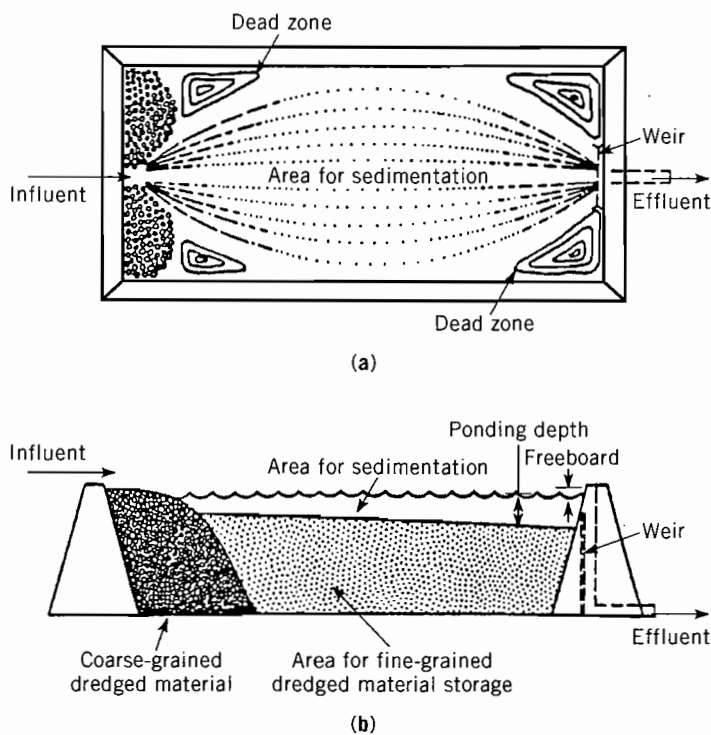


Figure 1. Conceptual diagram of a CDF: (a) plan (b) cross section.

sider the following factors: dike stability with respect to shear strength, settlement, seepage, erosion, and available building materials or construction equipment. The influent dredged material may be a slurry if hydraulic dredging processes are used or a water/soil-clod matrix if bucket excavators are used. This dredged material influent and the decanted effluent are normally characterized by the suspended solids concentration, suspended particle size gradation, type of carrier water (fresh or saline), and rate of flow.

The containment basin must be sized to provide an adequate volume to contain the dredged slurry and to provide sufficient retention time for the associated water to allow solids to fall out of suspension. Flocculent may be used to increase the rate at which solids fall out of suspension if the site area is restricted. Weirs are designed such that the water depth above the solids can be maintained constant as the CDF fills with sediment.

The Great Lakes CDFs were designed so that the effluent leaving the CDF has a concentration of suspended solids less than 1 to 2 grams per liter for freshwater conditions (EM 1110-2-5027). Typical effluent requirements in EPA Region 5 are usually in terms of tens of milligrams per liter and are enforced at those CDFs having a measurable point discharge.

CDF Contaminant Pathways

The design of the CDF must be concerned with potential pathways by which the contaminant can leave the containment system. For an upland or typical island CDF such pathways are shown on Figure 2 and include the following:

1. effluent drained through the weir or dikes
2. leachate drained from the sediments that may move into the groundwater

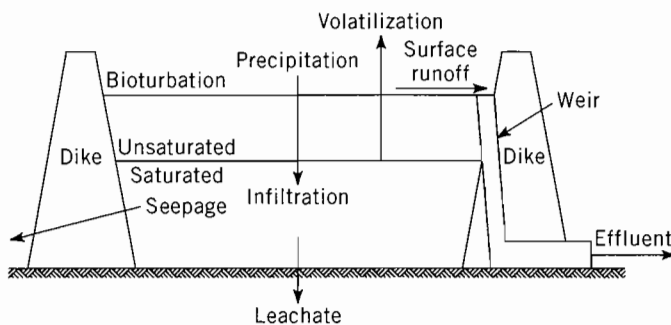


Figure 2. Contaminant pathways for upland CDF (7).

3. surface water runoff
4. plant uptake through vegetation growing within the CDF or on its dikes
5. animal uptake in animals living or nesting within the CDF
6. from volatilization or wind borne migration of fine-grained soils and bound contaminants into the atmosphere.

DEVELOPMENT OF ENVIRONMENTAL PERFORMANCE CRITERIA

In 1971, Region 5 of the EPA issued "Criteria for Determining Acceptability of Dredge Spoil Disposal to the National Waters" as a first effort to identify and classify polluted sediments in the nation's waterways for purposes of controlling dredging and disposal operations. These ambient concentration thresholds were published before there was adequate scientific data to define the type, quantity, and partitioning potential of contaminants which are associated with dredged material which impact water and sediment quality at the dredging or disposal site and, thus, become bioavailable. Sediments that failed this evaluation were considered unsuitable for aquatic (open water) disposal and required confined disposal or remediation. In 1977, EPA Region 5 began to use sediment pollution criteria defined by the Great Lakes guidelines shown on Table 3.

During this same time period the U.S. ACE was developing an approach for evaluating the pollution potential and bioavailability of contaminated dredged materials during dredging and disposal operations. The U.S. ACE position about establishing regulatory criteria for the disposal of clean and contaminated dredged materials in the oceans and other aquatic bodies such as lakes and rivers has been discussed (8). It was noted that the criteria for defining environmental protection should:

1. be meaningful and based on the best possible knowledge
2. not precede the current technical state of the art
3. be based on laboratory procedures that can be performed satisfactorily at routine testing laboratories
4. attainment and implementation should not be prohibitively expensive

The first guidelines for the discharge of dredged materials into waters of the United States were issued in 1975 and were quickly followed by interim guidance manuals for dis-

charge into navigable waters and into ocean waters (9). The latter manual is referred to as the Green Book. In 1991, EPA and U.S. ACE jointly published an update of the 1977 Green Book for the discharge of dredged material into ocean waters (7). This update was intended to address the differences between the regulations governing disposal under CWA and MPRSA and is specifically intended for CWA 404(b)(1) compliance determinations. EPA and U.S. ACE are currently drafting a guidance manual for evaluation of material proposed for discharge in inland and near coastal waters (Inland Testing Manual). Because the Green Book applies to ocean and coastal waters it has not been used by EPA Region 5 for the Great Lakes. EPA Region 5 has instead used a case-by-case approach using the 1977 Great Lakes Guidelines (see Table 3), International Joint Commission guidelines, and other criteria to make the decision of whether the dredged materials are contaminated and thus inappropriate for open water disposal. While the proposed Inland Testing Manual is national in scope, the U.S. ACE North Central Division and Region 2, 3, and 5 are also developing a Great Lakes Testing Manual.

Joint U.S. ACE/EPA Sediment Management Strategy

Based on the USACE decision-making framework (10) as applied to Commencement Bay, Washington (11), a joint USACE/EPA guidance document for evaluation of environmentally acceptable dredged material management alternatives was developed. The document is intended to serve as the technical framework for U.S. ACE and EPA personnel in evaluating the environmental acceptability of dredged material management alternatives. Three dredged material management alternatives are considered in the joint framework: open water disposal, confined (dike) disposal, and beneficial use application. The joint EPA/USACE dredged material management program is summarized in the flow chart on Figure 3. This proposed management program is divided into five major elements as follows.

Evaluation of Dredging Project Requirements. The need for the dredging project must be established under NEPA, CWA, and/or MPRSA. Under NEPA, the initial impact assessment for the dredging project relates to the purpose and need for the proposed action in the case of new work and the continued viability in the case of an existing project. The needs determination under CWA or MPRSA is specifically concerned with a justification of the necessity for dredged material disposal in waters of the U.S. or ocean, respectively.

Identification of Alternatives. Under NEPA, the environmental impact of disposal options such as CDFs, open water, and beneficial uses must be considered. The NEPA document must discuss all reasonable alternatives even if they are beyond the capability of the applicant or lead agency making the application. Note that NEPA does not specify performance standards but simply requires the evaluation of alternatives.

Initial Screening of Alternatives. Reasonable dredged material management alternatives include those that are practical or feasible given environmental, technical, and economic constraints. All potential alternatives (ie, CDF, open water, beneficial use, etc) are evaluated with respect to the availability of the required and suitable disposal site, design limitations, climatic conditions, dredging equipment availability, physical

Table 3. EPA Guideline Values for Harbor Sediment Classification^a

Compound/Element, Ranking	Nonpolluted	Moderately Polluted	Heavily Polluted
Volatile solids %	<5	5–8	>8
COD	<40,000	40,000–80,000	>80,000
TKN	<1,000	1,000–2,000	>2,000
Oil and grease	<1,000	1,000–2,000	>2,000
Lead	<40	40–60	>60
Zinc	<90	90–2000	>200
Ammonia	<75	75–200	>200
Cyanide	<0.10	0.10–0.25	>0.25
Phosphorus	<420	420–650	>650
Iron	<17,000	17,000–25,000	>25,000
Nickel	<20	20–50	>50

^a Value in mg/kg dry weight unless otherwise specified.

and chemical aspects of the sediments, local interests or concerns, and known environmental regulatory (eg, endangered species) and economic concerns. The initial screening is based on available sources of sediment contamination information.

- Available results prior physical, chemical, and biological tests of the materials proposed to be dumped.
- Available results of prior field characterization studies of the materials proposed to be dumped (eg, physical characteristics, organic–carbon content, and grain size).
- Available information describing the source(s) of the material to be dumped which would be relevant to the identification of potential contaminants of concern.
- Existing data contained in files of either the EPA or COE or otherwise available from public or private sources. Examples of sources from which relevant information might be obtained include:
 - Selected Chemical Spill Listing (EPA)
 - Pesticide Spill Reporting System (EPA)
 - Pollution Incident Reporting System (USCG)
 - Identification of In-Place Pollutants and Priorities for Removal (EPA)
 - Hazardous waste sites and management facilities reports (EPA)
 - COE studies of sediment pollution and sediments
 - Federal STORET, BIOS, CETIS, and ODES databases (EPA)
 - Water and sediment data on major tributaries (USGS)
 - NPDES permit records
 - Fish and Wildlife Service
 - CWA 404(b)(1) evaluations
 - Pertinent and applicable research reports
 - MPRSA 103 Evaluations
 - Port Authorities
 - Colleges/Universities
 - Records of state agencies (eg, environmental, water survey)
 - Published scientific literature
 - CERCLA/RCRA Facility Files

Detailed Assessment of Alternatives. Environmental acceptability of a dredged material management alternative must include the following:

1. evaluation of the adequacy and timeliness of existing data
2. evaluation of the physical characteristics of the sediments
3. evaluation of sediment contamination
4. perform appropriate CWA testing and assessments
5. evaluation of sediment management/control options

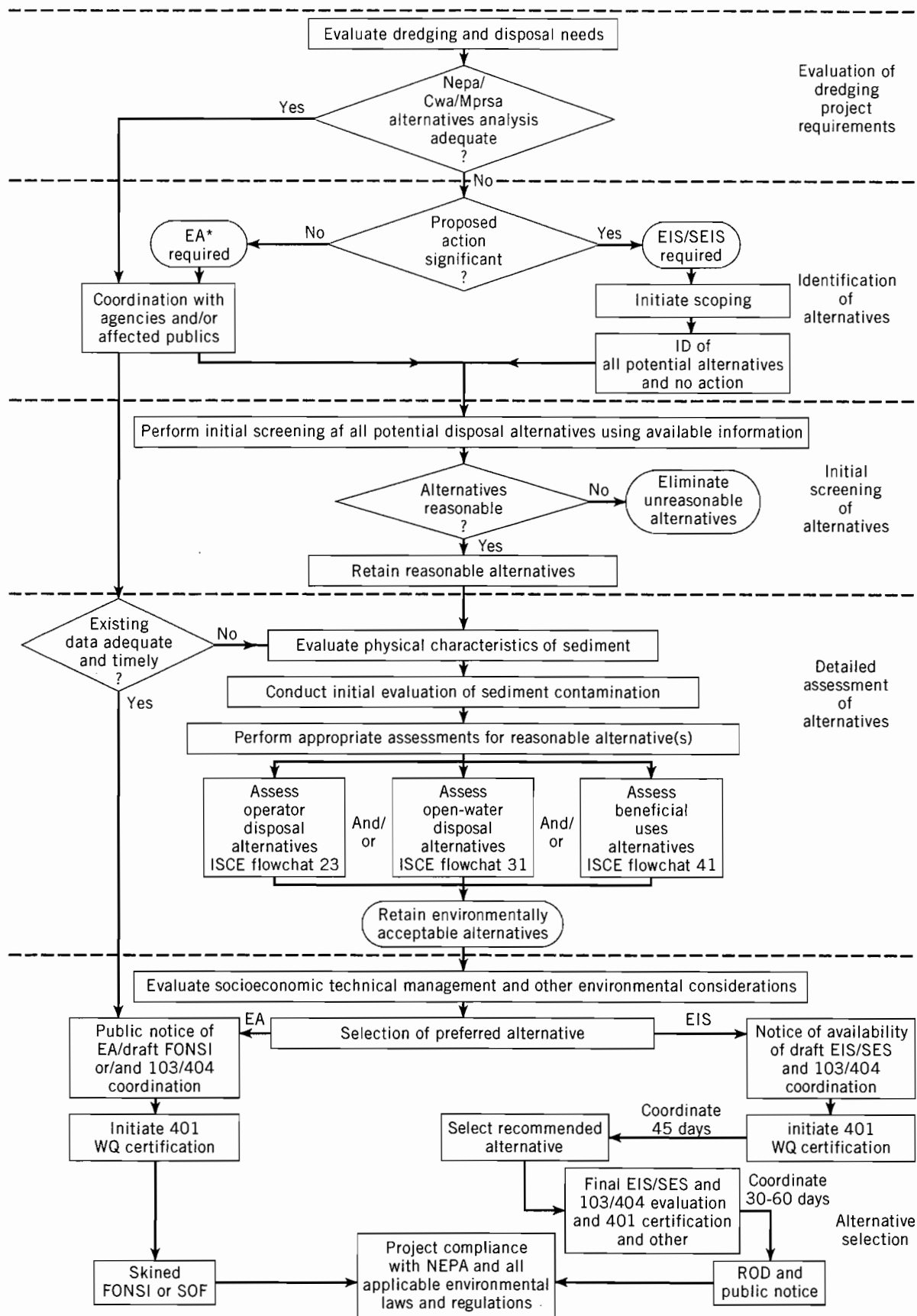
Once a detailed assessment of the alternatives is completed and the CDF alternative has been selected, the flow chart on Figure 4 is used for the detailed assessment of the CDF alternative to include testing and related evaluations. This requires a site assessment of all potential CDF locations including an evaluation of physical impacts, site capacity, and possible management options. The primary concern of this flow chart is the short- and long-term impact of contaminated dredged material placement into the CDF and the need for additional control measures.

