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State of the Art: CDF Contaminant Pathway Control

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ABSTRACT: Contaminants from sediments contained within a confined disposal facility (CDF) can be discharged to the environment via six potential pathways. These pathways include three waterborne pathways, the direct uptake of the contaminants by plants or animals, and airborne emission of contaminants. Conventional CDF design focuses on retention of sediment particles with perimeter dikes. Depending upon the nature of the site, the contaminants of concern, method of dredging, physical properties of the dredged material, operational aspects, and many other factors, including sociopolitical factors, supplemental environmental design criteria may be required for the CDF. This paper reviews design alternatives to control contaminant loss from the CDF basin through the six identified contaminant pathways. These alternatives include the use of both additional design components and operational constraints. The need for a specific pathway control measure is shown to depend on both site and sediment specific evaluation criteria.

KEYWORDS: dredged material, contaminant, pathway, containment, confined disposal facility (CDF)

Throughout the Great Lakes, about 4 million cubic yards (5.2 million cubic metres) of sediments are dredged annually to maintain navigation in channels and harbors for commercial, military, and recreational users, and as part of environmental remediation projects (EPA 1990). Within the United States, about 400 million cubic yards (520 million cubic metres) of sediments are dredged annually (COE 1987). Sediment is the material that settles to the bottom of a body of water and includes soil particles consisting of clays, silts, and sands; organic matter; shells; and residuals from industrial discharges, which can include organics and heavy metals. Many of the waterways are adjacent to urban and industrial areas and the sediments in these areas are often contaminated from various adjacent sources. Such contamination is typically historical and predates modern regulatory controls. A portion of the sediments are so highly contaminated with anthropogenic substances that they require remedial action by EPA. About one half of the total sediments dredged in the Great Lakes [approximately 2 million cubic yards (2.6 million cubic metres)] are sufficiently contaminated to be problematic sediments and require placement in a confined disposal facility

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(CDF). These contaminated sediments require special consideration during dredging and disposal operations because of the potentially adverse impact on water quality and local organisms. Sound planning and design of dredging operations and disposal facilities are necessary to protect the environment and yet keep these activities economically viable. The remaining half of the sediments are generally classified by EPA as clean and suitable for unconfined, open water disposal. This paper focuses on CDF contaminant pathway control in freshwater environments. In the following sections the issues of the regulation of dredging activity, contaminant pathway control, CDF basin design recommendations, and closure practices will be discussed.

Regulation of Dredging Activity

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, ground water, or surface water. Although release routes of concern commonly include emissions to the atmosphere and can include more exotic pathways such as the discharge of free phase organics, the ubiquity of water in all aspects of sediment dredging and disposal have focused consideration on contaminant release routes to water. This is reflected in Table 1, which depicts several pertinent relationships between the level of sediment contamination, the degree of contaminant partitioning to the water associated with the sediments, three conceptual categories under which sediment disposal can occur, and the significant disposal regulations. As depicted on Table 1, these three approaches to sediment disposal are labeled "beneficial use or open water disposal," "solids retention," and "hydraulic isolation."

TABLE 1—*CDF design criteria based on contaminant level and pathway.*

Uncontaminated Sediments				Highly Contaminated Sediments
	CWA 404 Guidance	Partitioning in Excess of State WQS	Significant Partitioning	
Minor Sediment Contamination Minimal Partitioning	PROBLEMATIC SEDIMENTS			
	Minor Partitioning	Moderate Partitioning	Extensive Partitioning	RCRA/TSCA Sediments
Beneficial Use or Open Water Disposal CWA 401 Certification for Dredged Material Discharge	Solids Retention Approach Increasing Degree of Sediment Isolation Filter Intake CDFs CWA 401 Certification for Diffuse Discharge	Hybrid Approach Hydraulic Isolation During Sediment Disposal Only CWA 401 Certification for Point or Diffuse Discharge	Hydraulic Isolation Approach Increasing Degree of Hydraulic Isolation CWA 401 Certification for Point Discharge	Hydraulic Isolation CDF MTG Design CWA 402 Permit for a Point Discharge Conformance with RCRA-C Minimum Technology Guidance
	←------- 87 COE CDF DESIGN MANUAL ----------→ ----------→			
	←------------------ 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 ------------------------------------→				

The Clean Water Act (CWA) governs the discharge of dredged material into "waters of the United States." If the level of sediment contamination is sufficiently low so that the uncontained release of the sediments into the environment would not have an unacceptably adverse environmental impact and would not result in an exceedance of the applicable State Water Quality Standards (WQS), the sediments could be disposed of at an approved open water disposal site or placed in the environment in an unrestricted manner. An example of such unrestricted or unconfined placement would be the use of dredged material for beach nourishment or as fill. As shown in Table 1, compliance with the State WQS for the disposal of dredged material via open water or beneficial use could entail the issuance of a Section 401 Certification under the CWA. Dredged materials that cannot meet the CWA standards for open water disposal or beneficial use, e.g., problematic dredged materials, must be segregated from the environment to some extent. Sediments that cannot be released to the environment in an unrestrictive manner are labeled problematic dredged material in Table 1. The disposal of problematic dredged materials is the focus of this paper.

The U.S. Army Corps of Engineers (COE) uses CDFs to contain contaminated sediments that cannot be released without control to the environment. As shown in Fig. 1, CDFs can be located at both upland and in-lake sites depending on the level of isolation that the sediments under consideration warrant. CDF designs can be grouped based on their extent of isolation: (1) CDFs that physically isolate the sediment solids from the adjacent environment (solids retention) and (2) CDFs that hydraulically isolate the sediments and any derived effluent from the adjacent environment (hydraulic isolation) (see Table 1).

Dredged materials typically contain large amounts of water. Depending upon the method used to excavate the materials, dredged materials typically have solids to water ratios of 5 to 50% by weight. The disposal of large quantities of material with a high percentage of both solids and water presents both technical and regulatory challenges unique to dredged materials. Generally, the disposal of wastes that have a high percentage of water is regulated by the CWA, while the disposal of wastes that are not liquids, e.g., solids, is regulated under the Resource Conservation and Recovery Act (RCRA). Given the large quantities of water and solids, CDFs commonly incorporate aspects of both regulatory programs into their designs.

The basic framework for federal water pollution control regulation was established by the Federal Water Pollution Control Act (FWPCA) established in 1972. In 1977, FWPCA was renamed the Clean Water Act (CWA) and amended to provide regulatory control of toxic water pollutants. Section 404 of the 1977 amendments to the CWA provide the source of the current regulatory control over dredging and disposal activity. The CWA is currently undergoing reauthorization. The need for a given federally sponsored dredging activity must be evaluated under the National Environmental Policy Act (NEPA) based on a review of alternative solutions. Note that NEPA does not establish performance objectives, but simply requires the evaluation process.

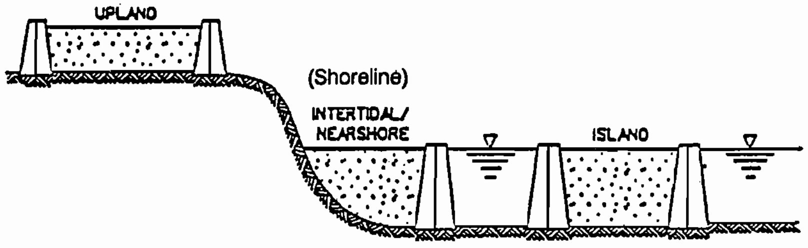


FIG. 1—*Upland, shoreline, and island CDF.*

Contaminated Dredged Sediments

Dredged materials are considered contaminated when the ambient or leachable concentration of metals or organic compounds exceed federal RCRA or Toxic Substance Control Act (TSCA) regulatory limits or when contamination exists in high enough concentrations and are sufficiently available to affect human or ecosystem health, or both. RCRA and TSCA regulations provide for the disposal of contaminated materials in landfill cells that hydraulically isolate the waste from proximal ground and surface waters. Wastes placed within such landfill cells must not be a liquid 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.

Confined Disposal of Problematic Dredged Materials

Problematic sediments are defined as those that contain contaminants that have the potential to adversely impact human health or the proximal ecosystem but that are not regulated by RCRA-C or TSCA, but can be controlled by Section 404 of the CWA or the Rivers and Harbors Act (RHA). For example, sediments can become highly contaminated by point and nonpoint source contamination related to preregulatory industrial activities. Such contamination may not trigger RCRA-C or TSCA regulatory control but can lead to the degradation of navigable water and as such can be regulated by the combination of National Environmental Policy Act (NEPA) Environmental Impact Statement (EIS), CWA Section 404, and state authority.

The placement of problematic sediments within a CDF may pose design problems not adequately addressed by current TSCA and RCRA-C Minimum Technology Requirements (MTR). However, containment of contaminants remains a high priority in federal regulations. Recently promulgated RCRA Subtitle D (RCRA-D) regulations have extended containment requirements in common municipal solid wastes. Under these regulations, a composite (soil plus geomembrane) liner is required unless the designer can demonstrate that contaminants in the upper most aquifer will remain below the Maximum Contaminant Level (MCLs) at a specified point of compliance adjacent to the landfill. Similarly, CDFs for problematic sediments may require some form of lining system unless it can be demonstrated that WQS will not be exceeded in the ground water or surface water adjacent to the facility.

