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Effects of Confined Disposal Facility and Vadose Zone Characteristics on Leachate Quality

PURPOSE: This technical note presents the results of an analysis of the impact of confined disposal facility (CDF) design, site climatology, and the characteristics of the foundation soil on leachate transport to the water table below. The results serve as guidance in CDF design and assist in decision-making regarding the use of leachate controls. This technical note presents the main factors that affect leachate production and its transport out of the facility and through the vadose zone to the water table. The significance of these factors to the potential contamination of the groundwater is examined, and relationships among the dominant factors are developed to aid in screening procedures. This technical note provides guidance for evaluating the effects of the leachate source and the vadose zone as part of the three-step leachate screening protocol presented in Schroeder (2000).

BACKGROUND: Contaminated dredged material is often placed in CDFs designed and operated to control environmental impacts of the disposed sediment. A CDF is a diked enclosure having structures that retain dredged material solids. When contaminated dredged material is placed in a CDF, contaminants may be mobilized in leachate that may be transported to the site boundaries by seepage. Subsurface drainage and seepage through dikes may reach adjacent surface water and groundwater and act as a source of contamination (Figure 1).

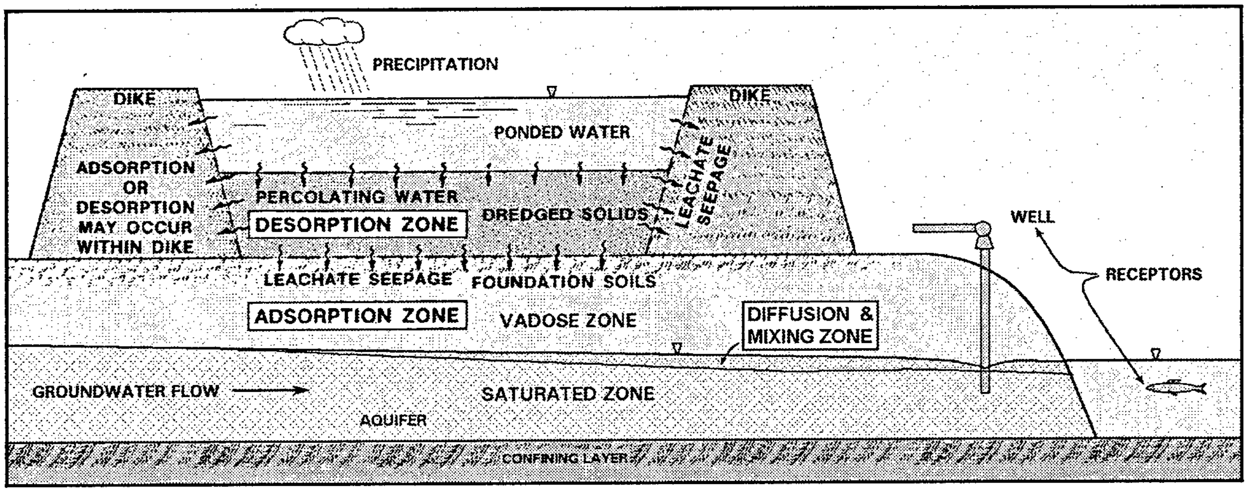


Figure 1. Model of dredged material leaching

Leachate seeping into the groundwater from dredged material placed in a CDF is produced by several potential sources: gravity drainage of the original pore water and ponded water, inflow of groundwater, and infiltration of rainwater and snowmelt. Thus, leachate generation and transport depend on many disposal site-specific and sediment-specific factors.

Contaminant migration via leachate seepage is a porous-media contaminant transport problem. Leaching is defined as interphase transfer of contaminants from dredged material solids to the pore water surrounding the solids and the subsequent transport of these contaminants by pore-water seepage. The interphase transfer is the first step or source of contaminated leachate generation. Interphase mass transfer during dredged material leaching is a complicated interaction of many elementary processes and factors (Myers and Brannon 1991; Schroeder 2000). A complete description of all these processes, factors, and interactions is not presently possible. Instead, a lumped parameter, the distribution coefficient, is used to describe the distribution of contaminant between aqueous and solid phases.

The contaminants in the aqueous phase move with pore water (by convection) in the dredged material as leachate. As leachate is transported through porous media, the contaminants are redistributed between the advected pore water (leachate) and the new solids encountered (the surrounding porous media), and a new equilibrium between the leachate and the solids is reached. This redistribution reduces the contaminant concentration in the leachate as it passes through cleaner layers of dredged material, foundation soils, and fine-grained soils in the vadose zone (unsaturated zone).

The contaminant concentration of leachate exposed to a receptor is further impacted by diffusion or mixing as the leachate is transported from the CDF locale to the receptor through the coarse-grained layers of an aquifer. In effect, the contaminant concentration in the leachate is diluted by the groundwater flow. Attenuation by adsorption to organic matter and interactions with fine-grained materials will also occur in the aquifer, but the effect is generally small due to low concentration of organic and clayey materials in the main regions of saturated groundwater flow.

INTRODUCTION: Section 404 of the Clean Water Act of 1972, as amended, the National Environmental Policy Act of 1969, the U.S. Army Corps of Engineers (USACE) management strategy for dredged material disposal (Francingues et al. 1985), and the USACE/U.S. Environmental Protection Agency (USEPA) technical framework for evaluating the environmental effects of dredged material management alternatives (USACE/USEPA 1992) require the evaluation of the confined disposal alternative for dredged material to include groundwater impacts. Time-varying leachate flow and leachate quality must be predicted to evaluate potential impacts. Several factors affect the rate and quality of leachate leaving the facility. These factors are discussed in the following paragraphs.

CDF Design and Operation. CDF design and operation can affect both leachate quantity and quality. Leachate quantity increases with the area of the CDF. Leachate quantity may decrease with increasing dewatering efforts and promotion of runoff. Dewatering and consolidation of the dredged material decrease both the pressure head that drives drainage through the CDF and the hydraulic conductivity of the dredged material, both serving to decrease leachate production.

