Kansas Landfills: Regulations, general characteristics, and modeling tools

(Progress report to EPA Region 7 and KDH&E/BWM)

by

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This is a first progress report towards establishing a Kansas Geological Survey (KGS) technical support to Kansas Department of Health and Environment (KDH&E) Bureau of Waste Management (BWM) Program. The goal of this project is to assist BWM in developing guidance criteria for managing municipal landfills through numerical modeling, and provide additional technical assistance in solving particular problems related to BWM disposal sites in Kansas. The project tasks are given certain flexibility in order to better fit the needs of the BWM program, and specific deliverables are determined in regular joint EPA-KDH&E-KGS progress meetings. This first quarterly report summarizes the Kansas Solid Waste Regulations for municipal landfills with respect to hydrogeologic investigations, and leachate and ground-water monitoring systems (section I), provides some general summary characteristics of typical Kansas landfills in alluvial, limestone-shale, and deep aquifer environments (section II), and describes and evaluates the latest versions of two EPA-sponsored landfill-related computer models—HELP and MULTIMED (section III).

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I. Summary of State of Kansas Solid Waste Regulations applicable to municipal landfills with respect to hydrogeologic investigations and leachate and ground-water monitoring systems

In the US, two key pieces of federal legislation, and amendments to these two legislative benchmarks, drive the states' technical approach to problems. Disposal of newly-generated solid waste is regulated under the Resource Conservation and Recovery Act (RCRA) and the Hazardous and Solid Waste Amendments (HSWA) to RCRA. Hazardous waste is covered in Subtitle C of RCRA, and non-hazardous waste, such as municipal waste, is regulated in Subtitle D. These federal programs are implemented in whole or in part by state administrative agencies, such as the Kansas Department of Health and Environment. Here we review selected aspects of the solid waste regulations which were recently (as of October 24, 1994) enacted in Kansas.

A. Hydrogeologic site investigations

Purpose:
1) to determine an appropriate design for the municipal landfill unit;
2) to establish a ground-water monitoring system.

Hydrogeologic site investigations shall be conducted in a minimum of two phases:

Phase I shall consist of:

1) A minimum of one continuously sampled boring down to the bottom of the uppermost aquifer. The boring should be drilled as close as possible to the geologic center of the site to characterize site-specific hydrogeology.
2) Information on
   a) climatic aspects of the study area
   b) geology and hydrogeology of the region and study area
   c) other information needed for designing a phase II investigation

A report shall be compiled from phase I investigations and submitted with evaluations and recommendations to Kansas Department of Health & Environment (KDH&E) for review and approval.

Phase II shall consist of:

1) Two borings, one as close as possible to the topographic high point and another as close as possible to the topographic low point of the study area.
2) Additional borings to characterize the subsurface geology of the study area.
3) Determining the direction and ground-water flow characteristics in all strata down to the bottom of the uppermost aquifer using piezometer and ground-water monitoring wells, and sampling ground-water from the monitoring wells to establish background concentrations.
4) Additional site-specific information, as necessary, to augment the data collected during the phase I investigation such as the following:
   a) lithology, mineralogy and hydraulic characteristics of underlying strata including those below the uppermost aquifer;
   b) soil characteristics;
   c) hydraulic conductivities of the uppermost aquifer and all strata above it;
   d) vertical extent of the uppermost aquifer;
   e) direction and rate of ground-water flow; and
   f) ground-water quality analyses of all units down to the bottom of the uppermost aquifer.

A report shall be compiled combining phase I and phase II investigations and including the following:

(i) structural characteristics and distribution of underlying strata, including bedrock;
(ii) characterization of potential pathways for contaminant migration;
(iii) correlation of stratigraphic units between borings;
(iv) continuity of petrographic features including, but not limited to, sorting, grain size distribution, cementation and hydraulic conductivity;
(v) identification of the confining layer, if present;
(vi) characterization of the seasonal and temporal, naturally and artificially induced, variations in ground-water quality and ground-water flow;
(vii) identification of unusual or unpredicted geologic features, including fault zones, fracture traces, facies changes, solution channels, buried stream deposits, cross cutting structures and other geologic features that may affect the ability of the owner or operator to monitor the ground-water or predict the impact of the disposal facility on ground-water; and
(viii) recommendations for landfill siting and conceptual design for the KDH&E to review and approve.

B. Leachate and ground-water monitoring systems

1. Leachate monitoring

Leachate samples shall be collected annually and tested for:

i) BOD_5,
ii) total suspended solids,
iii) total iron,
iv) pH,
v) each of the Appendix I parameters (44 in all), and
vi) any other constituents as specified by the KDH&E.

This list of constituents may be modified by KDH&E if it can be shown that some of these constituents are not reasonably expected to be contained in or derived from the waste at the site. An alternative sampling and analysis frequency of leachate constituents may be specified by KDH&E.

Sampling shall continue for a minimum of five years after closure and thereafter until KDH&E determines that such sampling is no longer necessary.

2. Ground-water monitoring

A sufficient number of wells shall be installed at appropriate locations and depths (based upon site-specific technical information) to yield ground-water samples from the uppermost aquifer that

a) represent the quality of background ground-water unaffected by leakage from the unit, and
b) represent the quality of ground-water passing the point of compliance.

- The monitoring wells shall be constructed to standards in accordance with K.A.R. 28-30-6.
- Each well shall be screened to allow sampling only at the desired interval.
- Location, design, and construction information for each well shall be maintained by the landfill owner or operator.
- Each well shall be developed to allow free entry of water and minimize turbidity of the sample.
- The transmissivity of the zone surrounding each well screen shall be established by field-testing techniques.

Standards for the location of monitoring points are outlined in section 28-29-111 (f) (4).

A sampling and analysis plan shall be submitted to KDH&E that includes:

a) a quality assurance and quality control program for field sampling procedures and laboratory analysis;
b) a sampling preservation and shipment procedure that maintains the integrity of the sample collected for analysis;
c) a chain of custody procedure;
d) the sampling procedures and analytical methods that will be used; and
e) the statistical method(s) to be used in evaluating monitoring data for each constituent detected.

Section 28-29-112(h) lists acceptable statistical methods to be utilized in evaluating ground-water monitoring data.

Ground-water levels in wells as well as the direction and rate of ground-water flow shall be determined each time ground-water is sampled.

The monitoring frequency for each constituent listed in Appendix I of K.A.R. 28-29-113 shall be semiannual during the active life of the facility, including closure and the post-closure period, except that monitoring shall be quarterly for the first year.

At least one sample from each well, background and downgradient, shall be collected and analyzed.

An alternative frequency for sampling and analysis may be specified by KDH&E; however, the alternative frequency shall be no less than annually.

Section 28-29-113(a)(3) and thereafter describe the procedures to follow if a statistically significant increase over background for one or more constituents at any monitoring well has been determined.

Ground-water monitoring requirements may be suspended by KDH&E if the landfill owner or operator demonstrates that there is no potential for migration of hazardous constituents from that landfill to the upper-most aquifer during the active life of the unit and the post-closure care period. This demonstration shall be based upon

a) site-specific field-collected measurement, sampling, and analysis effecting contaminant fate and transport, and
b) contaminant fate and transport predictions that maximize contaminant migration and consider impacts on human health and environment.