Contaminant Pathway Control

Contaminants from sediments contained within a CDF can be discharged to the environment via six potential pathways. These pathways are shown in Fig. 2 and include three waterborne pathways, two pathways related to the direct uptake of the contaminant by plants or animals, and an airborne pathway.

Waterborne Contaminants

The control of waterborne contaminants must consider both the contaminants dissolved in the effluent and the solid contaminant fraction associated by sorption or ion exchange with the total suspended solids (TSS) within the effluent (Thackston and Palermo 1990). Given sufficient retention time in a containment area, noncolloidal suspended solids will settle out of the effluent and be retained. This design practice of "solids retention" is the basis for the COE design process but may be limited by contaminant concentration and partitioning as previously shown in Table 1. The approach presented in this paper considers the impact of contamination associated with both the TSS and the aqueous phase.

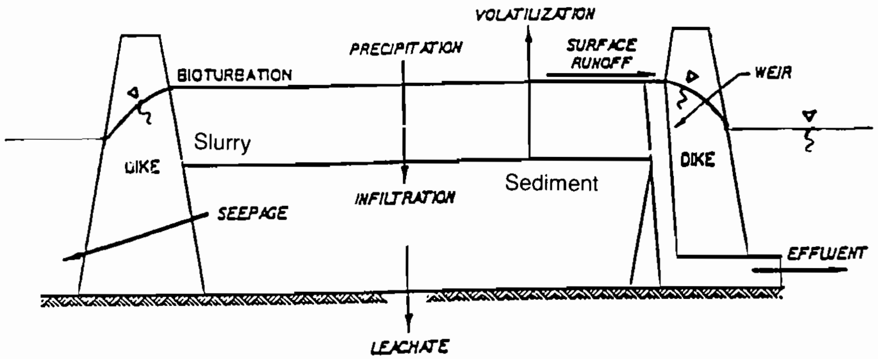


FIG. 2—*Contaminant pathways for in-lake CDF.*

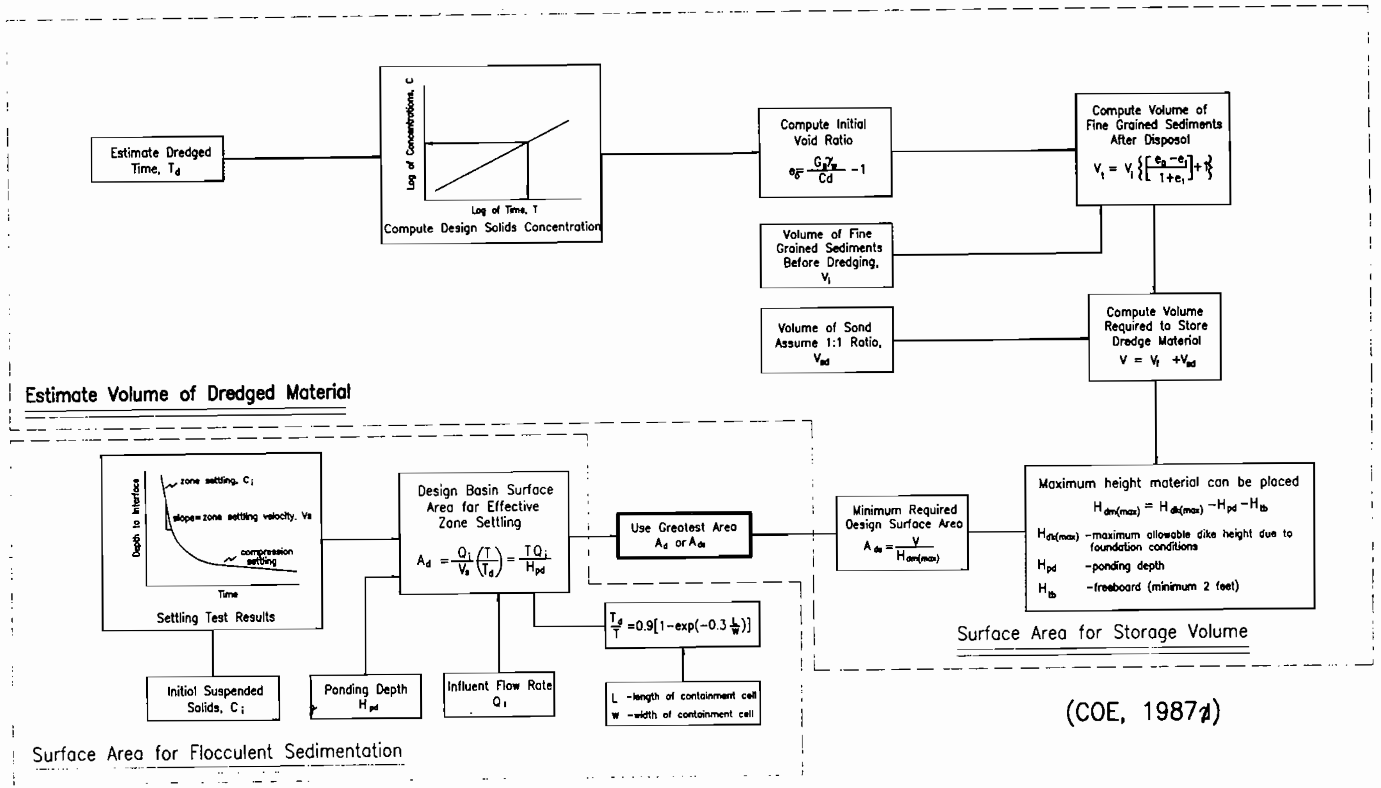
For noncolloidal dredged materials, the suspended solids concentration in effluent water is influenced by the pond surface area and residence time for the effluent within the CDF. The conventional COE design procedures for determining the surface area or the residence time required for sedimentation to meet effluent suspended solids requirements are summarized in Figs. 3 and 4, respectively. Both design procedures assume that the CDF dikes are impermeable to the effluent and that the dredged material was hydraulically dredged. Contaminated dredged materials generally have a high percentage of colloidal material that remains in suspension due to physiochemical factors.

The procedure for calculating the minimum required surface area, shown in Fig. 3, recognizes that sediments fall out of suspension quicker in ponds having larger surface areas and shallow depths. In deep ponds, the falling sediment particles begin to collide, accumulate, and create a condition of compression settling, e.g., consolidation under self weight. Compression settling is very slow and therefore results in an increase in the required retention time. The minimum required surface area for the pond is calculated in two ways: (1) based on the storage volume required for the dredged material once it settles out of suspension and (2) based on the surface area for flocculent sedimentation. The larger of the two areas is then assumed to be the minimum required surface area for the pond within the CDF.

Having solved for the minimum pond area the COE procedure then calculates the minimum residence time for the supernatant within the pond as shown in Fig. 4. A percent solids removal versus time relationship is first established based on the pond depth and a range of assumed times. Knowing the suspended solids requirement for the effluent, the residence time (T_d) based on pond depth is established. The actual design residence time (T) is obtained by modifying T_d based on the actual length and width of the pond.

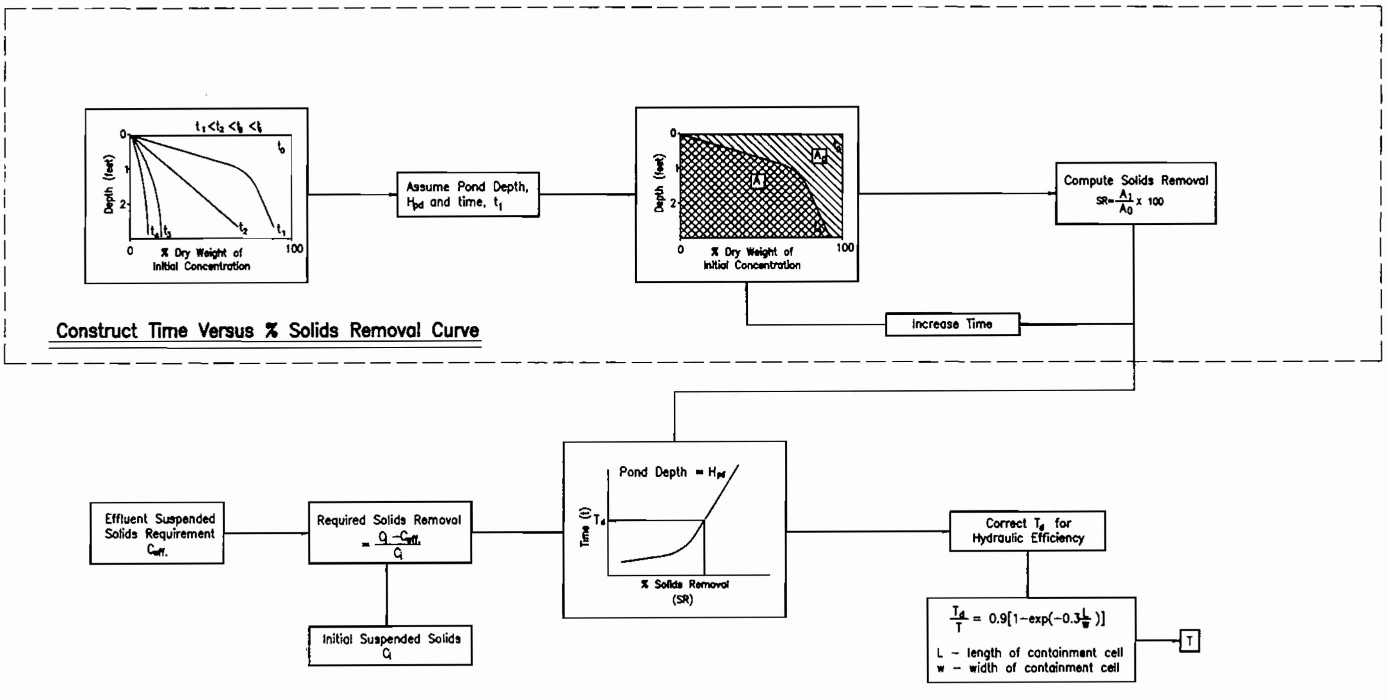
Effluent Flow through Weirs and Filters—Typical effluent filter systems include pervious dikes and downflow/upflow weirs or cartridges. The pervious dikes are designed to filter out the suspended solids by selecting the filter media particle size distribution using conventional geotechnical filter criteria. Clogging of the pervious dike is minimized by using stratified or baffled dike sections that provide a control over the maximum flow gradients that develop within the dike section. The larger the potential flow gradient, the smaller the potential for clogging of the filter.