Desiccation of the dredged material will cause volatile and semivolatile organic contaminants to volatilize, which reduces their concentrations in the leachate. If the entire thickness of dredged material in the CDF is fully desiccated, the material will become oxidized and the pH may drop if the sediment is high in acid volatile sulfides. Oxidation and pH reduction increase the concentration of a number of metals of concern in the leachate. Additionally, oxidation increases the quantity of the metals in the dredged material that can leach (leachable fraction).

Hydraulic dredging or disposal as opposed to mechanical dredging and disposal greatly increases the initial water content of the dredged material, which provides a greater short-term source of leachate. As such, the necessary storage volume for a given quantity of in situ sediment is much larger and requires a CDF with greater depth or area. Increasing the area increases the leachate volumetric flow rate. Increasing the depth of dredged material increases the pressure head driving leachate production as can be seen in Figure 1. Additionally, hydraulic operations greatly increase the short-term hydraulic conductivity of the dredged material, which increases the rate of leachate production. In the long term (after several years), the leachate flux for the hydraulically dredged or placed material will approach the flux for mechanically dredged and placed material as the material consolidates from the dewatering.

Hydraulic dredging or disposal also separates the material into a mound of predominantly coarse-grained material and a layer of fine-grained material. This process serves to concentrate the contaminants in the layer of fine-grained material. This may change both the leachate flow rate and quality in the short and long term. Leaching from the sand mound may increase leachate production rates due to its low contaminant retardation and high permeability; however, the concentration of contaminants in the sand mound would be expected to be much lower than in the fine-grained layer.

Liners and drains are the primary control features for leachate. Liners can greatly restrict leachate flow rates from CDFs. Liners also divert leachate to drains that collect the leachate and route it to a treatment facility. These control measures prevent nearly all of the leachate from reaching any of the receptors.

Climate. Climate influences the infiltration of precipitation into the CDF and the evapotranspiration from materials in the CDF. Greater precipitation increases potential infiltration and leachate generation. Greater temperature, solar radiation, wind, and lower humidity increase potential evapotranspiration and leachate generation. The distribution of precipitation throughout the year also affects potential infiltration and evapotranspiration. Higher precipitation during winter months when potential evapotranspiration is lowest produces conditions for greater infiltration and leachate generation. Precipitation from large, intense storms produces greater runoff and, therefore, less infiltration and leachate than gentle rainfall for precipitation events of equal magnitude. Precipitation on frozen soil also produces greater runoff and, therefore, less infiltration and leachate than precipitation on unfrozen soil.

Siting. Several siting factors influence the leachate evaluation. Among the more important factors are foundation properties, foundation thickness, location of receptors, and geohydrology. Foundation soils that are in a reduced state and have high pH, high organic matter, high mineral oxides, and high acid volatile sulfides retard contaminant mobility by increasing contaminant retention. Foundation soils with low permeability restrict leachate flow. These properties are more common in fine-grained soils. Thicker foundations of fine-grained soils provide greater retention of contaminants. The location of receptors and geohydrology are important because greater distance from the CDF and the path of leachate flow reduces the contaminant concentration exposed to the receptor. Similarly, siting a CDF for saltwater dredged material over a saltwater aquifer reduces the potential for contaminating a freshwater aquifer. Areas with high groundwater velocities provide greater dilution of the leachate plume, but spread the leachate plume more quickly.

Contaminant Properties. Chemicals diffuse from a region of high chemical potential to a region of low chemical potential. In order for contaminants to cross the interface between dredged material solids and water, a difference in chemical potentials must exist. When chemical potentials are equal, the net transfer of contaminant across the solid-water interface is zero; the mass of contaminant in each phase is constant, but not necessarily equal. The processes control the rate at which equilibrium is reached and the equilibrium distribution of contaminant between solid and aqueous phases. Once equilibrium is reached, the ratio of contaminant mass in the solid phase to the contaminant mass in the aqueous phases does not change.

In practice, a true equilibrium between dredged material solids and pore water never exists because some of the processes have very slow reaction rates. However, a pseudo-steady state can be reached between dredged material solids and water if the water moving past the solids is sufficiently slow. The distribution coefficient can be used as a lumped model to describe the distribution of contaminant between aqueous and solid phases. The use of equilibrium partitioning eliminates the need for predictive laboratory tests and mathematical models to evaluate the transfer kinetics. This would be too complicated for routine application to dredged material leaching. Thus, application of the equilibrium assumption is imperative for the development of predictive techniques suitable for routine use.

Once equilibrium has been reached, only the relative distribution of the contaminant between the solid and aqueous phases is needed to predict leachate quality. For a single contaminant in dredged material, the distribution coefficient is

$$K_d = \frac{q}{C} \tag{1}$$

where

K_d = equilibrium distribution coefficient, L/kg
q = leachable solid-phase contaminant concentration at equilibrium, mg/kg
C = aqueous-phase contaminant concentration at equilibrium, mg/L

Equilibrium distribution coefficients are contaminant and dredged material specific and are affected by various factors such as sediment oxidation status, pH, and ionic strength. Varying these factors during leaching can alter the chemical equilibrium of the system and change K_d.

For non-ionizable organic contaminants, the distribution coefficient is estimated as a function of soil organic matter content f_{om} (kg/kg), and the soil adsorption coefficient normalized to organic matter K_{om} (L/kg) as

$$K_d = f_{om} K_{om} \tag{2}$$

where K_{om} is related to the soil organic carbon adsorption coefficient K_{oc} (L/kg) as

$$K_{om} = \frac{K_{oc}}{1.724} \tag{3}$$

K_{oc} is a function of the octanol-water partition coefficient K_{ow}.

