Dredging Research Technical Note EEDP-06-21
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ADDAMS Application: Hydrologic Evaluation of Leachate Production and Quality (HELPQ) Module in CDFs

PURPOSE: This technical note describes the application of the Hydrologic Evaluation of Leachate Production and Quality (HELPQ) computer program, which facilitates the design of confined disposal facilities (CDFs) for contaminated dredged material by estimating leachate production rates and leachate quality. HELPQ is part of the Automated Dredging and Disposal Alternatives Modeling System (ADDAMS).

BACKGROUND: The HELPQ model is developed based on contaminant mass balance and utilizes the principle of conservation of mass as it applies to the sediment solids, the percolating fluid (leachate), and the contaminants dissolved in the fluid and associated with the sediment solids. The hydrologic modeling for contaminant routing in the soil profile is composed of balancing the water budget at the ground surface and then routing the infiltrated water and the available contaminants throughout the soil profile. The Hydrologic Evaluation of Landfill Performance model (HELP) is used for surface water hydrology, infiltration, and drainage in the soil.

Since the HELP model was developed for evaluating landfill performance, it offers additional features that are useful in CDF design and performance evaluation. These features include the use of sand or gravel layers for lateral drainage or leachate collection and clay and synthetic materials as liners. To allow for flexibility in the design of confined disposal facilities, lateral drainage of leachate and barrier liners can also be used in HELPQ for preliminary design and CDF performance evaluation.

A special treatment is provided for estuarine sediments to simulate salt washout effects on contaminant partitioning. The model is capable of simulating lined facilities with or without leachate collection systems and unlined facilities. Input is via a user-friendly interface that accepts user-supplied partitioning coefficients or calculates partitioning coefficients from user-supplied sequential batch leach data or column leach data. Model output includes contaminant concentrations in the CDF profile, contaminant concentration and mass releases through the bottom of the CDF, and contaminant masses captured by leachate collection systems.

INTRODUCTION: In order for contaminants to cross the interface between dredged material solids and water, there must be a difference in chemical potentials. When chemical potentials are equal, the net transfer of contaminant across the solid-water interface is zero, and the mass of contaminant in each phase is constant but not necessarily equal. This stage is considered to be the equilibrium condition, and the ratio of contaminant mass in the solid phase to contaminant mass in the aqueous phase does not change. The equilibrium-partitioning coefficient K_d is written as:

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

where K_d = equilibrium distribution coefficient, l/kg, q = contaminant concentration in the solid phase at equilibrium, mg/kg, and C = contaminant concentration in the aqueous phase at equilibrium, mg/l. Equation 1 describes the equilibrium distribution of a single contaminant in a dredged material and indicates that equilibrium distribution coefficients are contaminant and dredged material specific.

By assuming equilibrium between solid and aqueous phases, the need for determining which processes are controlling and the rate coefficients for these processes is eliminated. Without the equilibrium assumption, laboratory testing and mathematical modeling would involve determination of controlling processes and investigation of the kinetics for these processes. Thus, the equilibrium assumption is of tremendous importance for the development of predictive techniques suitable for routine application.

Sequential batch leaching of estuarine sediments with distilled-deionized water (Brannon et al. 1991) often yields the type of desorption isotherm shown in Figure 1. The partitioning coefficient changes as the solid phase concentration and the ionic strength decrease during sequential leaching until a turning point is reached. At the turning point (point 5), the partitioning coefficient becomes constant, and desorption begins to follow a somewhat classical isotherm. The turning point is the point at which most of the salt has been washed out. After the turning point, there is little change in ionic strength and no further deflocculation of sediment colloidal matter. The desorption isotherm shown in Figure 1 is referred to as a Dissolved Organic Carbon (DOC)-facilitated desorption isotherm. Since the relationship of q versus C is not a one-to-one correspondence for DOC-facilitated desorption isotherms, q as a function of C cannot be developed from the isotherm.

