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**MODELING FOR IMPACT OF SMALL KANSAS LANDFILLS ON
UNDERLYING AQUIFERS**

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Modeling the Impact of Small Kansas Landfills on Underlying Aquifers

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Abstract

Small landfills are exempt from compliance with RCRA Subtitle D standards for liner and leachate collection. We investigate the ramifications of this exemption under western Kansas semi-arid environments and explore the conditions under which naturally occurring geologic settings provide sufficient protection against ground-water contamination. The methodology we employed was to run water budget simulations using the HELP model, and fate and transport simulations using the MULTIMED model for several western Kansas small landfill scenarios in combination with extensive sensitivity analyses. We demonstrate that requiring landfill cover, leachate collection system (LCS), and compacted soil liner will reduce leachate production by 56%, whereas requiring only a cover without LCS and liner will reduce leachate by half as much under western Kansas conditions. The most vulnerable western Kansas small landfills are shown to be the ones with no vegetative cover underlain by both a relatively thin vadose zone and aquifer; and which overlie an aquifer that is characterized by cool temperatures and low hydraulic gradients. The aquifer-related physical and chemical parameters proved to be more important than vadose zone and biodegradation parameters in controlling leachate concentrations in the underlying aquifer at the point of compliance, i.e., 150 m downgradient from the landfill boundary.

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Key Words: Small exempt landfills; HELP model; MULTIMED model; cover; liner; leachate collection system; western Kansas; Wallace County; landfill-parameter sensitivity analysis.

Introduction: Statement of the problem and study objectives.

The federal Resource Conservation and Recovery Act (RCRA) Subtitle D regulations establish minimum national standards for municipal solid waste landfills. The regulations include a requirement for a composite liner composed of a flexible plastic membrane underlain by a compacted soil layer. A leachate collection system (LCS) on top of the liner is also required. The regulations also created a category of landfills referred to as exempt small landfills. By definition, exempt small landfills are those which receive less than 20 tons of solid waste per day, have no pre-existing groundwater contamination, are in an area which receives less than 635 mm (25 inches) of precipitation per year, and have no practicable alternative for waste management. The U.S. Environmental Protection Agency (EPA) exempted these landfills from complying with the liner and leachate collection standards. Most western Kansas municipal landfills fall into the category of exempt small landfills.

The Kansas Department of Health and Environment (KDHE) developed the Kansas municipal solid waste regulations in 1994 but did not retain the exemption from liner and leachate collection standards. This was based upon ground-water monitoring results from western Kansas landfills including several which were eligible for exempt status. These results showed that several small landfills had indeed contaminated the groundwater beneath the landfill (KDHE, 1995, facility files). The Kansas regulation proposed an alternative liner system that consisted of a compacted soil layer. The level of compaction was less than that required for a large Subtitle D landfill. The regulation also included a leachate collection system. The KDHE received many negative comments about the liner and LCS requirement when the Kansas regulations were placed on public notice. In response, the Kansas legislature passed a bill in 1995 directing KDHE to adopt regulations which establish criteria for performing a demonstration for small landfills ". . .that naturally occurring geological conditions provide sufficient protection against ground-water contamination. . ." If a landfill owner or operator successfully makes this demonstration, no liner or leachate collection systems would be required at the landfill. KDHE then recommended three methods for making this demonstration, one of which involves a contaminant fate and transport modeling approach. (The other two involve ground-water monitoring and liner-equivalency demonstrations).

In the present climate of reducing government regulations, people often ask questions about the minimum requirements for small landfills that protect the public health and environment and about the risks for doing nothing, i.e., imposing no regulations at all. How important is it to have a landfill cover, a liner, a leachate collection system, or any combination

of these for small landfills? What are the most critical geologic, hydrologic, and chemical factors that are likely to cause a small landfill to fail to prevent a leachate release, thus creating a contaminant plume? The objective of this paper is to provide answers to such questions for a semiarid environment such as that found in western Kansas.

Methodology

To answer such questions, we performed a modeling study involving a landfill water budget model (HELP) and a contaminant fate and transport model (MULTIMED), both of which are well-established, EPA-sponsored landfill models. The two models are not alternatives but complement each other. HELP is a water budget model of the landfill itself; it outputs the leachate quantity, which can be used as a source term (input) for MULTIMED. MULTIMED models the transport of contaminants in the subsurface, both in the unsaturated and saturated zones. MULTIMED also includes a source module that can be used in place of HELP, although the use of this module has not yet been approved by the EPA for analysis of Subtitle D waste facilities. A brief overview of each one of these models follows.

HELP Model (version 3.01; Schroeder et al., 1994 a,b)

The HELP model is a quasi-two-dimensional, gradually varying, deterministic, PC-based water budget model. It is quasi-two-dimensional because it contains a one-dimensional vertical drainage model and a one-dimensional lateral drainage model coupled at the base of lateral drainage layers or the tops of liner systems. The program computes free downward vertical drainage to the top of a liner, at which point the liner restricts drainage and a zone of saturation can develop. The program then uses the height of saturated material above the liner to compute simultaneously the rates of lateral drainage to collection systems and vertical leakage through the liner. The model is also gradually-varying because the simulation progresses through time using analyses that are assumed steady for each time period. The hydrologic processes modeled by the program can be divided into two categories: surface processes and subsurface processes. The surface processes modeled are snowmelt, interception of rainfall by vegetation, surface runoff, and surface evaporation. The subsurface processes modeled are evaporation from soil profile, plant transpiration, unsaturated vertical drainage, barrier soil liner percolation, geomembrane leakage, and saturated lateral drainage.

The HELP model uses many process descriptions that were previously developed and used in other hydrologic models. The optional synthetic weather generator is the WGEN model of the

U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) (Richardson and Wright, 1984). Runoff modeling is based on the USDA Soil Conservation Service (SCS) curve number method presented in Section 4 of the National Engineering Handbook (USDA, SCS, 1985). Potential evapotranspiration is modeled by a modified Penman method (Penman, 1963). Evaporation from soil is modeled in the manner developed by Ritchie (1972) and used in various ARS models including the Simulator for Water Resources in Rural Basins (SWRRB) (Arnold et al., 1989) and the Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980). Plant transpiration is computed by the Ritchie's (1972) method used in SWRRB and CREAMS. The vegetative growth model was extracted from the SWRRB model. Evaporation of interception, snow and surface water is based on an energy balance. Interception is modeled by the method proposed by Horton (1919). Snowmelt modeling is based on the SNOW-17 routine of the National Weather Service River Forecast System (NWSRFS) Snow Accumulation and Ablation Model (Anderson, 1973). The frozen soil submodel is based on a routine used in the CREAMS model (Knisel et al, 1985). Vertical drainage is modeled by Darcy's law using the Campbell (1974) equation for unsaturated hydraulic conductivity based on the Brooks-Corey (1964) relationship. Saturated lateral drainage is modeled by an analytical approximation to the steady-state solution of the Boussinesq equation employing the Dupuit-Forchheimer assumptions. Leakage through geomembranes is modeled by a series of equations based on the compilations by Giroud et al. (1989, 1992). The processes are linked together in a sequential order starting with a surface water balance; then evapotranspiration from the soil profile; and finally drainage and water routing, starting at the surface with infiltration and then proceeding downward through the landfill profile to the bottom. The solution procedure is applied repetitively for each day as it simulates the water routing throughout the simulation period.

The layers in the landfill are defined by the hydraulic function that they perform. Four types of layers are available: vertical percolation layers, lateral drainage layers, barrier soil liners, and geomembrane liners. The topsoil and waste layers are generally vertical percolation layers. Flow in such layers is by unsaturated vertical drainage. Sand layers above liners are typically lateral drainage layers; compacted clay layers are typically barrier soil liners. Lateral drainage layers promote lateral drainage to collection systems at or below the surface of liner systems. Vertical drainage in a lateral drainage layer is modeled in the same manner as for a vertical percolation layer, but saturated lateral drainage is allowed. Liners are assumed to be saturated at all times.