Alternative Selection. The selection of a preferred/proposed alternative during the NEPA EIS phase is based on environmental acceptability, technical feasibility, costs, and other factors.

Evaluation of Contaminant Pathways

The evaluation of the impact of the disposal of contaminated dredged materials on the local environment is based on a detailed laboratory testing protocol that considers each of the possible contaminant pathways. Based on the test results and analysis, the laboratory testing program will determine if additional control measures are required for the proposed CDF. Additional control measures consist of liners, covers, and filters.

Effluent Discharge Quality. The large volumes of fluids generated during dredging may contain undesirable levels of dissolved contaminants and suspended fine solids with adsorbed contaminants. The modified elutriate test (12) is the current method which the U.S. ACE uses to predict effluent



* If at any time in the EA process, the federal action is released as being significant, EIS scoping is inflated.

EA • Environmental assessment
 EIS/SES • Environmental impact statement/supplement
 FONSI • Finding of no significant impact

ROD = Record of decision
 SOF = Statement of findings

Figure 3. Flow chart illustrating framework for determining environmental acceptability of dredged material disposal alternatives (7).

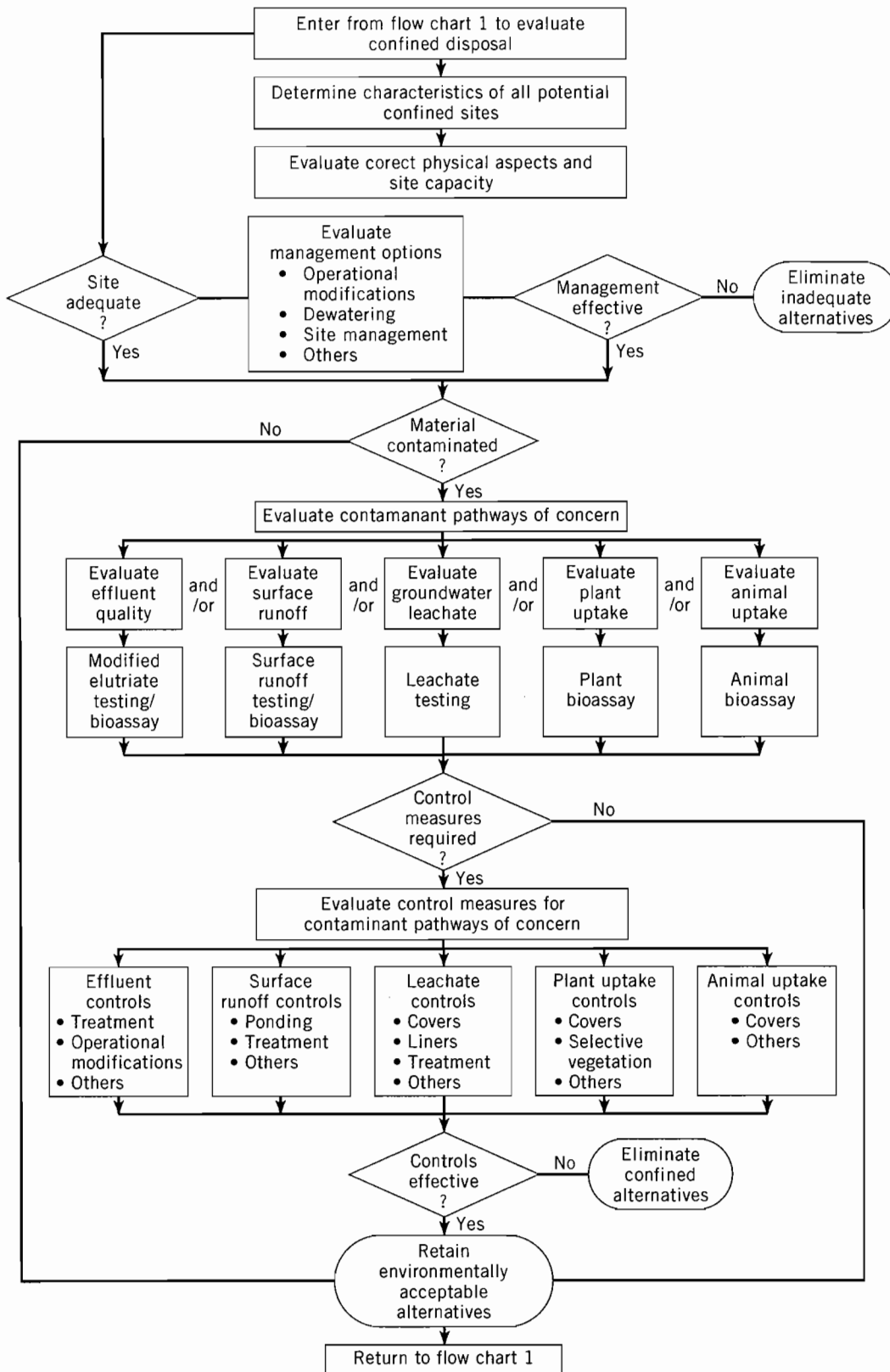


Figure 4. Flow chart illustrating framework for testing and evaluation for confined (diked) disposal (7).

quality from a CDF. This is a modification of the standard elutriate test used for assessment of aquatic disposal of dredged material.

A review of the standard elutriate test is presented here to aid in understanding the transition represented by the "modified" elutriate test. The U.S. ACE has always based its criteria on the change in ambient water quality (dissolved chemical concentrations) that might be expected during dredging and disposal in a CDF. The compliance of a dredged material operation with state water quality standards (WQS) is assessed by the elutriate test which is designed to simulate the dredging/disposal process. A schematic diagram of the original elutriate test (8) is presented in Figure 5 as designed for the disposal of hydraulically dredged material. As noted in the diagram, four volumes of disposal site water and one volume of contaminated dredged material are shaken vigorously in a beaker for 30 minutes to simulate hydraulic dredging and to allow for the exchange of contaminants from the solid phase (adsorbed organics and metals) to the dissolved phase. Also, prior to mixing the water with sediments, the dissolved concentrations of pollutants in the disposal site water are measured and listed as X_1 . After shaking the sediment/water suspension, the mixture is allowed to settle for one hour. The supernatant is then filtered to remove particles and analyzed for the same chemical constituents previously determined and listed as X . Although the test method simplifies the complex interaction between polluted sediment and water, it has shown that there is little migration from the solid to dissolved phase.

The modified elutriate test, as summarized in Figure 6, was developed by U.S. ACE to be a more realistic laboratory simulation of effluent quality during hydraulic disposal of dredged material in open water or within a CDF. The test involves mixing contaminated sediment and water from the dredge site in proportion to the expected influent concentra-

tion as influenced by the dredging method. The mixture is then aerated and settled in a column. Modifications to the test can be made to simulate transport and deposition for an estimated CDF retention time (13,14). The unfiltered supernatant (effluent) is subjected to chemical analysis to define the concentration of the contaminants associated with the total suspended solids (TSS). Similarly, a chemical analysis is performed on the filtered water to determine the concentrations of contaminants dissolved in the water. This allows prediction of both the dissolved and the total concentration of contaminants in the effluent.

The modified elutriate test is generally used with a parallel column settling test to predict actual effluent TSS as outlined in Figure 7. The estimated total concentration of effluent contaminants is compared to state water quality standards. If the effluent does not meet the state WQS standards, the U.S. ACE can propose the use of a mixing zone to further dilute the effluent.

The modified elutriate test provides conservative estimates of contaminants within the effluent; bulk quantities (mass released) of contaminants released are highly dependent on the volume of dredging fluids generated during dredging. The percentage of dredging fluids by weight can range from more than 90% for hydraulic methods, eg, using a cutterhead dredge, to less than 20% using clamshell excavations. For a hypothetical annual dredging volume of 200,000 cubic yards of the highly contaminated sediments associated with Indiana Harbor in the Great Lakes, the U.S. ACE estimated the quantities of PCBs expected to be released with the effluent for three CDF filling scenarios including hydraulic transfer from scow, direct pumping from dredge site using a matchbox-type dredgehead, and mechanical placement. The projected annual PCBs released for these three methods relative to a common size CDF are 6.3, 4.2, and 0.0027 kg, respectively. Ironically, methods of dredging that minimize contaminant transport at the site of dredging can lead to a maximum potential for contaminant release at the point of discharge from the containment facility and ultimately into the local environment. For example, the use of a cutterhead dredge minimizes the generation of turbidity and the potential for contaminant migration at the dredging site. However, the high water to solids effluent produced by the cutterhead hydraulic dredging does produce a potential for contaminant migration in the effluent.

The effluent is generated by both the supernatant that remains after the dredged material falls out of suspension and from rainfall runoff coming from dredged material that rises above the water elevation. The quality of the effluent is influenced by type and quantities of pollutants, sediment mineralogy, and organic content, and the dissolution kinetics discussed below.

Organic Contaminants. An alternative approach to evaluate the relationship between sediments and bioavailability of toxic organic contaminants is the equilibrium partitioning (EqP) method. The EqP approach relies on established water quality criteria to assess sediment toxicity. The first basic assumption of the EqP approach is that sediment toxicity is correlated to the concentration of the contaminants in the interstitial water and not to the total sediment concentration. The second basic assumption is that contaminants partitioned between the interstitial water and the sediment sorbents (ie, organic carbon) are in equilibrium. Such equilibrium concentrations are significantly larger than developed in the elutriate tests.

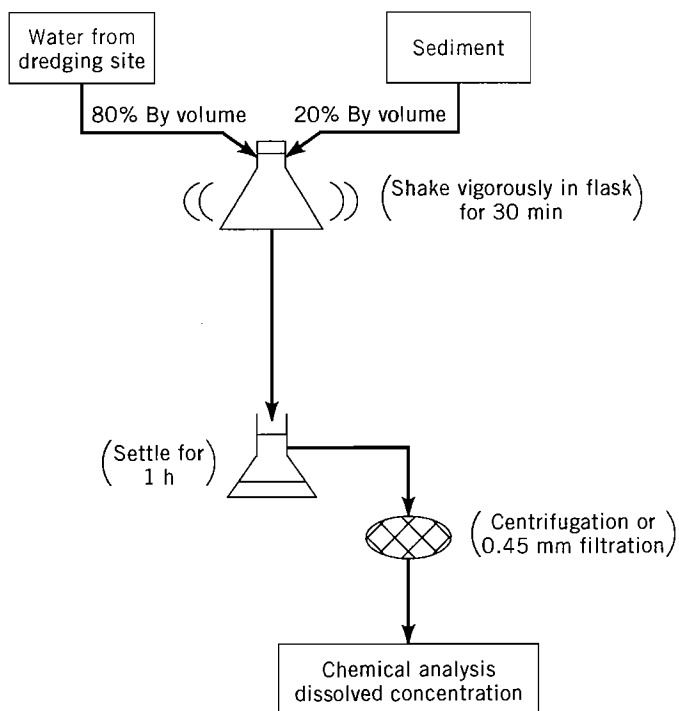


Figure 5. Elutriate test (8).

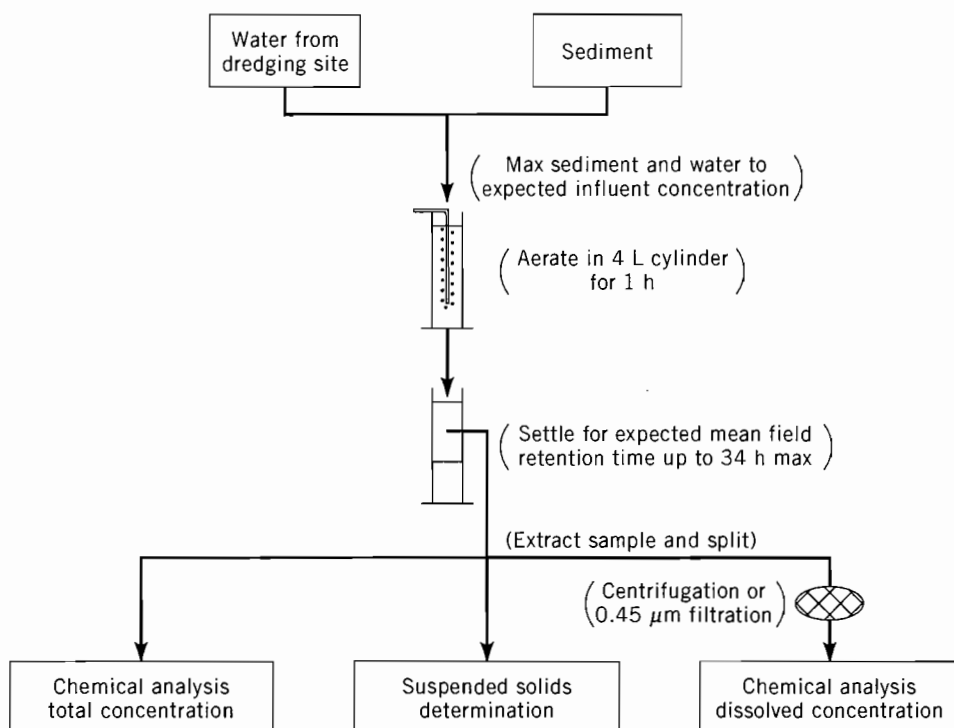


Figure 6. Modified elutriate test (12).

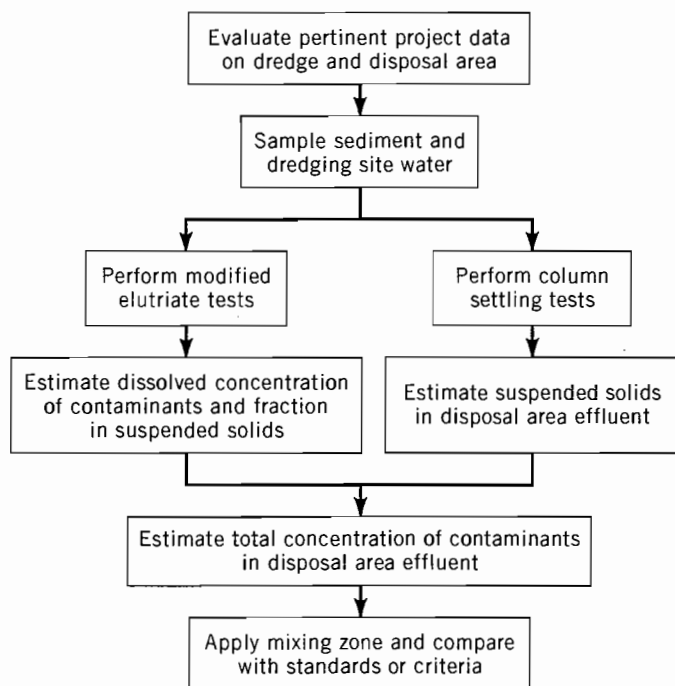


Figure 7. Effluent quality predictive technique.