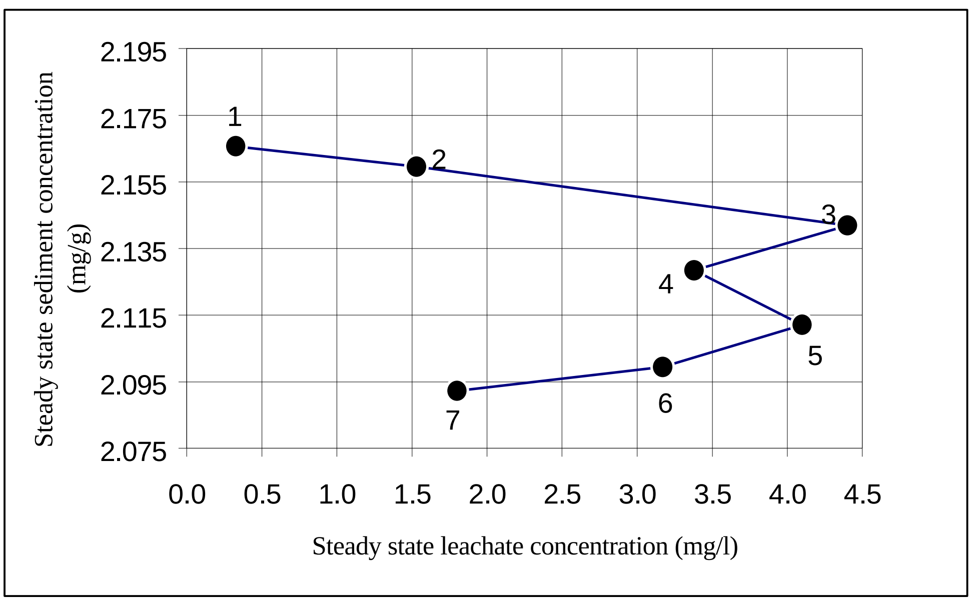


Figure 1. Desorption plot for total PCB in New Bedford sediment sequential leach testing

Aziz (1991, 1993) analyzed PCB data from New Bedford Harbor and Baltimore Harbor sediments in terms of the applicability of the Langmuir isotherm to model equilibrium partitioning. He concluded that the traditional models might fit the data in the late stages of sequential leaching but do not represent properly the partitioning coefficient trends in the early stages of the test. Myers and Brannon (1989) present the New Bedford sequential batch leaching tests data.

In an effort to better determine the partitioning coefficients of dredged material for estuarine sediments, the column leaching test is recommended. The recommended procedure is described in Myers et al. (1996). These tests are designed to obtain leachate concentration as a function of pore volumes eluted (V). In freshwater sediment leaching, the maximum contaminant concentrations occur at the beginning of the leaching process. However, maximum leachate contamination concentrations for estuarine sediments yield maximum leachate contaminant concentrations after a number of pore volumes have been leached. This phenomenon is due to release of colloids as ionic strength decreases. Column tests provide estimates of the number of pore volumes needed to reach this concentration peak. Electrical conductivity starts high and rapidly decreases as the number of pore volumes leached increases. Peak concentration observed during elution can be used to represent contaminant source input into groundwater models.

The number of pore volumes required to reach the peak on contaminant elution curves can be used to estimate the time to reach the maximum contaminant concentrations in a CDF. This time will depend on a number of site-specific factors that govern hydraulic flux. These factors include dredged material hydraulic conductivity, moisture content, and water flow rate.

INPUT DATA CONSIDERATIONS: The HELPQ model may be used to model CDFs with up to 20 layers of soil and geosynthetic material. Figure 2 shows an example of a CDF composed of five layers. The model recognizes four general types of layers: vertical percolation, lateral drainage, barrier soil liners, and geomembrane liners. Correct classification of layers is very important because the HELP model routes the flow of water through the four types of layers in different ways. Contaminant routing also requires knowledge of layer types so that lateral drainage can be modeled properly.

Contaminant routing in the soil profile relies heavily on the results of the subsurface water routing performed by the HELP model. Routing of contaminants begins after vertical drainage, lateral drainage, and soil moisture contents are computed. Except for lateral drainage layers, contaminants enter a layer from above and leave from below. In lateral drainage layers, contaminants may also leave the layer laterally to a drain, and hence out of the CDF, thus reducing the amount of contaminant entering the barrier soil liner and eventually contaminating the groundwater. Since the HELP model allows for evapotranspiration, contaminant mass may increase in the soil segments affected by this process; volatilization of contaminants is not modeled in HELPQ. When lateral drainage layers are used, lateral drainage occurs at the top of barrier soils. Therefore, lateral drainage in the contaminant routing model is taken into consideration in the mass balance for contaminants at the bottom of lateral drainage layers. The net result is a decrease in the amount of contaminants that may percolate into the underlying barrier soil.