EVALUATION OF CDF AND VADOSE ZONE EFFECTS: Two aspects of leachate generation from CDFs are of particular concern: leachate quality and leachate quantity. Leachate generation depends on site-specific hydrology and geohydrology, engineering controls at the disposal site, CDF operation, disposed dredged material hydraulic conductivity, initial water content, and nature of contaminants. Evaluation of potential leachate impacts will be greatly affected by the nature of the site and the engineering controls in place. Varying the engineering controls and site operation during the evaluation also allows selection of the optimum controls.

To evaluate the impact of the factors discussed in the previous section on leachate concentration, site-specific factors affecting leachate generation must be considered. After disposal, dredged material is initially saturated (all voids are filled with water). As evaporation and seepage remove water from the voids, the amount of water stored and available for gravity drainage decreases. After some time, usually several years for conventional CDF designs, quasi-equilibrium is reached in which water that seeps or evaporates is replenished by infiltration through the surface. The amount of water stored when a quasi-equilibrium is reached and the amount released before a quasi-equilibrium is reached depend primarily on the local hydrology, dredged material properties, and facility design factors. To predict time-varying leachate flow, all of these factors must be considered.

Preproject estimation of leachate flow, therefore, requires coupled simulation of local weather patterns and hydrologic processes governing leachate generation. Important climatic processes and factors include precipitation, temperature, solar radiation, wind speed, and humidity. Important hydrologic processes include infiltration, snowmelt, runoff, and evaporation. Important subsurface processes include evaporation from dredged material voids and flow in unsaturated and saturated zones. The Hydrologic Evaluation of Leachate Production and Quality (HELPQ) model (Aziz and Schroeder 1999) can be used to simulate these processes for selected disposal scenarios.

Quantifying the CDF and vadose zone effects on leachate concentration from its source to the saturated zone for a wide range of the dominant factors including interactions among these factors provides a basis for evaluating the leachate at the point of entry into the saturated zone without running the HELPQ model. This quantification is incorporated in the development of the screening procedure. The HELPQ model could be run for the site-specific conditions if increased accuracy in the predictions is needed to pass the screening.

Approach. Dredged materials are usually placed in a CDF on top of foundation soil. A layer of clean soil may cover the contaminated material to isolate the contaminants from other exposure pathways. Leachate percolates through the dredged material, and if there is no active measure to capture the leachate, it will migrate to the foundation soil below and may eventually reach the water table, posing a contamination potential. Whether leachate reaching the groundwater has unacceptable contaminant concentrations depends on the various conditions explained in the previous sections. Due to the variability of soil and contaminant properties that may be encountered in confined disposal facility design, a variety of parameters were studied to provide guidance. The screening procedure was developed based on the properties of contaminated sediment in the CDF, the foundation soil, and the partitioning coefficient of the contaminant in both. The main concern of this screening procedure is to determine the peak contaminant concentration reaching the water table and the time of travel of contaminants from the CDF to the water table. The peak concentration reaching the water table can be written in a functional form as

$$C_P = f\left(C_O, T_d, T_f, K_{d_d}, K_{d_f}, \phi_d, \phi_f, SG_d, SG_f\right) \tag{4}$$

where

C_P = peak contaminant concentration reaching the water table

C_O = initial contaminant concentration in the dredged material pore water

T_d = thickness of the dredged material in the CDF

T_f = thickness of the foundation soil (distance from bottom of CDF to water table)

K_{d_d} = partitioning coefficient in the dredged material

K_{d_f} = partitioning coefficient in the foundation soil

ϕ_d = porosity of the dredged material in the CDF

ϕ_f = porosity of the foundation soil

SG_d = specific gravity of the dredged material

SG_f = specific gravity of the foundation soil

The screening procedure developed in this study will predict the effects of CDF design, vadose zone, and contaminant on leachate quality. The results may be used to determine whether specific leachate control measures are needed.

CDF Design. In order to evaluate the impact of the CDF design on the quantity and quality of the leachate reaching the water table, a traditional CDF design (without leachate controls) was used in the analysis. The CDF consisted of three components in which the contaminated sediment was sandwiched between a clean foundation soil below and a clean soil cover on top as shown in Figure 2. In order to cover a wide range of dredged material and foundation soil thicknesses, a maximum ratio of foundation soil thickness to contaminated dredged material thickness of 20 was used. The soil textures used for the clean soil cover and the contaminated dredged material remained unchanged throughout the analysis.

The soil texture of the foundation soil was varied to reflect a wide range of possible foundation soils. As a base condition for the dredged material, the porosity was set to 0.5, the hydraulic conductivity was set at 1.2×10^{-4} cm/s, and the specific gravity was set to 2.7. However, the porosity of the foundation soil was varied from one-half to one and one-half times that of the dredged material porosity. The specific gravity of the foundation soil was varied from one-half to two times that of

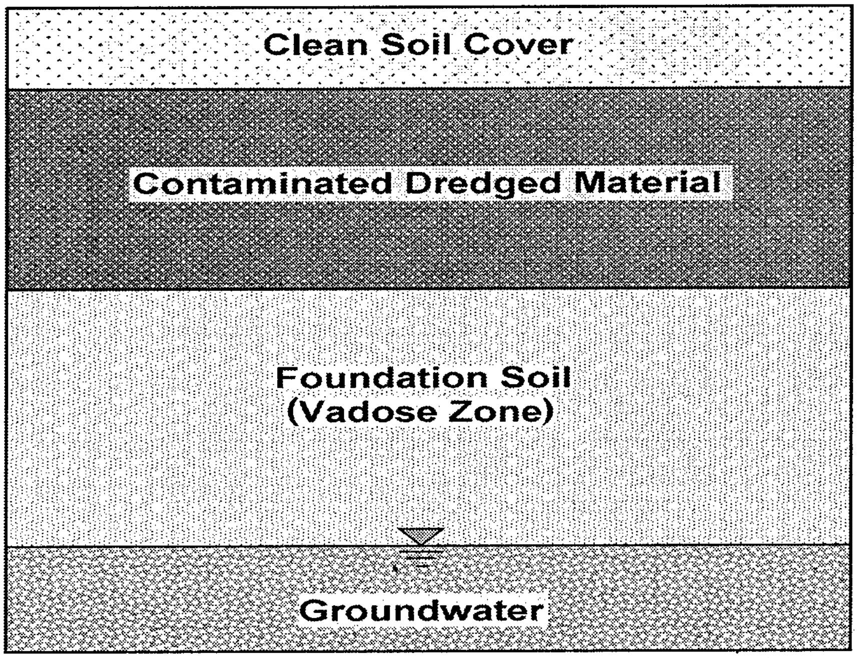


Figure 2. Schematic of CDF used in study

the dredged material specific gravity, thus providing a wide range of foundation soil material properties.