MULTIMED Model (Salhotra et al., 1993; Sharp-Hansen et al., 1993)

MULTIMED simulates the transport and transformation of contaminants released from a waste disposal facility into the multimedia environment. Although it is possible to model releases to air and streams using MULTIMED, we focus our attention on releases to soil and the resulting transport in the unsaturated and/or the saturated zones. When applying MULTIMED to Subtitle D facilities, the landfill, surface water, and air modules in the model are not accessible to the user; only flow and transport through the unsaturated zone and transport in the saturated zone can be considered. A one-dimensional, semi-analytical module simulates steady-state flow in the unsaturated zone. The output from this module, water saturation as a function of depth, is used as input to the unsaturated zone transport module. The latter simulates transient, one-dimensional (vertical) transport in the unsaturated zone using either an analytical model that includes the effects of longitudinal dispersion, linear adsorption, and first-order decay, or a numerical model that includes the effects of longitudinal dispersion, nonlinear adsorption, first-order decay, time-variable infiltration rates, volatilization of chemicals, and arbitrary initial conditions of chemical concentration in the unsaturated zone. The unsaturated zone transport module calculates steady-state or transient contaminant concentrations. Output from either steady-state or transient unsaturated zone modules is used to couple the unsaturated zone transport module with the steady-state or transient, semi-analytical saturated zone transport module. The latter includes one-dimensional uniform flow, three-dimensional dispersion, linear adsorption, first-order decay, and dilution due to direct infiltration into the groundwater plume.

Version 2.0 of MULTIMED includes four new features in the numerical unsaturated zone transport module. This module can simulate (1) nonlinear (equilibrium) adsorption, (2) initial contamination conditions, (3) time-varying infiltration rates, and (4) volatilization of chemicals in the unsaturated zone. The numerical unsaturated zone transport model in MULTIMED version 2.0 originated from the VADOFT code in the EPA RUSTIC model (Dean et al., 1989), which was later modified for nonlinear adsorption and incorporated into the EPA CML model (GeoTrans, 1990). The original analytical unsaturated zone transport model is also in version 2.0, and the user has the option of using either the analytical or numerical unsaturated zone transport modules. The analytical model may be preferred for less complex problems, especially in the Monte Carlo mode, because it is computationally more efficient. However, if the user wishes to simulate either nonlinear adsorption, arbitrary initial conditions, time-varying infiltration rates, or volatilization in the unsaturated zone, then the numerical model must be used.

Nonlinear adsorption typically results in deviations from the Gaussian plume behavior associated with linear adsorption. Initial contamination conditions can be input —when known— in the form of a concentration profile in the unsaturated zone. Time-varying infiltration rates can alter both the volume and concentration of leachate from the landfill. Volatilization of chemicals from the unsaturated zone adds one more transport mechanism, so that the available contaminant mass can be released to the air or groundwater. However, the last two features (time-varying infiltration rates and volatilization of chemicals in the unsaturated zone) are not yet approved by the EPA for applications involving Subtitle D waste facilities.

The aquifer dispersivities are calculated as a fraction of the distance to the downgradient receptor well based on values presented in Gelhar and Axness (1981) as follows: longitudinal dispersivity, $\alpha_L = 0.1 X_r$; transverse dispersivity, $\alpha_T = \alpha_L/3$; and vertical dispersivity, $\alpha_v = 0.056 \alpha_L$, where X_r = distance to the receptor well (m). The longitudinal dispersivity in the unsaturated zone is estimated from a linear regression analysis based on data presented by Gelhar et al. (1985) as a function of the thickness, L (m), of the unsaturated zone as follows: $\alpha = 0.02 + 0.022 L$, with $R^2 = 0.66$ (Salhotra et al., 1993). To avoid excessively high values of dispersivity for deep unsaturated zones, a maximum dispersivity of 1.0 m is used in MULTIMED for all depths greater than 44.5 m. The relationship between relative hydraulic conductivity and water saturation is described using either the Brooks and Corey (1964) or the van Genuchten (1976) parameters.

Chemical degradation within the saturated zone is limited to hydrolysis, and the by-products of hydrolysis are assumed to be non-hazardous. The acid catalyzed, K_a^T , base catalyzed, K_b^T and neutral hydrolysis K_n^T rate constants —all influenced by ground-water temperature, T — are combined to yield the composite, first order, dissolved phase hydrolysis or decay rate, λ_1 , as follows: $\lambda_1 = K_a^T [H^+] + K_n^T + K_b^T [OH^-]$, where $[H^+] = 10^{-pH}$ is the hydrogen ion concentration and $[OH^-] = 10^{-(14-pH)}$ is the hydroxyl ion concentration, both computed from the pH of the aquifer. The fate of a chemical is also dependent on its sorptive characteristics. In MULTIMED, the linear relationship between the equilibrium concentrations of the dissolved and adsorbed phases is characterized by the chemical distribution coefficient, K_d (cc/g). Hydrophobic binding is assumed to dominate the sorption process; thus, the distribution coefficient is related directly to soil organic carbon content using $K_d = K_{oc} f_{oc}$, where K_{oc} is normalized distribution coefficient for organic carbon (ml/g), and f_{oc} is organic carbon content in the saturated zone (dimensionless fraction). In MULTIMED, the retardation factor, R_s (dimensionless) is related to the distribution coefficient, K_d using $R_s = 1 + \rho_b K_d/\theta$, where ρ_b is bulk density (g/cc), and θ is saturation water content (vol/vol).

A typical small landfill in western Kansas

To address the posed questions, we identified a representative or typical western Kansas small landfill. After briefly examining the available information on landfills in Cheyenne, Greely, Rawlins, and Wallace counties, we concluded that the Wallace County landfill, was a representative western Kansas small landfill, which had more detailed and probably more reliable information for answering the posed questions. Table 1 profiles the Wallace County landfill.

The tool we first employed to evaluate a number of conceptual small landfill scenarios based on the Wallace County landfill is the HELP model. The base case landfill scenario consists of a 152 m by 24 m (500 ft by 80 ft) waste cell which is 7.5 m (25 ft) deep and is underlain by a water table at 13.5 m (45 ft) below land surface. Temperature and precipitation data (1951—1976) from nearby Sharon Springs and other climatic data from Dodge City, are considered representative for the study region.

Results and discussion

Importance of cover, liner, and leachate collection system in a small landfill.

Using the HELP model, we evaluated the significance of having versus not having a landfill cover, having a liner versus no liner, having a leachate collection system (LCS) versus no such system, and any combination of these options. We also evaluated two different slopes (2% and 4%) and two different slope lengths (152 m [500 ft] and 76 m [250 ft]) for the leachate collection system, and two soil composition sets (initial and modified, Table 2). Other HELP model input data are shown in Table 2. Figure 1 details some HELP case runs employed in this study. Figure 2 displays the precipitation and air temperature time series (climatic forcing) for twenty-years, the simulation period employed in this study.

It is worth noting two non-standard extensions of the HELP model we employed in this study. (1) Instead of simply calculating the leachate produced at the bottom of the landfill liner, we calculated the leachate quantities at the water table by inserting a vertical percolation layer, representing the natural soil material, between the landfill bottom and the water table. All case profiles depicted in Fig. 1 extend from the surface to the water table. (Later on we employed the MULTIMED model to evaluate the attenuating impact of this vadose zone.) (2) The HELP model

does not allow inclusion of a leachate collection system without having a liner underneath this system. Because KDHE was also interested in evaluating the impact of a leachate collection system by itself, without the presence of an underlying liner, we "tricked" the HELP model in simulating such a case by inserting a "pseudo-liner" under the leachate collection system of the same composition and physical properties as the rest of the underlying naturally existing vertical percolation layer.

The results of all these HELP simulation scenarios are summarized in Tables 3 through 5. The worst case scenario (no cover, no liner, no leachate collection system) results in a landfill leachate percolation rate to the water table equal to approximately 10% of the average annual precipitation (441 mm [17.38 in.]) at the Wallace County landfill. As shown in these tables, any combination of landfill cover, liner (compacted soil layer) and leachate collection system (LCS) will significantly reduce this leachate percolation rate. The results show that landfill cover is extremely important in reducing leachate percolation to the water table (Table 3). The presence of a landfill cover alone (with no liner, no LCS) reduces leachate by approximately 23% under typical western Kansas conditions, whereas in combination with a liner and LCS reduces leachate by approximately 56% (relative to no cover, no liner, no LCS; modified soil set, Table 3; i.e., compare bold values of first and last row entries of Table 3). Requiring compacted clay liner as opposed to using native compacted material, usually SiCL, reduced leachate production by an additional 4%.