Therefore, for a given contaminant, if the total sediment concentration, the concentration of sorbent(s), and the partitioning coefficient are known, then the interstitial pore water contaminant concentration can be calculated. Given the third assumption that organic carbon is the significant sorbent, the contaminant concentration can be predicted based on the total organic compound (eg, TOC normalization).

Metal Contaminants. Of particular recent interest is research into the relationship between sediment sulfide content and bioavailability of toxic metals. Studies have shown that sulfide content of freshwater and marine sediments is a predominant determinant of metal toxicity (15–17). This is based on the fact that many toxic metals form insoluble sulfides in anoxic or reduced environments (eg, cadmium, copper, lead, nickel, and zinc) and most freshwater and marine sediments have significant sulfide contents. Note that this includes uncontaminated sediments. These researchers examined acid volatile sulfide (AVS) content of sediments, the solid-phase sediment sulfides (FeS and MnS, H₂S, HS, and S₂²⁻) that are soluble in cold acid, and the concentration of simultaneously extracted metals (SEM) using the ratio (SEM)/(AVS). AVS binding of metals reduces their bioavailability by decreasing metal solubility and is a precursor to formation of more insoluble pyritic sulfides (eg, FeS₂). Formation of pyritic metal sulfides is one mechanism of potential permanent removal of toxic metals. AVS of marine sediments in relation to cadmium toxicity to three species of amphipods has been measured, and it was found that AVS is the sediment phase that determines the LC₅₀ for cadmium and also that correlations occurred between mortality and interstitial water metal activity (15). Cadmium and nickel were studied in estuarine sediments in 10-day exposure tests with an amphipod and oligochaete species (17). In this study, molar [SEM (cadmium and nickel)]/[AVS] ratios greater than one were consistently toxic to the amphipod (*Hyallolella azteca*) and ratios of less than one were not. Metal availability was apparent through bioaccumulation in the oligochaete worm (*Lumbriculus variegatus*) when [SEM]/[AVS] ratios exceeded one. Freshwater sediments were spiked with cadmium and tested by a 10-day exposure with the same species of oligochaete worm, and the snail *Helisoma* sp (16). Here again, toxicity was not observed when the cadmium/AVS ratio was less than or equal to one.

Metal bioavailability is decreased by AVS, which acts as a sink for metals as long as the sediment remains anaerobic and the redox potential is too low to allow for oxidation of sulfides. Decreasing solubility of metal sulfides coincides with an increased AVS affinity for metals, that is $Mn < Fe < Ni < Zn < Cd < Pb < Cu < Hg$ (15). These studies suggest an important sediment and interstitial water metal toxicity assessment technique which may be useful in developing sediment quality criteria. Note that potential effect associated with dredging and dredge material disposal alternatives can significantly impact the beneficial role played by AVS. The importance of microbial processes to sediment [AVS] should be noted, considering this a critical need in future research (17). General rules of thumb for sediments are:

$[metal]/[AVS] < 1$ sediment has little toxicity

$1 \leq [metal]/[AVS] \leq 10$ sediment has little to high toxicity

$[metal]/[AVS] > 10$ sediment is highly toxic

Copper may be an exception to this rule due to its affinity to also bind to organic compounds, and most of this research was performed on marine and lake sediment (ie, high in Fe and aluminum oxides).

Surface Water Runoff Quality. Concerns regarding surface water runoff from the dredged material in the CDF begin when the elevation of the dredged material exceeds that of the water in the CDF. This concern can be mitigated by an adequate residence time for the supernatant (eg, water draining from the dredged materials) and runoff waters in the CDF such that the fines settle out and are not carried out of the CDF by the effluent. Final contours of sediment within the CDF can exceed the elevation of perimeter dikes. Thus, there is the long-term potential for sediment and contaminant mobility with the runoff water if the dredged material is not properly managed.

The quality of surface runoff water within a CDF can be expected to vary with time as a result of the changing physico-chemical condition of the dredged material. When initially placed in a CDF, the dredged material is saturated, reduced, anaerobic, and of neutral to slightly basic pH. However, dredged material placed above the zone of saturation within the CDF are subject to drying. This promotes aerobic microbial degradation or volatilization of organic components, oxidation of some metals and sulfides, and changes in pH (usually lower and more acidic depending on the mineral composition of the dredged material). This reduction in pH can increase the solubility of metals and organic contaminants, leading to release of the contaminants.

A laboratory testing protocol has been developed by the U.S. Army Waterways Experiment Station (WES) to simulate the complex process of rainfall runoff (18,19). The WES surface runoff simulator is shown in Figure 8. The test protocol requires a large sediment sample from the dredge site to be placed in the soil lysimeter in the saturated reduced state. At various stages of the drying process, rainfall events are applied to the dredge material and surface runoff water samples are collected for analysis of water quality parameters. Rainfall simulations are performed several times over the full range of air drying. These results have been shown to accurately predict surface runoff water quality which can be compared to water quality standards and thus determine the need for

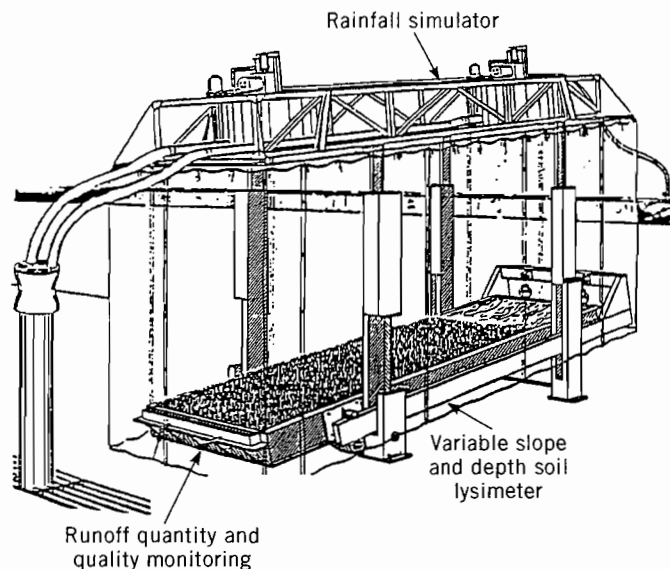


Figure 8. Surface runoff evaluation system (19).

runoff water treatment or the need to apply control measures to the CDF (eg, an engineered final cover). This apparatus can also be used to evaluate control measures such as lime treatment, soil covers, and plant stabilization.

Plant Uptake. Most dredged sediments contain large amounts of nitrogen and phosphorus which promote vigorous plant growth. As a result, plants are easily established in a CDF following placement of sediments. When contaminated dredged materials are placed in the CDF, there is the potential that contaminants will move into the food chain from bioaccumulation in the plants. A summary of sources and pathways of toxic trace elements to plants is presented on Table 4. Organic contaminants typically have large molecules that will not pass through the cell walls of plants, thus limiting the plant uptake of organics. Also, because most contaminated dredged materials contain a suite of pollutants they may interact to affect biological systems.

The U.S. ACE has developed a plant bioassay test protocol (19,20) which has been applied to freshwater and marine sediments. For freshwater sediments, the test protocol uses *Cyperus esculantus* (yellow nutsedge) as an index plant. This plant is grown in buckets filled with contaminated sediments from the dredge site under conditions that simulate the CDF environment. Plant growth, phytotoxicity (growth reduction), and bioaccumulation are monitored during the test in the apparatus shown in Figure 9. A chemical analysis is performed on plants harvested from the test buckets. The level of chemicals present in the plants can be compared to allowable threshold levels such as U.S. FDA crop limits. When limits are exceeded, the sediment management strategy invokes control measures such as restricted placement of polluted dredge materials in the CDF to minimize exposure, such as placement of clean surface layers, limiting plant growth to desirable plant species, etc. Dredged materials producing excessive plant uptake require designed control measures (eg, an engineered final cover).

Animal Uptake. Both upland and inlake CDFs are invaded and colonized by many animal species after each phase of

Table 4. Sources and Pathways of Toxic Trace Elements of Plants^{a,b}

Uptake	Sb	As	Be	B	Cd	Cr	Co	Cu	Pb	Hg	Ni	Se	Sn	V
By roots														
Soil or groundwater	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Fallout to soil from air pollution	x	x	x	x	x	x	x	x	x	x	x	x		x
Sewage sludge soil amendments		x			x	x		x	x	x	x	x		
Biocides applied to soil and/or seed		x		x	x			x	x	x			x	
Surface water contamination		x				x			x					x
Fertilizers		x			x	x		x		x	x		x	
Industrial pollution		x			x	x		x		x	x		x	
By leaves and stems														
Pollutant fallout from industrial sources	x	x	x		x	x	x	x	x	x	x	x		
Pollutant fallout from auto emissions									x					
Biocide applications to plants		x		x	x			x	x	x			x	
Pollution fallout from incineration of fossil fuels and refuse	x	x	x	x	x	x	x	x	x	x	x	x	x	x

^a Sb, antimony; As, arsenic; Be, beryllium; B, boron; Cd, cadmium; Cr, chromium; Co, cobalt; Cu, copper; Pb, lead; Hg, mercury; Ni, nickel; Se, selenium; Sn, tin; V, vanadium.

^b Ref. 19.

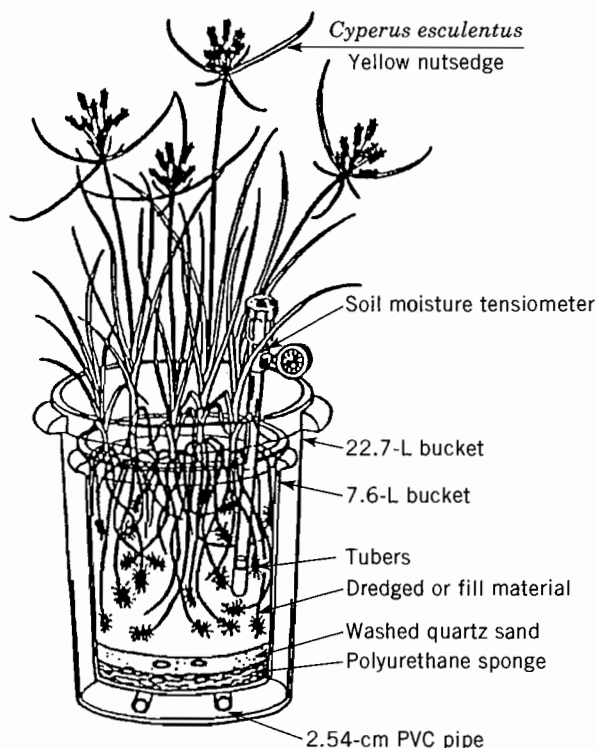


Figure 9. Plant bioassay procedure (19).

dredge material placement. The type of wildlife depends to some degree on the nature of the setting; particularly whether the CDF filling stage exhibits dry pastoral or marsh-like environment. Given the long life of many CDFs, significant animal colonies may be established during various interim phases of dredged material placement. Surface ponds may exist during the operational life of a CDF. Such ponds can support the presence of fish and benthic organisms. Bioavailable metals and organic compounds can then be transferred from the dredged material to fish or benthic organisms. The

contaminants then can move quickly up the food chain. Such interim uptake problems can be reduced by the application of clean dredged material to the surface of problematic dredged material. Hierarchical food chain development is dependent on the lowest form of plant and animal species. Contaminants that are bioavailable at small concentrations to the lowest species may be magnified during migration up the food chain. The more recent view of biomagnification is that the levels of organic chemicals accumulating in animals has more to do with lipid content than the species position in the food chain. A summary of the sources and pathways of toxic trace elements to animals is presented on Table 5. The test protocol used by the U.S. ACE to evaluate animal uptake of contaminants from dredged sediments was borrowed from the European Economic Community (EEC). This test was used by the EEC to determine the hazardous nature of manufactured chemicals prior to sale in Europe.

As adapted by the U.S. ACE, the EEC test involves placement of ordinary earthworms in a container filled with polluted dredge materials as shown in Figure 10. The material is kept in moist, semim moist, and air-dried conditions to simulate the expected range of CDF environments. For a period of 28 days, the earthworms are monitored for toxicity and bioaccumulation of contaminants. It has been noted that this test protocol can indicate potential environmental effects for dredged material placed in upland environments (19). It has also been shown useful for identifying bioavailable metals and organic contaminants. Contaminant problems are identified by comparing body burdens with allowable FDA limits. Contaminated sediments producing excessive uptake in the earthworms will require CDF control measures for the dredge materials (eg, an engineered final cover).

Groundwater Leachate Quality. When a dredged material is placed in an upland CDF or above the water elevation in an in-lake CDF, a downward hydraulic gradient develops as the slurry consolidates. This gradient forces leachate into the underlying strata. The degree of leachate penetration into the underlying strata is influenced by the site hydraulics. For instance, CDFs located at near-shore settings may be within a

Table 5. Sources and Pathways of Toxic Trace Elements to Animals^{a,b}

	Sb	As	Be	B	Cd	Cr	Co	Cu	Pb	Hg	Ni	Se	Sn	V
Terrestrial														
Breathing contaminated air	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Eating contaminated plant or animal tissue	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Drinking contaminated water	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Licking or preening fur or leathers									x					
Receiving therapeutic drugs (domestic animals)		x												
Eating biocides or poison baits		x											x	
Aquatic														
Metal in water	x	x	x	x		x	x	x	x	x	x	x	x	x
Runoff and fallout		x			x	x		x	x	x	x	x	x	x
Sewage and industrial waste outfalls	x	x		x	x	x	x	x	x	x	x		x	
Mine tailings or smelter waste leachate		x			x	x		x	x	x			x	
Contaminated plants, animals, or sediment		x	x	x	x	x	x	x	x	x	x	x	x	x
Biocides or runoff		x		x				x					x	
Lead shot									x					

^a Sb, antimony; As, arsenic; Be, beryllium; B, boron; Cd, cadmium; Cr, chromium; Co, cobalt; Cu, copper; Pb, lead; Hg, mercury; Ni, nickel; Se, selenium; Sn, tin; and V, vanadium.

^b Ref. 19.