Contaminant Properties. In order to determine how various contaminants contribute to concentration levels that could potentially reach the water table, a variety of contaminant partitioning coefficients was used. The partitioning coefficient is a function of the contaminant type and soil as explained previously. Keeping in mind the various possible combinations of dredged material and foundation soil properties, the partitioning coefficient in the contaminated sediment ranged from being 30 times greater to 30 times smaller than the partitioning coefficient in the foundation soil.

Location Climate. The quantity and quality of leachate generated at a disposal site depend on the initial conditions in the CDF and on the amount of infiltration that penetrates the contaminated sediment. Since the dredged material is initially saturated, the effect of climate is the only factor that can be used in the evaluation of potential contamination to the groundwater. The hydrologic processes that take place are a function of site location. The percolation of infiltrated water affects the rate at which contaminants are transported through the contaminated dredged material and the foundation soil, and hence affect the time of travel of the contaminants. Therefore, in this analysis, the effect of climate at the site will be evaluated in terms of percolation rates as a function of precipitation.

Simulation. In order to determine peak contaminant concentrations reaching the water table, the HELPQ model was used to simulate leachate generation rates and contaminant concentrations for a variety of conditions. For the simulation of the flow and contaminant transport in the CDF, soil data, weather information, and contaminant data were entered into the HELPQ model. The weather data required by the model (precipitation, temperature, and solar radiation) were synthetically generated within the model for 100 years and were used for all simulations.

In modeling subsurface flow, the HELPQ model recognizes four general types of layers: vertical percolation layers in which the flow is restricted to the vertical direction; lateral drainage layers, which allow percolation as well as lateral flow; barrier soil liners that are saturated low-permeability soil layers; and geomembrane liners. In the simulation results presented here, only vertical percolation layers were used, which is typical of CDFs without leachate controls. Flow in these layers is either downward due to gravity drainage or upward due to evapotranspiration.

The contaminant fate and transport processes in the HELPQ model are convection and equilibrium partitioning. The model output includes contaminant mass and concentration profiles in the soil layers used. For the purpose of this analysis, the peak (maximum) concentration at the bottom of the foundation soil is the concentration of interest. This concentration indicates the appropriateness of the specific CDF design.

Results. The results of the HELPQ simulations were reduced to be in terms of the relative concentration of the peak contaminant concentration C_P reaching the water table to that of the initial concentration in the dredged material C_O. This relative concentration represents the level of reduction of the contaminant when it reaches the water table. A discussion of the impact of the parameters described by Equation 4 follows.

Effects of Foundation Soil Thickness on Leachate. The thickness of foundation soil represents the distance from the bottom of the contaminated dredged material in the CDF to the water table. In order to assess the effect of thickness on the peak contaminant concentration, the results of the simulations in which the dredged material and foundation layers have identical properties, except for the thickness ratio, are shown in Figure 3. The results indicate that for a constant partitioning coefficient, as the thickness ratio increases (i.e., foundation thickness increases with respect to sediment layer thickness), the peak contaminant concentration reaching the water table decreases. This decrease is due to the diffusion of the concentration as it travels in the vadose zone of the foundation soil. In this part of the analysis, the partitioning coefficients in the dredged material layer and the foundation layer were identical in each run. The various curves shown are for partitioning coefficients ranging from 2 to 200 L/kg. The plot indicates that the effect of increasing partitioning coefficients while keeping the other parameters constant is a slight increase in peak concentrations reaching the water table. However, this increase becomes insignificant when