The ground-water monitoring requirements are to be complied with according to the following schedule:

1) Landfills located less than or equal to one mile from a drinking water intake (surface or subsurface) shall be in compliance by Oct. 9, 1994.

2) Landfills located greater than one mile but less than or equal to two miles from a drinking water intake shall be in compliance by Oct. 9, 1995.

3) Landfills located greater than two miles from a drinking water intake shall be in compliance by Oct. 9, 1996.

4) Landfills which meet the requirements of the "small landfills" designation (Section 28-29-103(a)) and are less than or equal to two miles from a drinking water intake shall be in compliance by Oct. 9, 1995, while those that are greater than two miles shall be in compliance by Oct. 9, 1996.

II. Some general characteristics of landfills of concern in Kansas

The distribution by county of the various types of landfills in Kansas are shown in Fig. 1. Table 1 (prepared by KDH&E/Bureau of Waste Management) groups landfills according to their distance from a drinking water intake (surface or subsurface) and their dates of compliance with applicable ground-water monitoring requirements as summarized in section I of this report. General characteristics of landfills listed in Table 1 were briefly discussed in a KDH&E and KGS meeting in Topeka in November 1994. Most of the classified landfills in Table 1 were grouped into hydrogeologic-setting categories, such as alluvium, deep aquifer, limestone-shale environments. The objective was to initially select some Kansas landfills, under different hydrogeologic environments, to be used as prototypes in developing conceptual numerical simulations for the purpose of assisting KDH&E/BWM in developing guidance criteria for managing municipal landfills. Thus, in this preliminary selection process emphasis was put on which landfills in different hydrogeologic environments had the most hydrogeologic information. It should be noted that no known presence or absence of contamination, nor any sensitivity to nearby receptors were considered in this selection process. Therefore, the following landfills were initially selected for further study:

1) Finney County landfill, representing deep aquifer environments.

2) Johnson County-Deffenbaugh Phase III landfill, representing limestone-shale environments; and

3) Reno County landfill, representing alluvial environments.

After a preliminary study, these three type landfills were comparatively analysed as to their climate, geology, vadose zone thickness and nature, depth to water table, regional and local potentiometric gradients, monitoring network, available hydrogeologic data, effluent quality and groundwater quality impact, and information/data sources. These characteristics are summarized in Table 2 and the accompanying figures 2, 3 and 4 (taken from the information sources listed in Table 2). These and additional landfills may need to be further studied and analyzed as this project progresses.

LANDFILLS IN KANSAS

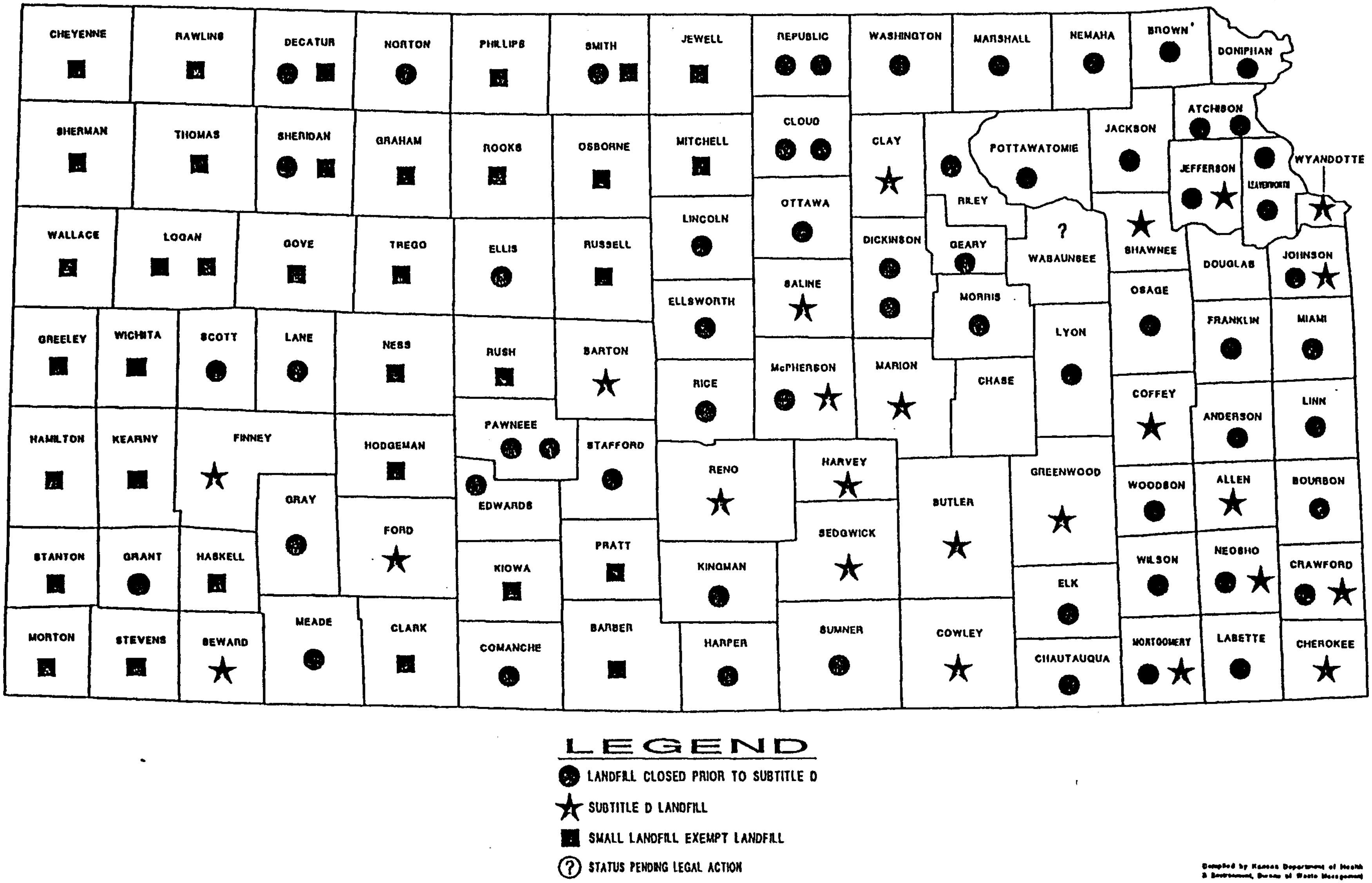


Figure 1.