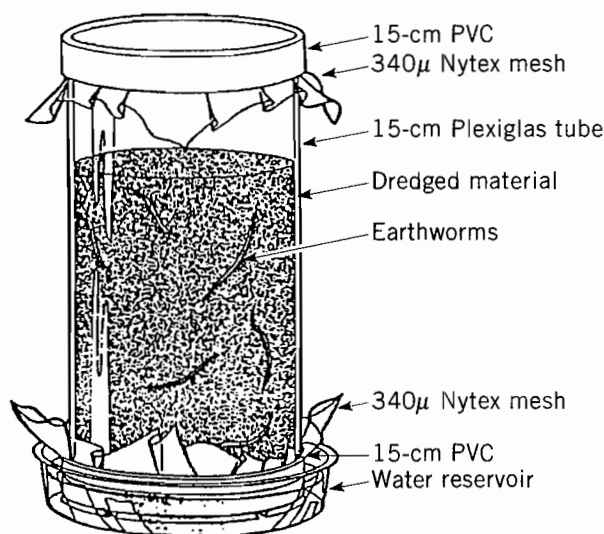


Figure 10. Earthworm bioassay procedure (19).

zone of groundwater discharge that would limit or prevent leachate penetrations. Following consolidation, water seepage through the sediment may continue to generate leachate due to surface infiltration of rainwater. Movement of contaminants due to a hydraulic gradient is termed advective transport. Simultaneously with the advective transport, the contaminants undergo molecular diffusion. This process is more significant through fine-grained sediments due to their low hydraulic conductivity. Diffusion of contaminants occurs due to contaminant concentration gradients and typically at rates so slow that it can be neglected. The quantity of leachate can be accurately predicted from advective flow theory if the site and CDF hydrogeological parameters are known. However the quality of leachate is affected by the type and quantities of pollutants, sediment mineralogy and organic content, equilibrium concentration of contaminants and pH of the pore fluid, and disso-

lution kinetics to name a few. Many of these parameters that influence leachate quality are influenced by the geochemical factors that change as the CDF is being filled.

There is presently no routinely used leachate testing protocol to define the type and quantity of contaminants carried by leachate from dredged material. There are a number of standardized test methods that could simulate leachate generation from both consolidation and percolation. For example, a soil/sediment press as shown in Figure 11 (21) is commonly used to extract pore fluids from marine sediment samples. Contaminant concentrations in such pore waters will generally be at equilibrium. This test could be used to simulate leachate generation from soluble contaminants during consolidation. Additionally, the soil press sample can be extracted from the press for use in a flexible wall permeameter cell to simulate leachate generation due to percolation. The fluids removed from the dredged material by either a soil press or permeameter could be subjected to analysis for typical water quality parameters. Field samples of pore water fluids can also be obtained using cone penetrometers equipped with porous stone sampling ports. The cone is pushed into the sediments hydraulically. Once at the depth a sample is required, the cone shaft is withdrawn slightly to expose the porous stone sampling part. At this time, an inner shaft is pushed downward to break a rubber septum that separates the porous stone and a glass vacuum sample tube. A sample of the pore water is then drawn by the vacuum into the glass tube. The pore water sample is then recovered by the withdrawal of the cone penetrometer. Pore water samples obtained in this fashion are filtered and represent the actual soluble contaminant present in the subgrade (see CONE PENETROMETER-DEPLOYED CHEMICAL SENSORS).

The U.S. ACE has applied a sequential batch leaching procedure and a column leaching test to evaluate confined disposal of dredged material from Indiana Harbor; Everett Harbor, Washington; and New Bedford Harbor, Massachusetts (12,22). The U.S. ACE has not yet endorsed a leachate test for routine testing and continues to perform research and evaluation testing on leachate generation.

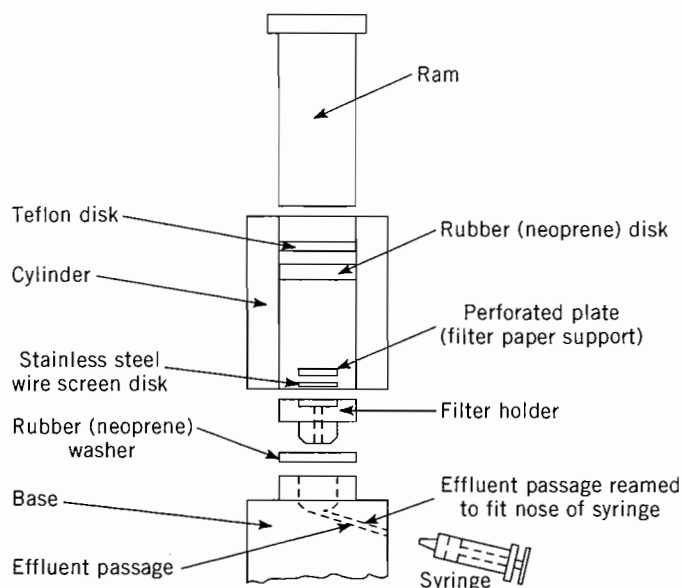


Figure 11. Soil press for sediment leachate sampling (21).

Water Column Discharge Quality. During much of the operational life of an in-water CDF, the surface of the dredged material is below the water level within the CDF. The surface water can act as a host to aquatic animals and provides a contaminant uptake pathway. An interim cover of clean dredged material may be required to limit this short-term contaminant pathway. If required, an interim cover placed over the contaminated sediments must be able to limit the advective movement of contaminants vertically through the interim cover and biological uptake of the contaminants. It is assumed that the sediments and cover are saturated and in direct communication with the water column. The impact of contaminants moving through the interim cover have been assessed using small and large-scale laboratory water column discharge reactor units (23). These units were designed to assess the effectiveness of subaqueous capping at open water sites, but the same principles apply for overlying soil covers for CDFs. The effectiveness of the cover is assessed by following the movements of chemical contaminants and microbial spores found in the contaminated sediments into the overlying water column and by monitoring the biological uptake of chemical contaminants by clams and polychaetes. Such tests on Dutch Kills sediments from New Jersey indicated that as little as 10 cm of sand cover was effective in isolating the water column but 50 cm was required to eliminate biological uptake. No test standards currently exist for the water column uptake reactor test.

ADEQUATE ENVIRONMENTAL PERFORMANCE AND PROTECTION (AEPP) EVALUATION CRITERIA FOR CDFS

Prior to reviewing AEPP criteria for potential contaminant pathways from a CDF, it is important to understand the difficulties associated with even the identification of problematic dredged materials. The current confusion regarding sediment testing guidelines and criteria were expressed by the U.S. General Accounting Office as follows (24):

According to EPA, some scientists believe that the 1975 testing guidelines EPA developed in conjunction with the Corps under section 404(b)(1) of the Clean Water Act—guidelines the Corps is currently using for disposal decisions on dredged material—are technically inadequate. However, Corps headquarters officials maintain that the guidelines have evolved substantially, have been tested thoroughly, and are adequate. Both the Corps and EPA have conducted detailed research on contaminated sediment, but the agencies have not always agreed on how the research should be used to determine which sediment needs confinement. The lack of agreement occurs generally because of the difficulty in establishing clear cause-and-effect relationships between the contaminant concentration in sediment and a biological impact on humans and wildlife.

In 1991, EPA and U.S. ACE jointly published testing guidance for the discharge of dredged material into ocean waters. Currently EPA and U.S. ACE are developing a similar testing guidance for evaluation of material proposed for discharge to inland and near coastal waters (referred to as Inland Testing Manual).

The environmental performance of a CDF should be verified by a monitoring program that assesses the success of control measures for each of the contaminant pathways that are identified during the testing protocol. Evaluation criteria are required to serve as the standard by which the test results from laboratory simulations and field monitoring are evaluated. Although finalized evaluation criteria are not currently available for all contaminant pathways, there are sufficient data in the literature from EPA, FDA, the European Economic Community, and research data to help with the decision-making process. Table 6 summarizes the type of existing information that might be useful for evaluating each contaminant pathway. The contaminants or nutrients of concern must be selected on a case-by-case basis. Contaminants of interest are those that have FDA limits, are the subject of state fisheries advisories, or have EPA water quality criteria.

Effluent Criteria

The factors influencing effluents from CDFs are shown on Figure 12. An unacceptable effluent discharge is one in which the concentration of any dredged material constituent, after allowance for mixing, exceeds applicable state water quality standards (WQS). Effluents from a CDF may be discharged as a point-source flow through a weir system or filter cells, or as a nonpoint-source flow through the dikes. Assuming that the sediments have been established as potentially contaminated, the modified elutriate and column settling tests are used to

Table 6. Evaluation Criteria for Contaminant Pathways^a

Pathway	Criteria
Effluent	EPA water quality standards (Table B1) State water quality standards CWA mixing zone criteria State mixing zone criteria
Runoff	EPA water quality standards (Table B1)
Plant uptake	Research results (Table B2)
Animal uptake	FDA and European action levels for foodstuffs (Table B3)
Leachate	EPA drinking water standards (Table B4)
Air emissions	Pending EPA air quality standards

^a Ref. 3.

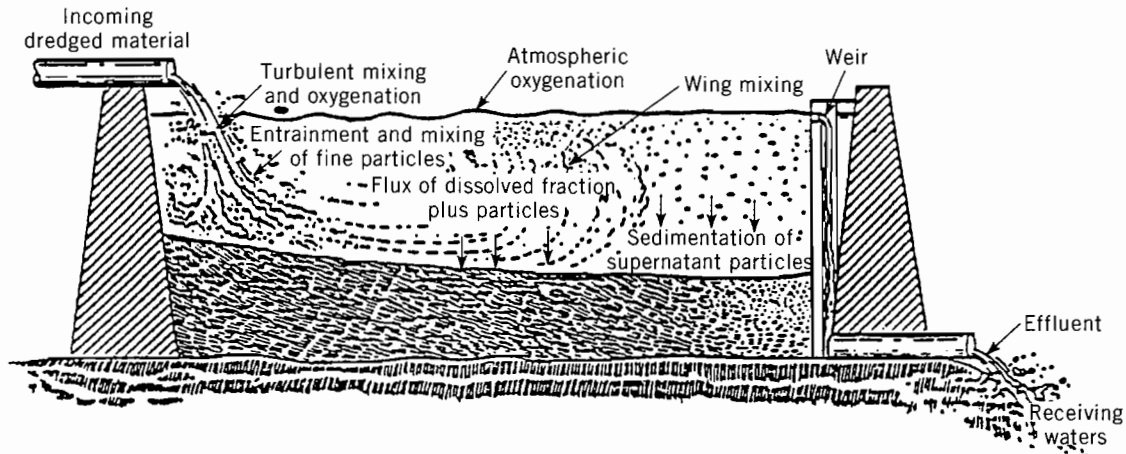


Figure 12. Factors influencing CDF effluents.

predict effluent quality as shown on Figure 7. The standards used for final comparison include turbidity criteria from state WQS as required under Section 401 of the CWA.

Surface Water Runoff Criteria

The final closure of the CDF must ensure that water runoff from the facility meets the same criteria discussed above for effluent discharge. Additionally, many states require a sediment control plan and potential discharge control structures, eg sedimentation ponds, to limit erosion and siltation of adjoining bodies of water. As discussed previously, current CDFs do not have a standard approach to closure but are consistently very flat in profile. Such minimal grades provide for control of water runoff related erosion at the expense of increased infiltration potential. Site specific testing can be performed using the test device shown on Figure 8 (18).

Plant Uptake Criteria

The potential for movement of unacceptable levels of contaminants from the dredged material into the environment through plants and eventually into the food chain must be restricted. Appropriate management strategies therefore are formulated to place problematic dredged material to minimize plant uptake. The management strategies control and manage plant species on the site so that desirable plant species that do not uptake and accumulate contaminants are allowed to colonize the site, while undesirable plant species are removed or eliminated. Plant uptake can be limited during interim periods of the CDF life when a significant surface area of problematic dredged material may be exposed for years. Therefore control of plant uptake is considered throughout the life of the CDF and not just after final closure.

Animal Uptake Criteria

A potential for animal uptake of unacceptable levels of contaminants from dredged material may exist. Appropriate management strategies therefore need to be formulated that consider the ultimate environment in which the dredged material is placed, the anticipated ecosystem developed, and the physicochemical processes governing the biological availability of contaminants for animal uptake. Interim periods during the

operational life of the CDF may be more critical than after the final closure. Surface ponds created during the filling of a CDF may support aquatic life that will provide the basis for contaminant uptake through the food chain via visiting avian and terrestrial species.

Groundwater Leachate Criteria

Pollutants that are dissolved in the excess water of the dredged sediments can contaminate the underlying groundwater. Such migration of contaminants may be caused by pressure gradients that develop in the pore water during consolidation of the dredged sediments or at sites that are natural groundwater recharge zones and result in advective transport of the contaminant to the groundwater or by diffusion of the contaminant caused by concentration gradients.

Contamination of underlying groundwaters is also a design consideration in common landfills. For instance, the recent promulgation of RCRA part 257.3-4 provides groundwater contamination criteria for solid waste landfills. These revised regulations state that the solid waste facility shall not contaminate underground drinking water sources beyond its boundary or point of compliance. For purposes of this requirement, contamination is defined as concentrations of substances exceeding maximum contaminant levels (MCLs) developed by EPA under Section 1412 of the Safe Drinking Water Act (SDWA) or existing ambient groundwater quality. The list of current MCLs is given on Table 7. EPA is in the process of amending this list so adjustments to the MCLs can be anticipated. The point of compliance is usually taken as the water table at the nearest monitoring well. In addition, many states have nondegradation and cleanup criteria that may be orders of magnitude more stringent than MCL levels. Such small levels of acceptable contaminant presence are commonly due to biologically concentrating contaminants (or biomagnification) that result in toxicity concerns.

SELECTION OF REMEDIAL OPTIONS

The Clean Water Act (CWA) requires the surveillance and monitoring of effluents and water quality. Since many contaminants have very low solubilities in water, the monitoring

Table 7. Maximum Contaminant Levels^a

Chemical	CAS Reg. No.	MCL, mg/L
Chromium (hexavalent)	[7440-47-3]	0.05
2,4-Dichlorophenoxy acetic acid	[94-75-7]	0.1
1,4-Dichlorobenzene	[106-46-7]	0.075
1,2-Dichloroethene	[107-06-2]	0.005
1,1-Dichloroethylene	[75-35-4]	0.007
Endrin	[75-20-8]	0.0002
Fluoride		4.0
Lindane	[58-89-8]	0.004
Lead	[7438-82-1]	0.05
Mercury	[7438-87-6]	0.002
Methoxychlor	[72-43-5]	0.1
Nitrate		10.0
Selenium	[7782-49-2]	0.01
Silver	[7440-22-4]	0.05
Toxaphene	[8001-35-2]	0.005
1,1,1-Trichloroethene	[71-55-6]	0.2
Trichloroethylene	[79-01-6]	0.005
2,4,5-Trichlorophenoxy acetic acid	[93-76-5]	0.01
Vinyl chloride	[75-01-4]	0.002

^a Section 1412 of the Safe Drinking Water Act.

of effluents and water quality may not indicate the presence of contaminants in sediments. Sediment particles reach the water body by a variety of routes. The particles vary in chemical composition and in their physical properties. The constituents of sediments such as clay, organic matter, hydrated iron, manganese oxides, and associated characteristics such as particle size distribution, pH, oxidation-reduction condition, and salinity of the water body all affect the interaction between the individual sediment particles and the contaminants present in the surrounding water. As an example the behavior of particles having a high surface area to mass ratio (ie, specific surface) will be controlled predominantly by surface forces, whereas a particle having a low specific surface will be controlled by body forces (ie, gravity). As a consequence materials with high specific surfaces will contain more contaminants. Thus sediment particle size influences the presence of contaminants with the sediment and the potential for contaminant migration. The finer the particle size the greater the potential for higher concentrations of contaminants. Smaller particles remain suspended for longer periods of time, are easily resuspended in high tides and floods, and travel further from the source of contamination. Although contaminants are generally found associated with fine particles in any water body, their distribution is not uniform. They typically are found in pockets and in the deeper water. In addition, the vertical profile of contaminants are strongly affected by benthic organisms that are present in the water body. In summary, the particle size, organic content, and mineralogy can affect the selection of a remediation technology. The selection of the appropriate remediation technology is described in detail in a later section.