Pathway controls, filter weirs, and cartridges for contamination related to TSS in effluent leaving the CDF through a weir are presented in Fig. 5. Current COE weir design procedures focus on the removal of suspended solids from the effluent. Four design alternative courses of action for the control of effluent have been presented by Krizek et al. (1976). Pervious dikes are recommended by the COE to filter effluents with concentrations of TSS up to 0.5



(COE, 1987d)

FIG. 3—*COE design procedure for determining the surface area required to meet effluent suspended solids requirement.*



(COE, 1987)

FIG. 4—*COE design procedure for determining residence time* (T) *required to meet effluent suspended solids requirement.*

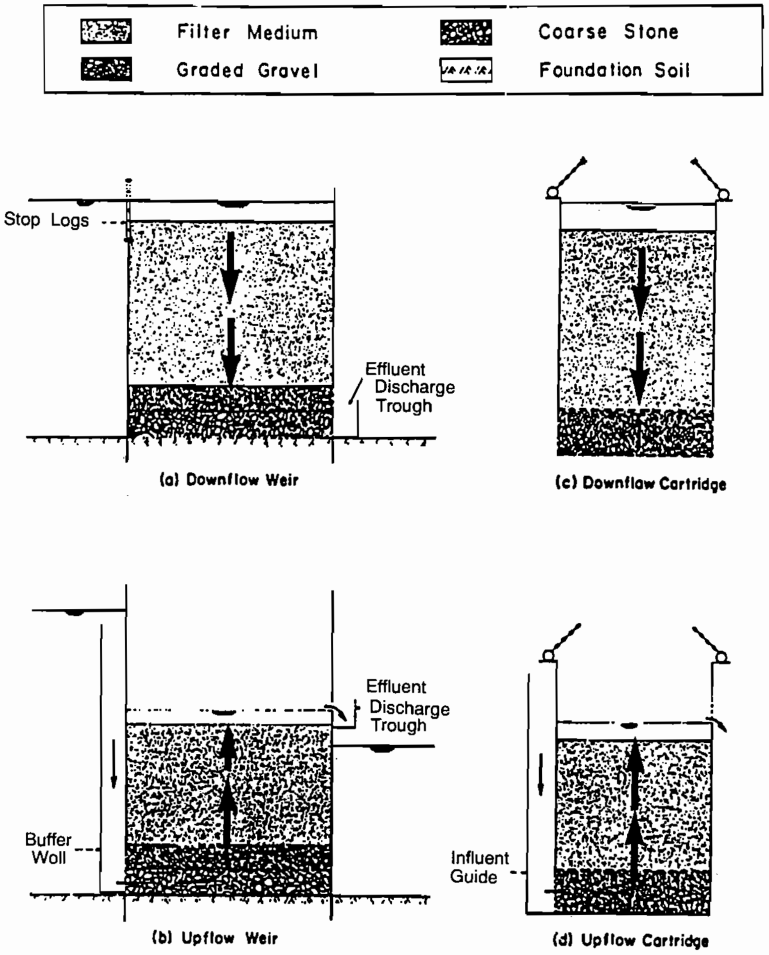


FIG. 5—*Filter weirs and cartridges.*

g/L. Such dike filters constitute a low-maintenance filter that is characterized by long effective lifetimes. For cases where the effluents are expected to have TSS concentrations up to 1 to 2 g/L, the sandfill weir offers an attractive alternative. Sandfill weirs designed without backwash capabilities require maintenance to replace clogged filter media at periods significantly shorter than pervious dike lifetimes. Although the type of effluent to be treated with the sandfill weir is similar to that for pervious dikes, its mode of operation is much more flexible. Granular media cartridges can be used with waters having TSS up to 10 g/L; however, maintenance requirements are expected to be excessive at loads higher than a few grams per litre.

The TSS concentration of an effluent can be significantly influenced by the length of the weir (sharp crested, rectangular, or shaft type) and the depth of the pond as shown in Fig. 6. Waterborne suspended solids and the associated contaminants that cannot be removed by basin or weir design may render the effluents from disposal areas unacceptable for discharge to open waters, and it may be necessary to employ a filter system or chemical methods (Schroeder 1983) to clarify disposal area supernatant.

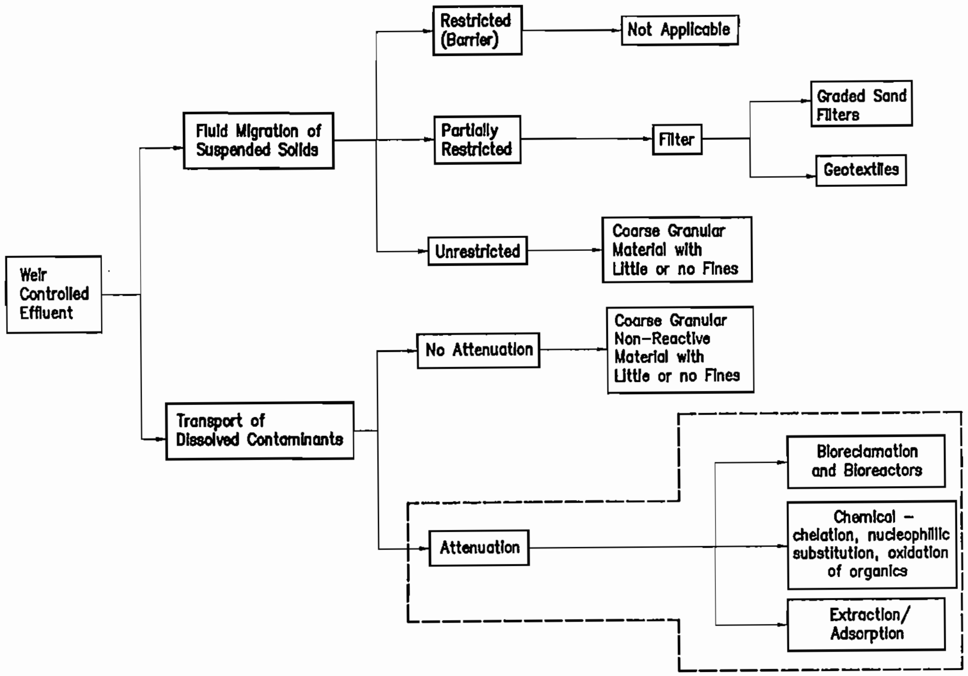


FIG. 6—*Control of contaminant pathway through weir.*

Dike Seepage—Movement of contaminated pond water through the dike structure will occur unless a mechanism is provided to either restrict the actual water migration or attenuate the waterborne contaminants. The flow through a dike can be restricted either by controlling the hydraulic gradient that exists across the dike or by reducing the permeability of the dike. Dye tracer studies performed in Great Lakes CDFs (Pranger and Schroeder 1986) showed that zones of significantly higher dike seepage existed at several CDFs that had dikes constructed using both sheet pile cutoff walls within a rip-rap dike and cores of crushed limestone gravels and sands. During the studies by Pranger it was also observed that significant decreases in outflow occurred in areas where deltas of previously dredged material were placed against the dike within the CDF.

Design considerations to limit the release of contaminants through dike seepage are shown in Fig. 7. The design of dike seepage control systems must reflect the nature of the subgrade upon which the dike is built. Vertical barrier systems must intercept and key into an underlying low-permeability soil layer (i.e., aquitard) that prevents contaminated ground water from flowing beneath the barrier. Obviously the economy of a vertical barrier system is significantly influenced by the depth of penetration required to intercept such a confining layer. Lacking a natural aquitard, a low-permeability liner may need to be incorporated in the basin design.