Table 1: Subtitle D Landfill Compliance Dates

< 1 Mile **October 9, 1994**

Cowley County
Ford County
Reno County
Barton County
Finney County
City of Salina

> 1 Mile < 2 Miles **October 9, 1995**

ADS - Wheatland Landfill
City of Chanute
Coffey County
Johnson County - Deffenbaugh

> 2 Miles **October 9, 1996**

Clay County
Grosse - Marion County
Rolling Meadows
Forest View - Wyandotte County
Hamm - Douglas County

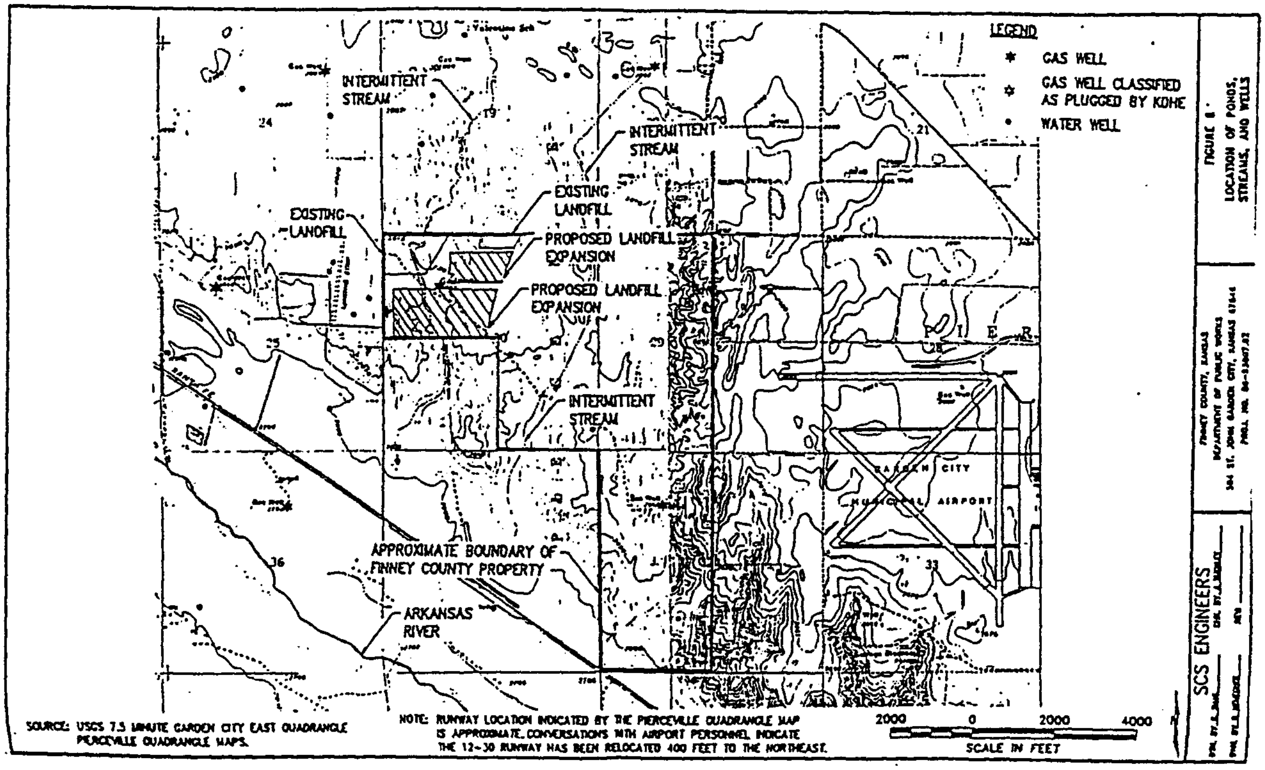
Unclassified Landfills

Brooks Landfill - Sedgwick County
Seward County
Harvey County
Greenwood County
Allen County
Butler County > 2 miles
Montgomery County
Crawford County - Deffenbaugh
Thomas County - City of Colby
McPherson County

Table 2: LANDFILL SUMMARY NOTES

Environment	Finney Co. Landfill (deep aquifer)	Johnson Co. Deffenbaugh: Phase III (limestone-shale sequence)	Reno Co. Landfill (alluvium)
Location	Finney Co. (SW 1/4 NW 1/4 S30, T24S, R31W) 3.5 mi E of Garden City & 1.5 mi S of Hwy 50 ~ 1.5 mi from Arkansas River	Kansas City-Holliday Dr. <0.5 mi from Kansas River	W. of Hutchinson (S 16 & 17, T23S, R6W) A few tens of feet from Salt Cr. <0.5 mi from Arkansas River
Climate	Average annual pecipitation 17.9" (May 3.11"; Jan. 0.33")	Average annual precipitation 38"	Average annual precipitation 30.2"
Geology	Bedrock: Carlile shale (Cret.) Surficial material: Alluvium/Pleistocene loess (Ogallala/Pleistocene aquifer) Arkansas River influent (losing) stream	Bedrock: Quivira shale; Westerville limestone; Wea shale (Pennsylv.). see Fig. 3 Surficial material: Outcropping bedrock formations: Lane, Iola, Chanute, Drum (Pennsylv.) Faults mapped SW, S & SE of site; horiz. fractures	Bedrock: Ninnescah shale (100-140') Surficial material: Alluvium/Quaternary terrace
Depth to WT (Vadose zone thickness)	~ 80 ft (variable); 40 ft min. seperation between landfill bottom and WT.	15—115ft (variable) Landfill bottom: Quivira shale; Westerville limestone: underlying aquifer	~ approximately 20-40 ft from land surface; 0-15 ft thickness of vadose zone under landfill (see Fig. 4)
Nature of vadose zone	Sand and silt	Limestone, shale	Clay
Liner	natural clay or silty clay	Synthetic liner plus native Quivira shale (6-7ft)	Recompacted clay
Regional/local potent. gradients	Regional flow E-SE: local flow to NE (see Fig. 2)	Local gradient: N-NW (Fig. 3)	Regional and local flow: E-SE (see Fig. 4)
Monitoring network	6 monitoring wells; several wells exist in the vicinity (see Fig. 2)	7 monitoring wells	14 monitoring wells (see Fig. 4)
Effluent quality	Xylene and toluene detected but below KAL	VOC's and some metals detected in G/W and springs from phase II landfill	Leachates from landfill affect G/W quality. Organic compounds detected (1,1-dichloroethane, trichloroethylene, vinyl chloride, 1,2 trans-dichloroethylene), other VOCs
Hydrogeology data	3 slug tests; 5 soil samples for K	5 packer tests on Quivira sh; 10 piezom. tests on Westerville lst; tests available on Wea shale too	4 slug tests
Information source	SCS Engineers Hydrogeologic Investigations Report 1994	Black&Veach Hydrogeology Report, 1994	Heck et al, 1992, USGS WRIR 92-4169