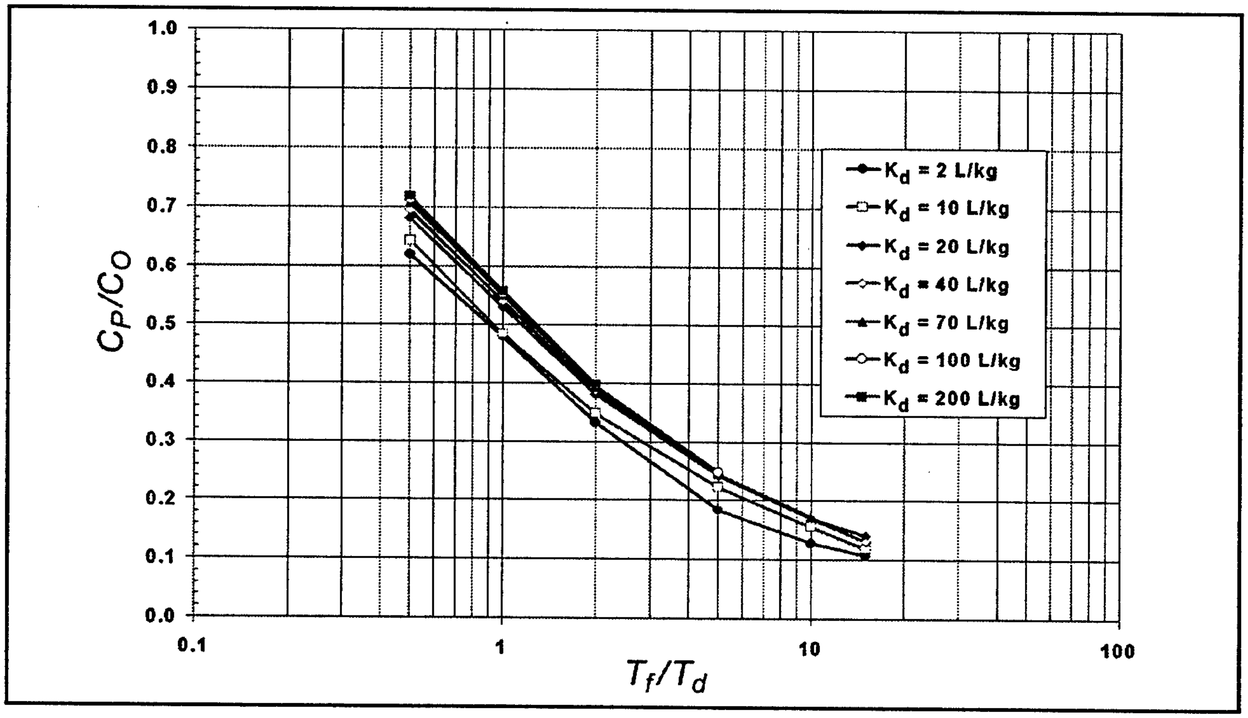
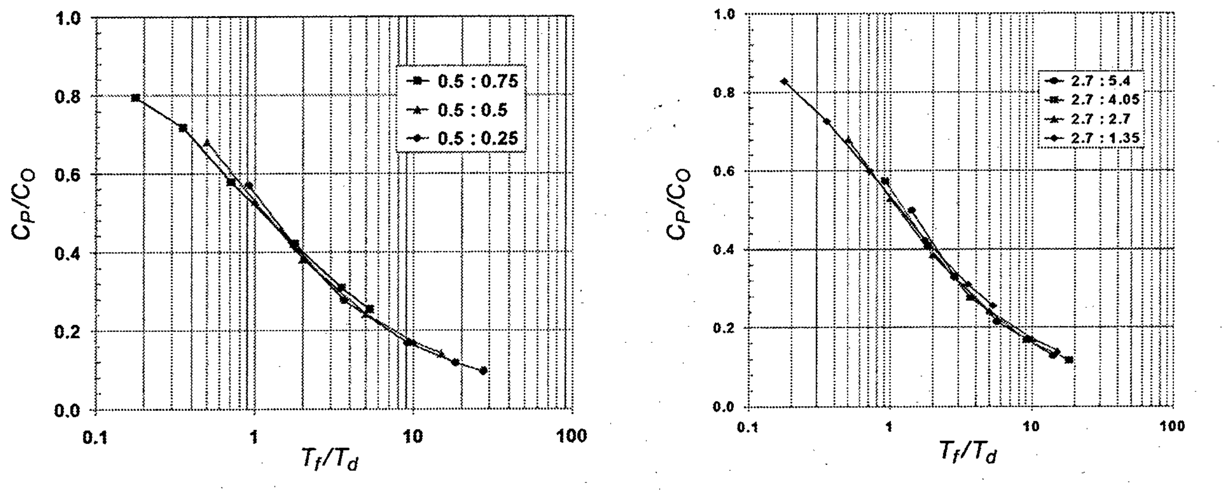


Figure 3. Effect of vadose zone thickness on peak contaminant concentration

the partitioning coefficients are greater than 40 L/kg. The increase occurs only for small thickness ratios after 100 years of simulation. Larger partitioning coefficients are indicative of the tight bond between the contaminant and the solid particles, and hence, more flushing is needed to cause the high concentrations to travel farther.

Effect of Soil Properties on Leachate. The porosity of the soil is an indication of the volume of solids in the soil, and the specific gravity is an indication of the mass of solids present in the soil. For the same constant partitioning coefficient in the disposed sediment and in the foundation soil, the peak concentration reaching the water table is not affected by the porosity and the specific gravity of the material as shown in Figures 4a and b.



a. Porosity ratio

b. Specific gravity ratio

Figure 4. Effect of porosity and specific gravity on peak leachate concentration

Effect of Contaminant Properties on Leachate. Contaminant properties are defined by the partitioning coefficient as a lumped parameter. In Figure 3, the impact of the partitioning coefficient on the peak contaminant concentration reaching the water table is illustrated for the case of constant partitioning coefficient in both the dredged material layer and the foundation soil. The figure shows that as K_d increases, contaminant mobilization is restricted and affects only the cases in which the water table is a short distance below the contaminated sediment. As discussed earlier, the partitioning coefficient is dependent on the fine particles in the soil as well as on the organic material content. In order to evaluate the effect of the partitioning coefficients in the foundation soil being different from those in the contaminated sediment, the simulation results for varying partitioning coefficients are plotted in Figure 5. The results indicate that the peak concentration reaching the water table is sensitive to the partitioning coefficient in each layer. Three scenarios may be identified as follows:

1. The partitioning coefficient in the dredged material is much greater than the partitioning coefficient in the foundation soil. In this case the amount of contaminants released from the dredged material solids is small. However, when it reaches the foundation soil with

the lower partitioning coefficient, a large portion of the released contaminant mass will move with the percolating water and reach great depths. Tthe peak concentration reaching those depths will be very similar to the initial concentration in the dredged material.

2. The partitioning coefficient in the dredged material is much smaller that the partitioning coefficient in the foundation soil. In this case, a large mass of contaminants is mobilized from the dredged sediment solids. However, when the contaminant mass percolates to the foundation soil, the mass of contaminant in the pore water will be easily adsorbed to the foundation soil particles, causing a reduction in contaminant mass in the pore water. Hence, high peak concentrations will not travel far below the dredged material layer.

3. The partitioning coefficients in the dredged material and foundation soil are between these two extremes. In this case the contaminant is released from the dredged material solids and may reach deeper locations with high or low concentrations depending on the relative partitioning coefficients in the dredged material and the foundation soil.