Contaminants typically found in sediment can be classified as follows:

- Polynuclear aromatic hydrocarbons (PAHs)
- Pesticides
- Chlorinated hydrocarbons

- Mononuclear aromatic hydrocarbons (such as benzene)
- Phthalate esters
- Metals
- Cyanides and organo-metals + others

These contaminants enter the water body from various sources and contact the sediment particles by either direct sinking or solubilization of the organic matter and subsequent adsorption on the sediment particles.

In most aquatic systems the suspended sediments and the top part of the soil column contain a higher concentration of contaminant than the overlying water column. The sediment thus becomes a sink of contaminants which can become remobilized back into the water column. In addition, the contaminants that are bound to sediments also have the potential to undergo chemical changes and thus evolve into potentially different chemical species. For example oxidation of organic matter in sediment can lead to conditions favorable to the release of bound metals into the water column (25). Other bound trace metals, especially mercury, can be methylated or converted to other organo-metallic forms by the action of micro-organisms. These organo-metals have been shown to bioaccumulate in fish (26).

CONTAMINATED SEDIMENT TREATMENT

Treatment of contaminated sediment usually involves combining several appropriate technologies into an overall scheme for achieving a cleanup objective. The treatment of dredged contaminated sediment and subsequent placement in a confined disposal facility (CDF) typically include the following steps: removal, transport, interim storage, pretreatment, treatment, disposal, and effluent (including surface runoff) or leachate treatment. In this section the pretreatment and treatment steps will be discussed. All processes in this article were recommended for study in the ARCS program (27,28) or have been used in the mining industry (29).

Soil Chemistry

Properties of Sediments Affecting Contaminants. Sediments requiring remediation can vary widely in terms of physical and chemical properties. The primary physical characteristic is texture (ie, the distribution of sand, silt, and clay-sized particles). In general, sandy sediments have little attraction for either toxic metals or synthetic organics (pesticides and industrial organics). In contrast, fine-textured sediments such as silt and clay have a much greater affinity for all classes of contaminants. Fine-textured material at the sediment-water interface and suspended silt and clay particles effectively remove contaminants from the water column. These fine-textured materials have large surface areas when compared to either their volume or mass (eg, specific surface). This large surface area serves as a site for colloidal chemistry to occur. These particles tend to accumulate in more quiescent reaches of waterways. Separation of the less contaminated gravel and sandy fractions from contaminated sediments may be possible, yielding material clean enough for disposal without restriction, while also reducing the volume of the contaminated sediment requiring treatment.

A second important physical property is the organic matter content. Fine-textured sediments generally contain from one

Table 10. Typical Fate of Potentially Available Metals In a Changing Chemical Environment^a

Metal Type	Initial Condition	Environmental Changes	Result
Carbonates, oxides, and hydroxides	Salts in the sediment	Reductions of pH	Release of the metals as the salts dissolve
Adsorbed on iron oxides	Adsorbed in sediment	Sediment becomes reducing or acidic	Iron oxides become unstable and release metals
Chelated to humic	Chelated in sediment	Strongly immobilizes metal in both reducing and oxidizing sediments (however, there is some indication that the process is less effective if a reduced sediment becomes oxidized)	
Sulfides	Very insoluble precipitate	Sediment becomes oxidized	Sulfides become unstable, oxidize to sulfates, and release the metals

^a Ref. 30.

- To separate coarser, potentially cleaner, solids from the fine-grained, more contaminated solids (particle classification)
- To reduce the overall cost for the remedial action

Pretreatment technology processes include (1) dewatering, (2) particle classification (separation), and (3) slurry injection.

Dewatering. Dewatering technologies are processes used to reduce the moisture content of slurries or sludges to expedite the handling and to prepare the material for further treatment or disposal. The water generated during dewatering generally contains contaminants as well as suspended solids. Types of dewatering processes include mechanical, evaporative, and settling ponds. Dredged material dewatering has traditionally been accomplished in ponds or CDFs, which rely on a combination of seepage, drainage, consolidation, and evaporation. Evaporative processes by themselves alone are not considered a viable alternative for use in the Great Lakes region due to the climate. Most mechanical dewatering processes reduce the moisture of the feed material to a level comparable to *in situ* sediment (about 50 wt %) and work best on homogeneous waste streams.

Implementability for dewatering processes other than settling ponds is poor primarily because of the high processing rates required for most dredging operations. The primary purpose for dewatering to minimize the loss of leachate through the dikes and bottom of the CDF. A summary of recommended dewatering techniques for use in the ARCS program (27) is presented in Table 13.

Particle Classification. Separation by grain size is important in the management of soils and sediments contaminated with toxic materials since the contaminants tend to sorb primarily onto fine-grain clay and organic matter. The most appropriate solids separation technology for a given site depends on the volume of contaminated sediments; composition of the sediments (particle size distribution of the feed); specific gravity and chemical analysis of the soil; mineralogical composition; characteristics of the soil; percentage of sand, humus, clay, or silt; composition of the organics in each soil fraction; moisture content; pH; characterization of the contaminants; types of dredging or excavation equipment employed; site location and site surroundings (Fig. 15). Particle classification options include screening processes that depend on size, processes that depend on a combination of size and density or density alone, and processes that depend on conductive

or magnetic properties of the particles. A summary of recommended particle classification technologies evaluated by EPA are shown in Figure 15, by the ARCS program (27) in Table 14, and mining industry techniques in Table 15 (29).

Slurry Injection. Slurry injection technologies are used as a pretreatment step either to add chemicals that condition the sediment for further treatment and/or accelerate the settling of the suspended solids or to provide nutrients or microbes that enhance biodegradation of organics. The process involves the injection of chemicals or microorganisms into the dredged material slurry to take advantage of the mixing process available in the pipeline from a hydraulic dredge. A summary of recommended slurry injection techniques for use in the ARCS program (27) is presented in Table 16.

Treatment

This section discusses the various treatment technologies available for the decontamination/detoxification of contaminated sediment. Many of the process options are not stand-alone processes, but are components of a system that may involve multiple treatment steps to address multiple contaminant problems. Specific treatment objectives include the following:

- Destruction of toxic organic contaminants by conversion to nontoxic end products
- Removal of heavy-metal or organic contaminants from contaminated dredged material, thereby concentrating toxic material into a media of smaller volume (extraction), and/or to reduce the volume of solids for further treatment or disposal
- Reduction of the mobility of contaminants in dredged material to a level compatible with acceptable risks
- Compatibility with removal and final disposal options
- Compliance with acceptable capital and operating costs
- Minimization contamination of other environmental media
- Avoidance of the addition of potentially toxic materials or the production of toxic materials during the treatment process

In addition, most of the processes outlined below will also require one or more pretreatment processes.

Table 11. Half-Life Range of Typical Contaminants^a

Chemical Name	Half-Life Range in Surface Water, days		Other Half-Life Ranges
	Low	High	
PCBs	2	12.9	
Acenaphthene			
Acenaphthylene	0.125		
Anthracene			
Benzo(a)anthracene	0.10	5.00	
Benzo(a)pyrene	0.40		
Benzo(b)fluoranthene	1.00	2.00	
Benzo(ghi)perylene			
Benzo(k)fluoranthene			
Chrysene	0.20		
Dibenzo(a,h)anthracene	0.02		
Fluoranthene	1.00	2.00	
Fluorene			
Indeno(1,2,3-cd)pyrene	0.02	2.1	
Naphthalene			
Phenanthrene	0.38	2.00	
Pyrene			
Dieldrin	723 d		
Chlordane	Very persistent		
Vinyl chloride	25 min		
Chloroform	15 months		Blue gill, 1 d
1,1,1-Trichloroethane	5-9 months		
Carbon tetrachloride			Blue gill, 1 d
Dibromochloromethane	274 yr		
Bromoform	686 yr		
Chlorobenzene	5.8 h		
Bis(2-chlorethyl)ether			Blue gill, 4-7 d
2-Chlorophenol			Blue gill, 1 d
2,4-Dimethylphenol	1 d		
2,4-Dichlorophenol	8-9 d		
Hexachlorocyclopentadiene	11 d		
2,4,6-Trichlorophenol			Rat blood, 20 h
2-Chloronaphthalene	Biomagnified in water		
2,4-Dinitrophenol	No significant microbial degradation in 64 d		
2,6-Dinitrotoluene	>64 d		
Benzidine			Dogs and rats, 68-88 h
3,3'-Dichlorobenzidine			Long life in soil
Bromoform	686 yr		
Chlorobenzene	5.8 h		
Bis(2-chlorethyl)ether			Blue gill, 4-7 d
2-Chlorophenol			Blue gill, 1 d
2,4-Dimethylphenol	1 d		
2,4-Dichlorophenol	8-9 d		
Hexachlorocyclopentadiene	11 d		
2,4,6-Trichlorophenol			Rat blood, 20 h
2-Chloronaphthalene	Biomagnified in water		
2,4-Dinitrophenol	No significant microbial degradation in 64 d		
2,6-Dinitrotoluene	>64 d		
Benzidine			Dogs and rats, 68-88 h
3,3'-Dichlorobenzidine			Long life in soil

^a Refs. 5 and 31.

Biological Treatment. Biological degradation technologies use bacteria, fungi, or enzymes to break down PCBs, pesticides, and other organic constituents into less toxic compounds. The microorganisms may be indigenous microbes, conventional mutants, or recombinant DNA products. Biological degradation proceeds with slower reaction rates than thermal or chemical techniques. A summary of recommended

biological techniques evaluated by the ARCS program (27) is presented in Table 17.

Chemical Technologies. The objective of chemical processes, such as chelation, oxidation, or reduction, is to change the form of a toxic material to render it less toxic or to change its solubility, stability, separability, or other properties affecting

Table 12. Sediment Quality Assessment Methods^a

Method	Type			Concept
	Numeric	Descriptive	Combination	
Bulk sediment toxicity	x			Test organisms exposed to sediments containing unknown quantities of potentially toxic chemicals; at end of specific period, response of test organisms is examined in relation to specified biological endpoint
Spiked-sediment toxicity	x			Dose response relationships established by exposing test organisms to sediments spiked with known amounts of chemicals or mixtures of chemicals
Interstitial water toxicity	x			Toxicity of interstitial water is quantified and identification evaluation procedures are applied to identify and quantify chemical components responsible for sediment toxicity; procedures are implemented in three phases: (1) characterization of interstitial water toxicity, (2) identification of the suspected toxicants, and (3) confirmation of toxicant identification
Equilibrium partitioning	x			Sediment quality value for given contaminant is determined by calculating sediment concentration of contaminant that corresponds to interstitial water concentration equivalent to EPA water quality criterion for contaminant
Tissue residue	x			Safe sediment concentrations of specific chemicals established by determining sediment chemical concentration that results in acceptable tissue residues; methods to derive unacceptable tissue residue based on chronic water quality criteria and bioconcentration factors, chronic dose response experiments or field correlations, and human health risk levels from the consumption of freshwater fish or seafood
Freshwater benthic community structure		x		Environmental degradation measured by evaluating alterations in freshwater benthic community structure
Marine benthic community structure		x		Environmental degradation measured by evaluating alterations in marine benthic community structure
Sediment quality triad	x	x	x	Sediment chemical contamination, sediment toxicity, and benthic infauna community structure measured on the same sediment; correspondence between sediment chemistry, toxicity, and biological effects used to determine sediment concentrations that discriminate conditions of minimal, uncertain, and major biological effect
Apparent effects threshold	x		x	AET is sediment concentration of contaminant above which statistically significant biological effects (eg, amphipod mortality in bioassays, depressions in abundance of benthic infauna) is always expected; AET values empirically derived from paired field data for sediment chemistry and range of biological effects indicators

^a Ref. 28.

handling or disposal. Chemical treatment technologies use chelating agents, acid or base addition, chlorine displacement, oxidation, or reduction in the destruction, detoxification, or removal of contaminants found in contaminated sediments. A summary of recommended chemical technologies reviewed/evaluated by the ARCS program (27) is presented in Table 18.

Extraction Technologies. Extraction is the removal of a contaminant (organic/inorganic) from soils or sediment by dissolving it in a fluid that is later recovered and subsequently treated to remove the contaminant or recycled. Extraction is often used to remove volatile organics from permeable soils and can also be used to treat soils and sludges contaminated with the following: metals, inorganics, organics (PCBs, TPH, halogenated solvents, aromatics), amines, ethers, and anilines. Extracting agents that are employed vary according to the contaminants to be treated. They include water, acids, bases, complexing and chelating agents, surfactants, and certain reducing agents.

There are two basic methodologies employed utilizing extraction processes: (1) containerized extraction, and (2) *in situ* extraction. In the containerized extraction process soil/sediment is excavated and placed in a container to allow contact with the extracting liquor. The extracting liquor is then injected into the soil, and contaminants are extracted from the soil and concentrated in the washing solution. The washing solution leaches the contaminants out of the soil and is collected and recycled by a specific treatment technology appropriate for the type of contaminants involved. For *in situ* extraction processes, the contaminated site is typically flooded with an appropriate extraction solution and the elutriate leaching from the site is collected either by a series of shallow well points or subsurface drains. The leachate is then treated and recycled back into the site.