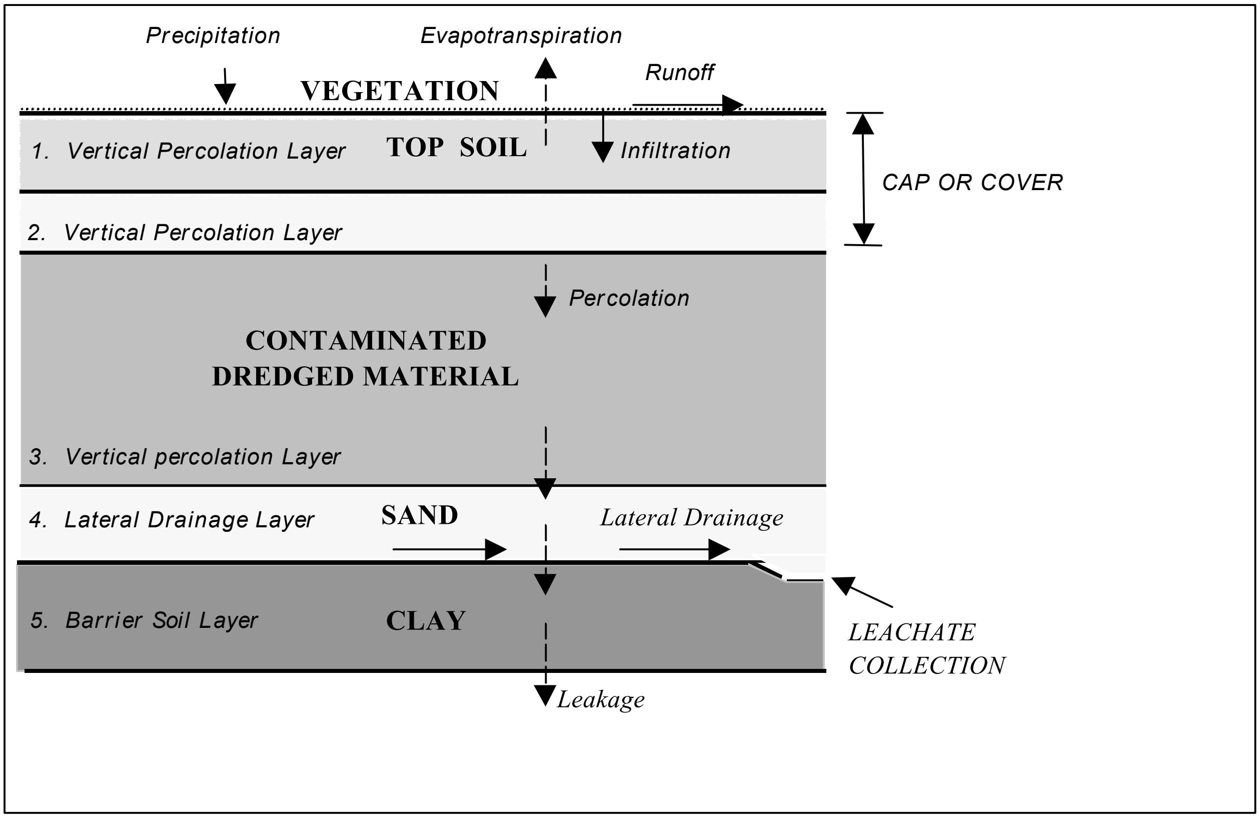


Figure 2. Schematic profile of a CDF

As noted earlier, estuarine sediments do not have a trend similar to the traditional partitioning coefficients observed in freshwater sediments. Data analysis indicates that adsorption and desorption in estuarine sediments are a function of leachate salinity. Salinity routing using mass balance in the soil profile is modeled in HELPQ in a way similar to that of contaminants.

Flow in a vertical percolation layer is either downward due to gravity drainage or upward due to evapotranspiration. The rate of gravity drainage (percolation) in a vertical percolation layer is assumed to be largely independent of conditions in adjacent layers. Dredged material layers and layers designed to support vegetation are normally designated as vertical percolation layers. Layers 1, 2, and 3 in Figure 2 are vertical percolation layers.

Lateral drainage layers (e.g. layer 4 in Figure 2) may be placed above barrier soil liners to facilitate dewatering of the dredged material. Vertical flow in a lateral drainage layer is modeled in the same manner as vertical percolation layers, but additional lateral drainage is allowed. The hydraulic conductivity of a lateral drainage layer should be greater than or equal to the hydraulic conductivity of the overlying layer. A lateral drainage layer may be underlain by only another lateral drainage layer or a barrier soil liner. The slope of the bottom of the layer may vary from 0 to 30 percent.

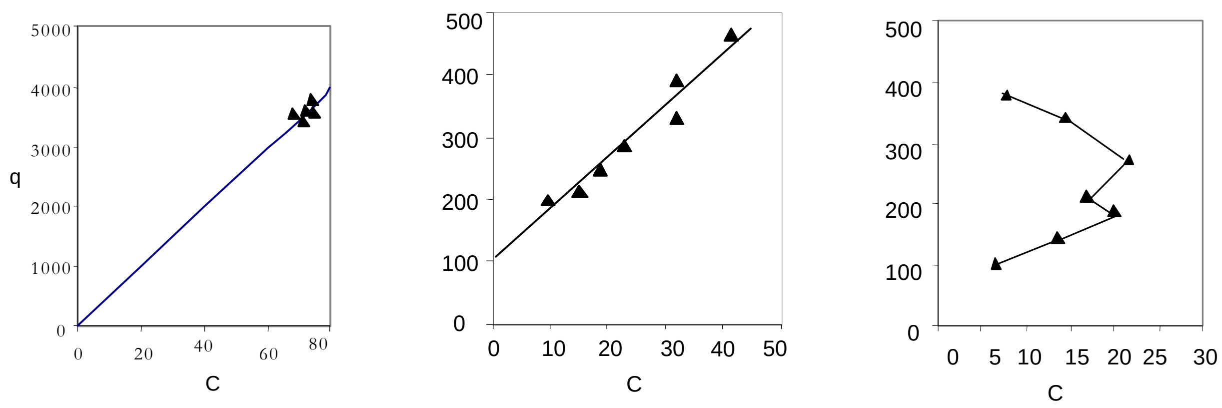
Barrier soil liners, such as layer 5 in Figure 2, are intended to restrict vertical flow. These layers should have hydraulic conductivities substantially lower than those of the other types of layers. The model allows only downward flow in barrier soil liners. Thus, any water moving into a barrier liner will eventually percolate through. Percolation rate depends upon the depth of water-saturated soil (head) above the base of the layer. The program recognizes two types of barrier liners: those composed of soil and those composed of an impermeable synthetic membrane. For the latter type, the user must specify a membrane leakage fraction. This is used to determine the daily percolation that occurs with the membrane in place as opposed to the daily percolation that would occur without the membrane. The net effect of specifying a membrane leakage fraction is to reduce the effective hydraulic conductivity of the layer. Layer 5 shown in Figure 2 is a barrier liner.