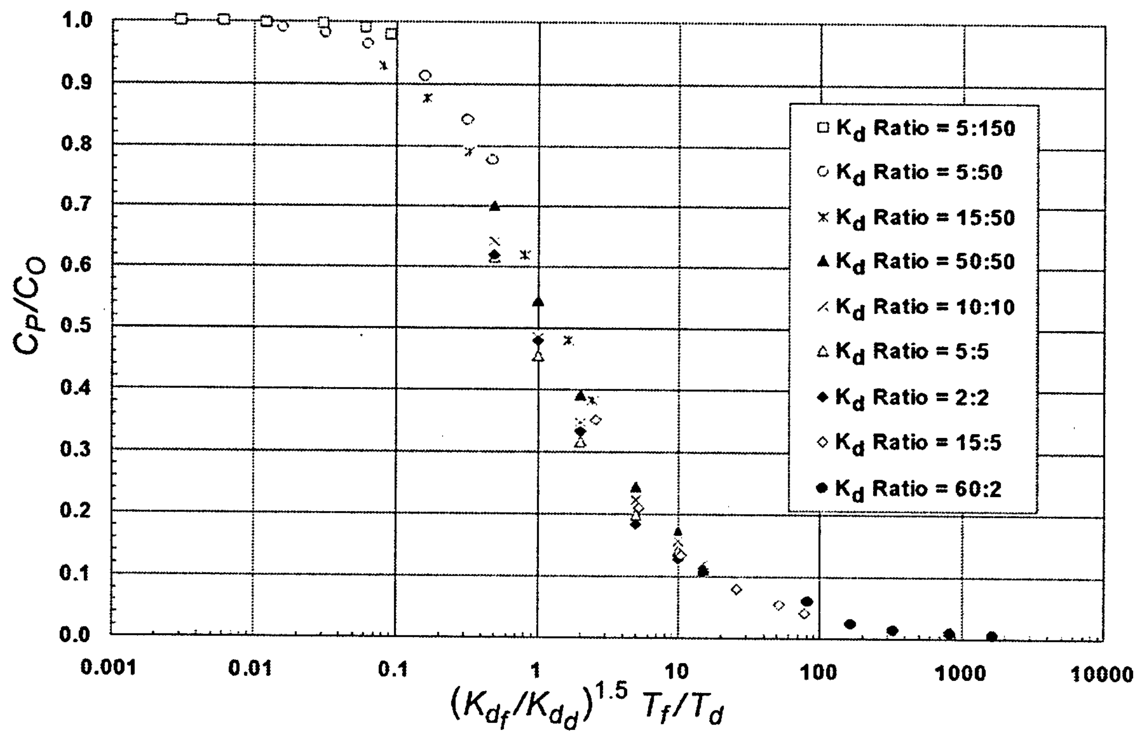


Figure 5. Effect of relative partitioning coefficients on peak contaminant concentration

Based on this analysis, the relative concentration is a function of the relative thickness of the dredged material layer to the foundation layer, the relative partitioning coefficient of the dredged material and the foundation soil, and the relative mass of solids in the dredged material and the foundation soil. Regression analysis of the results indicates that the relative concentration reaching the water table can be represented as

$$\frac{C_P}{C_O} = f\left\{\left[\left(\frac{K_{d_f}}{K_{d_d}}\right)\left(\frac{1-\phi_f}{1-\phi_d}\right)\left(\frac{SG_f}{SG_d}\right)\right]^{1.5}\left(\frac{T_f}{T_d}\right)\left(\frac{1}{T_d}\right)^{0.25}\right\} \tag{5}$$

The relation described by Equation 5 is represented graphically in Figure 6.

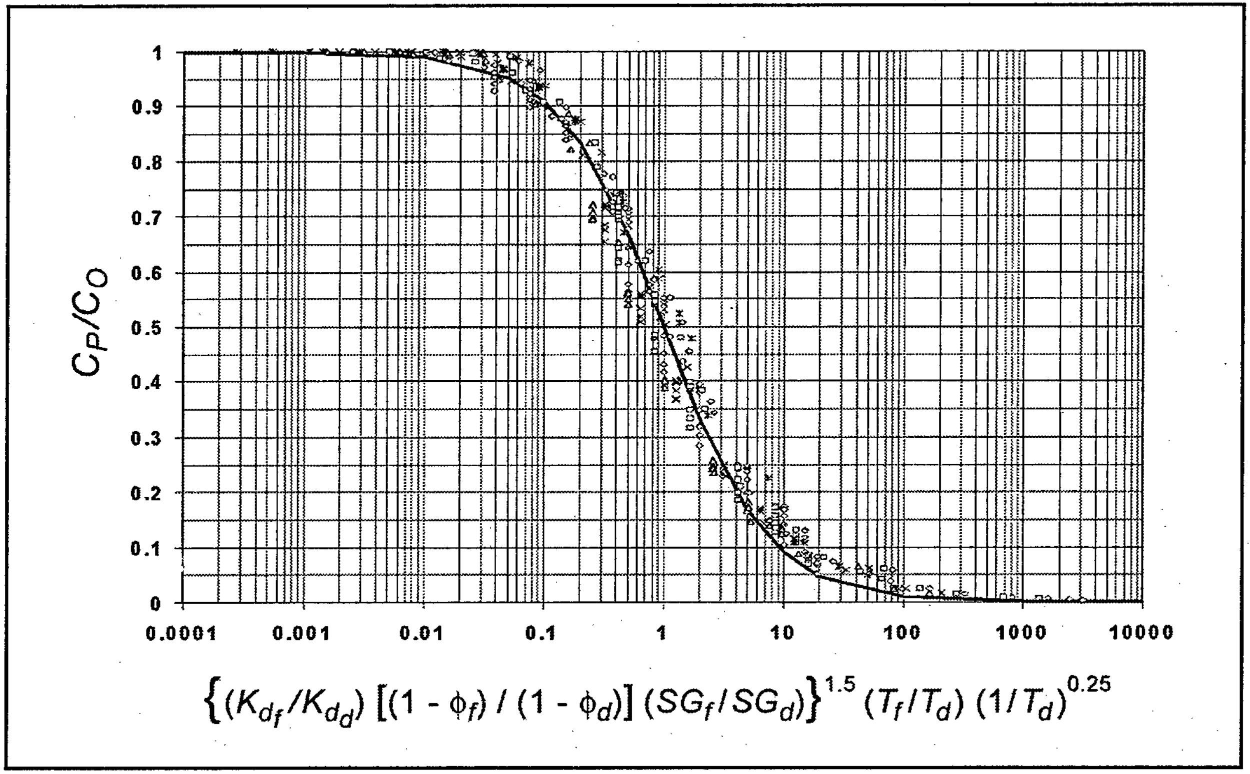


Figure 6. Peak contaminant concentration as function of CDF, vadose zone, and contaminant