A summary of recommended extraction technologies reviewed/evaluated by the ARCS program (27) is presented in Table 19. The technologies presented in Table 20 include (1)

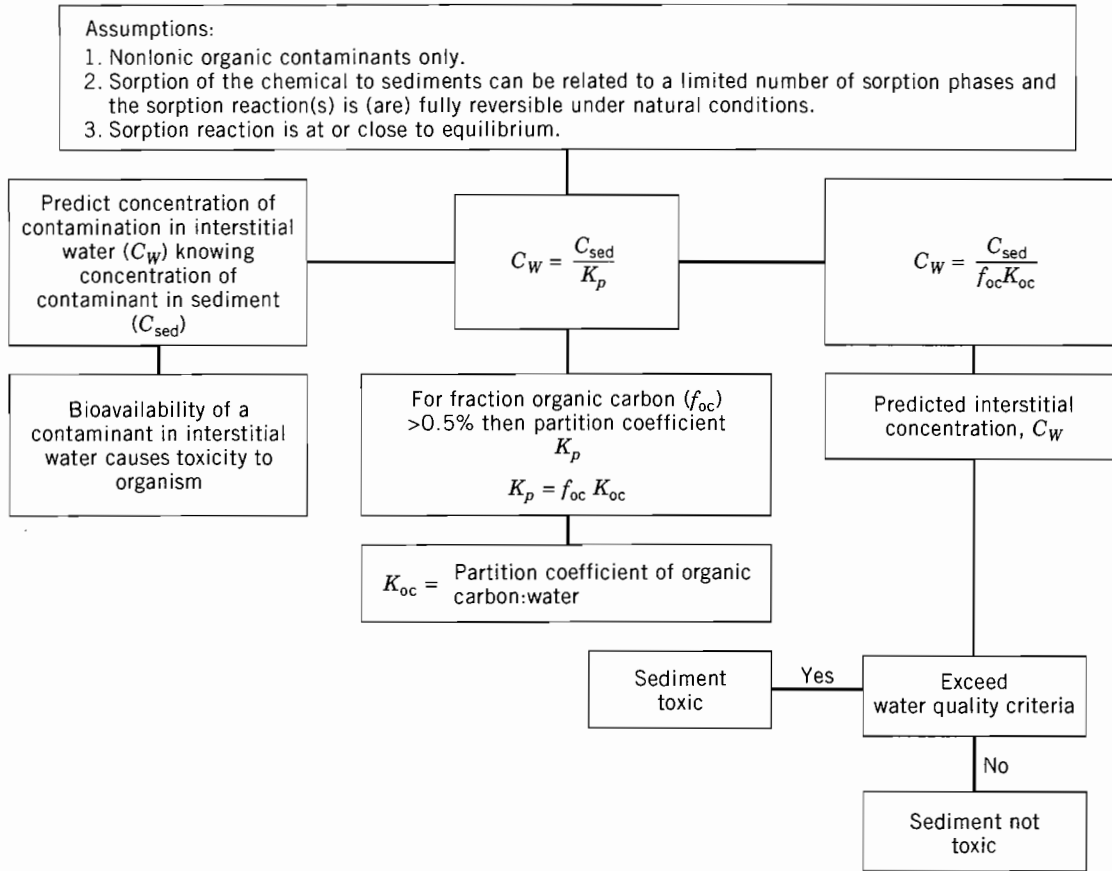


Figure 13. Summary of EPA's EqP model for estimating toxicity of nonionic organic chemicals in sediments.

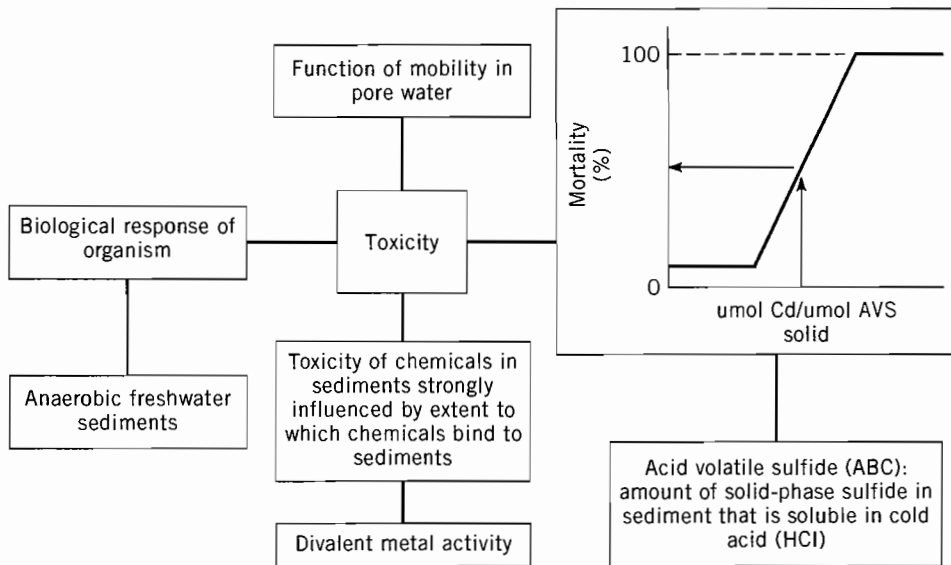


Figure 14. Summary of acid volatile sulfide method for determination of toxicity of cadmium in sediments.

acid leaching, (2) BEST, (3) C. F. Systems-Propane, (4) Low Energy (acetone/kerosene), and (5) surfactants.

Immobilization Technologies. The purpose of immobilization technologies is to limit the mobility of contaminants that

are present in sediments. Most immobilization techniques take the form of solidification or stabilization (S/S) processes performed prior to placement of the dredged material in the CDF. The objectives of S/S are generally to improve the handling and physical characteristics of the material, decrease

Table 13. Pretreatment Component Dewatering

Process Option	Treatment Methodology	Factors Controlling Performance	Minimum Input Slurry Range, wt %	Output Slurry Range, wt %	Cost ^a
Belt filter press	Use single or double moving belts to dewater sludges. Consists of three stages: (1) conditioning by adding of flocculent or thickening drum; (2) gravity drainage of free water, and (3) compression zone. Compression zone is provided by top belt pressing against bottom belt which serves as filter.	Sediment solids feed concentration, flocculent, amount of pressure between rollers, filter opening size	1-40	50-60	Capital cost for 500,000 yd ³ facility \$6 million; operation and maintenance \$20-\$100 per yd ³
Carver-Greenfield evaporation	Food-grade carrier oil injected into waste as fluidizing agent to maintain liquid phase as solids content increases. Oil-soluble contaminants extracted from waste by carrier oil, and volatile compounds stripped out and condensed with carrier oil and water. Water removed by thermal treatment. Carrier oil removed by evaporation and stream stripping, and contaminants removed for distillation. Useful for sediments and wastes containing oil-soluble contaminants such as PCBs, dioxins.	Temperature, carrier oil	8		
Centrifugation	Uses rapid rotation of fluid mixture inside rigid vessel to separate components based on mass. Types are solid bowl, basket, and disk. Concentrates soil/sediments from fine gravel to silt.	Particle size; efficiency drops drastically for particles <10 μm	Disk = 1	Solid basket = 15-40; basket = 9-25; disk = 6	Capital cost for 50 lb/h dry \$500,000; operation and maintenance \$20-\$100 per yd ³
Chamber filtration	Utilizes rigid individual filtration chambers operated in parallel under high pressure to dewater slurry. Used in situations requiring large area of filtration in minimal area.	Pressure plate warpage and deterioration of plate gasket.		>50	Operation and maintenance cost \$20-\$100/yd ³
Gravity thickening	Operates on differences in specific gravity between solids and water to accomplish separation. Process accomplished in circular vessel similar to conventional clarifier.	Maximum flow, waste type, volume of solids per day, percent solids, specific gravity, surface chemistry, maximum particle size, percent solids required in underflow.			Operation and maintenance \$20-100/yd ³
Primary settling (CDF)	Functions like large settling pond. Effective settling area reduced by wind, turbulence, and short-circuiting.	Efficiency controlled by hydraulic characteristics of settling pond and drainage mechanism.		~50	Operation and maintenance <\$20/yd ³

Table 13. (continued)

Process Option	Treatment Methodology	Factors Controlling Performance	Minimum Input Slurry Range, wt %	Output Slurry Range, wt %	Cost ^a
Subsurface drainage (CDF)	Consists of network of perforated pipes or filter material placed under or around perimeter of CDF. Pipes or filter material drain to series of sumps where water is withdrawn.	Permeability of dredge and filter material, time.			Operation and maintenance <\$20/yd ³
Vacuum filtration	Consists of rotating cylindrical drum mounted horizontally and partially submerged in trough containing slurry. Vacuum supply applies negative pressure to inside of drum while the moist solids adhere to filter.	Vacuum, degree of drum submergence, drum speed, filter media, porosity, feed type, solids, concentration, chemical conditioning, management.		20–40	Operation and maintenance \$20–\$100/yd ³
Wick drains (CDF)	High permeability polymeric strips to promote both radial and vertical drainage. Normally placed on 1.5 m (5 ft.) centers to depths of 12 m (40 ft.) Surcharge used to promote dewatering. Have been used on CDFs.	Wick spacing, depth of CDF, material type, amount of surcharge.			Operation and maintenance cost \$20–\$100/yd ³

^a 1 m³ ≈ 0.77 yd³.

the surface area of the sediment mass across which transfer or loss of contaminants can occur, and/or limit the solubility of contaminants by pH adjustment or sorption phenomena. Immobilization techniques are typically used for heavy-metal contaminants because they cannot be destroyed and extraction from soils is a difficult process. Solidification or stabilization is also effective for limiting the volume of leachate leaving the site. It should be noted that placement of contaminated dredged material in a low permeability landfill covered with a low permeability cap is in itself a physical immobilization technique. Thus immobilization techniques can include chemical techniques that modify the dredged materials and containment techniques that simply prevent the movement of water to or from the waste. A summary of immobilization techniques for use in the ARCS program (27) is presented in Table 20.

Thermal Technologies. Thermal technology processes include low temperature thermal desorption, incineration, pyrolysis, vitrification, supercritical and wet air oxidation, and other processes that require heating the sediment up to thousands of degrees above the ambient temperature. Thermal processes are generally the most effective options for destroying organic contaminants. As a first step, low temperature thermal desorption may be needed to change the contaminant to the vapor phase so that the gas can be collected. Incineration typically achieves destruction/removal efficiencies greater than 99% for organic contaminants. Heavy metals in the incineration processes generally pass through the process, except that some of the most volatile metals (such as lead and mercury) can volatilize from the higher temperature processes.

Pyrolysis in contrast involves heating the material in the absence of oxygen. Volatile materials are driven off and collected or destroyed by secondary processes, and metals, salts, and other nonvolatile materials melt into molten glass. Vitrification processes use high voltage graphite electrodes to provide the primary heat source. A summary of thermal techniques reviewed/evaluated by the ARCS program (27) is presented in Table 21.

SUMMARY AND CONCLUSIONS

Sediments serve as "sinks" for contaminants discharged into receiving waters. If these contaminants are toxic, they constitute a significant problem since these contaminants have the potential for bioaccumulation and for infecting the overlying waters if they are released from the sediments. Determination of the persistence and fate of these toxic pollutants in contaminated sediments requires a knowledge of the contaminant types within the sediment, and the manner in which these are "held".

The strategies for management of contaminated sediments generally pertains to the stewardship of natural and financial resources or the development of cost effective solutions. The terms *contaminated* and *clean*, as they pertain to sediments, are somewhat arbitrary. At the national level, agencies such as EPA, U.S. ACE, and Environment Canada continually research and develop guidelines for determining the levels of various pollutants in sediments that cause adverse ecological and human health effects. Sediment quality criteria have been evolving for the last two decades by using a wide range of biological

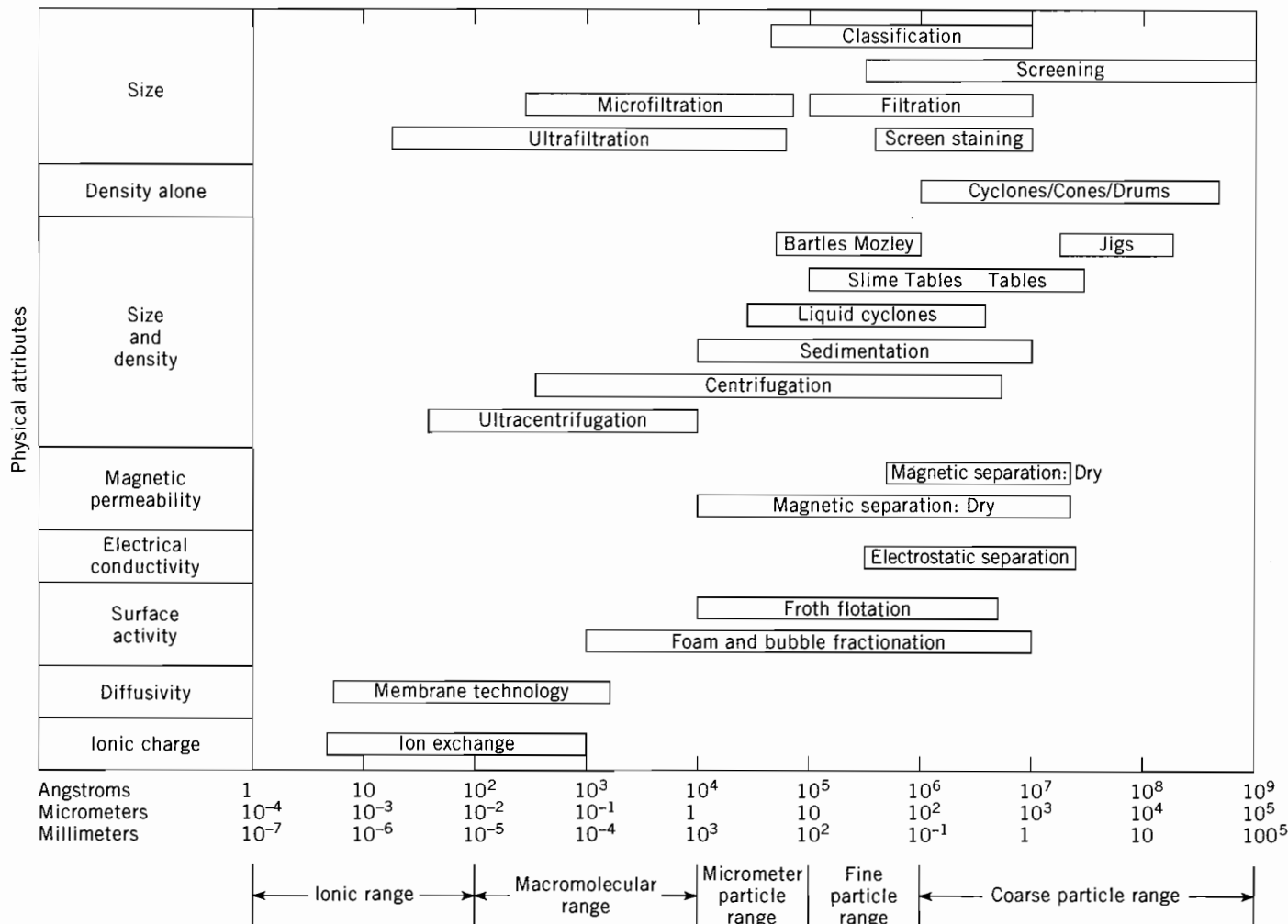


Figure 15. Physical separation technology and particle size.

and chemical assessment techniques for evaluation of both water column and benthic impacts. Although it is arguable that these criteria are adequately defined, the primary remediation problem is the high cost of field sampling and laboratory testing to define that portion of a site that fails the criteria and requires remediation from the portions which are clean and those which are at a problematic contaminant level, ie, higher than the remediation criteria. Several hundred core samples may be required for a single site.