FINNEY CO LANDFILL



1-3

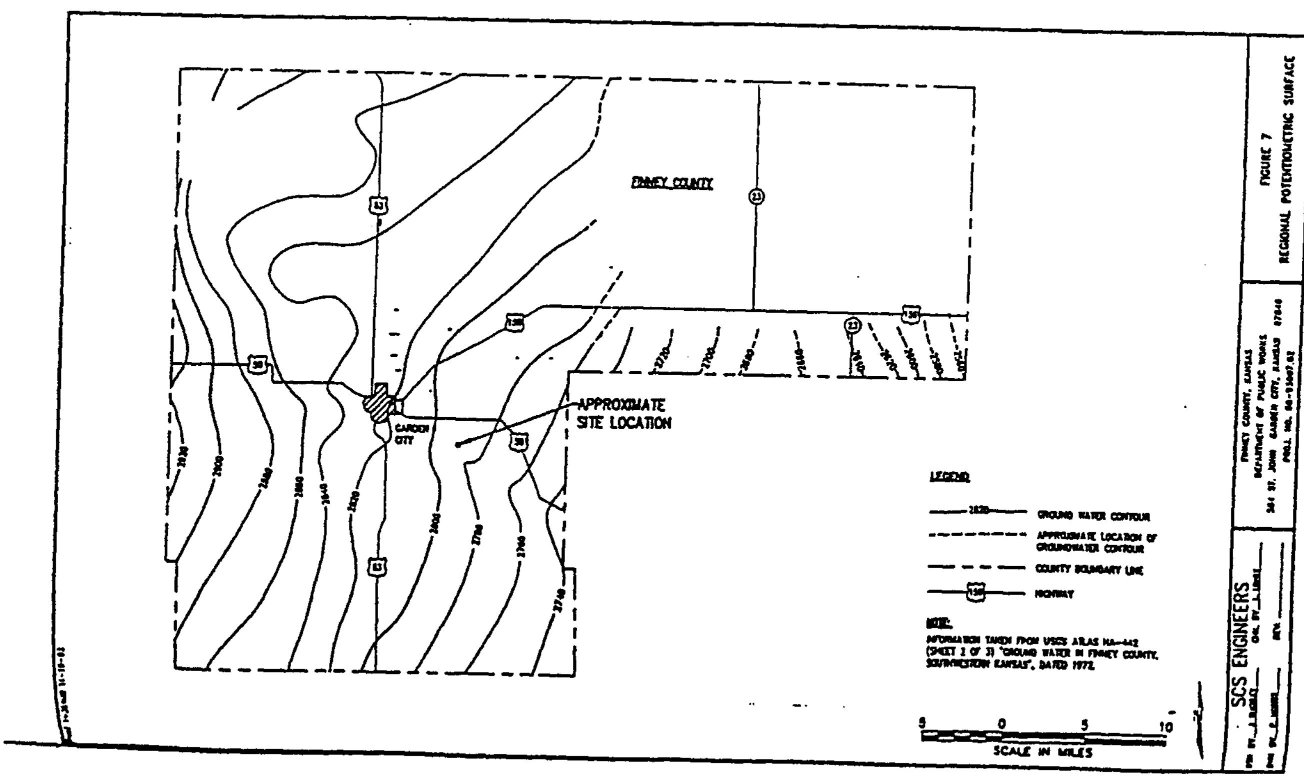
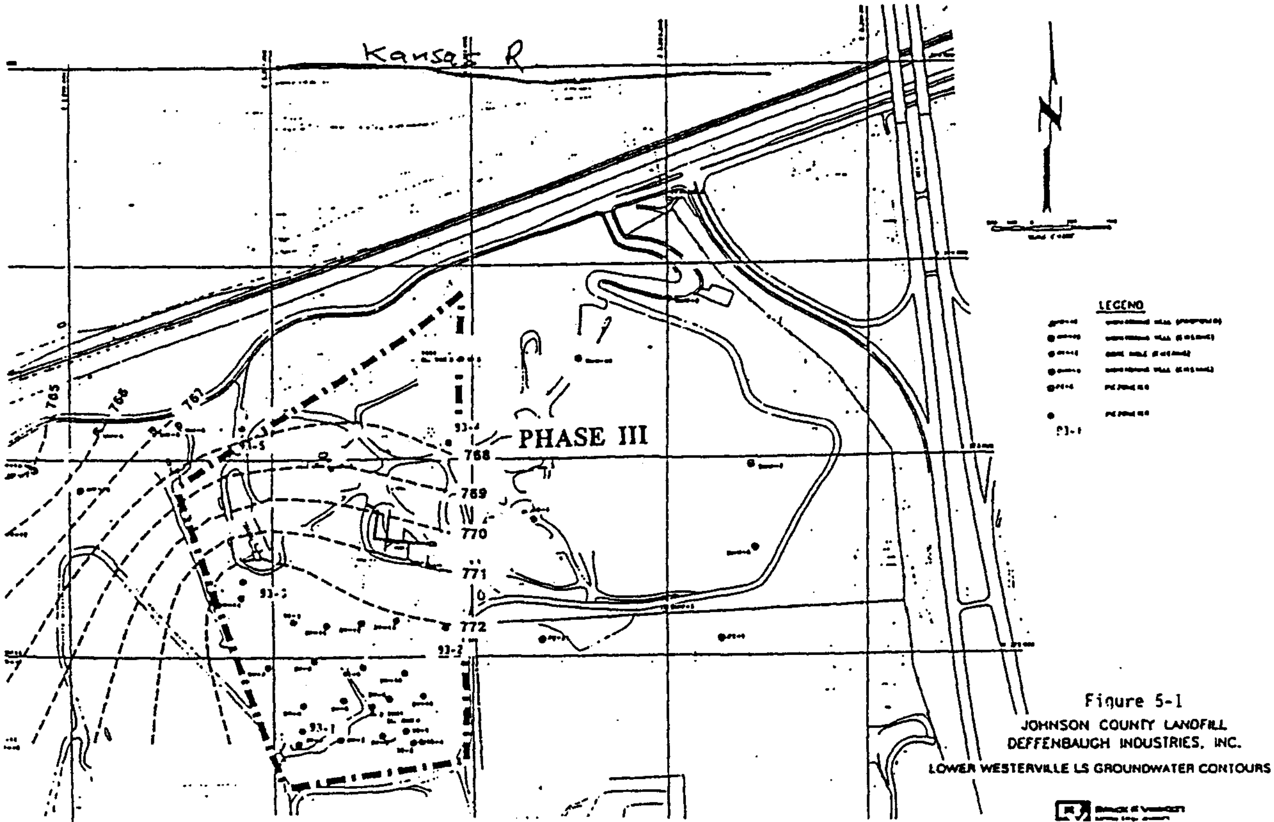