Mechanisms to totally restrict water migration through the dike involve constructing an impermeable barrier in or on the dike consisting of either a low-permeability soil, a geomembrane, or a geosynthetic clay liner (GCL). The low-permeability soil barrier can be constructed using either a compacted clay line (CCL) or GCL designed into the CDF dikes or by an intentional operations placement of clean, fine-grained sediments against the surface of the dike structures. Table 2 reviews the placement of alternative barriers to restrict the

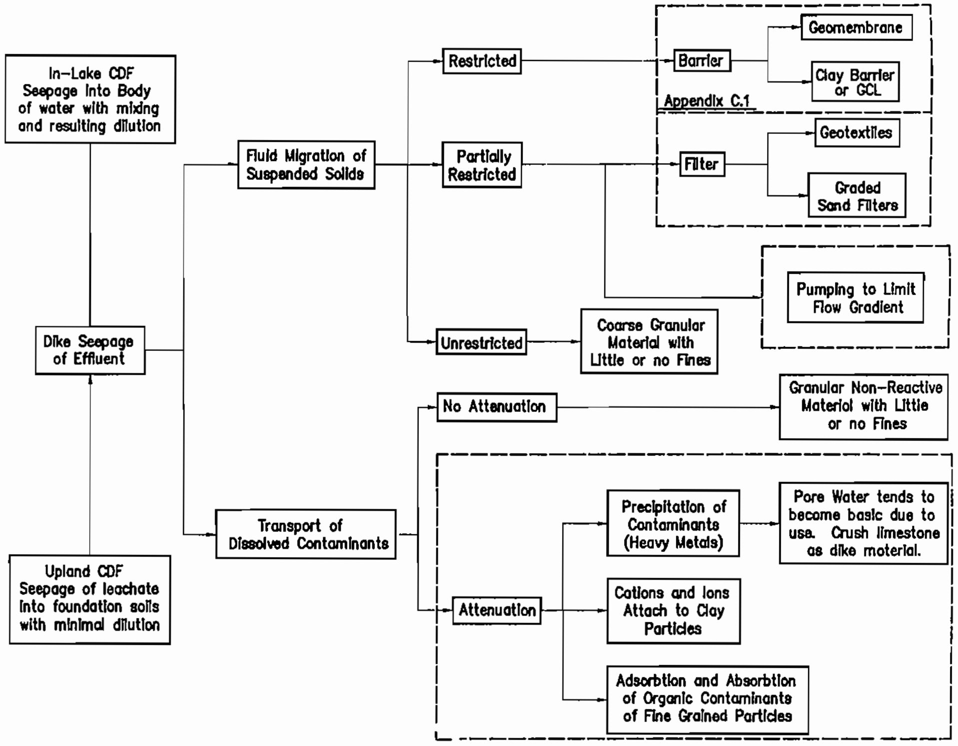


FIG. 7—*Seepage of effluent through dike.*

flow through perimeter dikes. While geomembrane and clay barriers will be highly restrictive, the operationally placed barrier may be only partially restrictive depending upon the sediment particle size and placement method.

In summary, adequate attenuation of water borne contaminants in the seepage can require the removal of both suspended solids and dissolved contaminants from the effluent. The suspended solids can be allowed to settle out of the effluent or can be physically filtered as described above. Removal of soluble contaminants from the effluent may require changing the effluent water chemistry.

Foundation Seepage of Leachates—The migration of contaminants into the foundation soils involves two different mechanisms, as shown in Fig. 8. These two mechanisms are: (1) advective transport of suspended particles or dissolved contaminants, and (2) diffusion. Laboratory and field investigations have shown that foundation leachate problems can exist even when the discharged effluent quality is acceptable (Chen et al. 1978). Foundation leachate problems were observed in facilities where the supernatant and effluent had very low contaminant concentrations.

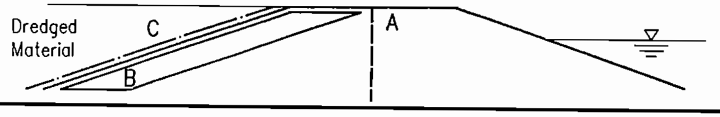
Advective transport of contaminants into the foundation soils is caused by the flow of leachate under Darcy's Law. The rate of flow is controlled by the hydraulic gradient and the permeability of the soils. Shoreline CDFs are commonly located in ground water discharge zones (e.g., wetlands) that have natural flow gradients towards the CDF. Such natural inward gradients minimize leachate migration into foundation soils. Under these conditions, leachate migration into foundation soils is driven by hydraulic heads produced by the varying depth of effluent within the CDF, surface water, (e.g., precipitation) infiltration, and excess pore pressures generated during placement of dredged sediments. The extent or significance of surface water infiltration is dependent upon whether a final cover is in place or interim conditions exist. During interim periods where the dredged material is exposed, the advective mobility of contaminants may be greater due to the chemical actions of acid rains or oxidation related breakdown of contaminants.

TABLE 2—*Dike barrier system applications in CDFs.*

	Barrier System	Barrier Location*	COE Usage	In-Lake CDF	Shoreline CDF	Upland CDF
"Impermeable" Barriers	Compacted Clay Liner (CCL)	C		N/A	N/A	●
	Geomembrane Liner (GML)	C	X	○	○	●
	Geosynthetic Clay Liner (GCL)	C		N/A	○	●
	Geomembrane Cut-off Wall	A		●	●	●
	Bentonite Slurry Cut-off Wall	A	X	●	●	●
	Fabric Form w/ Grout	C		●	●	●
"Low" Permeability Barriers						
	Clean 'Fine' Sediments	C		●	●	N/A
	Clogged Geotextile	C	X	○	●	N/A
	Graded Soil Filter	B	X	○	●	N/A
	Fabric Form w/Sand	C		●	●	N/A

N/A Not Applicable ● Good Application ○ Maybe Difficult to Construct

* Barrier Locations



The actual flow of contaminants into the foundation soils is controlled by the type of liner material in the CDF. The types of liner material are the following: (1) restricted/no flow barrier, (2) partially restrictive barrier, and (3) unrestrictive barrier. The fully restricted or no flow barrier is typically the result of a CDF foundation liner of compacted clays or a geomembrane. In contrast, a partially restricted barrier can be a function of site stratigraphy, site hydrogeology, or the presence of a filter media at the bottom of the CDF. The filter media can be constructed of a clean dredged fine sediment layer either by itself or in combination with a geosynthetic filter fabric. An unrestricted barrier is typically comprised of clean granular foundation soils.

The advective transport of soluble contaminants in the leachate can potentially undergo attenuation depending on three different processes. These processes are (1) attachment of anions/cations to clay minerals, (2) adsorption/absorption of organic contaminants on humic materials, and (3) biodegradation of the contaminant.

Diffusion transport of dissolved contaminants is driven by concentration gradients and is evaluated using Fick's First Law. This contaminant transport can occur in the absence of

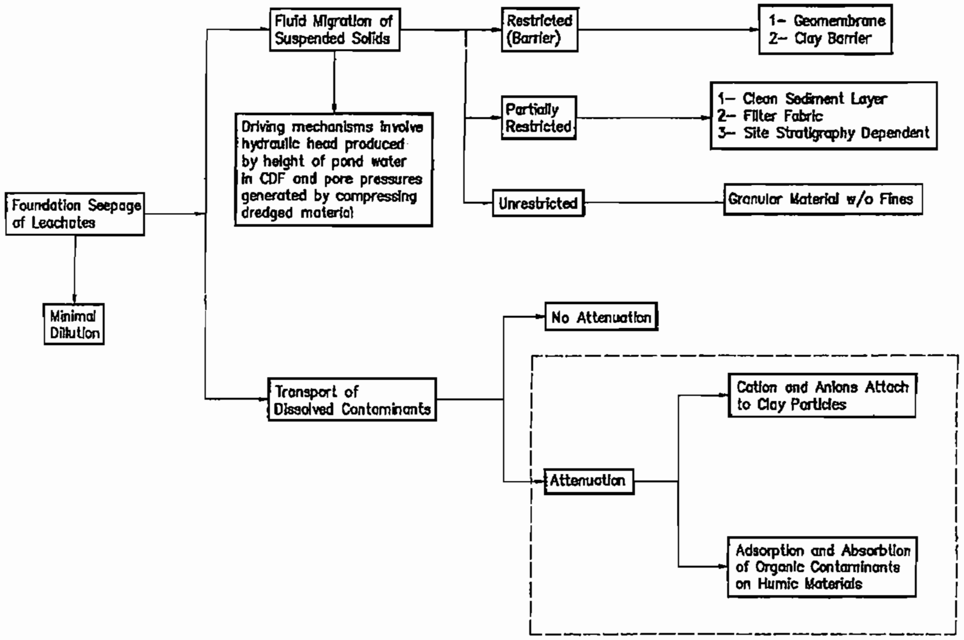


FIG. 8—*Control of foundation leachate generation.*

water movement. Fortunately, the concentration of contaminants within the pore water is typically low and does not lead to significant diffusion rates.

Runoff Contaminant Control—Precipitation falling on a CDF can contribute to contaminant migration by increasing infiltration and surface water runoff as shown in Fig. 9. The acidic nature of precipitation in the northern United States may lower the pH of the exposed dredged material and supernatant and place more metal contaminants into solution. The potential for contaminant transport due to runoff is influenced by whether the dredged material remains exposed to air during interim operations such that geochemical changes in the sediments are possible, and whether a final cover has been placed over the dredged material.

During interim operations, the surface water runoff over air exposed dredged materials can cause significant erosion losses if no vegetation or large slopes (<5%) exist. Contaminant losses from runoff during the interim operations period can be reduced by providing surface vegetation, limiting slopes to less than 5%, and ensuring that runoff does not over top perimeter dikes. It should be noted that interim operations may last several decades so that the interim vegetation of exposed dredged materials may be very cost-effective. During this same period, consolidation settlement of the dredged material may result in ponds forming within the CDF. Such ponds provide the potential for plant and animal uptake.