The landfill liner is most important when no leachate collection system is in place (Table 4). The combination of landfill cover and liner reduces leachate by approximately 37% relative to no liner (Tables 3 and 4). The landfill liner becomes less important when a cover and leachate collection system are present (it decreases leachate percolation to the water table by an additional 3-7%). The presence of a landfill liner alone (no cover, no LCS) reduces leachate by approximately 9% (Table 4).

We also evaluated the impact of installing on top of the waste layer a 0.6m (2-ft.) compacted clay barrier with a 0.46m (1.5-ft.) vegetated cover layer. Employing this system, reduced leachate production by an additional 33 percent for case 2 (Fig. 1), relative to not having the compacted clay barrier layer covering the waste layer.

The landfill leachate collection system becomes most important when no liner is present in a landfill with cover (Table 5). The combination of landfill cover and LCS reduces leachate by approximately 40% relative to no LCS (Tables 3, 4, 5). When a liner is present in a covered

landfill, the leachate collection system becomes less important (it decreases leachate percolation to the water table by an additional 7-10%). The presence of a LCS alone (no cover, no liner) reduces leachate by approximately 11% (Table 5). The LCS slope and slope length employed had minor to negligible impact on leachate percolation rates.

All summary tables (3 through 5) quantify the impact of any combination of cover, liner, and leachate collection system on leachate percolation to the water table. Table 6 ranks the relative importance of these scenarios with respect to their efficiency in reducing leachate percolation to the underlying aquifer.

Small landfill parameter sensitivity analysis using the HELP model.

Having determined the relative significance of covers, liners, and LCS using the HELP model, we next identified the most important HELP parameters in the context of small landfills. We performed a HELP -parameter sensitivity analysis by systematically varying each parameter within their expected ranges while keeping the rest constant at their base values, without violating the conditions that porosity must be greater than the field capacity, the field capacity must be greater than the wilting point, and initial soil moisture content cannot be greater than the porosity or less than the wilting point. Two base or test case scenarios were used in this sensitivity analysis. The first one consisted of a variant of the three-layer case 1 in Fig. 1, where the bottom natural soil layer (layer 3) was considered to be a sandy loam of 0.6 m (2-ft) thickness. The physical parameters of this layer, as well as surface hydrologic parameters were the subject of our sensitivity analysis. The second test case was identical to case 2 in Fig. 1, consisting of four layers, the properties of the fourth layer being the subject of our sensitivity analysis, in addition to evaluating surface hydrologic parameters.

A sampling of the results of the sensitivity analysis for the two above-mentioned test cases is shown in Figs. 3 and 4. The most important variable in the semi-arid environment of western Kansas is the depth of the evapotranspiration zone (Figs. 3a and 4a). The hydraulic parameters of the layer in question (layer 3 for case 1, layer 4 for case 2)— that is the saturated hydraulic conductivity (Figs. 3e and 4d), porosity (Figs. 3b and 4e), wilting point (Figs. 3d and 4b), field capacity (Figs. 3c and 4f), and initial soil water content (Figs. 3f and 4c)— are the next most sensitive (important) parameters. The thickness of the vertical percolation layer under study, the leaf area index, the surface runoff curve number, and the percent of landfill area where surface runoff is possible are the least sensitive parameters for these cases. These results show (1) that it is extremely important to seed the landfill cover with grasses (or other vegetation) in order to

increase the evapotranspiration zone depth to at least 0.46 m (1.5 ft); (2) that the hydraulic properties of the vertical percolation layer underlying the landfill waste layer should be determined as reliably as possible; and (3) that under western Kansas small landfill conditions, accurate determinations of leaf area index, surface runoff curve number, or percent of landfill area contributing to surface runoff are not critical.

Small landfill vadose and aquifer zone parameter sensitivity analysis using the MULTIMED model.

Finally, we identified the physical, geological, chemical and biological parameters in both the vadose and aquifer zones that are the most critical in reducing the leachate concentration in the underlying aquifer at the point of compliance (POC), i.e., at a receptor well located at a distance of 150 m downgradient from the landfill boundary. For Subtitle D applications of MULTIMED, EPA has employed several restrictions in an effort to develop a conservative approach for simulating leachate migration from Subtitle D facilities. For example, consideration of volatilization of chemicals from the unsaturated zone, time-varying infiltration rates, source decay, non-continuous contaminant pulses, and nonlinear adsorption, among others are not considered for Subtitle D applications of MULTIMED, although the model is equipped to handle most of these additional complexities. One additional restriction for Subtitle D applications is to use only steady-state transport simulations. However, it is important to know how long it might take for a contaminant to reach the POC. In order to be both conservative and at the same time evaluate transient effects of pollutant transport, we ran parameter sensitivity analysis using transient simulations lasting for 500 years, to ensure that eventually a steady-state condition is reached. It is also evident that using the vadose zone module of MULTIMED to calculate the leachate percolation rate to the water table requires many more input parameters using than an equivalent HELP model. Therefore, we decided to compare the effectiveness of the HELP model in simulating the vadose zone with the more sophisticated MULTIMED model.

To assess the effectiveness of the HELP model in simulating the vadose zone, we used the following approach. We ran the HELP model case 1 of Figure 1 to simulate the vadose zone in combination with the saturated flow module of MULTIMED to simulate the underlying aquifer. The input data we used for these simulations are based on the Wallace County landfill data (see Table 7). We then compared the resulting leachate concentration at the POC with the leachate concentration at the POC generated by running the HELP model using only layers 1 and 2 of case 1 (Fig. 1) and the unsaturated and saturated zone modules of MULTIMED. In this run, the unsaturated zone parameters in MULTIMED were identical to those of layer 3 of the previous case. The results were similar in both cases, with a relative difference of approximately 17% for both a

conservative tracer and a reactive chemical (carbon tetrachloride). This difference may be acceptable in first order, approximate analyses before deciding to use the more data-demanding vadose zone simulation of MULTIMED.

The base case we employed for the MULTIMED sensitivity analysis is derived from available and estimated data at the Wallace County landfill, using carbon tetrachloride as our index pollutant. These input data for the MULTIMED model are summarized in Table 7. Each of the MULTIMED model parameters were systematically varied within reasonable limits, while the rest of the parameters were kept constant at their base case values (Table 7). A sampling of the results of this sensitivity analysis is shown in Figs. 5 through 8. All concentrations reported in these figures are relative to a unit concentration (1 mg/ℓ) at the source. It is evident that the source parameters (landfill area and leachate percolation rate, Fig. 5) and aquifer-related parameters (Fig. 6) are much more important, as far as the simulated contaminant concentrations at the POC are concerned, than the vadose zone and biological (biodegradation rate) parameters (Fig. 7 and 8). The top seven most sensitive MULTIMED parameters under western Kansas conditions are the landfill area, landfill leachate percolation rate, aquifer saturated thickness, aquifer transverse dispersivity, neutral hydrolysis rate constant, aquifer temperature and vertical dispersivity, all shown in Figs. 5, 6, and 8. The preceding overview of the MULTIMED model describes how a number of these parameters are calculated in the model. The seven least sensitive MULTIMED parameters from those tested are the bulk density for both the unsaturated and saturated zones, the α and β van Genuchten coefficients, the air entry pressure, and the biodegradation rates for both the unsaturated and saturated zones. We found the vadose zone parameters relatively unimportant, especially for conservative tracers under Subtitle D applications. The most important vadose zone parameters proved to be the thickness of the zone and its porosity (Fig. 7). Of the chemical-specific parameters, chemical degradation by hydrolysis and sorption processes (dominated by the normalized distribution coefficient for organic carbon) proved to be the most sensitive (Fig. 8).

The temporal evolution of the contaminant concentration at the POC and their relatively long time lag effects are clearly demonstrated in Figs. 5 through 8. Under western Kansas conditions similar to those of the Wallace County landfill, it will take at least 70 years from the time of waste emplacement to notice the impact of the top six sensitive MULTIMED parameters on contaminant concentrations at the POC.