Figure 2



JOHNSON COUNTY LANDFILL – DEFFENBAUGH INDUSTRIES, INC

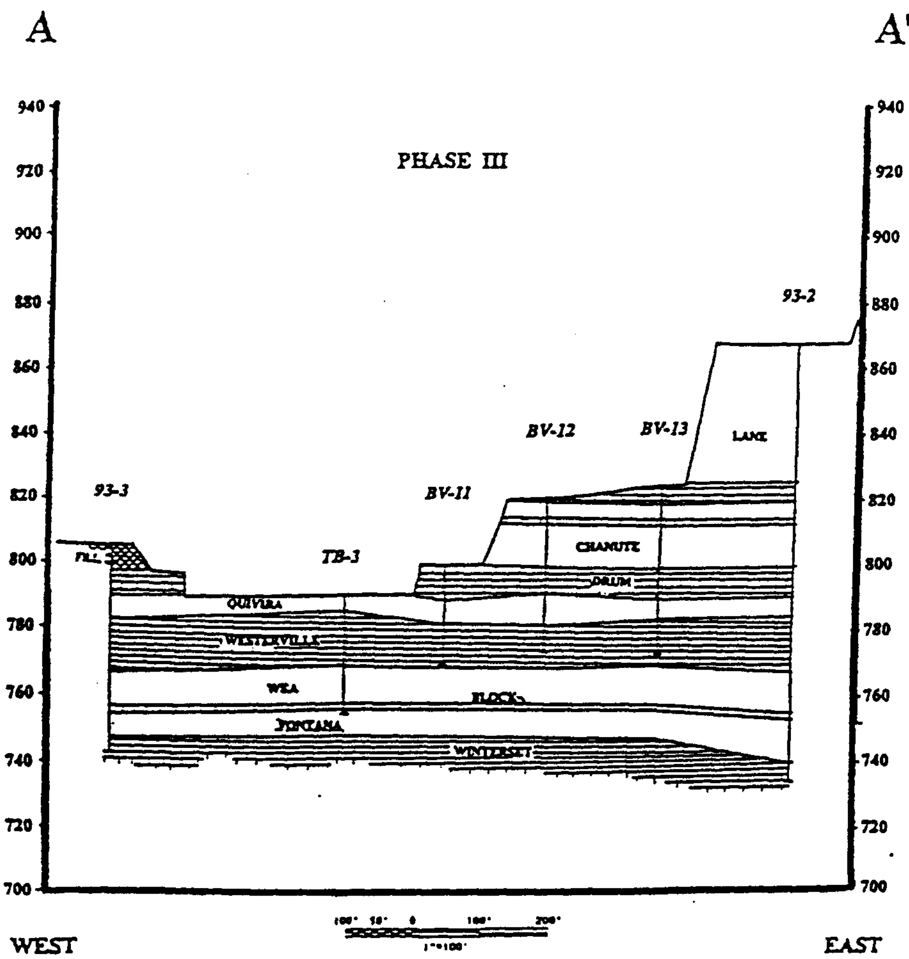
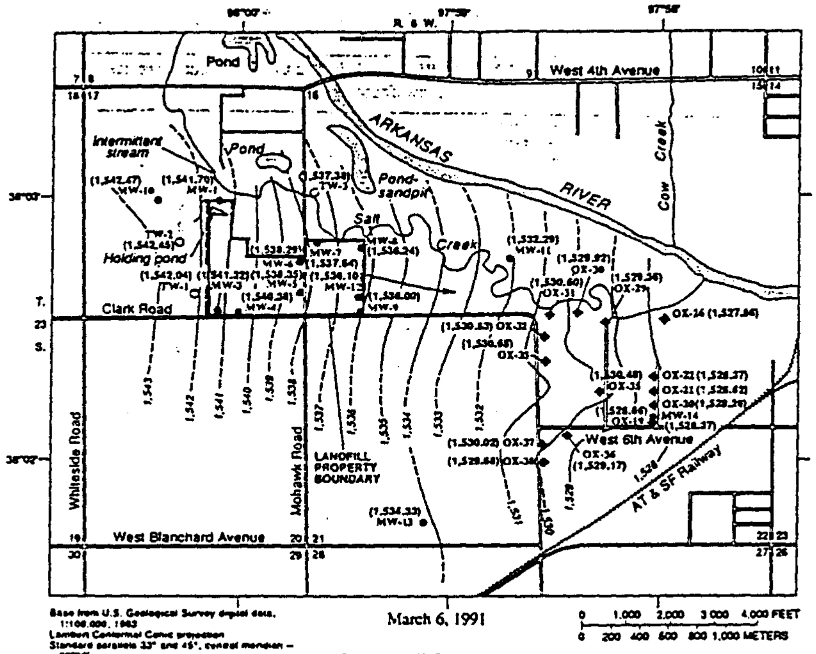


Figure 3

RENO CO LANDFILL



EXPLANATION

—1,542— POTENTIOMETRIC CONTOUR—Shows altitude at which water would have stood in tightly cased wells. Dashed where approximately located. Contour interval 1 foot. Datum is sea level

——→ APPROXIMATE DIRECTION OF GROUND-WATER FLOW

TW-1 ○ TEMPORARY WELL AND NUMBER

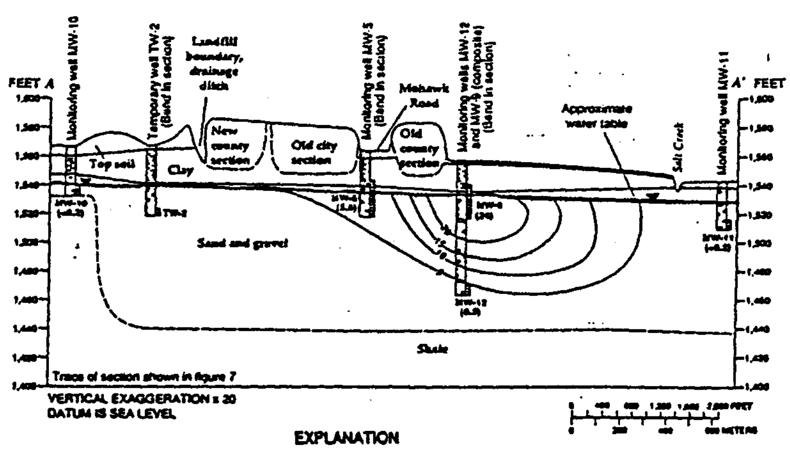
MW-1 ● MONITORING WELL AND NUMBER

CR-1 ▲ SURFACE-WATER SAMPLING SITE AND NUMBER

OX-19 ◆ INDUSTRIAL-OBSERVATION WELL AND NUMBER

(1,541.15) WATER-LEVEL ALTITUDE—In feet. Datum is sea level

Figure . Potentiometric surface in Quaternary sediment, Reno County Landfill and vicinity, March 6, 1991 (water-level altitudes listed in table 6).



EXPLANATION

TOP SOIL

CLAY

SAND AND GRAVEL

—20— LINE OF EQUAL TRICHLOROETHYLENE CONCENTRATION—Interval 5 micrograms per liter

——— LITHOLOGIC CONTACT—Dashed where approximately located

WELL-SCREEN INTERVAL AND NUMBER—Number in parentheses is trichloroethylene concentration, in micrograms per liter. <, less than indicated reporting level

Figure . Distribution of concentrations of trichloroethylene, indicating general location of leachate plume, Reno County Landfill and vicinity, August 7-8, 1990.

Figure 4.

III. Landfill-related Models

A. Introduction to landfill modeling applications

The large number of interrelated physical, chemical and biological processes involved in the migration of leachates from waste disposal facilities makes the prediction of groundwater contamination from these facilities a complex task. Mathematical models are useful tools which provide insight into the effects of facility design, operation and failure on groundwater quantity and quality.

All models are simplified representations of the real system; no model will ever reproduce the exact characteristics of a site. Therefore, model results should always be interpreted as estimates of groundwater flow and contaminant transport, and not as exact predictions. Bond and Hwang (1988) recommend that models be used for comparing various cases or scenarios, since all cases are subject to the same limitations and simplifications. It is important to understand the limitations of mathematical models, and to use them correctly in evaluation of actual environmental conditions.