The results plotted in Figure 6 can be approximated by a simple relationship that was fitted to the results in Figure 6. The relationship is given in Equation 6, and it describes the attenuation in the vadose zone due to retardation and diffusion. The reduction of the peak contaminant concentration in the leachate passing through the vadose zone would be much greater if degradation, irreversible adsorption, hydrolysis, precipitation, or other processes occur to reduce the soluble concentration of the contaminants. The units used in Equation 6 must be consistent with the restriction that the dredged material thickness in the last term of the denominator is in inches.

$$\frac{C_P}{C_O} = \frac{1}{1+\left(\frac{K_{d_f}}{K_{d_d}}\right)^{1.5}\left(\frac{1-\phi_f}{1-\phi_d}\right)^{1.5}\left(\frac{SG_f}{SG_d}\right)^{1.5}\left(\frac{T_f}{T_d}\right)\left(\frac{1}{T_d}\right)^{0.25}} \tag{6}$$

For a set of design parameters, the peak contaminant concentration reaching the water table can be obtained from Figure 6 or from Equation 6. This concentration represents the maximum pore-water concentration reaching the saturated zone. If this peak concentration exceeds regulatory limits, then a design modification may be warranted. However, it is also important to know how long it takes for this concentration to reach the water table. In order to study the contaminant travel time in the foundation soil, the HELPQ model was also used to determine the time of travel for 0.1, 1, 10, and 50 percent of the initial contaminant concentration in the pore water C_O of the dredged material to reach the bottom of the vadose zone. The time of travel is a function of the same parameters discussed previously, and the analysis of the HELPQ model simulation results using the CDF designs described earlier are shown in Figure 7. In Figure 7, the data generated by HELPQ model are represented as symbols for the various percentages of the initial dredged material concentration.

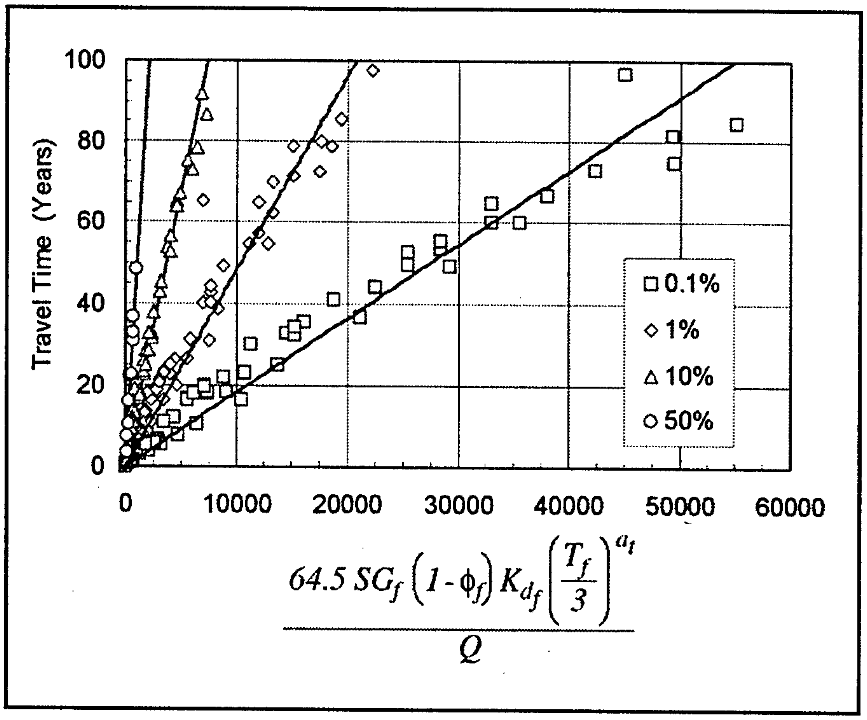


Figure 7. Contaminant time of travel in the vadose zone

The solid lines in Figure 7 represent the regression lines for the specific data. The exponent a_t in the abscissa is defined in the following equations of the times of travel represented in Figure 7:

$$t_{0.1} = \frac{0.116\, SG_f \left(1 - \phi_f\right) K_{d_f} \left(\dfrac{T_f}{3}\right)^{a_{0.1}}}{Q} \tag{7}$$

where $a_{0.1} = 0.112 \ln\left[SG_f \left(1 - \phi_f\right) K_{d_f}\right] + 1.38$

$$t_1 = \frac{0.31\, SG_f \left(1 - \phi_f\right) K_{d_f} \left(\dfrac{T_f}{3}\right)^{a_1}}{Q} \tag{8}$$

where $a_1 = 0.096 \ln\left[SG_f \left(1 - \phi_f\right) K_{d_f}\right] + 1.22$

$$t_{10} = \frac{0.86\, SG_f \left(1 - \phi_f\right) K_{d_f} \left(\frac{T_f}{3}\right)^{a_{10}}}{Q} \tag{9}$$

where $a_{10} = 0.036 \ln\left[SG_f \left(1 - \phi_f\right) K_{d_f}\right] + 1.21$

$$t_{50} = \frac{3.04\, SG_f \left(1 - \phi_f\right) K_{d_f} \left(\frac{T_f}{3}\right)^{a_{50}}}{Q} \tag{10}$$

where $a_{50} = 0.118 \ln\left[SG_f \left(1 - \phi_f\right) K_{d_f}\right] + 0.97$

in which $t_{0.1}$, t_1, t_{10}, and t_{50} represent the time in years for the 0.1, 1, 10, and 50 percent of the initial contaminant concentration to reach the water table, respectively; K_d is the partitioning coefficient in L/kg, T_f is the thickness of the vadose zone in inches, and Q is the average annual percolation rate through the vadose zone in inches.