The lateral drainage sub-model is applicable for barrier-layer slopes from 0 to 30 percent. Maximum lateral drainage distance is measured horizontally rather than along the slope; however, for slopes of less than 10 percent, the difference is negligible. The maximum horizontal drainage distance is the maximum horizontal distance that water must travel to reach a free discharge.

The components of the HELPQ model are the HELP program and a contaminant routing model. The program includes a user-friendly interface that enables the user to interactively enter data and view and print results. The contaminant routing model allows for the layers of soil in the CDF to have different initial contaminant concentrations. This is of particular importance if a cover system is designed for the CDF or if a clay liner is placed at the bottom of the CDF. The soils used for these layers may not have significant, if any, concentrations of the contaminants being considered.

The HELPQ program requires partitioning coefficient data, such as sequential batch leaching test results for the contaminants to be considered, initial concentrations of the contaminants in each soil layer, and the salinity (conductivity) in each layer if the dredged material is of estuarine origin. Equilibrium-partitioning data for pollutants that are typically present in dredged material are classified as one of the following types: a constant partitioning coefficient, a point K_d (methods 1 and 2), a data-averaged K_d (method 3), a best fit K_d (method 4), or a salinity-dependent K_d (methods 5 and 6), as depicted in Figure 3. In addition, HELPQ requires the same data needed to run the HELP model such as weather data (precipitation, temperature, evapotranspiration) and soil and design data (soil properties, layer types, etc). The HELP model input requirements are explained in Schroeder and others (1994).

In running the HELP model, the user can assign soil characteristics to a layer in the cover system or in the liner using the default option or the manual option. These soil textures are classified according to two standard systems--the U.S. Department of Agriculture system and the Unified Soil Classification System. The default characteristics are typical of agricultural soils, which may be less dense and more aerated than soils typically placed in landfills. Clays and silts in landfills would generally be compacted except within the vegetative layer, which might be tilled to promote vegetative growth. However, consolidation data must be used for soil description of the dredged material layer.



a) Methods 1, 2, and 3 b) Method 4 c) Methods 5 and 6

Figure 3. Partitioning coefficient methods in HELPQ

Weather data include daily precipitation, temperature, and solar radiation. Up to 5 years of data are available as default weather data for several cities in the United States. Synthetic data can also be generated for a host of cities. Complete lists of cities for which default data are available and cities for which synthetic data can be generated are given in the user's guide of the HELP model (Schroeder and others 1994).

ALTERNATIVE CDF DESIGNS: Sediments in a CDF are placed in a relatively short period of time so that the underlying layers may not have significant concentrations at the beginning of CDF operation. This is an important fact, since in a multi-layered system, the initial contaminant concentration in each layer of the facility is required for running the simulation.

Simulation using HELPQ is carried out using two designs. The first design simulates a traditional CDF in which dredged material is placed on top of foundation soil (compacted clay). In this case leachate percolates through the foundation soil since there are no active measures to capture the leachate and prevent it from contaminating the surrounding ground. The second design incorporates a liner system with a drainage layer that intercepts leachate after it percolates through the dredged material.

Partitioning coefficients have a strong effect on routing contaminants in CDFs. PCBs having a very high partitioning coefficient require a very long time to be flushed out of the facility, and after a period of 50 years of simulation the concentrations may remain unchanged. To have a better feel for the routing process, arsenic (As) having much smaller K_d is chosen for this demonstration. For this purpose, the source of sediment is the New Bedford, MA, harbor. Hence, the partitioning coefficient is salinity dependent.

In the traditional CDF design, when contaminated dredged material is deposited in a CDF, the sediment settles and forms a layer of contaminated sediment. The base of the facility, which is usually a low permeability soil, such as clay, may be used as a barrier layer.

The first CDF design is simply a 12-ft layer of dredged material placed above a 2-ft compacted clay layer as shown in Figure 4. Thus, in Figure 4, the top layer is the contaminated sediment layer represented by a vertical percolation layer and the bottom layer represents a barrier soil liner.