For navigation dredging projects the U.S. ACE and U.S. EPA have developed a technical framework for environmental evaluation of dredged material disposal alternatives. The framework uses a tiered approach which on a site specific basis evaluates the alternatives including (1) no action, (2) contain in place, (3) treat in-place, (4) remove and contain, and (5) remove and treat.

For contaminated sediment remediation projects, management strategies are not well established but the U.S.ACE and U.S.EPA are presently cooperating to develop and implement a strategy. The legal authorities for remediation and enforcement are provided in legislation of the Clean Water Act, CER-

CLA/Superfund, RCRA, TSCA, the Oil Pollution Act of 1990, and many state regulations.

Technical and scientific evaluations would be expected to dominate any remediation strategy, however other factors are also important, such as public support for the project; consensus of all affected groups such as business, industry, commerce, and the general public is necessary. The common goal is to develop an environmentally sound plan which reflects the views of the community and satisfies the overlapping jurisdictions of the many national, regional, and local agencies involved.

Containment and isolation are important components in the regulation of contaminated sediment disposal in the United States. The basic design considerations are to control all potential contaminant migration pathways. The applicable regulations covering the disposal of contaminated sediments is shown to be a function of both the concentration of contaminant and the partitioning coefficient for the contaminant in water. Those sediments that have very low levels of contamination or are contaminated with constituents having a very low solubility in water, eg, having a low partitioning coefficient can

Table 14. Pretreatment Particle Classification Technologies

Process Option	Size of Particle Handled	Treatment Methodology	Equipment Requirements	Advantages	Limitations	Size Requirement	Cost*
Flotation	Fines	Physiochemical process to concentrate contaminants. Material is ground finer than 48-65 mesh so that contaminants are able to float by air bubbles. After grinding, suspended particles treated with chemicals to cause particles to be air-avid and water repellent. Mixture agitated with air and contaminants attached to air bubbles, float to surface, forming froth.	Mechanical flotation device uses upright impeller for agitation and aeration. Pneumatic device uses air blowers.	Corrosion resistance	Dependent on surface chemistry, particles size, shape distribution of feed, contaminant distribution with particle size, characteristic of soil, specific gravity and chemical analysis of soil, mineralogical analysis, solids to liquids ratio, pH.		Capital cost \$24-\$160K. Operation and maintenance \$20-\$100 yd ³ .
Grizzlies	Debris to gravel, >1.0 in.	Concentrated froth skimmed off leaving clean product. Vibrating or fixed separation units used to remove oversized material and reduce slurry velocity prior to subsequent processing.	Device consists of parallel frame mounted bars spaced 1-5 in. apart. Units can be used in series or parallel.	Improves the reliability and efficiency of separation technologies. Maintenance costs minimal.	None.	Typically 6-9 ft wide and 12-18 ft long.	Operation and maintenance cost <\$20/yd ³

Table 14. Pretreatment Particle Classification Technologies

Process Option	Size of Particle Handled	Treatment Methodology	Equipment Requirements	Advantages	Limitations	Size Requirement	Costs
Hydraulic classifiers	Gravel to fine sand	Physical separation and classification by grain size of sand and gravel from fines by settling velocity through water.	Typically V-shaped rectangular trough or cone in which slurry of dredge material is directed. Sand and gravel particles fall to bottom and recovered through discharge valves; fine-grained material carried off by water flow.	Units typically designed for mobile system application with quick startup and shutdown time. Fairly simple maintenance requirements.	Removal and classification of solids from 3/8 in. to ~74 μm . Some fines removed with sand and gravel		Capital cost varies with size and capacity. Typical range \$30-\$76K. Operation and maintenance \$20-\$100/yr ³
Hydrocyclones	Separates clay/silt from coarser particles	Separates solids (gravels and sands) from slurry by vortex-generated centrifugal forces.	Cone-shaped vessel with tangential feed inlet at top. Discharge pipe located short distance into vessel to form vortex.	Applicable to sites with limited space. Wide variety of sizes and can be operated in series or parallel.	Not effective with highly viscous, high clay content slurries, slurries with solids concentration >30%, or particles with specific gravity ~2.5-3.2.	Small size	Capital cost varies according to size and number. Typical range \$1-\$5K. Operation and maintenance <\$20/yr ³ .
Impoundment basins	Gravel to fine silt	Physical separation and classification by grain size of gravel to fine silt by settling velocity through water	Diked area or CDF	Handles large dredging operations.	Requires large area. No solids removal system. Needs backhoe or clamshell dredge. Minimal control when used employed as particle separator	Large area	Operation and maintenance <\$20/yr ³
Magnetic/electrostatic	$\leq 100 \mu\text{m}$	Separates slurry based on difference in magnetic and conductive properties between contaminant and soil.	Slurry forced through magnetized steel wool containing 95% void space. Intensity of magnetic field can vary from 1-100 kG.	Soils may be dry or in slurry form.	Particles must be <100 μm . If contaminants finely disseminated throughout soil, unlikely to work.		Operation and maintenance \$20-\$100/yr ³

Moving screens 1/8-6 in. Plain screening surface in rectangular frame. Typically nested from coarse to fine at slope of 20° to allow for a cascading effect. Screens may be vibrated, revolving, or gyrated. Vibrated most common.

Can typically handle 300-950/t of material. Soil must be dry or washed through screen with water. Screen replacement frequent.

Vibrated rectangular framed screen arranged in nest. Usually placed at 20° slope to allow particles to cascade from one screen to next.

Capital cost for screen 10' long, 5' wide, 5' deep with a capacity of 200 t/h ~\$25K. Operation and maintenance \$20-\$100/yd³.

Shaking table Wide range from slimes to rocks

Rectangular table with a slope 0-6°. Surface smooth with riffles. Table capable of being shaken.

Rectangular table with a slope 0-6°. Surface smooth with riffles. Table capable of being shaken.

Operation and maintenance \$20-\$100/yd³.

Shaking table Wide range from slimes to rocks

Rotating screws mounted in inclined rectangular vessel with capability of washing, dewatering, and sediment.

Rotating screws mounted in inclined rectangular vessel with capability of washing, dewatering, and sediment.

Typically 22-34 ft long, 8-19 ft wide and 8-12 ft deep.

Spiral classifiers Sand and gravels ≤3/8 in.

Settled solids fed from hydraulic classifier into spiral classifier by rotating screw placed on incline. Fines carried to bottom of incline while sand and gravel carried up incline by screw.

Removes clay and silt adhering to sand and gravel. Designed for mobile systems. Capable of processing up to 950 t/h.

\$14-\$77K for single screw; \$37-\$150K for double screw. Operation and maintenance from \$20-\$100/yd³.

Table 14. Pretreatment Particle Classification Technologies (continued)

Process Option	Size of Particle Handled	Treatment Methodology	Equipment Requirements	Advantages	Limitations	Size Requirement	Cost ^a
Stationary screens	Separates fines from sands and gravels.	Screen surface continuously curved. Slurry passed over screen with velocity high enough to produce centrifugal force to keep slurry in contact with screen.	Curved screen surface. The screen consists of frame mounted parallel bars spaced close together for finer particle separation. Pressurized water spray can be added to increase efficiency.	No moving parts; wedge bar screen more resistant to abrasion.	Less efficient than vibrating screen.	Small size.	Operation and maintenance \$20-\$100/yd ³ .

^a 1 m³ ≈ 0.77 yd³.

Table 15. Screen Types^a

Distinguishing Characteristics	Classifications	Description	Motion	Speed, Amplitude	Applications	Advantages/Disadvantages
Heavy-duty surface of fixed bars	Conventional	Heavy bars running in flow direction, sloped to allow gravity transport. Bars may spread along length to minimize blinding	Stationary		Scalping before crushers	Simple, robust, probability form-blinding, resistant
	Probability	Bars divergent in vertical plane				
Surface of rotating rolls		Stationary screen surface, but nonuniform shape of rolls conveys material.			Coarse separations before crushing, primarily conveyor.	Conveying action allows near horizontal operation in low head room situations.
	Slurry feed, fixed bar surface	Straight or curved surface	Stationary, parallel bars at right angles to slurry flow. Surface may be straight (with steep incline) or curved to 300°.		Separations in range 2 mm to 45 μm , or those too coarse for hydrocyclone, or where density effects make classifier unsuitable, dewatering.	Relatively high efficiency and capacity. Sharpness of cut less than true screen. Separation slightly affected by mineral density. Excessive dewatering can be a problem.
Screen surface rotating around cylinder axis	Trommel	Slightly inclined cylindrical screen, may have concentric surfaces	Stationary	15–20 rpm	Wet or dry separations 60 to 10 mm if dry, smaller if wet.	Simple, useful for scrubbing or rough size separations. High wear, low surface utilisation.
	Centrifugal	Vertically mounted cylindrical screen; centrifuges particles through screen.	Revolving screens	60–80 rpm	Wet or dry separations 12 mm to 400 μm ; dewatering.	High wear
	Probability	Particles drop through "surface" formed by bars radiating out like wheel spokes.	Vibrating screens		Developed for separating coal <6 mm	Relatively high capacity with fine separations, cut size easily changed and controlled by varying speed

Table 15. Screen Types^a (continued)

Distinguishing Characteristics	Classifications	Description	Motion	Speed, Amplitude	Applications	Advantages/Disadvantages
			<i>Stationary grizzly</i>			
	Inclined (sub-classified by vibrator mechanisms)	Inclined rectangular screening surface which allows material to flow with aid of vibrations.	Mechanical vibrations give circular motion at center; elsewhere it depends on vibrator. Electromagnetic vibrators may give linear vibration at center.	600–7000 rpm Low <25 mm	Wide applications, generally down to 200 μm in mineral industry, but down to 38 μm in chemical industry, using the high speeds.	Relatively high efficiency and capacity, but capacity generally inadequate below 200 μm .
High speed motion, designed primarily to lift particles off surface.	Horizontal	Horizontal rectangular screening surface. Linear vibration must have horizontal component to convey material along screen.	Linear motion, with vertical component to provide lift, and horizontal component for conveying.	600–3000 rpm Low <25 mm	Similar to inclined screens.	Similar to other vibrating screens, but can also be used where head room is restricted.
	Probability	Series of relatively small inclined screen surfaces: separates by statistics rather than physical constraint.			Similar to inclined screens	Generally superior to conventional vibrating screen. High capacity and efficiency for given space: low noise, low power. Low efficiency at low loading.
Slow linear motion essentially in plane of screen.		Usually slightly inclined. May have several surfaces in series with different apertures.	<i>Shaking screens</i>			
			Linear motion, essentially in plane of screen; particles tend to remain in contact with screen surface.	30–800 rpm 25–1000 mm	Down to 12 mm for coal preparation and nonmetallic minerals. Higher speeds may size down to 250 μm .	Low headroom and power requirements. May be used for conveying and sizing. Accurate for large sizes. High maintenance cost, low capacity.
	Reciprocating	Rectangular screen surface with slight (~5°) incline.	<i>Rotary sifters</i>			
			Circular motion is applied at feed end, and produces reciprocating motion at discharge end.			
Circular motion applied to screen surface	Gyrating	Circular screen surface.	Circular motion over most of the screen surface.	500–600 rpm Low <25 mm	Generally used for finer separations (12 mm to 45 μm , wet or wet or dry) in non-metallurgical industries.	Suitable for finer separations, but with low capacity.

Table 15. (continued)

Distinguishing Characteristics	Classifications	Description	Motion	Speed, Amplitude	Applications	Advantages/Disadvantages
	Gyrating	Circular screen surface.	Screen moves with circular motion, but also has oscillating vertical component.			

^a Ref. 28.

Table 16. Pretreatment: Slurry Injection

Process Option	Size of Particle Handled	Treatment Methodology	Equipment Requirement	Advantages	Limitations	Costs ^a
Chemical clarification	Silt and clays	Use of conditioners to promote coagulation or flocculation of smaller size colloidal size particles. Process increases rate of sedimentation. Coagulants include inorganic chemicals (salts of iron and aluminum), organic polyelectrolytes. Polyelectrolytes recommended for dredged material.	Pipeline transport of dredged material slurry required to mix conditioner to mix conditioner. Method to inject conditioner required.	Polyelectrolytes are less dependent on pH and require lower dosages compared to inorganic chemicals.	Settling process required after injection of conditioners. Prolonged periods of mixing reduce effectiveness.	Operation and maintenance <\$20/yd ³ .
Microbe addition	Silt and clays	Use of microorganisms acclimated to degrade toxic materials. Microorganisms injected into pipeline slurry, mixing through sediment mass.	Pipeline transport of dredged material slurry required to mix microorganisms. Method to inject microorganisms required.		Different microorganisms required for different types of toxics.	Operation and maintenance \$20-\$100/ yd ³

^a 1 m³ ≈ 0.77 yd³.

be controlled by designing the CDF for solids retention. For higher concentrations of contaminants, or for contaminants having high partitioning, the CDF must be designed based on hydraulic isolation of the waters released by the sediments.

Dredged material contaminants placed within a CDF can leave the system using the following pathways: (1) waterborne pathways including effluents drained from the waste, effluent seeping through the dikes, leachate seeping into the groundwater within the foundation of the CDF, and surface water runoff; (2) via plant or animal uptake; and (3) from airborne emissions. Each contaminant pathway may be controlled by engineered components, ie, with a liner or by selective placement of the dredged materials.

Waterborne contaminants moving through the dikes or leaching into the subgrade can be controlled either with

engineered barriers such as clay or synthetic liners or by placement of clean fine-grained dredged materials initially on the bottom of the CDF to provide hydraulic isolation. Similarly, water runoff, animal and plant uptake, and air emissions can be controlled either through the use of an engineered cover system or the placement of clean dredged material over the contaminated dredged material. A number of testing protocols are available to evaluate the need for pathway control.

Remedial technologies can be broadly divided into either active remediation or in-place remediation. Active remediation involves dredging of the contaminated sediments and then treating them *ex situ* under highly controlled conditions. In contrast, in-place remediation involves processes such as isolation by natural burial, capping and armoring or bioremediation. A treatment/remediation method is selected after a

Table 17. Contaminant Sediment Treatment: Biological

Process	Applicable Contaminants	Mechanism	Factors Affecting	Demonstrated for Remediation of Sediments	Typical Cost ^a	Comments
Aerobic bioreclamation	Organic materials	Microorganism are encouraged to grow in aerobic environment utilizing the organic contaminant as food source.	Nutrients for growth of micro-organisms, oxygen, temperature, soil moisture, pH.	Bench	Operation and maintenance \$20-\$100/ yd ³	Methodology can be used to treat soils and groundwater contaminated with organic materials
Anaerobic bioreclamation	Organic contaminants such as halogenated compounds, various aromatics, some pesticides.	Process uses anaerobic metabolism that includes anaerobic respiration using nitrate or sulfate as terminal electron acceptor and fermenting methanogenic processes using methanogenic consortium (strictly anaerobic bacteria).	Temperature, redox potential of ≤ -250 mV, no oxygen, nitrates, or sulfates present.	Bench	Operation and maintenance \$20-\$100/ yd ³ .	Process is slower and fewer compounds can be degraded in comparison to aerobic bioreclamation.
Bioreactors	Organic materials	Aerobic biodegradation technology that functions to increase availability of contaminants and nutrients to microbes within tank. Slurry dewatered and resultant water treated, if necessary.	Nutrients, oxygen, pH.	No	Operation and maintenance \$20-\$100/ yd ³ .	Limitations of technology include inhibition of microbial metabolism by chloride substitution and heavy metals, and temperatures outside the optimum range.