Figure 7 can be used for determining the time it takes for a certain concentration to reach the water table. Therefore, using Figure 6 (or Equation 6), the peak concentration reaching the water table can be determined. Then the time of travel for that percentage of the initial concentration can be obtained by using either Figure 7 or Equations 7 through 10. Obviously, Figure 7 can be used to determine the time of travel for any concentration of leachate to reach the water table.

Effect of Climate on Leachate. As indicated in the discussion on contaminant time of travel, the percolation rate plays a significant role in the transport and mixing of the contaminants in the vadose zone. The percolation rate is a function of the site hydrology, i.e., location or climate.

Six disposal locations with different climates were evaluated in terms of the effect of climate on leachate generation: San Francisco, CA; Mobile, AL; Chicago, IL; New York City, NY; Buffalo, NY; and Seattle, WA. The climatological classification for these cities was based on the methodology proposed by Vladimir Koppen that utilizes the temperature and precipitation patterns for the location (Trewartha 1954). Thirty-year averages of temperature and precipitation were used at each location to select a Koppen classification type. This classification indicates that the six cities selected for this study represent four climatic types. San Francisco, CA, and Seattle, WA, are representative of the Csb type, which is characteristic of the West Coast of the United States and is classified as Mediterranean, dry climate. Mobile, AL, and New York, NY, are representative of the Cfa type, which is characteristic of a midlatitude rainy climate with mild winter. These areas are typically hot and humid and have winters that are relatively mild with sufficient moisture. The southern United States has large areas within this climate type. Chicago, IL, is representative of the Dfa type, which is characteristic of a midlatitude rainy climate with cold winter. Dfa zones stretch from South Dakota eastward in a narrowing band to the western edge of Lake Erie and include a small area around western Massachusetts. This climate type also represents the Sierra Nevada-Cascade range. Finally, Buffalo, NY, is representative of the Dfb type, which is characteristic of a midlatitude rainy climate with a cold, snowy winter. Two bands found through southern Canada and the northern United States are typical of this climate type. In the United States, this zone also includes the "Snow Belt" of western New York State, northwestern Pennsylvania, and northeastern Ohio.

Average annual rainfall and average percolation rates for the six cities are given in Table 1. These percolation rates for three designs with different thicknesses of foundation soil were obtained by simulation using the HELP model (Schroeder et al. 1994). These percolation rates are based on 100 years of simulation. The results indicate that the ratio of percolation to rainfall at the same location was similar for all three designs. In addition, percolation to rainfall ratios for San Francisco and Seattle were similar as well as for Mobile and New York City, but the ratios for the difference climate classifications varied significantly, ranging from 0.19 to 0.58.

Table 1
General Climate Characteristic of the Selected Sites

Disposal Location	Average Annual Rainfall, in.	Average Annual Percolation Through Foundation Layer, in.		
		Design 1	Design 2	Design 3
San Francisco, CA	20.35	11.00	11.00	10.75
Mobile, AL	64.60	21.20	21.20	21.00
Chicago, IL	34.15	6.50	6.50	6.22
New York, NY	43.86	11.50	11.50	11.00
Buffalo, NY	37.00	7.90	7.90	7.75
Seattle, WA	50.86	29.80	29.80	29.60

SUMMARY: This technical note outlined the important parameters that impact the concentration of leachate percolating through a clean foundation soil. These parameters include foundation, contaminant, and CDF properties in addition to climate. The results provide a conservative screening tool for managers and designers of CDFs by evaluating the peak contaminant concentration that could reach the water table, and the time of travel of the contaminant in the foundation soil.

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> Schroeder, P. R., and Aziz, N. M. (2003). "Effects of confined disposal facility and vadose zone characteristics on leachate quality," *DOER Technical Notes Collection*

(ERDC TN-DOER-C31), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/dots/doer*

REFERENCES

Aziz, N. M., and Schroeder, P. R. (1999). "Documentation of the HELPQ module for ADDAMS: Hydrologic evaluation of leachate production and quality for confined disposal facilities," *Environmental Effects of Dredging Technical Notes* EEDP-06-20, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. *www.wes.army.mil/EL/dots/eedptn.html*

Francingues, N. R., Jr., Palermo, M. R., Lee, C. R., and Peddicord, R. K. (1985). "Management strategy for disposal of dredged material: Contaminant testing and controls," Miscellaneous Paper D-85-1, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Myers, T. E., and Brannon, J. M. (1991). "Technical considerations for application of leach tests to sediments and dredged material," *Environmental Effects of Dredging Technical Notes* EEDP-02-15, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. *www.wes.army.mil/EL/dots/eedptn.html*

Schroeder, P. R., Dozier, T. S., Zappi, P. A., McEnroe, B. M., Sjostrom, J. W., and Peyton, R. L. (1994). "The hydrologic evaluation of landfill performance (HELP) model: Engineering documentation for version 3," EPA/600/R-94/168b, U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory, Cincinnati, OH.

Schroeder, P. R. (2000). "Leachate screening considerations," *DOER Technical Notes Collection* (ERDC TN-DOER-C16), U.S. Army Engineer Research and Development Center, Vicksburg, MS. *www.wes.army.mil/el/dots/doer*

Trewartha, G. T. (1954). *An introduction to climate*. McGraw-Hill, New York.

U.S. Army Corps of Engineers/U.S. Environmental Protection Agency. (1992). "Evaluating environmental effects of dredged material management alternatives — A technical framework," EPA-842-B-92-008, U.S. Environmental Protection Agency and U.S. Army Corps of Engineers, Washington, DC.