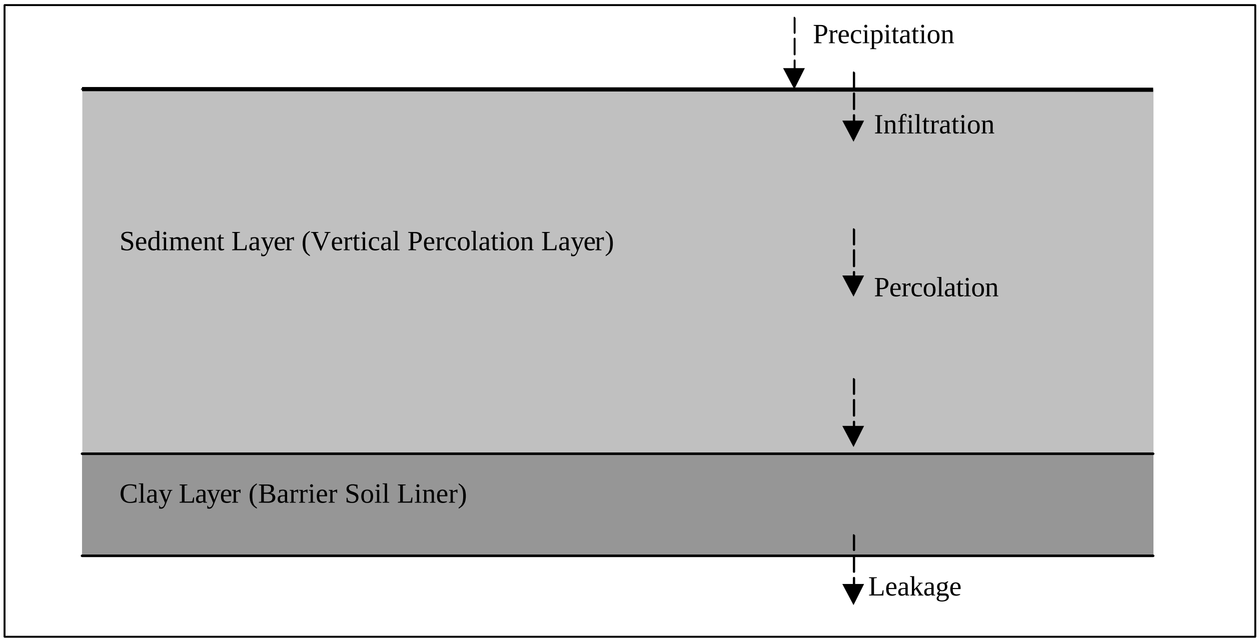


Figure 4. Schematic representation of a traditional CDF

The initial concentration of arsenic on the dredged material is 9.03 mg/kg. The initial salinity in the pore liquid is 30 ppt. The partitioning coefficient data are obtained from actual sequential batch leaching tests on New Bedford Harbor sediment.

HELPQ plots on the screen the annual leachate concentrations, solids concentrations, and salinity. It also prints to a file the leachate concentrations and salinity (if any) at ten equally spaced vertical locations in the CDF. The amount of contaminant leaving the facility through lateral drainage and percolation (leakage) through the bottom of the CDF into the neighboring area are reported on a monthly or yearly basis. HELPQ also reports the percentage of contaminants left in the facility at the end of the simulation.

Using weather data for Boston, MA, a 50-year simulation of moisture movement and contaminant routing through and out of the CDF is performed. The results of the 50 years of simulation are shown in Figure 5 as predicted salinity profiles in the CDF and in Figure 6 as predicted arsenic concentrations in the solid phase over the CDF depth. The results clearly show that salinity is washed out at a much faster rate than contaminants. After a period of 20 years of simulation, almost the entire facility is free of salt, while after 50 years of simulation, arsenic is washed out only from the upper levels of the CDF. Moreover, HELPQ reports a total of 54 kg of arsenic per acre leaked through the CDF base. This amount represents 22.5 percent of the original amount present in the CDF. In addition, HELPQ predicts that 100 percent of the salt originally present in the CDF leaked from the base.

With the increased concern on the effect of contaminated dredged material on the environment, it is important to reduce the amount of percolation into the ground. One way to reduce the percolation into the ground is by choosing a different design for the CDF; for example, using a liner system below the contaminated dredged material. Such a system may be composed of a compacted clay liner and a lateral drainage layer as shown in Figure 2. A lateral drainage layer is a layer where flow is allowed both vertically and laterally. This layer is used to drain leachate laterally into a collection system. Leachate may then be pumped out from the collection system for treatment, thus reducing groundwater contamination potential. The net result is the reduction of the amount of contaminants that might percolate into the bottom layer and eventually out of the facility.