Once the final cover is placed over the dredged material, the significance of surface water runoff as a contaminant transport mechanism significantly diminishes. The presence of a thick vegetative layer improves the resistance to soil erosion and the removal of suspended solids and soluble nutrients such as ammonia, nitrogen, and soluble phosphorous (Chen 1978). Such runoff will have no contact with contaminants if a barrier layer is incorporated in the final cover and therefore would not be a potential contaminant transport mechanism.

The primary control of the surface water runoff contaminant pathway is conventional erosion control practices such as limiting slopes and surface vegetation. Fortunately vegetation/revegetation of CDFs commonly occurs naturally and with vigor. A typical erosion control program will include limiting slopes to <5%, vegetation of cover surfaces with native grasses, and temporary containment of all runoff in sedimentation basins.

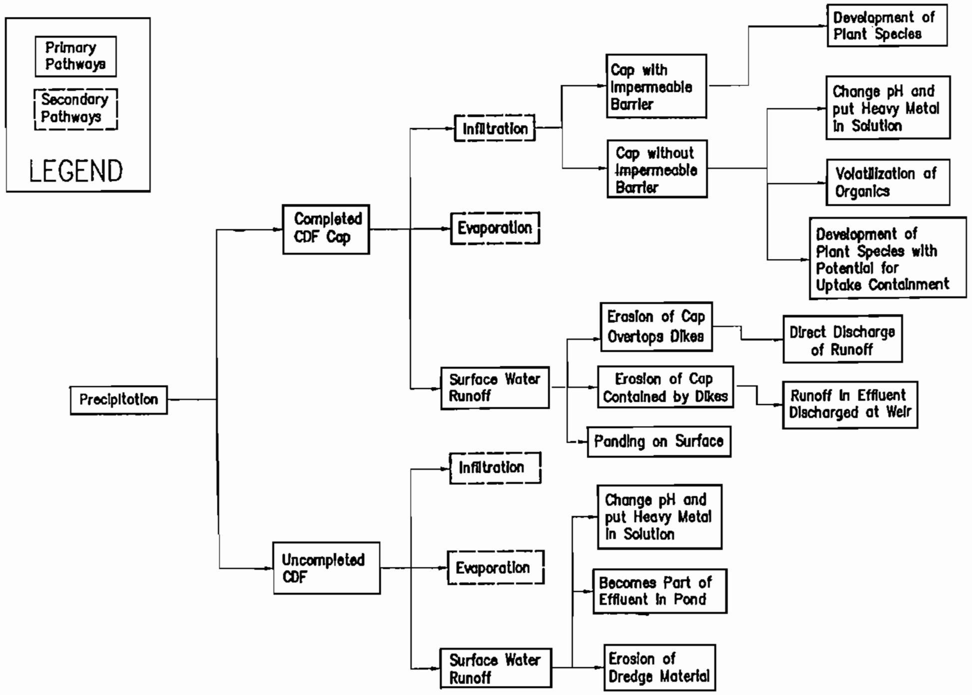


FIG. 9—*Surface water mechanisms related to precipitation of CDF.*

Contaminant Pathway Control for Proximal Plant and Animal Communities

Pathway controls to protect plant and animal communities immediately adjacent to the CDF can be identified using a general food web flow relationship as presented in Fig. 10. Such food web flow diagrams show the general movement of nutrients and contaminants within and between the plant and animal community. This movement can be "up" the food chain, e.g., fish in ponds within the CDF, or "down" the food chain, e.g., excretion or death. Such movement of contaminants by biological mechanisms is in addition to the movements caused by the nonbiological flow shown in Fig. 11. Interactions between various metals and other contaminants influence the toxicity and bioavailability to organisms. There are three basic relationships identified for systems containing concentrations of two or more toxic metals (Kelly 1988):

1. Additive—the combined toxic effect of the metals equals the sum of the individual toxicities.
2. Synergism—the combined toxic effect exceeds the sum of individual toxicities.
3. Antagonism—the combined toxic effect is less than individual toxicity.

Contaminant pathways to plant and animal communities must be considered during both the operational and postclosure time periods. The uptake of contaminants by plants and animals

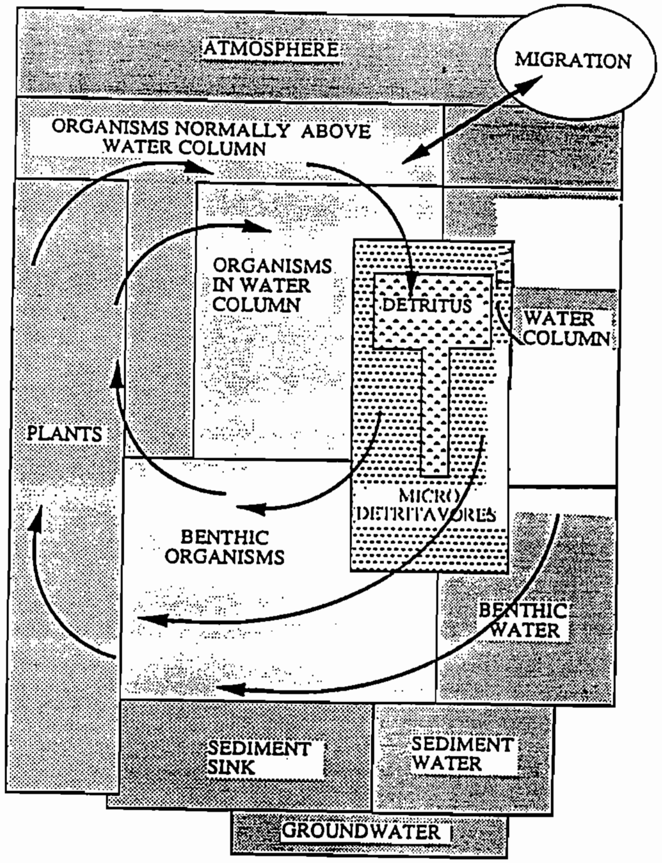


FIG. 10—*Food web drawing showing general flow of nutrients and metals.*

can be estimated by the use of simple mathematical relationships using empirical constants (animal bioconcentration factor (BCF), plant uptake factor). In particular, ponds that form on the dredged materials during the decades-long operation of the CDF may offer the most significant opportunities for plant and animal uptake. The ability to limit these contaminant transport mechanisms prior to placement of the final cover should be evaluated.

Airborne Emissions Control

The control of airborne contaminant emission from a CDF includes limiting the direct volatilization of contaminants into the air and the wind-related loss of soil particles that are contaminated. The direct volatilization of contaminants is a concern during placement of the dredged materials in the CDF and when the dredged materials rise above the supernatant and are exposed to the atmosphere. Thus the volatilization of contaminants can be limited by keeping the dredged materials below the elevation of the supernatant. Alternatively, the problematic dredged materials can be covered with clean dredged materials to limit volatilization.

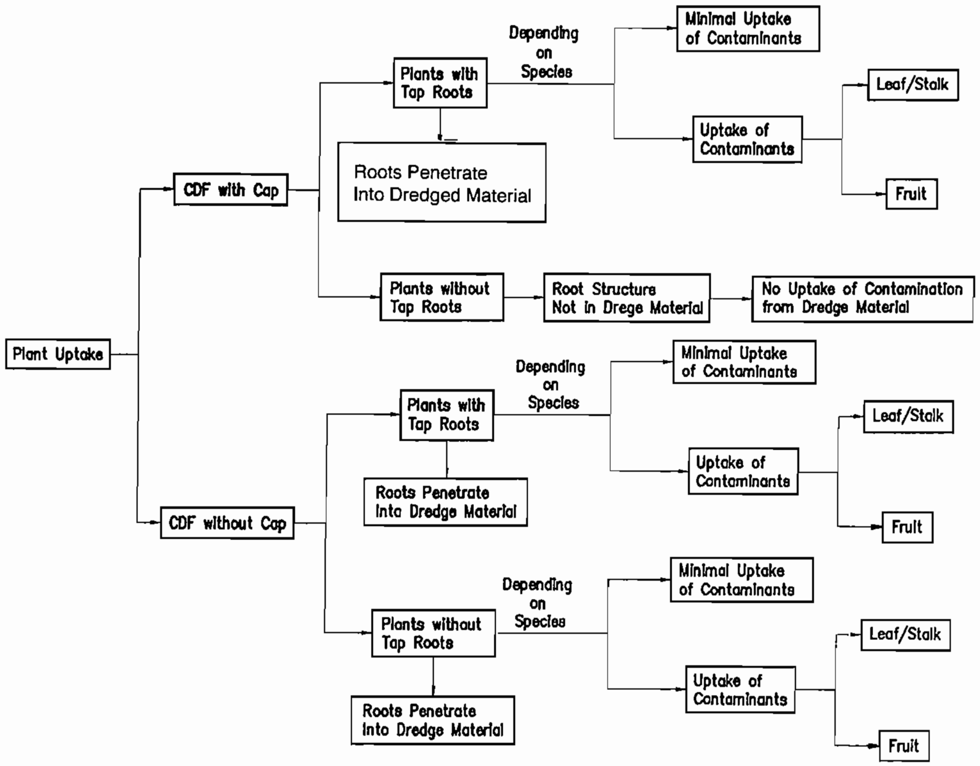


FIG. 11—*Mechanisms involved in plant uptake of contaminants in capped and uncapped CDFs.*

The wind-induced erosion of the dredged material is controlled by limiting the exposure of contaminated dredged material. If historic surface wind velocities and the grain-size distribution of the dredged material, e.g., the soil has a large percentage of soil particles smaller than 10 μm, indicates significant wind erosion, then the use of a clean granular soil cover over the air-exposed dredged materials would be warranted.