Conclusions

The major conclusions from this study are as follows:

- 1) The presence of a landfill cover in combination with a LCS and a compacted soil liner reduces leachate percolation rates by approximately 56%. Requiring only a landfill cover without a LCS and a compacted soil liner reduces leachate percolation rate by approximately 23%, i.e., by half as much as when requiring all three protective measures. Including a compacted clay barrier on top of the waste, in addition to a landfill cover, reduces leachate percolation by an additional 33% for a typical western Kansas landfill. Requiring the compacted soil liner underlying the waste layer to be made up of clay ($K \leq 1 \times 10^{-7}$ cm/s), instead of silty clay loam ($K = 1.9 \times 10^{-6}$ cm/s), as employed in this study, reduces leachate percolation by an additional 4 percent.
- 2) In landfill operations under western Kansas conditions, it is extremely important to have the landfill cover seeded with grasses or other vegetation with relatively long rooting systems so that water percolation beyond the thickness of the landfill cover is minimized by the evapotranspiration process.
- 3) The physical (hydraulic) properties of landfill layers are much more important under western Kansas conditions than surface runoff-related parameters.
- 4) The landfill-underlying aquifer physical parameters are much more important than the vadose zone parameters in reducing the leachate pollutants at the POC, i.e., 150 m downgradient from the landfill boundary. The most important aquifer-related parameters are the saturated thickness, transverse dispersivity, neutral hydrolysis rate, aquifer temperature, and vertical dispersivity.
- 5) Chemical degradation by hydrolysis and hydrophobic-binding sorption in the saturated zone are much more important than biodegradation rates under western Kansas environments, as simulated using the MULTIMED model.
- 6) Under western Kansas conditions, the time elapsed between landfill emplacement and leachate pollutant detection at the POC is relatively long, on the order of a century.

- 7) Combining the easier-to-use and less data-demanding HELP model with the saturated-only module of MULTIMED will give results comparable to the more data-intensive combination of the HELP model and the vadose plus saturated zone modules of MULTIMED.
- 8) The most vulnerable small landfills under the semi-arid western Kansas environment are the ones with no vegetative cover that are underlain by very thin vadose as well as aquifer zones and which are above an aquifer that is characterized by relatively low temperatures and low hydraulic gradients as far as leachate concentrations at the POC are concerned.

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Table 1. Wallace County Landfill Profile

Location: 17.8 hectares (44 acres) located in the SE 1/4 of Section 3, and the NE 1/4 of Section 10, both located in Township 14 South, Range 40 West, approximately 3 km south of the town of Sharon Springs, Kansas. Latitude 38° 51' 01" N, longitude 101° 45' 00" W.

Operation Authorization: 1974

Topography: The active portion of the landfill is situated along the north side of a northeasterly running intermittent stream channel. Side slopes are up to twenty percent at the east end of the property.

Site History and Operation: Trenches have been dug and filled on the west-central portion of the landfill property, all on the north side of the draw. Expansion room is left to the north and east.

Geology and Soils: The local geology consists of soils of the Colby-Kim-Midway Association underlain by Pleistocene Loess of the Sanborn Formation. These formations are underlain by the Miocene Ogallala Formation. The Ogallala is an unconfined aquifer and is the primary groundwater aquifer in the region. Bedrock is the Cretaceous Pierre Shale.

Ground-water and Monitoring : Groundwater availability in this area is limited. Three monitoring wells ranging in depth from 15 to 17.5 m (50 to 58 ft) were installed at the landfill in 1993. The static water level was 12.5 to 14 m (41 to 46 ft). One well was dry. Water analyses from the wells indicate no adverse impact on the groundwater has occurred at this landfill.

Table 2. Soil and Waste HELP Model Input Data

<u>Initial Soil Set</u>	<u>Modified Soil Set</u>
Cover = SiCL (HELP #12) ¹	Cover = SiCL (HELP #12)
Waste = (HELP #18)	Waste = (HELP #18)
Leachate Collection System = Sand (HELP #2)	Leachate Collection System = Gravel (HELP #21)
Barrier Layer = SiCL (HELP #12)	Barrier Layer = Compacted SiCL (HELP #26)
Natural Soil = SiL (HELP #9)	Natural Soil = SiCL (HELP #12)
Evaporative zone depth = 0.46 m	Initial soil moisture = field capacity
Maximum leaf area index = 2	Weather station: Sharon Springs and Dodge City, Kansas
Area = 3723 m ²	Average annual precipitation = 441 mm
Percent area where runoff is possible = 80	
Runoff curve number = 80	

¹Denotes HELP number identification for default characteristics for soil/material types.

Table 3. Wallace County Landfill - Comparison of No Cover versus Cover Scenarios

Case #	Leachate Collection System	Liner	Leachate Collection System			Leachate Production (mm/yr)	Leachate Production (mm/yr)	Percent Leachate Decrease *
			Slope Length (m)	Slope Percent	Soil Set	No Cover	With Cover	
35/36	Yes	Yes	76.2	4	Modified	31.3	17.3	44.73
15/16	Yes	Yes	76.2	2	Modified	32.2	17.6	45.42
33/34	Yes	Yes	152.4	4	Modified	32.2	17.6	45.38
13/14	Yes	Yes	152.4	2	Modified	32.9	17.8	45.99
39/40	Yes	No	76.2	4	Modified	35.3	18.3	48.24
19/20	Yes	No	152.4	4	Modified	35.4	18.3	48.28
37/38	Yes	No	76.2	2	Modified	35.4	18.3	48.28
17/18	Yes	No	152.4	2	Modified	35.4	18.3	48.28
23/24	No	Yes	NA	NA	Modified	35.9	19.3	46.39
5/6	Yes	Yes	152.4	2	Initial	36.2	19.8	45.22
7/8	Yes	Yes	76.2	2	Initial	36.2	19.8	45.22
9/10	Yes	No	152.4	2	Initial	36.2	19.8	45.22
11/12	Yes	No	76.2	2	Initial	36.2	19.8	45.22
25/26	Yes	Yes	152.4	4	Initial	36.2	19.8	45.22
27/28	Yes	Yes	76.2	4	Initial	36.2	19.8	45.22
29/30	Yes	No	152.4	4	Initial	36.2	19.8	45.22
31/32	Yes	No	76.2	4	Initial	36.2	19.8	45.22
3/4	No	Yes	NA	NA	Initial	37.3	21.3	42.86
1/2	No	No	NA	NA	Initial	43.2	33.8	21.76
21/22	No	No	NA	NA	Modified	39.6	30.6	22.71

*When cover is installed

Table 4. Wallace County Landfill - Comparison of No Liner versus Liner Scenarios

Case #	Cover	Leachate Collection System	Leachate Collection System			Leachate Production (mm/yr)	Leachate Production (mm/yr)	Percent Leachate Decrease *
			Slope Length (m)	Slope Percent	Soil Set	No Liner	With Liner	
40/36	Yes	Yes	76.2	4	Modified	18.3	17.3	5.15
20/16	Yes	Yes	76.2	2	Modified	18.3	17.6	4.03
38/34	Yes	Yes	152.4	4	Modified	18.3	17.6	3.89
18/14	Yes	Yes	152.4	2	Modified	18.3	17.8	2.91
10/6	Yes	Yes	152.4	2	Initial	19.8	19.8	0.00
12/8	Yes	Yes	76.2	2	Initial	19.8	19.8	0.00
30/26	Yes	Yes	152.4	4	Initial	19.8	19.8	0.00
32/28	Yes	Yes	76.2	4	Initial	19.8	19.8	0.00
22/24	Yes	No	NA	NA	Modified	30.6	19.3	37.10
2/4	Yes	No	NA	NA	Initial	33.8	21.3	36.84
39/35	No	Yes	76.2	4	Modified	35.3	31.3	11.16
19/15	No	Yes	76.2	2	Modified	35.4	32.2	9.05
37/33	No	Yes	152.4	4	Modified	35.4	32.2	8.98
17/13	No	Yes	152.4	2	Modified	35.4	32.9	7.03
9/5	No	Yes	152.4	2	Initial	36.2	36.2	0.00
11/17	No	Yes	76.2	2	Initial	36.2	36.2	0.00
29/25	No	Yes	152.4	4	Initial	36.2	36.2	0.00
31/27	No	Yes	76.2	4	Initial	36.2	36.2	0.00
1/3	No	No	NA	NA	Initial	43.2	37.3	13.53
21/23	No	No	NA	NA	Modified	39.6	35.9	9.30