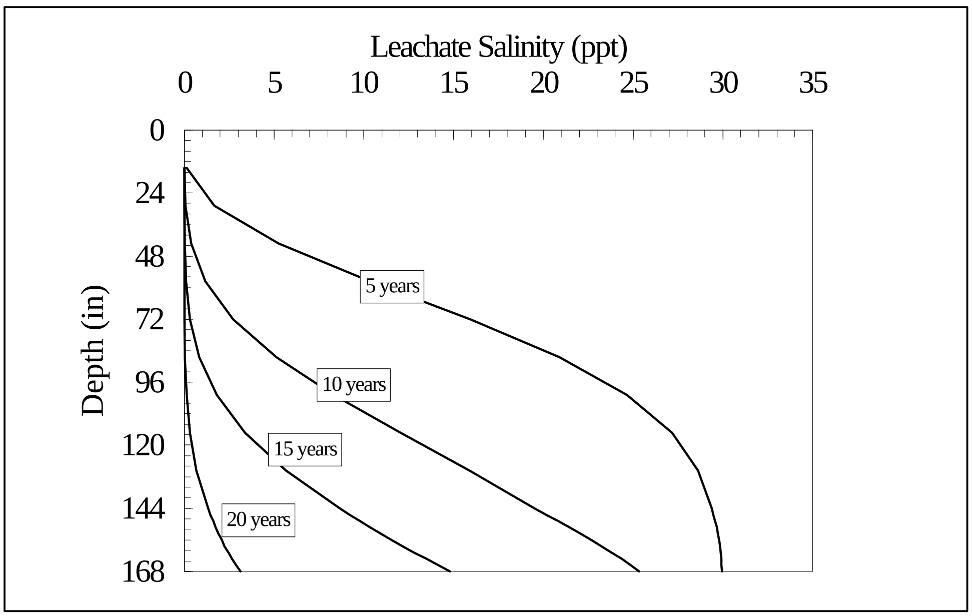


Figure 5. Predicted salinity profiles for the CDF in Figure 4

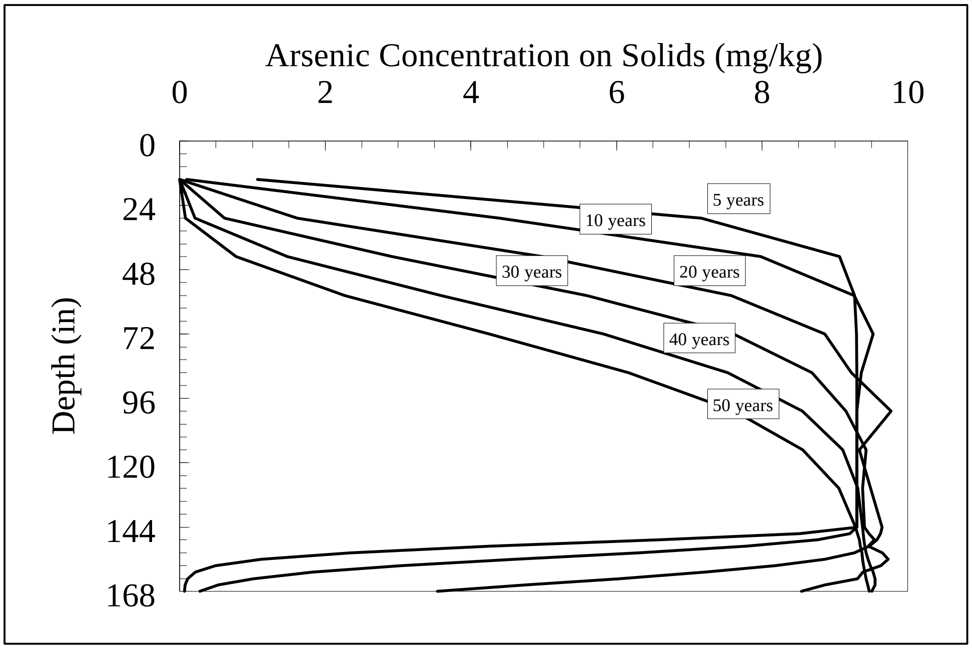


Figure 6. Predicted arsenic concentration profiles for the CDF in Figure 4

A 50-year simulation is performed for the same dredged sediment as that used in the previous example. The liner system is composed of compacted clay (2-ft thick) and a lateral drainage layer of sand (2-ft thick). The contaminated dredged sediment (12-ft thick) is placed on top of the liner system. In addition, two layers of soil are placed at the top of the CDF: one is a sand layer (1-ft thick) and the other a vegetative layer (2-ft thick). The purpose of these two layers is to help in the consolidation of the dredged sediment and to assist in vegetative growth at the top of the CDF.

A 50-year simulation predicts salinity profiles in the CDF as shown in Figure 7. Clearly the salt has almost totally washed out from the facility as indicated by the figure. However, the salt collected by lateral drainage represented 72.4 percent of all the salt originally present in the CDF. Only 27.6 percent leaked through the base of the facility.

Figure 8 shows the concentration profile of arsenic on the solids of the CDF. Even after 50 years of operation, the HELPQ model predicts very little contamination of the clay liner and hence very little arsenic left the facility from the base. HELPQ predicts that only 16.4 kg of arsenic per acre leaked from the base of the CDF. This represents 0.21 percent of the original arsenic present. Over the same period, 42.8 percent of the original arsenic present was captured by lateral drainage, thus reducing the potential for contamination of groundwater.