CDF Basin Design Recommendations

Conventional CDF design focuses on retention of sediment solids within the facility. Depending upon the nature of the site, the contaminants of concern, method of dredging, physical properties of the dredged material, operational aspects, and many other factors, including sociopolitical factors, supplemental environmental design criteria may be required for the CDF. This section presents design alternatives to control contaminant loss from the CDF basin through (1) effluent discharge through the dikes, and (2) leachate drained from the sediments that discharge into the ground water. These alternatives include the use of both additional designed components and operational constraints.

The basic containment basin of a CDF is formed by the perimeter dikes and the subgrade of the site. Water can potentially leave the basin as a nonpoint source by either seepage through the perimeter dikes or by leaching into the underlying subgrade. The control of either pathway is therefore dependent upon limiting hydraulic gradients and/or the design of a barrier to limit advective transport of contaminants, or design of a filter to attenuate the flow of the TSS itself. Hydraulic gradients may be significantly influenced by the type of CDF, e.g., in lake CDFs typically have very low gradients as compared to high gradients common to upland CDFs.

Effluent Discharge through the Dikes

Water carried by the dredged sediments must be removed from the CDF to provide space for additional sediments and to develop a stable base for construction of the final cover over the dredged material. Effluent can leave the CDF by seeping through perimeter filter dikes or through a weir point discharge system. The latter is particularly attractive if the effluent must be processed to remove or attenuate contaminants. Monitoring of effluent release through conventional CDF dikes indicates that point discharges from porous zones in the dikes occur rather than uniform seepage along the entire dike structure (Schroeder 1984).

The flow of water beneath the dike can be controlled using an impermeable basin liner or a dike vertical barrier that penetrates into a lower natural barrier layer. Impermeable dike barrier liner systems include the following: (1) compacted clay liner (CCL), (2) geomembrane liner (GML), (3) geosynthetic clay liner (GCL), (4) geomembrane cut-off wall (GCW), (5) bentonite slurry cutoff wall, (6) fabric form with grout, (7) clean fine sediments, (8) clogged geotextile, (9) graded soil filter, and (10) fabric forms with sand.

Integration of barrier systems into CDF dike sections must (1) not impair the stability of the dike, (2) allow construction of the barrier using conventional construction technology, and (3) key into a lower low permeable layer to minimize effluent discharge beneath the dike. A summary of applicable dike barrier systems is given in Fig. 12.

Leachate Discharge to the Ground Water

The possible flow of contaminated waters into the environment through the bottom of the CDF is site-dependent. Shoreline CDFs may be located in areas of ground water discharge such that ground water flows into the CDF and limits outward leachate movement into the environment. For CDFs located where effluent from contaminated sediments can move into the underlying soils, a barrier is required to seal the bottom. The basic barrier system previously discussed in the subsection, *Effluent Discharge through the Dikes*, can serve this function, with the exception of those appropriate only for vertical cutoff wall type systems. These barrier systems include CCLs, GMLs, GCLs, clogged geotextiles, and graded soil filters.

Construction of a bottom liner system in shoreline or in-lake CDFs would appear to significantly favor the use of a clean fine-grained slurry placed into the CDF initially to intentionally clog the native underlying soils. Extensive geotechnical data for dredged materials exist that clearly show they are capable of achieving field permeabilities low enough to equal the other natural material barriers. The actual permeability achieved is influenced by the plasticity of the dredged material and the loading that it experiences. This slurry could be hydraulically dredged silty sediments selected to seal the CDF and not specifically selected to meet a given dredging need. Operationally, such a sealing layer would only require an initial dredging operation contract that is specific about the type of dredging to be performed (hydraulic), the type of sediments to be moved (fine-grained), and a period of time for placement and limited consolidation of the sediments. On-going placement of sediments within the CDF increases the vertical effective stress acting on the sealing layer. This increase in vertical stress further consolidates the sealing sediments and reduces their permeability.

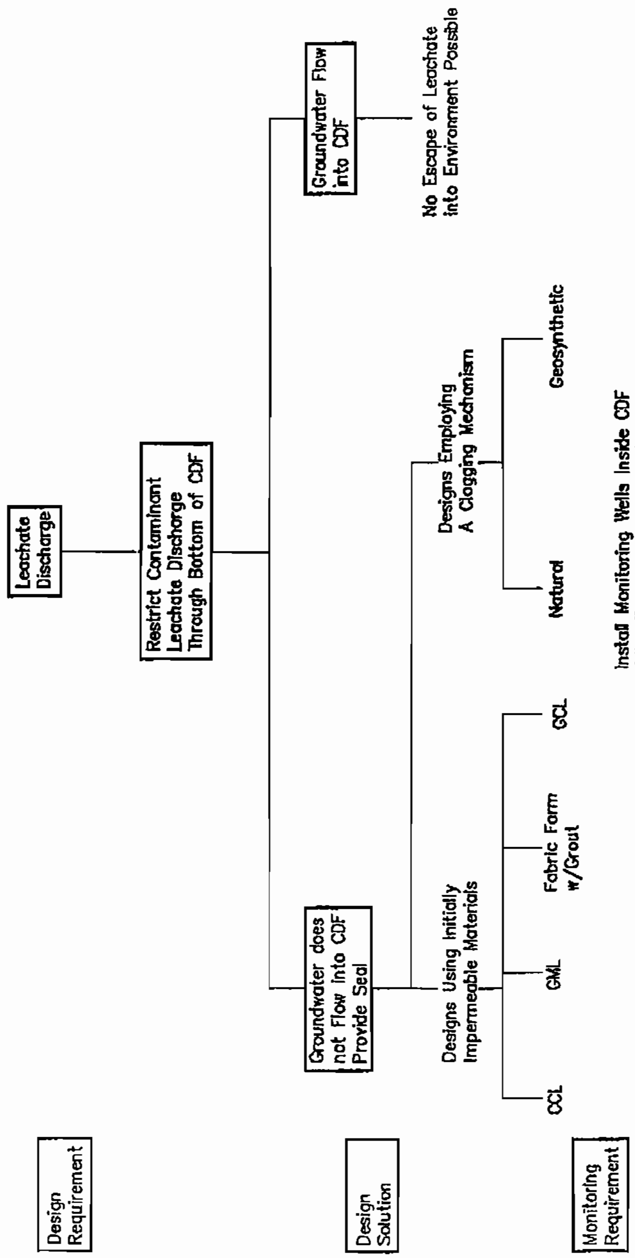


FIG. 12—*Effluent dike discharge control.*

Impoundment Basin Design Guide

The need for a low-permeable dike or ground water barrier can be evaluated using Fig. 13. A dike barrier layer is required for all upland CDFs to prevent discharge of effluent to the surrounding lands and underlying ground water. The economics of dike construction will favor those barriers commonly placed in nonaqueous site conditions. Such barrier layers include CCL, GCL, and GML systems. A dike barrier layer would generally be required in shoreline or in-lake CDFs if the WQS of the dike discharge exceeds applicable WQS beyond the zone of dilution. The zone of dilution should be estimated assuming random point discharge through the dike unless the designed dike section is specifically designed to prevent this occurrence.

A low-permeability barrier is required between the dredged material and ground water if both significant mobile contamination exists within the dredged material and significant potential for contamination of the ground water exists. For example, a CDF sited on low-permeability ($<1 \times 10^{-7}$ cm/s) glacial tills would not require a ground water barrier even if the problematic dredged sediments were close to regulatory limits of contamination. This is applicable to all CDF types and ground water discharge/recharge zones.

Closure Practices and Design Recommendations

The role played by the interim and final covers of a CDF is heavily dependent upon the nature of the contaminant and the type of CDF environment. For example, heavy metals contaminants potentially present in CDF sediments can be oxidized in a wetland environment common within an operational CDF. This precipitates the metals out of the water column to the sediments. Conversely, acidic rains common to the midwest can leach metals from the sediments and mobilize them. Specific design objectives for the cover must therefore consider the partitioning of the contaminants present, the impact of surface water generated infiltration and runoff, and the long-term environment at the CDF.