*When liner is installed

Table 5. Wallace County Landfill - Comparison of No Leachate Collection System versus Leachate Collection System Scenarios

Case #	Cover	Liner	Soil Set	Leachate Production (mm/yr) with No LCS	Leachate Production with Leachate Collection System (LCS)							
					Slope Length = 152.4 m				Slope Length = 76.2 m			
					2% Slope		4% Slope		2% Slope		4% Slope	
					Leachate (mm/yr)	Percent Decrease*	Leachate (mm/yr)	Percent Decrease*	Leachate (mm/yr)	Percent Decrease*	Leachate (mm/yr)	Percent Decrease*
1	No	No	Initial	43.3	36.2	16.43	36.2	16.43	36.2	16.43	36.2	16.43
2	Yes	No	Initial	33.8	19.8	41.52	19.8	41.52	19.8	41.52	19.8	41.52
3	No	Yes	Initial	37.4	36.1	3.60	36.2	3.33	36.2	3.33	36.2	3.33
4	Yes	Yes	Initial	21.3	19.8	7.14	19.8	7.26	19.8	7.26	19.8	7.26
21	No	No	Modified	39.6	35.4	10.58	35.4	10.71	35.4	10.71	35.3	10.90
22	Yes	No	Modified	30.6	18.3	40.17	18.3	40.25	18.3	40.25	18.3	40.33
23	No	Yes	Modified	35.9	32.9	8.35	32.2	10.40	32.2	10.47	31.3	12.73
24	Yes	Yes	Modified	19.3	17.8	7.65	17.6	8.71	17.6	8.84	17.3	10.03

*When leachate collection system is installed

Table 6. Western Kansas Small Landfill HELP Simulation Conclusions

Order of Importance	Leachate Reduction
1. Cover plus Liner ^a plus LCS ^b	56%
2. Cover plus LCS	40%
3. Cover plus Liner	37%
4. Cover only	23%
5. LCS only	11%
6. Liner only	9%

^a Compacted soil layer

^b Leachate collection system

Table 7. Base Case MULTIMED Input Parameters (abridged)

Aquifer Parameters		Unsaturated Zone Parameters	
<u>Name</u>	<u>Base Value</u>	<u>Name</u>	<u>Base Value</u>
Aquifer Porosity	0.25 vol/vol	Number of Different Materials	1
Bulk Density	1.40 g/cc	Number of Different Layers	1
Aquifer Thickness	3.35 m	Depth of Unsaturated Zone	7.0 m
Hydraulic Conductivity	11,125 m/yr	Sat. Hydraulic Conductivity	0.175 cm/hr
Hydraulic Gradient	0.0015	Porosity	0.47 vol/vol
Longitudinal Dispersivity	15.0 m	Air Entry Pressure Head	0.2 m
Transverse Dispersivity	5.0 m	Residual Water Content	0.2 vol/vol
Vertical Dispersivity	0.84 m	Alpha van Genuchten Coeff.	0.02
Aquifer Temperature	16 °C	Beta van Genuchten Coeff.	1.41
Groundwater pH	7.0 pH units	Longitudinal Dispersivity	0.174 m
Organic Carbon Content	0.015	Percent Organic Matter	0.015
Point of Compliance	150 m	Bulk Density	1.50 g/cc
Angle off Center	0 degrees	Biological Decay Coeff.	0.0 1/yr
Source Parameters		Chemical Parameters	
<u>Name</u>	<u>Base Value</u>	<u>Name</u>	<u>Base Value</u>
Type of Source	Gaussian	Chemical	Carbon Tetrachloride
Leachate Percolation Rate	0.0406 m/yr	Acid Catalysis Hydrolysis Rate	0.0 l/M yr
Landfill Area	3710 sq. m	Neutral Hydrolysis Rate Constant	0.017 1/yr
Recharge Rate	0.04 m/yr	Base Catalysis Hydrolysis Rate	0.0 l/M yr
Source Decay Constant	0.0 1/yr	Reference Temperature	25.0 °C
Initial Concentration at Landfill	1.0 mg/l	Normalized Distribution Coeff.	257.0 ml/g
		Biodegradation Coefficient	0.0 1/yr

Case 1 - Individual Cell: Cover, No LCS, No Liner

1	Vertical Percolation Layer (Cover) HELP #12 SiCL K = 4.2×10^{-5} cm/sec	0.46 m
2	Vertical Percolation Layer (Waste) HELP #18 K = 1.0×10^{-3} cm/sec	7.6 m
3	Vertical Percolation Layer (Natural Soil) HELP#9 SiL K = 1.9×10^{-4} cm/sec Initial soil set or HELP #12 SiCL K = 4.2×10^{-5} cm/sec Modified soil set or HELP #6 SL K = 7.2×10^{-4} cm/sec Sensitivity case	6.1 m

Case 2 - Individual Cell: Cover, No LCS, Liner

1	Vertical Percolation Layer (Cover) HELP #12 SiCL K = 4.2×10^{-5} cm/sec	0.46 m
2	Vertical Percolation Layer (Waste) HELP #18 K = 1.0×10^{-3} cm/sec	7.6 m
3	Barrier Layer (Liner) HELP #26 Compacted SiCL K = 1.9×10^{-6} cm/sec	0.6 m
4	Vertical Percolation Layer (Natural Soil) HELP #9 SiL K = 1.9×10^{-4} cm/sec Initial soil set or HELP #12 SiCL K = 4.2×10^{-5} cm/sec Modified soil set	5.5 m

Case 3 - Individual Cell: Cover, LCS, Liner

1	Vertical Percolation Layer (Cover) HELP #12 SiCL K = 4.2×10^{-5} cm/sec	0.46 m
2	Vertical Percolation Layer (Waste) HELP #18 K = 1.0×10^{-3} cm/sec	7.6 m
3	Leachate Collection System HELP #2 Sand K = 5.8×10^{-3} cm/sec Initial or HELP #21 Gravel K = 3.0×10^{-1} cm/sec Modified	0.6 m
4	Barrier Layer (Liner) HELP #26 compacted SiCL K = 1.9×10^{-6} cm/sec	0.6 m
5	Vertical Percolation Layer (Natural Soil) HELP #9 SiL K = 1.9×10^{-4} cm/sec Initial soil set or HELP #12 SiCL K = 4.2×10^{-5} cm/sec Modified soil set	4.9 m

Figure 1. Selected HELP Simulation Scenarios. The layer number and type, the HELP number identification for default soil or waste characteristics, soil texture, and saturated hydraulic conductivity (K) are indicated in the schematic layer profiles.