^a 1 m³ \approx 0.77 yd³.

preliminary estimate of the magnitude and extent of sediment contamination and the associated risks to human health and the environment.

The nature of contaminated sediments effects the selection of treatment technologies. The volume of sediments present at contaminated underwater sites tend to be quite high, while the concentrations of contaminants in the sediments tend to be relatively low in comparison to the concentration of contaminants in soils at hazardous waste cleanup sites. In addition, the majority of contamination is typically associated with the fine-grained material. Because most of the contaminants are associated with the finer grained material, substantial cost savings can be achieved for active remediation by first applying extractive technologies, thus reducing the volume of material requiring further treatment by more expensive destructive methods. Once the

volume of material has been reduced, a treatment strategy for the fine-grained material can then be devised. In addition dredged materials must first undergo a dewatering stage prior to treatment because of the high initial water content.

Treatment technologies can be broken down into two broad categories: (1) those that work on the sediments *in situ* and (2) those that process sediment after dredging. In general, *in situ* treatment technologies for contaminated sediments are less developed than the technologies that can be applied to dredged materials. Any decision to leave sediments in place is highly dependent on an evaluation of the relative risks posed by the sediments left untreated on the bottom, the risks of performing a treatment operation on *in situ* sediments, and the risks associated with the removal and subsequent disposal or treatment of the contaminated dredged materials.

Table 18. Contaminant Sediment Treatment: Chemical

Process	Applicable Contaminants	Mechanism	Factors Affecting	Demonstrated for Remediation of Sediments	Cost ^a	Comments
Chelation	Metals	Chelating molecule (ligand) forms multiple bonds with metal ions resulting in a heterocyclic (ringed) structure. Chelating agents either increase metal mobility for removal or immobilize by sorbing onto clay materials.	pH, chelate dosage, chelating agent, metal type	No	Operation and maintenance of \$100–\$200/ yd ³ .	Chelating agents must be used according to their affinity for particular metals.
Nucleophilic substitution	PCBs, acids, oils, thiols, dioxins, chlorobenzenes.	Chemically removes chlorine from organic (aromatic) compounds using electron donor principle.	Requires alkaline conditions (high pH level), temperature, reaction time, reagent dose, moisture content.	Yes	Operation and maintenance \$150–\$200/ yd ³ .	Two primary processes: APEG, alkali metal hydroxides in polyethylene glycol: KPEG, potassium–polyethylene glycol.
Oxidation of organics	Oxidation organics such as aldehydes, phenols and benzidine. Limited applications for slurries, tar, and sludge.	Oxidation state of atom increased by removal of electrons. Oxidation transforms, degrades, or immobilizes contaminants in soil system.	Oxidant concentration, pH, oxidation potential.	Yes	Operation and maintenance \$150–\$200/ yd ³ .	Toxic products may form if reaction not complete. Process not applicable for high strength complex waste systems, nor highly halogenic organics. Methodology can be employed <i>in situ</i> .

^a 1 m³ ≈ 0.77 yd³.

Treatment technologies for dredged material have been evaluated and demonstrated by a number of groups (27). A review of the literature indicates that all treatment technologies typically leave some degree of contamination in the sediment (3). No single technology has been shown to be effective for all contaminants. Typically, technologies are designed to deal with either the organic contaminants (such as PCBs) or heavy-metal contaminants. Some of the available technologies (eg, particle separation and solidification) may effectively treat both types of contaminants, but their application is limited to sediments with specific characteristics that are not present at all sites. Complications have been shown to arise due to the presence of certain contaminants in application of some technologies, and volatile contaminants may be lost unintentionally during the application of thermal treatment processes. In addition, treatment technologies are effective on only some types of sediment. These limitations suggest that

multiple step treatment processes will be necessary to treat sediment.

The following conclusions apply to contaminated dredged materials:

1. Contaminated sediment remediation projects are multidisciplinary in nature and are driven by federal and state regulations. Standards test methods and data are needed to provide a basis for improved communication and understanding between the involved parties.
2. Site investigations to characterize the nature and extent of contamination are difficult and costly. A tiered-testing approach has been proposed by U.S.ACE/ U.S.EPA to identify suspect sites.
3. There remains an urgent need to develop *in situ* chemical sensors such as the polyacrylamide gel probe for discrete data or possibly fiber optic sensors with telemetry

- for continuous data monitoring before, during, and after disposal.
4. There is a need to develop a number of analytical and stochastic models to support scientific and engineering evaluations of a remediation option such as the mass-balance analysis of contaminants during dredging, placement in a CDF and isolation.
 5. Natural sediments, by nature, are soft and difficult to sample and handle. Dredged sediments have entrained water and exhibit fluid-like behavior.
 6. Contaminated sediments usually contain oil and grease or other organic components with the potential to generate gas and odor following dredging. These may require special attention during dredging and remediation.

Table 19. Contaminant Sediment Treatment: Extraction

Process	Applicable Contaminants	Mechanism ^b	Factors Affecting	Remediation of Sediments, Dredged Materials	Typical Cost ^c
Acid leaching	Metals, amines, anilines, ethers, phenols.	Steam and/or weak acids (aqueous solutions of sulfuric, hydrochloric, nitric, phosphoric, and carbonic acid) used as dissolving agents for basic metal salts, amines, anilines and ethers processes. <i>In situ</i> treatment may be performed using weak acid solutions (acetic acid and sodium hydrogen phosphate). Basic solutions (NaOH) used as flushing agents for soils contaminated with metals (zinc, tin, lead, and phenols).		Pilot, no	Operation and maintenance \$63–\$200/ yd ³ .
Basic extraction sludge treatment (BEST)	PCBs, oils, creosote	Mixture of 1 part free water sediment and 1–7 parts amine-based solvent, usually TEA. Single liquid phase forms and solid matter removed by centrifugation and dried to remove residual TEA. TEA is then processed to remove contaminants.	Treatment must be sealed from atmosphere and operated under nitrogen blanket. Temperature must be below critical solution temperature. Alkaline conditions (pH 10) required.	Demonstrated, bench	Operation and maintenance \$60–\$300/ yd ³ .
C.F. Systems-Propane	PCBs and organics	Contaminated sediment fed to top of extractor and makes nonreactive contact with condensed propane solvent flowing up through the extractor at a pressure of 250 psi. Typically used in a series of three extractors. Contaminated propane is fed to a separator where it is vaporized and recycled by recompression.	Propane, pressure, temperature.	Pilot/pilot	Operation and maintenance \$100–\$200/ yd ³ .
Low energy acetone-kerosene ^a	PCBs and organics	This process separates sediment into liquid and solid, then leaches solid portion with hydrophilic solvent (acetone). Acetone is steam-stripped from sediment. PCBs treated with hydrophobic solvent (kerosene).	Water content >50%	Conceptual, bench	Operation and maintenance \$41–\$200/ yd ³ .

Table 19. (continued)

Process	Applicable Contaminants	Mechanism ^b	Factors Affecting	Remediation of Sediments, Dredged Materials	Typical Cost ^c
Surfactants	Hydrophobic organics, nonsoluble organics (PCBs, crude oil, tertiary oils).	Surfactants injected into soil to flush contaminants. Typically use mixture of anionic and nonanionic surfactants.		Demonstrated, no	Operation and maintenance \$100–\$200/ yd ³ .

^a Field and laboratory have exhibited mixed results.

^b TRA = triethylamine.

^c 1 m³ ≈ 0.77 yd³.

Table 20. Contaminant Sediment Treatment: Immobilization

Process	Applicable Contaminants	Mechanism	Factors Affecting	Remediation of Sediments, Dredged Materials	Typical Cost ^a	Comments
Chloranan encapsulation	Organic compounds, heavy metals, oil, grease.	Injection of cement, water, and chloranan into contaminated solids or sludges. Chloranan encapsulates organic contaminants to prevent interference with solidification process. Contaminants immobilized from soils in concrete-like leach-resistant matrix.	Water content, type of solid/ slurry density of soil.	Demonstrated, no	Operation and maintenance \$100–\$200/ yd ³ .	
<i>In situ</i> encapsulation	Organic and inorganic materials (metals, pesticides, phenols, and PCBs)	Injection and/or mixing of solidification/stabilization reagents with contaminated material. Mixing can be accomplished using agricultural spreaders and tillers, special augers, backhoes, or clamshells.	Type of material, contaminant, and reagent. Water content.	Demonstrated, no	Operation and maintenance \$100–\$200/ yd ³ .	
Lime-based pozzolan	Organics and low levels of metals.	Contaminated materials mixed with carefully selected reactive, pozzolanic additive (typically bituminous coal fly ash) to pasty consistency and subsequently blended with hydrated lime to form solid mass.		Demonstrated, bench-scale testing for dredged material	Operation and maintenance \$100–\$200/ yd ³ .	Only tolerates low levels of mercury and moderate levels of lead. Greater leachability than cement-based processes.
Portland cement-based	Arsenic, lead, zinc, copper, cadmium, nickel, PCBs.	Portland cement added as binding agent along with pozzolanic product (fly ash) to react with free calcium hydroxide and thus improve strength, handling characteristics, and chemical resistance of stabilized sediment.	Type of contaminant, water content.	Demonstrated, bench-scale testing for dredged material	Operation and maintenance \$100–\$200/ yd.	Cement reduces mobility of heavy metals due to conversion to insoluble hydroxides or carbonates because of elevated pH of cement. Other sorbents added to improve characteristics.

Table 20. Contaminant Sediment Treatment: Immobilization (continued)

Process	Applicable Contaminants	Mechanism	Factors Affecting	Remediation of Sediments, Dredged Materials	Typical Cost ^a	Comments
Proprietary processes	Typically metals and higher molecular weight organics.	Proprietary reagent typically mixed with contaminant, then combined with cement product to form stabilized mass. (large number of processes on market).	Type of contaminant, soil type, reagent type.	Demonstrated, bench-scale testing for dredged material	Operation and maintenance \$100–\$200/yd.	
Sorption	Organic and inorganics.	Involves adding solids material to soak up free liquid in soil or waste to produce product that is easier to handle. Sorbents include natural materials such as fly ash, klin dust, vermiculite, and bentonite, as well as synthetic materials such as activated carbon, resins, Hazorb, Locksorb, etc	Quantity of sorbent for removal of liquid varies according to the nature of liquid, solids content of waste, and chemical reactions that may occur.	Demonstrated, no	Operation and maintenance \$100–\$200/yd.	Sorbents inexpensive and plentiful, but often required in large amounts, producing disposal problem.

^a 1 m³ ≈ 0.77 yd³.

Table 21. Contaminant Sediment Treatment: Thermal

Process	Applicable Contaminants	Mechanism	Factors Affecting	Remediation of Sediments, Dredged Materials	Typical Cost ^a	Comments
Advanced electric reactor	PCBs, dioxins, heavily halogenated organics, nerve gas	Vessel with porous carbon core surrounded by carbon electrifies. Radiation heat shield surrounds core and electrodes. Nitrogen acts as gaseous blanket that isolates reactants from core and heat-transfer medium between carbon electrodes and porous core. Two post-reactor zones connected in series.	Temperature, residence time	Pilot/no	Operation and maintenance >\$200/yd ³ .	Transfers energy to the waste through radiation.
Circulating bed combustor	Halogenated, nonhalogenated hydrocarbons.	High air velocity to circulate solids and create larger and more agitated combustion zone. Dry limestone added to feed material to react with acid gas so that wet scrubber not necessary.	Temperature, residence time	Demonstrated, yes	Operation and maintenance \$100–\$200/yd ³ .	Uses relatively low temperatures (871°C) due to high degree of turbulence.

Table 21. (continued)

Eco-logic	Chlorinated wastes, organic wastes containing PCBs, halogenated benzen, phenols, cycloalkane, alkanes, dioxin, dibenzofuran.	Thermochemical destruction process relies on ability of hydrogen to dechlorinate organic compounds at high temperatures.	Temperature, residence time	Pilot/pilot	Operation and maintenance \$100-\$200/yd ³ .	Mobile unit
Fluidized-bed incineration	Halogenated and non-halogenated organics, phenols, methyl methacrylate, oil refinery wastes.	Process consists of a cylindrical, vertical, refractory-lined vessel that contains inert granular material, usually sand, on perforated metal plate. Combustion air introduced at bottom of incinerator and bubbles through inert bedding material, causing bedding material to become fluidized and agitated. Waste pumped into vessel and combusted within bubbling material.	Temperature, residence time	Demonstrated, no	Operation and maintenance >\$200/yd ³ .	
High temperature slag incineration	Waste including low level radioactive wastes and most stable chlorinated aromatics.	Transforms waste into mechanically strong and chemically stable basalt-like material in granular or bulk form. Homogenous waste stream fed into combustion chamber. Burner heats top of waste into layer of molten slag. Slag droplets flow to granulator where they are quenched, causing them to burst into granules.	Temperature, residence time	Demonstrated, no	Operation and maintenance >\$200/yd ³ .	
Infrared incineration	Halogenated and non-halogenated organics, dioxins, spent activated carbon.	Waste prepared to consistency and size required. Feed fed on wire mesh conveyor belt into infrared primary chamber. Material stirred gently by rotary rakes, or cake breakers.	Temperature, residence time, waste layer thickness, combustion air flow rate.	Pilot, no	Operation and maintenance >\$200/yd ³ .	

Table 21. Contaminant Sediment Treatment: Thermal (continued)

Process	Applicable Contaminants	Mechanism	Factors Affecting	Remediation of Sediments, Dredged Materials	Typical Cost ^a	Comments
<i>In situ</i> vitrification	Organics, inorganics, heavy metals, PCBs	Process converts waste into chemically inert and stable glass and crystalline product. Mechanism involves placing 4 large electrodes vertically inserted in square arrangement in soil. Graphite placed on surface to complete circuit between electrodes. Sand, glass frit, or soda ash can be added to soil to improve process. Combustion gases need to be processed.	Current, electrode spacing, water content.	Pilot, bench	Operation and maintenance >\$200/yd ³ .	
Low temperature thermal stripping	Volatile organics and PCBs	Only enough heat applied to volatilize contaminants.				

^a 1 m³ ≈ 0.77 yd³.

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