CDF Characteristic*	Dike Barrier Alternatives**	Groundwater Barrier Alternatives**
Minimum Cont. in DM Minimum Potential Cont. of GW	UP–CCL,GCL,GML SL or IL – None Required	None Required
Minimum Cont. in DM Maximum Potential Cont. of GW	UP–CCL,GCL,GML SL or IL – None Required	UP–CCL,GCL,GML SL or IL – Layer of Clean, Fine Grained DM
Minimum Cont. in DM Existing Cont. of GW	UP–CCL,GCL,GML SL or IL – None Required	None Required
Maximum Cont. in DM Minimum Potential Cont. of GW	UP–CCL,GCL,GML SL or IL – WQS OK – None Required WQS Exceeded – See Table 6.1	None Required
Maximum Cont. in DM Maximum Potential Cont. of GW	UP–CCL,GCL,GML SL or IL – WQS OK – None Required WQS Exceeded – See Table 6.1	UP–CCL,GCL,GML SL or IL – Layer of Clean, Fine Grained DM
Maximum Cont. in DM Existing Cont. of GW	UP–CCL,GCL,GML SL or IL – WQS OK – None Required WQS Exceeded – See Table 6.1	None Required

Cont. = Contaminated
DM = Dredged Material
GW = Ground Water

UP = Upland CDF
SL = Shore CDF
IL = Inlake CDF

CCL = Compacted Clay Liner
GCL = Geosynthetic Clay Liner
GML = Geomembrane Liner
WQS = Water Quality Standards

FIG. 13—*Impoundment basin design guide.*

The cover system selected for a CDF can influence all of the contaminant pathways that have been evaluated in this document, with the exception of the effluent discharge during filling operations. As such, the design of a cover system for a CDF must focus on minimizing the impact of such pathways when required. It is assumed in this paper that final CDF covers will be constructed above adjacent water surfaces, e.g., no submarine final covers are considered. A listing of cover related pathway control systems is presented in Fig. 14.

Cover systems must also be designed to ensure low maintenance, be easily monitored, and be economical to construct. Final covers are placed once the CDF is full and the dredged material is stable enough that future settlements will not damage the cover. Interim covers may be required when the facility is either inactive for a prolonged period of time or when the dredged material is unstable and future subsidence could impair the function of a final cover. This section reviews the existing cover criteria used by COE and EPA for CDFs or waste containment systems and concludes with a review of alternate cover systems that use geosynthetic components or sediment disposal strategies, or both.

	Pathways	Design Requirement	Design Solution	Monitoring Requirement
CDF Cover	Surface Water	(1) Meet water quality standards (2) Prevent erosion	NCDM CDM Conventional Erosion/Sediment Control Practices	NCDM Monitor Turbidity CDM Monitor turbidity and water quality of surrounding open water
	Plant Uptake	(1) Prevent uptake of contaminants by plant species that serve as food for various animal groups	NCDM No restrictions CDM (1) Select plant species that limit uptake and root penetration (2) Restrict volunteer vegetation by harvesting (3) Restrict ponding	NCDM None CDM Conduct assessment of uptake by species during harvesting
	Animal Uptake	(1) Prevent bioaccumulation	NCDM No restrictions CDM (1) Restrict predators (2) Restrict ponding (3) Restrict burrowing animal unless geosynthetic FML present in cover	NCDM None CDM Conduct bioassay and assessment of growth and reproduction

Notes: (1) NCDM — non contaminated dredged material
(2) CDM — contaminated dredged material

FIG. 14—*Cover related contaminant pathway control.*

COE Closure Objectives

The type of closure selected for a particular CDF is often dependent upon the needs and desires of the local sponsor. Local sponsors are typically a city, county, or state governmental agency. The local sponsor is required to provide all lands, easements, and rights of way to the COE for the CDF. Under the Diked Disposal Program (PL 91-611, Section 123) for constructing CDFs on the Great Lakes, a local government sponsor is required. It should be noted however, that local sponsors are not required for disposal of dredged materials from the Great Lakes connecting channels in the State of Michigan. The local sponsor may have planned or implemented productive and beneficial uses for CDFs. These uses include the development of recreational areas, new or expanded marinas, wildlife refuges, etc. The planned development must be compatible with the structural integrity of the facility and the types of sediments contained. These lands cannot be transferred from the local sponsor without the approval of the COE. In recent years, the COE has phased out the construction of CDFs under the authority of PL 91-611. Future maintenance dredging will, however, still require confined disposal. Future CDFs will be constructed under the operation and maintenance (O & M) authorities of individual navigational projects.

EPA Closure Objectives

The COE has played a significant technical role in the development of the current EPA hydraulic isolation covers incorporated in RCRA and TSCA. The COE involvement has ranged from development of design guidance documents (e.g., EPA 1979) to development and continued support of the HELP (Hydrologic Evaluation of Landfill Performance) computer model (Schroeder 1987, 1988). The HELP program is a water-balance model used to evaluate the effectiveness of hydraulic barriers. It has played a major role in the development of the EPA closure program. This COE technical assistance to EPA will aid in establishing applicable closure technologies for CDFs.

RCRA Subtitle C Hazardous Waste Landfills—The development of the RCRA Minimum Technology Guidance (MTG) cover resulted from the need to meet the requirements of RCRA 40 CFR 264.310. Here RCRA specifies that the final cover be designed and constructed to accomplish the following:

(a) promote long-term minimization of liquids infiltrating through the cover,
(b) function with minimal maintenance,
(c) promote surface water drainage to minimize erosion or abrasion of the cover,
(d) accommodate settling and subsidence so that the cover's integrity is maintained, and
(e) have a permeability less than or equal to the permeability of any bottom liner system or natural subsoil present.

COE prepared a technical guidance manual for EPA to assist in the implementation of the RCRA closure requirements (EPA 1985).

Under RCRA, final covers must as a minimum consist of a vegetated or erosion resistant top layer, a middle drainage layer to prevent mounding of surface water infiltration, and a composite barrier layer consisting of a geomembrane over a 2 ft (0.6 m) compacted clay liner (CCL). The vegetated layer minimizes erosion and can be replaced with hardened erosion control layers such as rip-rap or asphalt paving. The middle drainage layer prevents mounding of surface water infiltration and in that way limits the hydraulic head acting on the barrier system. The barrier layer limits infiltration of surface waters to the waste and limits the movement of gas from the waste through the cover.

Supplemental layers for the RCRA cover were proposed by COE to provide for gas collection from the waste and for biotic barriers to limit intrusion into the cover by burrowing animals. MTG for closure issued by EPA in 1989 has been consistent with COE closure guidance.

RCRA Subtitle D Nonhazardous Waste Landfill Covers—EPA closure criteria for RCRA-D nonhazardous waste landfill covers were established on 9 October 1991. The promulgated regulations require that RCRA-D covers have a permeability less than or equal to the liner system or natural soils beneath the waste. A minimum cover under RCRA-D for an existing unlined landfill consists of a 6-in. (15.2 cm) layer of top soil with vegetation and an 18-in. (45.7 cm) soil infiltration layer having a permeability less than 1×10^{-5} cm/s. For covers over landfill that incorporated a composite liner beneath the waste, EPA has recently (Federal Register, 26 June 1992) interpreted the closure criteria to allow an increase in the permeability and decrease in the thickness of the soil component of the cover composite barrier layer. Thus a landfill having a liner that consists of a geomembrane over 2 ft of 1×10^{-7} cm/s CCL would only need a cover barrier layer consisting of a geomembrane over 18-in. of 1×10^{-5} cm/s CCL.

The RCRA-D cover for unlined landfills represents EPA's perspective on what a minimum cover must contain. In general, the cover system components will be more rigorous than the minimal. For example, the 6-in. (15.2 cm) vegetated soil cover will commonly be substantially thicker to provide sufficient water storage so that the vegetation will not die during periods of extended drought. The thickness of the vegetated soil cover will be determined by the root depth of the selected cover vegetation and long-term soil moisture predictions made using the HELP model.

Additional Regulatory Closure Criteria—The RCRA covers described in the previous two sections are required for new landfill facilities receiving newly generated waste. Covers over older wastes being remediated *in-situ* under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) program show considerably more flexibility. This same flexibility would appear appropriate for CDF closures since sediment contamination is typically both at very low concentrations and due to historic events.

CERCLA closures vary significantly depending upon the potential exposure of the waste to either ground water or humans (EPA 1991). This cover design versus exposure concept is illustrated in Fig. 15. The required CERCLA cover ranges from the RCRA-C MTG cover for sites having high contaminant concentrations and high exposure of ground water and humans to a no action alternative for covers having low contaminant levels and little potential exposure to ground water or humans. Such a risk-based cover design is consistent with the pathway control alternatives discussed in this paper.

Design of Closure Components

As shown in Table 3, the existing closure of CDFs is commonly achieved by seeding grass on or allowing volunteer vegetation to germinate in the last lift of dredge material placed in the CDF. Dredged materials are typically rich in phosphorous, nitrogen, and potash, which promote rapid growth of vegetation. Only a limited number of presently closed CDFs incorporate a clay barrier layer in the cover. As an example, the Michigan City CDF cover has both a clay layer and a surface vegetated soil layer. The cover system must provide the following:

(a) an effective permeability that is low enough that the rate of infiltration through the cover is less than or equal to the rate of leakage of leachate through the liner,
(b) sufficient flexibility that long-term settlements of the waste will not damage the cover, and
(c) a design life that exceeds the projected life of the potentially mobile contaminants.