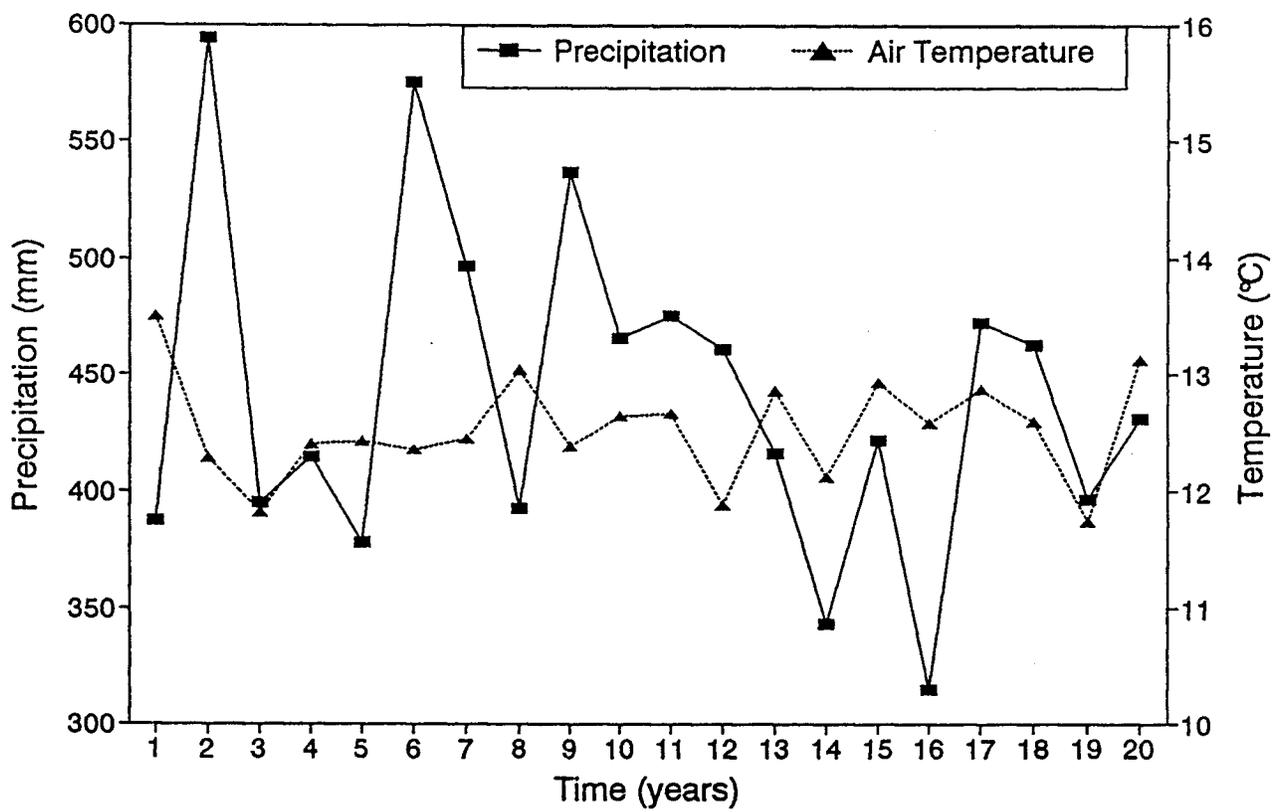


Figure 2. Annual Precipitation and Air Temperature: Wallace County Landfill.

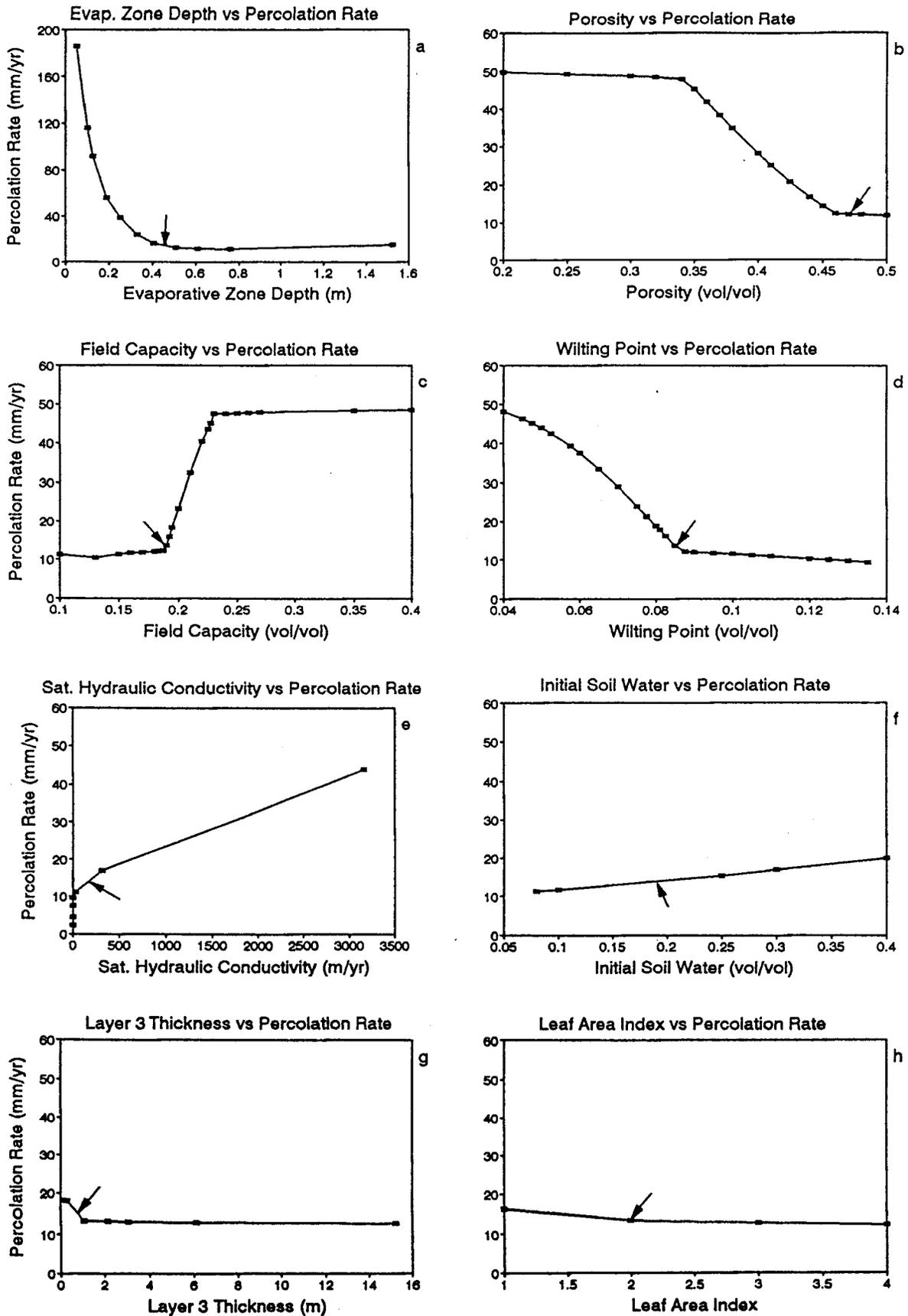


Figure 3. Wallace County landfill HELP model sensitivity analysis: Case 1. Arrows indicate base case values.