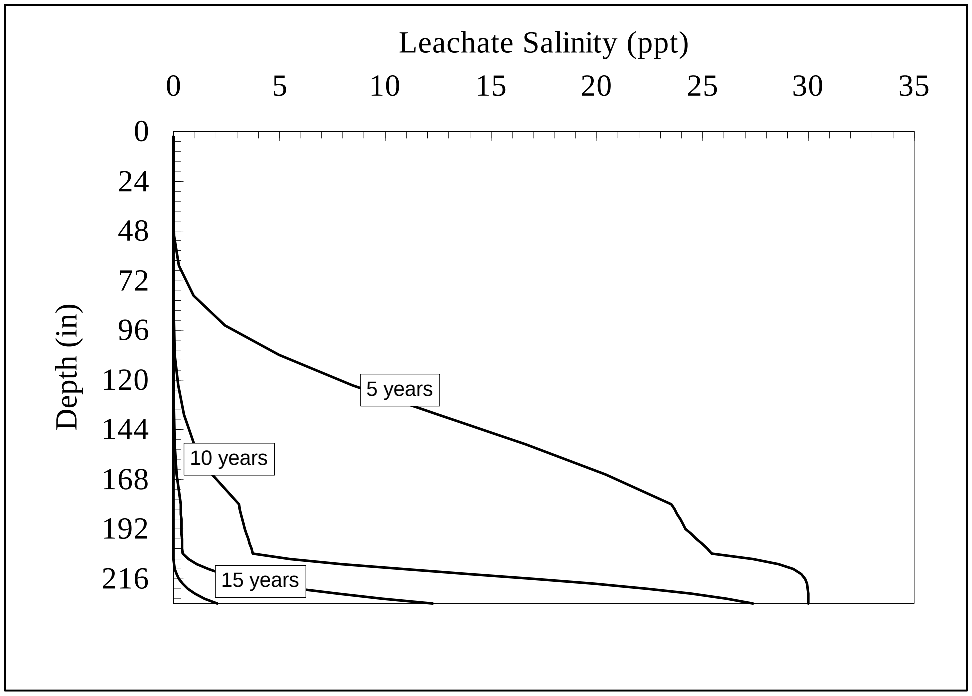


Figure 7. Salinity profile in the leachate of CDF of Figure 2

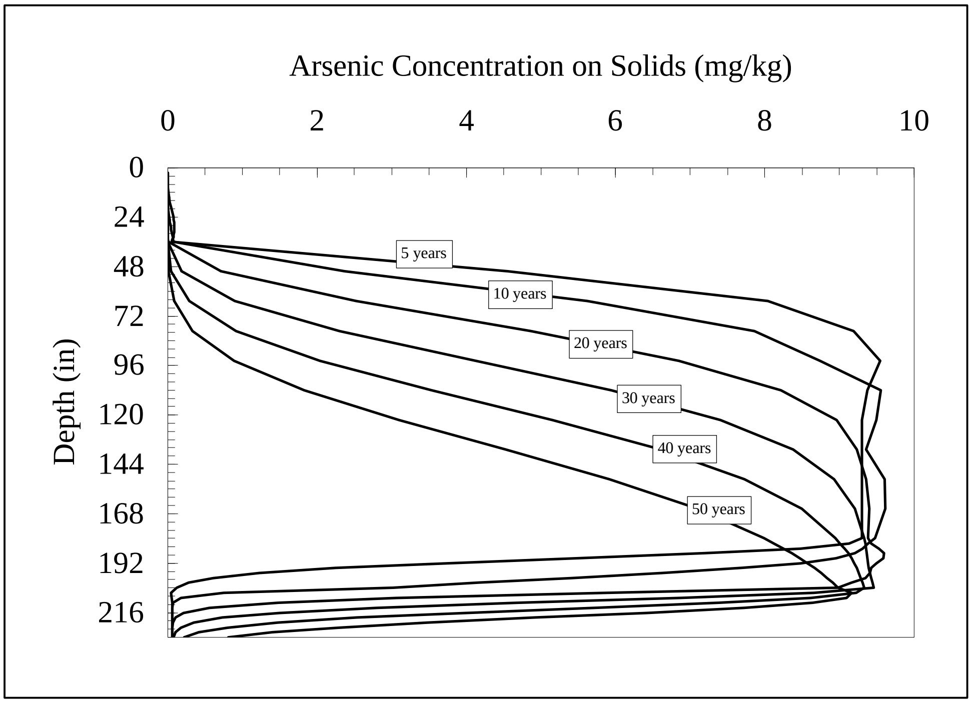


Figure 8. Arsenic concentration profile in the leachate of CDF of Figure 2

To explain the environmental advantage of the liner system in the second example, the amounts of leakage of salt and arsenic from both example designs are compared in Figures 9 and 10. Figure 9 compares the leakage of salt from the bottom of the lined and unlined facilities, and Figure 10 compares the leakage of arsenic from the bottom of both facilities. The presence of the lateral drainage layer above the compacted clay layer releases the water pressure (head) by draining leachate laterally, hence reducing the amount of saline water that would otherwise percolate through the clay. In the unlined CDF, such a relief is not present and the pressure build-up on top of the clay accelerates the leakage of saline water through the clay liner. In Figure 10, the amount of arsenic that leaked from the bottom of the CDF is very small, and therefore a semi-log scale is used for clarity of the comparison.