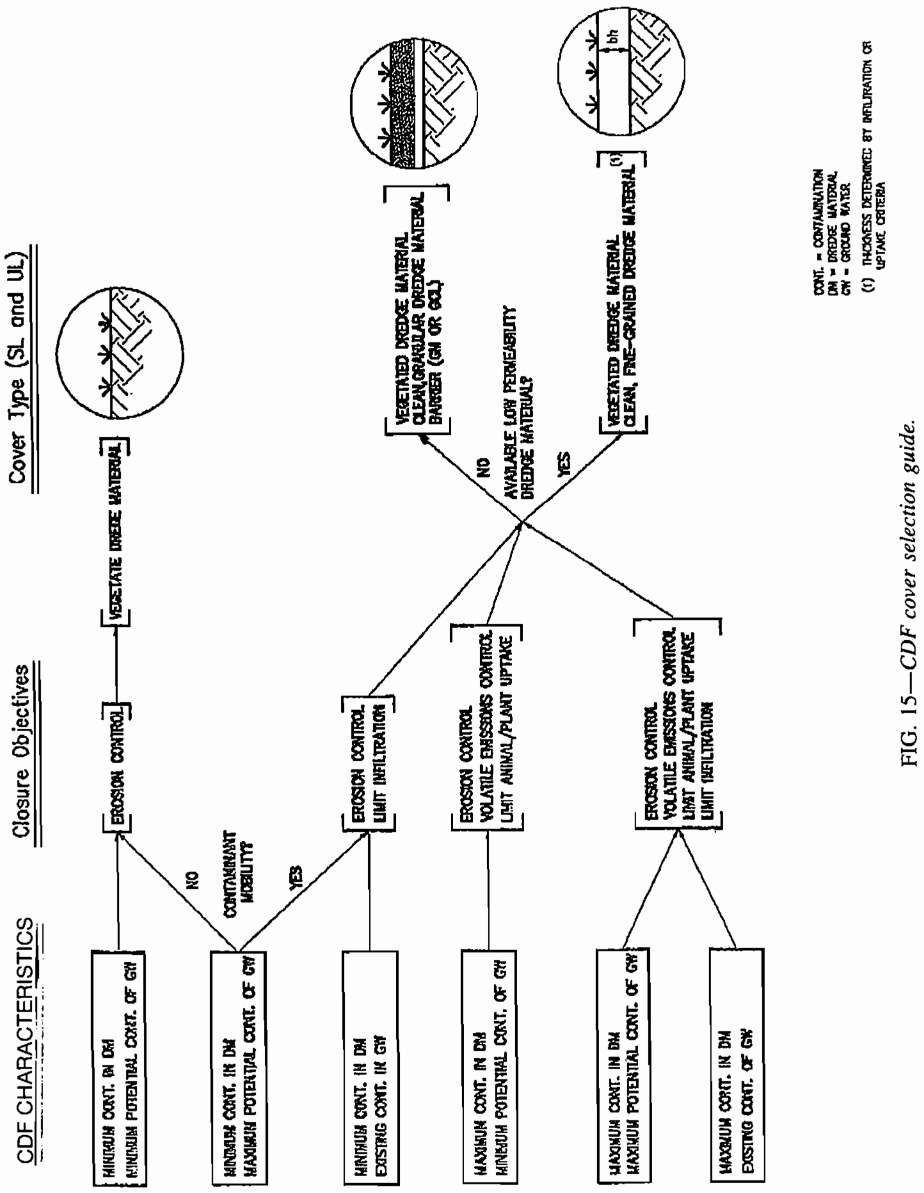


FIG. 15—*CDF cover selection guide.*

TABLE 3—*Summary of closed CDF's in the Great Lakes region.*

Facilities	Years of Operation	Capacity, yd^3	Local Sponsor	Cap Design	Ultimate Use
Harbor Island (Grand Haven)	1974–1985	310 000	State of Michigan	none	public use
Harsen's Island	1975–?	100 000	State of Michigan	restored to former soil level and revegetated	upland nesting habitat for waterfowl
Kawkawlin River	n/a	n/a	Bay County, MI	none	n/a
Kidney Island (Green Bay)	1979–1986	1 200 000	City of Green Bay	none	wildlife habitat
Monroe (Edison)	–1984	n/a	n/a—private site	none	Detroit Edison
Port Sanilac Village	1979–1983	143 300	Village of Port Sanilac	none	municipal landfill
Verplank	1974–n/a	134 000	Verplank Coal and Dock Company	none	not available
Whirlpool (St. Joseph Harbor)	1978–1990	25 000	State of Michigan	none	n/a
Windmill Island	1978–1988	160 000	State of Michigan	none	park facility
Cleveland Dike #12	1974–1979	2 760 000	Cleveland-Cuyahoga County Port Authority	none	waterfront development
Small Boat Harbor, Buffalo	1968–1972	1 500 000	Niagara Frontier Transportation Authority	6 ft (1.8 m) of soil	wildlife area/parking
Toledo (Grassy Island)	1967–1978	5 000 000	Toledo-Lucas Port Authority	none	wildlife/recycle as top soil
Michigan City	1978–1987	50 000	City of Michigan City	clay cap with top soil cover	park land
Bayport (Green Bay)	1965–1979	650 000	City of Green Bay	City of Green Bay plans to cap site	industrial development/marine terminal facility
Clinton River	1978–1990 (98% filled)	370 000	State of Michigan	clay	public access site and MDNR field station
Frankfort Harbor	1982–1990	30 000	State of Michigan	site to be seeded when completed	cherry orchard
Grassy Island (Detroit River)	1960–1984	4 320 000	none, U.S. Fish and Wildlife Service owns land	none	wildlife area

This section presents basic cover design concepts that may be required for the problematic sediments associated with CDFs.

Barrier Layer Design—The primary function of a cover is to limit the infiltration of precipitation and surface water into the waste. This barrier function can be achieved by incorporating a low-permeability barrier within the cover system or by designing the cover system as a water-balance system. EPA has favored the use of barrier systems in the cover while current cover development by the Department of Energy (DOE) favors the use of a water-balance cover. The DOE covers are generally designed to provide a minimum 1000-year service life.

Low-permeability barrier layers are typically constructed using either a single barrier layer or a composite barrier system. The single barrier layer may be a CCL, a geomembrane (GM), or a GCL. The composite barrier is a geomembrane over a CCL or GCL. The flow of water through a well constructed CCL is controlled by the permeability of the clay and the hydraulic gradient acting on the clay (Darcy's Law). A reduction in infiltration through a CCL requires either (1) reducing the permeability of the clay with admixtures or (2) reducing the hydraulic gradient by limiting the head of water standing on the barrier or increasing the barrier thickness. CCLs must be protected from freezing to maintain their low permeability (Zimmie and LaPlante 1990). In Region 5, this may require a minimum of 4 ft (1.2 m) of soil cover over the CCL.

Flow through a GM can be by diffusion of the liquid through the GM or flow through holes or defects. For most GMs, the rate of diffusion is very low [<1 gal/acre/day (1.5 L/hectare/day)] such that the flow through holes in the GM will dominate the leakage. The flow through a given penetration of a GM is significantly impacted by the permeability of the soil layer immediately below the GM (Giroud 1992). A composite barrier system places a CCL or GCL immediately beneath the GM to limit the flow rate through a penetration of the GM. The need for the CCL or GCL will depend upon the permeability of the last lift of dredged material placed in the CDF. Excellent composite action is achieved with soils having permeabilities as large as 1×10^{-5} cm/s. This permeability level can be achieved by may dredged materials. Thus an effect cover composite barrier may be constructed of a GM overlying a lift of low-permeability dredge material. The dredged material must have sufficient strength to work on and thus may require some form of preloading to preconsolidate it.

Water-balance barrier—A water-balance barrier system relies on Richards' Effect (Richards 1931) to store surface water infiltration in the upper soil layer and evapotranspiration to remove it from that same layer. A significant amount of DOE research has focused on development of water-balance barriers for long-term (1000-year) isolation of nuclear waste (Wing 1993). Richards' Effect is based on the observation that a fine-grained soil layer that overlies a coarse grained soil layer will not give up moisture to the deeper layer until it is completely saturated. This is due to the strong capillary forces acting on the liquid within the fine-grained soil. A water-balance barrier has a fined-grained vegetative layer that has sufficient hydraulic storage capacity to contain the maximum anticipated infiltration and relies on plants to remove the water from this layer.

A water-balance cover over a CDF would require that a portion of the available dredged materials be coarse sands so that the capillary break could be established beneath the fine-grained cover. If sands are available, the water-balance cover has a very low cost.

Erosion Control/Vegetative Layer Design—The erosion of a final cover on a CDF is limited by the gentle slopes associated with these facilities due to the nature of the dredged materials. By limiting the slopes to less than 5%, even minor rill erosion is eliminated. A significant design concern results if a barrier layer is incorporated into the cover system. As water percolates through the vegetative layer it mounds on the barrier layer unless drained. Allowing the water to mound increases leakage through the barrier layer and may kill the surface vegetation by "drowning" the roots. A drainage system must therefore be part of a barrier design unless a water-balance analysis indicates that the mounding is limited.

Summary and Conclusions

This paper has summarized alternative methods for limiting contaminant pathways from CDFs for problematic dredge materials. These alternatives include the addition of engineered barrier and/or water-balance components in the dikes, basin, and cover. Additionally, this paper includes operational alternatives for establishing the pathway barriers. Thus the basin of the CDF could be lined using and engineered CCL or it could be sealed by placing an initial layer of clean fine-grain dredged material in the CDF. Either barrier layer could be

effective in limiting the movement of leachate from the dredged material into the ground water beneath the CDF.

This paper also attempted to portray the overlapping federal regulations that may govern the design of a CDF depending upon site hydrogeologic conditions and the concentration and partitioning potential of the contaminants (see Table 1). CDF designs can be conceptualized into several categories that depend on the extent of partitioning of the contaminant of concern to water. The need for pathway controls should reflect the nature and extent of the contamination associated with the sediments.

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