Several recent reports present detailed discussions of the issues related to model selection, application, and validation. Donigian and Rao (1988) and Sophocleous (1988), among others, address each of these issues. Issues related to model selection and application are addressed in detail by Boutwell et al. (1986). Weaver et al. (1989) discuss the selection and field validation of mathematical models. In addition, a report by the National Research Council (1990) discusses model application and validation and provides recommendations for the proper use of groundwater models. Model users, particularly those who are relatively inexperienced, are encouraged to read these and similar reports before beginning a modeling study.

The validity of the results from mathematical models depends to a large extent on the proper application of the model. The application of a model to a leachate migration problem requires several steps. First, the modeling needs and the objectives of the study should be determined. Next, data should be collected for characterization of the hydrological, geological, chemical and biological conditions present in the system. These data should assist in the development of the "scenario" to be modeled, which provides the framework for the conceptual model of the system. The conceptual model and data are used to verify that the selected model is appropriate. During model application, results should be calibrated to obtain the best fit to observed data. Finally, these results should be validated by comparing them to independently-derived data or observations.

In this report we summarize in some detail two of the most well known landfill-related models[1] and their limitations. Both of these models are EPA-sponsored.

[1] In addition to these models, there are several other relevant models, such as those sponsored by the Electric Power Research Institute (EPRI), as well as other models which may need to be reviewed in future progress reports.

B. **HELP** Model

Introduction

A key step in the design of a solid waste disposal facility is the execution of a 'water balance' or 'water budget' analysis. A water balance is an accounting of the final disposition of precipitation falling on a site. Water balance analysis can be used to estimate the potential leachate production and liner/drain system performance and to compare the relative effectiveness of alternative cover and liner/drain designs. Knowledge of the possible range of leachate production is important for sizing the leachate collection system (e.g. pipes) and in making decisions about how to manage treatment of the leachate. Similarly, prediction of liner leakage and the depth of leachate buildup in a drain layer is important in the selection of liner and drain materials and in the design of collection pipe spacing and liner slope.

The state of the art in water balance analysis for landfills is a computer program known as HELP. The HELP model was developed by the US Army Corps of Engineers Waterways Experiment Station for the US EPA and is described by Schroeder et al. (1984a,b; 1994 a,b). Version 3 of the model has just been released (Dec. 1994) by the US EPA Risk Reduction Engineering Laboratory.

The HELP model is a tool developed specifically to aid analysis in the evaluation and comparison of alternative landfills designs. The HELP model was adapted from the Hydrologic Simulation Model for Estimating Percolation at Solid Waste Disposal Sites of the US EPA (Perrier and Gibson, 1980; Schroeder and Gibson, 1982), the Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980), and Simulator for Water Resources in Rural Basins (SWRRB) (Williams et al., 1985). The following subsections summarize the main features and assumptions of the model. The User's Manuals (Schroeder et al., 1984 a,b; 1994 a,b) should be consulted for further detail.

Overview of Modeling Procedure

The HELP model is a quasi-two-dimensional, gradually varying, deterministic, computer-based water budget model. It is termed 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 liners incorporated in the cover system or located below the waste. 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 models for lateral drainage and a leakage or percolation through the liner then use 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, respectively. The model is termed gradually varying because the simulation progresses through time using analyses that are assumed steady for each time period. The model is deterministic and quantitative. Finally, the HELP model is a computer-based water budget model that runs on a personal computer. 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, reported in the literature, 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.

Model Output

The HELP program can generate daily, monthly, annual, and long-term average water budgets. The output from HELP consists primarily of percolation or leakage through each liner and depth of saturation on the surface of liners (e.g., in drainage layers). Incremental and cumulative quantities of water budget for the various components are computed and printed.

Model Input

The HELP model requires general climate data for computing potential evapotranspiration; daily climatologic data; soil characteristics; and design specifications to perform the analysis. The required general climate data include growing season, average annual wind speed, average quarterly relative humidities, normal mean monthly temperatures, maximum leaf area index, evaporative zone depth and latitude. Default values for these parameters were compiled or developed from the "Climates of the States" (Ruffner, 1985) and "Climatic Atlas of the United States" (National Oceanic and Atmospheric Administration, 1974) for 183 U.S. cities. For Kansas, evapotranspiration-related data in the HELP database are available for Dodge City, Wichita, Topeka and Kansas City. Daily climatologic (weather) data requirements include precipitation, mean temperature and total global solar radiation. Daily rainfall data may be input by the user, generated stochastically, or taken from the model's historical data base. The model contains parameters for generating synthetic precipitation for 139 U.S. cities. For Kansas these include Dodge City, Wichita, Topeka and Kansas City. The historical data base contains five years of daily precipitation data for 102 U.S. cities. For Kansas these include Dodge City and Topeka. Daily temperature and solar radiation data are generated stochastically or may be input by the user.

Necessary soil data include porosity, field capacity, wilting point, saturated hydraulic conductivity, initial moisture storage, and Soil Conservation Service (SCS) runoff curve number for antecedent moisture condition II. The model contains default soil characteristics for 42 material types for use when measurements or site-specific estimates are not available. The porosity, field capacity, wilting point and saturated hydraulic conductivity are used to estimate the soil water evaporation coefficient and Brooks-Corey soil moisture retention parameters.

Design specifications include such items as the slope and maximum drainage distance for lateral drainage layers; layer thickness; layer description; area; leachate recirculation procedure; subsurface inflows; surface characteristics; and geomembrane characteristics.

In general the HELP model requires the following data, some of which may be selected from the default values.

1. Units
2. Location
3. Weather data file names
4. Evapotranspiration information
5. Precipitation data
6. Temperature data
7. Solar radiation data
8. Soil and design data file name
9. General landfill and site information
10. Landfill profile and soil/waste/geomembrane data
11. SCS runoff curve number information

Landfill features that can be modeled with HELP

Figure 5 is a definition sketch for a hazardous waste landfill profile simulated by HELP. The top portion of the profile (layers 1 through 4) is the cap or cover. The bottom portion of the landfill is a double liner system (Layers 6 through 11), in this case composed of a geomembrane liner and a composite liner. Immediately above the bottom composite liner is a leakage detection drainage layer to collect leakage from the primary liner, in this case a geomembrane. Above the primary liner are a geosynthetic drainage net and a sand layer that serve as drainage layers for leachate collection. Taken as a whole, the drainage layers, geomembrane liners, and barrier soil liners may be referred to as the leachate collection and removal system (drain/liner system) and more specifically a double liner system.