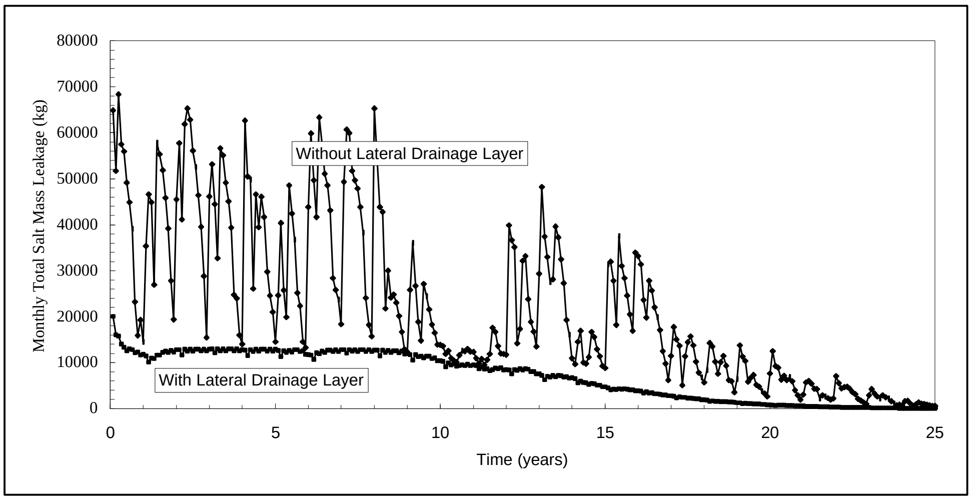


Figure 9. Comparison of monthly total salinity leakage for CDFs of Figures 4 and 2

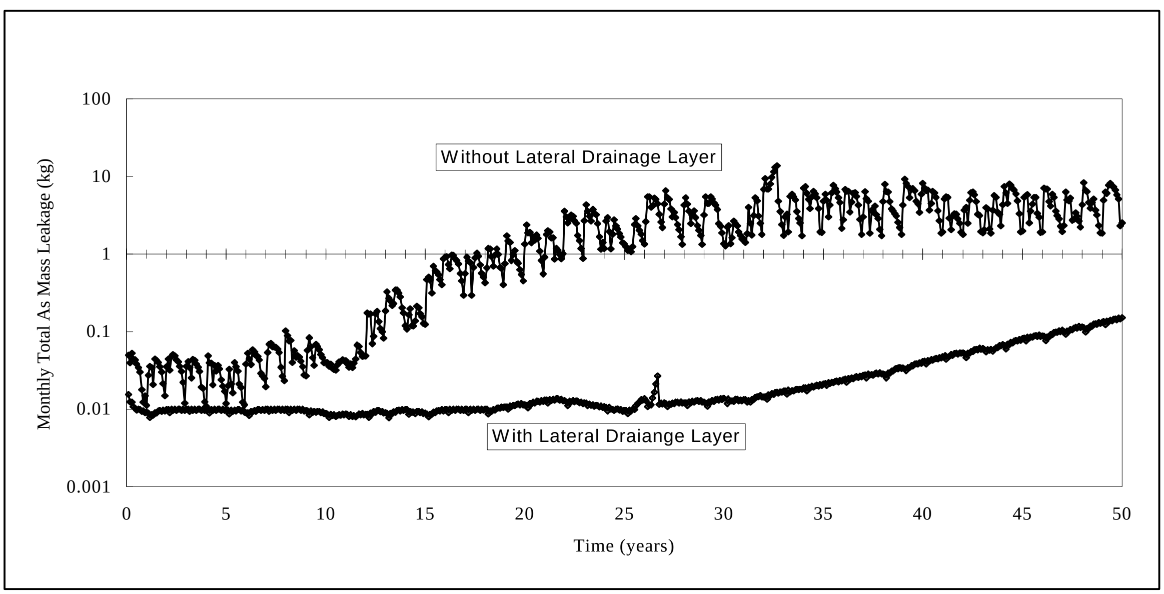


Figure 10. Comparison of monthly total as leakage from CDFs of Figures 2 and 4

Comparing the results of this design with the previous one shows that salt and contaminant washout proceeds at a much faster rate in the CDF with the lateral drainage. By introducing the lateral drainage, the drainage rate in the contaminated dredged material layer is increased so that the cleaning up is relatively faster in the second example, while in the first design, the barrier soil layer restricted the drainage, causing slower contaminant washout.

Leakage, as well as lateral drainage, of leachate from the CDF may be further reduced by using a cover system such as those used in hazardous waste landfills. By including another drainage layer and liner above the sediment layer, leachate generation can be further reduced significantly, and hence the amount of percolation through the bottom can also be reduced significantly since such a design restricts the infiltration of rainwater into the contaminated material.

CONCLUSIONS: The use of the water budget method for routing contaminants in CDFs provides an economic mean for preliminary design and for evaluating the performance of various CDF design alternatives. The HELPQ model produces results that can be used by management and planning personnel for assessing the potential contamination of surrounding waters due to the construction of a CDF. Moreover, the use of lateral drainage layers and clay liners to control and restrict the flow of contaminants provides valuable alternatives for design and operation of CDFs.

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