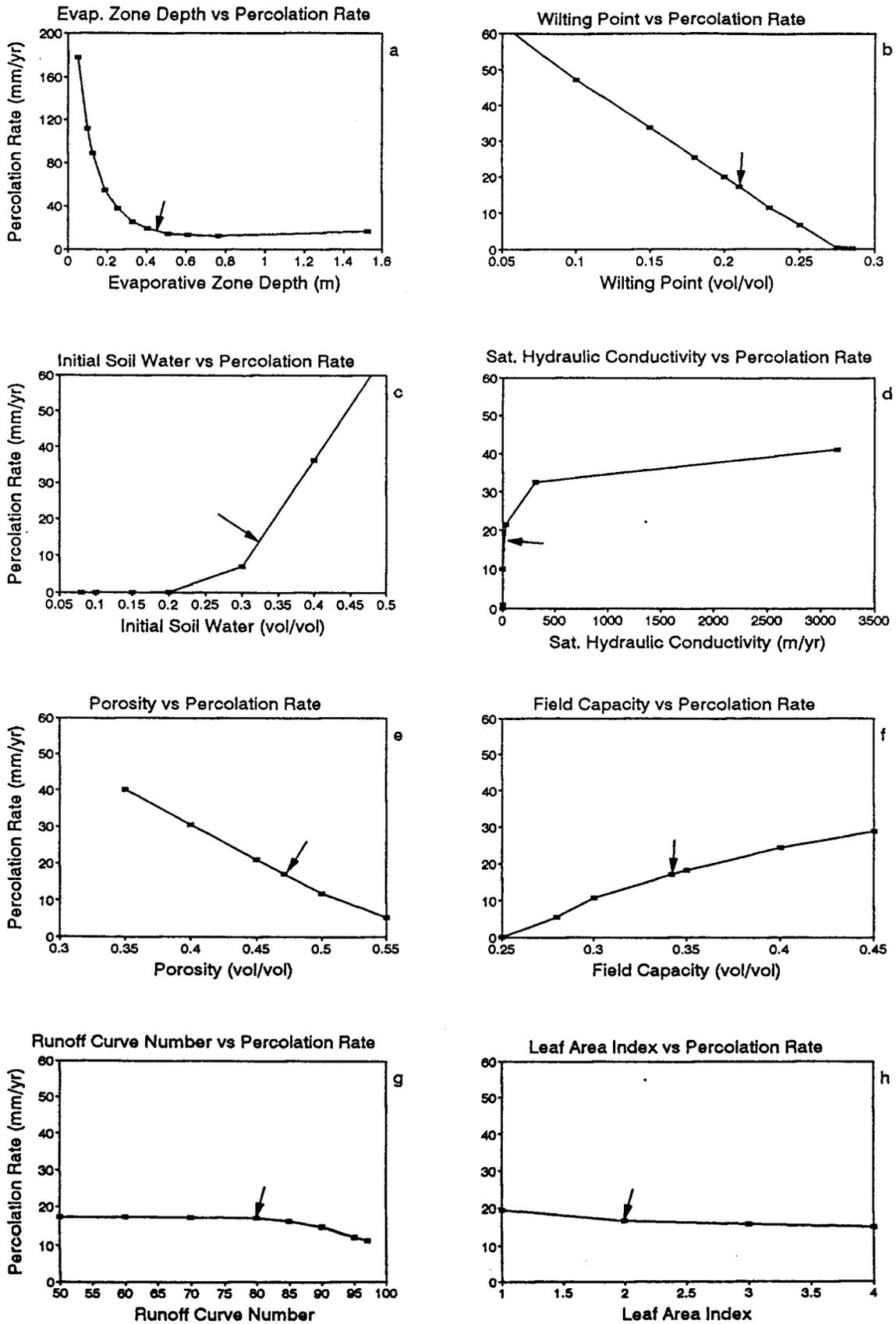


Figure 4. Wallace County landfill HELP model sensitivity analysis: Case 2. Arrows Indicate Base Case Values.

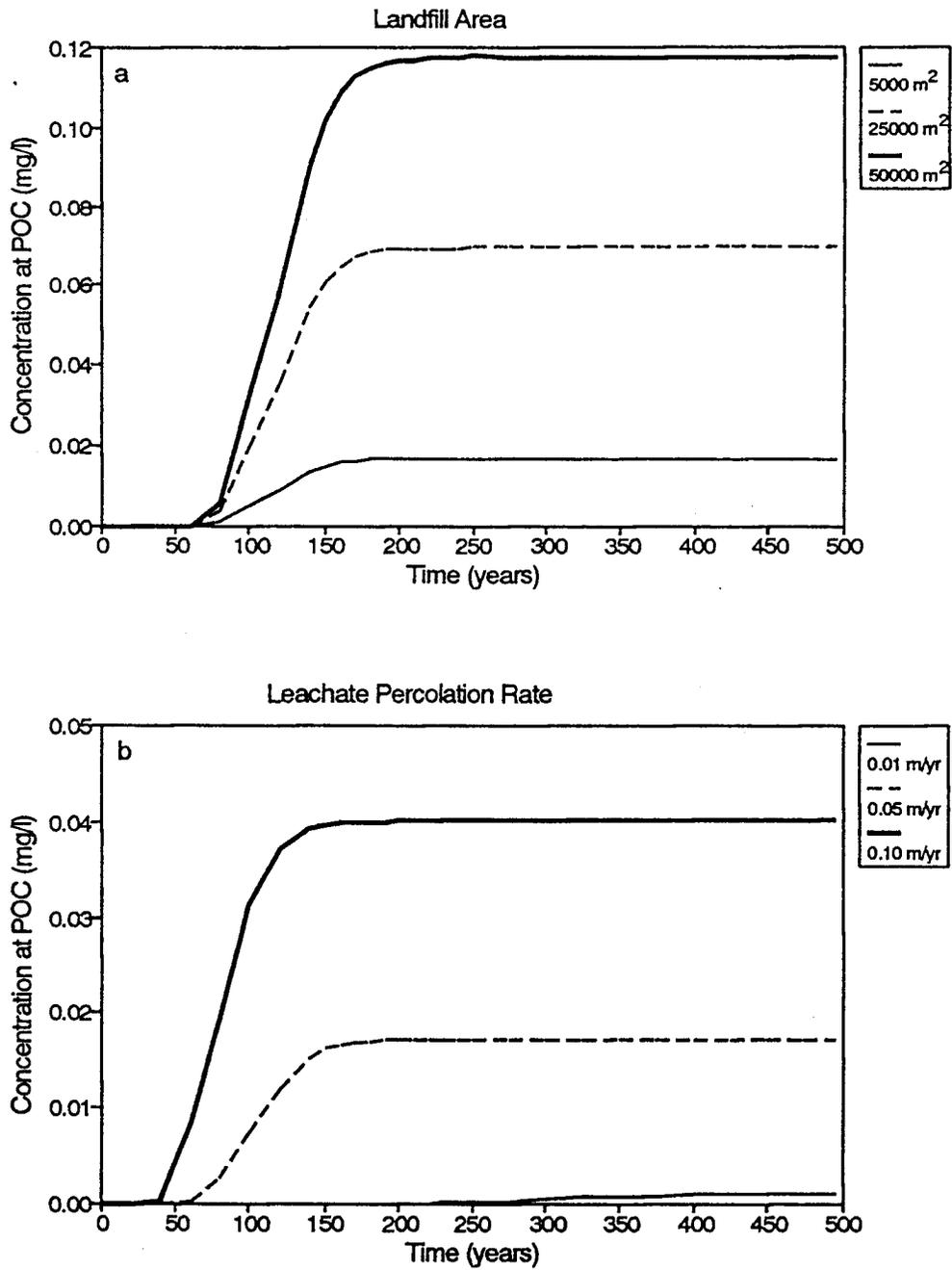


Figure 5. Carbon Tetrachloride Concentration at Point of Compliance (POC) vs Time: Wallace County Landfill, Source Parameters: Landfill Area (a), and Leachate Percolation Rate (b).