Figure 5 shows eleven layers--four in the cover or cap as the waste layers, three in the primary leachate collection and removal system (drain/liner system) and three in the secondary leachate collection and removal system (leakage detection). These eleven layers comprise three subprofiles or modeling units. A subprofile consists of all layers between (and including) the landfill surface and the bottom of the top liner system, between the bottom of one liner system and the bottom of the next lower liner system, or between the bottom of the lowest liner system

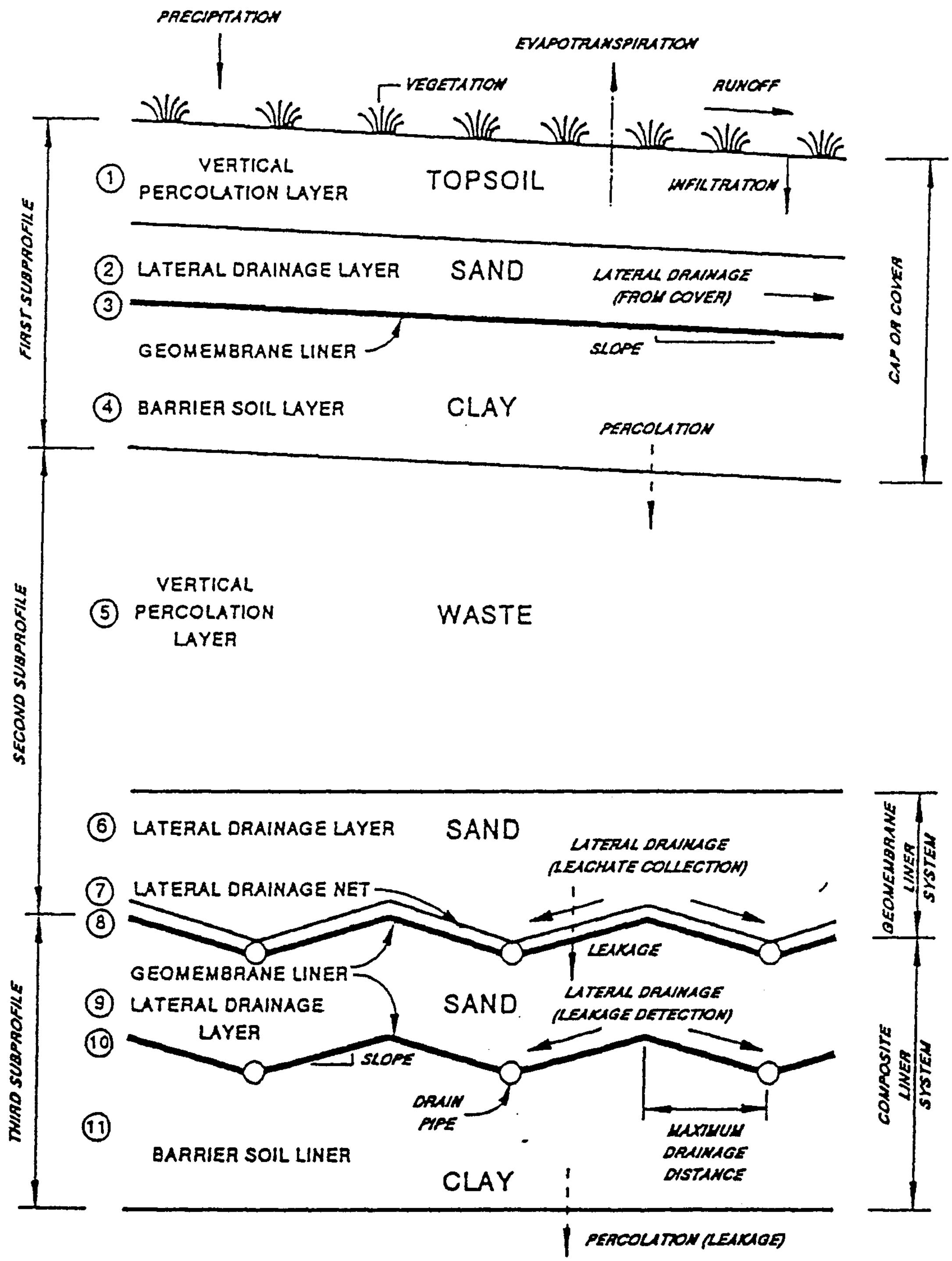


Figure 5. Schematic of Landfill Profile Illustrating Typical Landfill Features

and the bottom of the lowest soil layer modeled. In the sketch, the top subprofile contains the cover layers, the middle subprofile contains the waste, drain and liner system for leachate collection, and the bottom subprofile contains the drain and liner system for leakage detection. Six subprofiles in a single landfill profile may be simulated by the model.

The layers in the landfill are typed 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. These layer types are illustrated in Figure 5. The topsoil and waste layers are generally vertical percolation layers. Sand layers above liners are typically lateral drainage layers; compacted clay layers are typically barrier soil liners. Geomembranes are typed as geomembrane liners. Composite liners are modeled as two layers. Geotextiles are not considered as layers unless they perform a unique hydraulic function.

Flow in a vertical percolation layer (e.g., layers 1 and 5 in Figure 5) is either downward due to gravity drainage or extracted by evapotranspiration. Unsaturated vertical drainage is assumed to occur by gravity drainage whenever the soil moisture is greater than the field capacity (greater than the wilting point for soils in the evaporative zone) or when the soil suction of the layer below the vertical percolation layer is greater than the soil suction in the vertical percolation layer. The rate of gravity drainage (percolation) in a vertical percolation layer is assumed to be a function of the soil moisture storage and largely independent of conditions in adjacent layers. The rate can be restricted when the layer below is saturated and drains slower than the vertical percolation layer. Layers, whose primary hydraulic function is to provide storage of moisture and detention of drainage, should normally be designated as vertical percolation layers. Waste layers and layers designed to support vegetation should be designated as vertical percolation layers, unless the layers provide lateral drainage to collection systems.

Lateral drainage layers (e.g., layers 2, 6, 7 and 9 in Figure 5) are layers that 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. The saturated hydraulic conductivity of a lateral drainage layer generally should be greater than 1×10^{-3} cm/sec for significant lateral drainage to occur. A lateral drainage layer may be underlain by only a liner or another lateral drainage layer. The slope of the bottom of the layer may vary from 0 to 40 percent.

Barrier soil liners (e.g. layers 4 and 11 in Figure 5) are intended to restrict vertical flow. These layers should have hydraulic conductivities substantially lower than those of the other types of layers, typically below 1×10^{-6} cm/sec. The program allows only downward flow in barrier soil liners. Thus, any water moving into a liner will eventually percolate through it. The leakage (percolation) rate depends upon the depth of water-saturated soil (head) above the base of the layer, the thickness of the liner and the saturated hydraulic conductivity of the barrier soil. Leakage occurs whenever the moisture content of the layer above the liner is greater than the field capacity of the layer. The program assumes that barrier soil liner is permanently saturated and that its properties do not change with time.

Geomembrane liners (e.g., layers 3, 8 and 10 in Figure 5) are layers of nearly impermeable material that restricts significant leakage to small areas around defects. Leakage (percolation) is computed to be the result from three sources: vapor diffusion, manufacturing flaws (pinholes) and installation defects (punctures, cracks, tears and bad seams). Leakage by vapor diffusion is computed to occur across the entire area of the liner as a function of the head on the surface of the liner, the thickness of the geomembrane and its vapor diffusivity. Leakage through pinholes and installation defects is computed in two steps. First, the area of soil or material contributing to leakage is computed as a function of head on the liner, size of hole and the saturated hydraulic conductivity of the soils or materials adjacent to the geomembrane liner. Second, the rate of leakage in the wetted area is computed as a function of the head, thickness of soil and membrane and the saturated hydraulic conductivity of the soils or materials adjacent to the geomembrane liner.