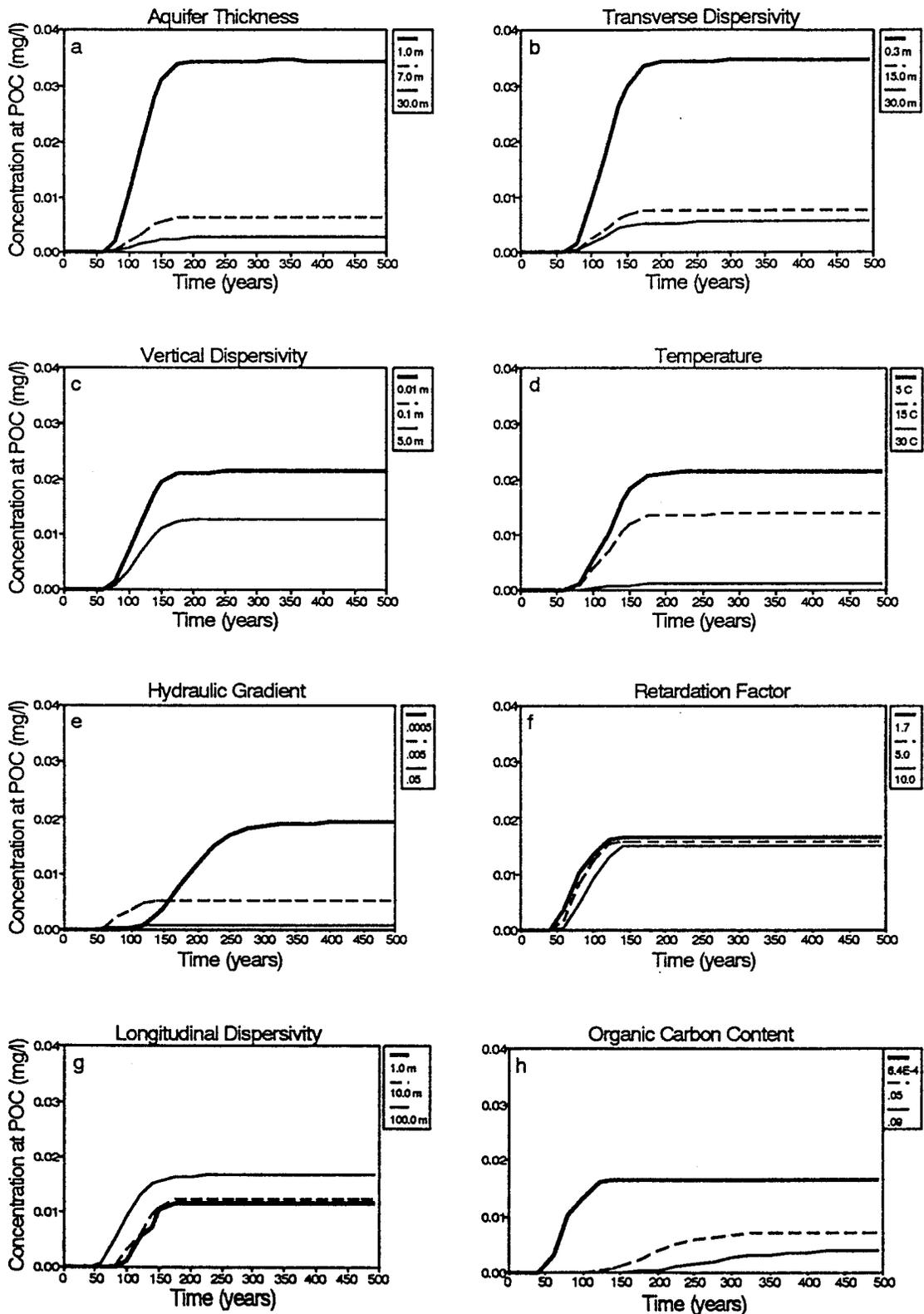


Figure 6. Carbon Tetrachloride Concentration at Point of Compliance (POC) vs Time: Wallace County Landfill, Aquifer Parameters.

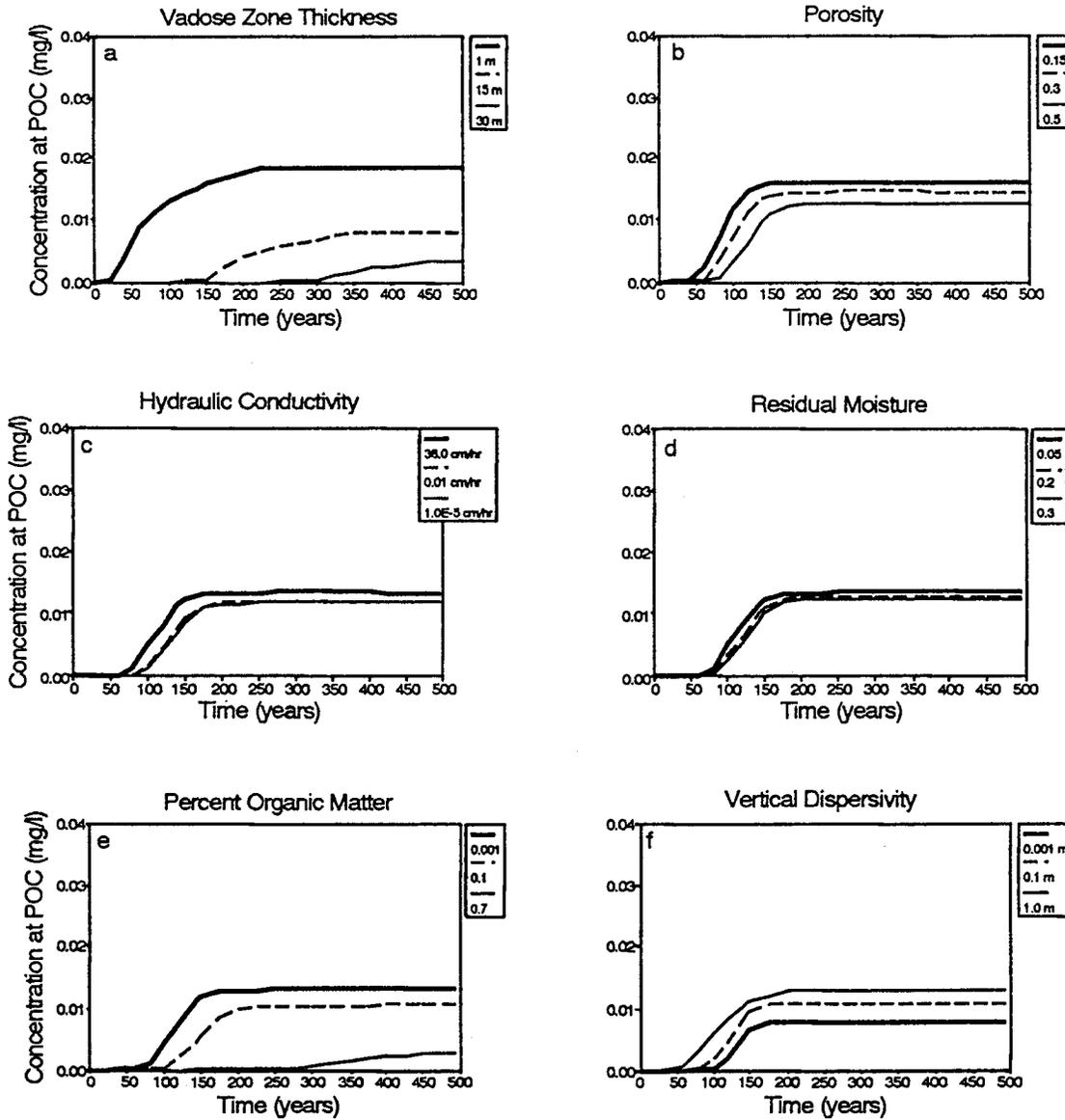


Figure 7. Carbon Tetrachloride Concentration at Point of Compliance (POC) vs Time: Wallace County Landfill, Unsaturated Zone Parameters.

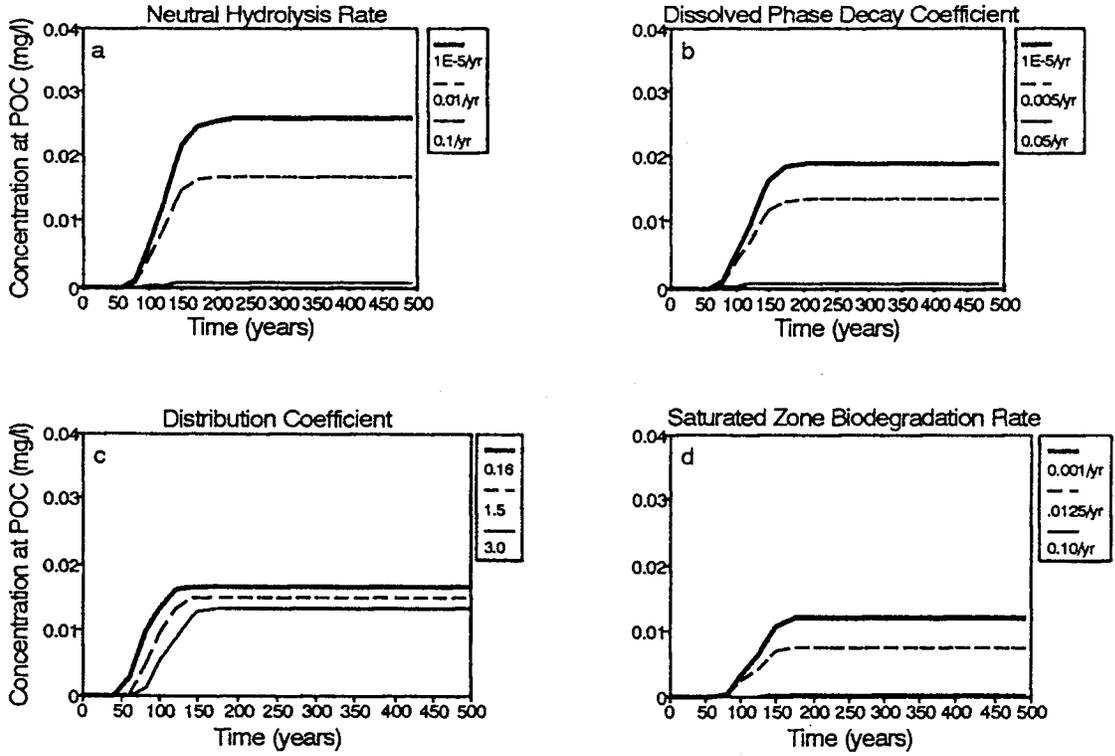


Figure 8. Carbon Tetrachloride Concentration at Point of Compliance (POC) vs Time: Wallace County Landfill, Chemical Parameters.