Assumptions and Limitations

a) Solution Methods

The modeling procedures employed in HELP are necessarily based on many simplifying assumptions. Generally, these assumptions may be reasonable and consistent with the objectives of the program when applied to standard landfill designs. However, some of these assumptions may not be reasonable for some landfills. The major assumptions and limitations of HELP are summarized below.

Runoff is computed using the SCS method based on daily amounts of rainfall and snowmelt. The program assumes that areas adjacent to the landfill do not drain onto the landfill. The time distribution of rainfall intensity is not considered. The program cannot be expected to give accurate estimates of runoff volumes for individual storm events on the basis of daily rainfall data. However, because the SCS rainfall-runoff relation is based on considerable daily field data, long-term estimates of runoff should be reasonable. The SCS method does not explicitly consider the length and slope of the surface over which overland flow occurs. This limitation has been removed by developing and implementing into the HELP (version 3) input routine a procedure for computing curve numbers that take into consideration the effect of slope and slope length. The limitation, however, remains on the user specified curve number.

The HELP model assumes Darcian flow by gravity through homogeneous soil and waste layers. It does not consider explicitly preferential flow through channels such as cracks, root holes, or animal burrows but allows for vertical drainage through the evaporative zone at moisture contents below field capacity. Similarly, the program allows vertical drainage from a layer at moisture contents below field capacity when the inflow would occupy a significant fraction of the available storage capacity below field capacity. The drainage rate out of a segment is assumed to equal the unsaturated hydraulic conductivity of the segment corresponding to its moisture content, provided that the underlying segment is not a liner and is not saturated. In addition to these special cases, the drainage rate out of a segment is assumed to equal the unsaturated hydraulic conductivity of the segment below it. When limited, the program computes an effective gradient for saturated flow through the lower segment. This permits vertical percolation or lateral drainage layers to be arranged without restrictions on their properties as long as they perform as their layer description implies and not as liners.

The model does not explicitly compute flow by differences in soil suction (soil suction gradient) and, as such, does not model the draw of water upward by capillary drying. This draw of water upward is modeled as an extraction rather than transport of water upward. Therefore, it is important that the evaporative zone depth be specified as the depth of capillary drying. Drainage downward by soil suction exerted by dry soils lower in the landfill profile is modeled as Darcian flow for any soil having a relative moisture content greater than the lower soils. The drainage rate is equal to the unsaturated hydraulic conductivity computed as a function of the soil moisture content. As such, the rate is assumed to be independent of the pressure gradient.

Vegetative growth is based on a crop growth model. Growth is assumed to occur during the first 75% of the growing season based on heating units. Recommendations for the growing season are based primarily for summer grasses and assume that the growing season is that portion of the year when the temperature is above 50 to 55°F. However, the user may specify a more appropriate growing season for different vegetation. The optimal growth temperature and the base temperature are based on a mixture of winter and summer perennial grasses. It is assumed that other vegetation have similar growth constants and conditions. It is further assumed that the vegetation is not harvested.

Leakage through barrier soil liners is modeled as saturated Darcian flow. Leakage is assumed to occur only as long as there is head on the surface of the liner. The model assumes that the head driving the percolation can be represented by the average head across the entire liner and can be estimated from the soil moisture storage. It is also assumed that the liner underlies the entire area of the landfill and conservatively, that when leakage occurs, the entire area of the landfill leaks. The model does not consider aging or drying of the liner and, therefore, the saturated hydraulic conductivity of the liner does not vary as a function of time.

Geomembranes are assumed to leak primarily through holes. The leakage passes through the holes and spreads between the geomembrane and soil until the head is dissipated. The leakage then percolates through the soil at the rate dependent on the saturated hydraulic conductivity and the pressure gradient. Therefore, the net effect of a geomembrane is to reduce the area of percolation through the liner system. The program assumes the holes do not vary as a function of time. In addition, it is conservatively assumed that the head on the holes can be represented by the average head across the entire liner and can be estimated from the soil moisture storage and that the liner underlies the entire area of the landfill.

The lateral drainage model is based on the assumption that the saturated depth profile is characteristic of the steady-state profile for the given average depth of saturation. As such, the model assumes that the lateral drainage rate for steady-state drainage at a given average depth of saturation is representative of unsteady lateral drainage rate for the same average saturated depth. In actuality the rate would be somewhat larger for periods when the depth is building and somewhat smaller for periods when the depth is falling. Steady drainage implies that saturated conditions exist above the entire surface of the liner, agreeing with the assumptions for leakage through liner systems.

b) Limits of Application

The model can handle water routing through or storage in up to twenty soil or waste layers; as many as five liner systems may be employed. The simulation period can range from 1 to 100 years. The model cannot simulate a capillary break or unsaturated lateral drainage.

The model has limits on the arrangement of layers in the landfill profile. Each layer must be described as being one of four types: vertical percolation layer, lateral drainage layer, barrier soil liner, or geomembrane layer. The model does not permit a vertical percolation layer to be placed directly below a lateral drainage layer. A barrier soil liner may not underlie another barrier soil liner. If a liner is not placed directly below the lowest lateral drainage layer, the lateral drainage layers in the lowest subprofile are treated by the model as vertical percolation layers. No other restrictions are placed on the order of the layers.

The lateral drainage equation was developed for the expected range of hazardous waste landfill design specifications. Permissible ranges for slope of the drainage layer are 0 to 50 percent. Due to dimensionless structure of the lateral drainage equation, there are no practical limits in the maximum drainage length.

Values for the maximum leaf area index may range from 0 for bare ground to 5.0 for an excellent stand of grass. Greater leaf area indices may be used but have little impact on the results. Detailed recommendations for leaf area indices and evaporative depths are given in the program. For numerical stability, the minimum evaporative zone depth should be at least 3 inches.

The program computes the evaporation coefficient for the cover soils based on their soil properties. The default values for the evaporation coefficient are based on experimental results reported by Ritchie (1972) and others. The model imposes upper and lower limits of 5.50 and 3.30 for the evaporation coefficient so as not to exceed the range of experimental data.

Surface runoff from adjacent areas does not run onto the landfill, and the physical characteristics of the landfill specified by the user remain constant over the modeling period. No adjustments are made for the changes that occur in these characteristics as the landfill ages. Additionally, the program cannot model the filling process within a single simulation. Aging of materials and staging of the landfill operation must be modeled by successive simulations.

The program performs water balance analysis for a minimum period of one year. All situations start on January 1 and end on December 31. The condition of the landfill, soil properties, thickness, geomembrane hole density, maximum level of vegetation, etc., are assumed to be constant throughout the simulation period. The program cannot simulate the actual filling operation of an active landfill. Active landfills are modeled a year at a time, adding a yearly lift of material and updating the initial moisture of each layer for each year of simulation.

In general, the accuracy and precision of the model is limited by uncertainty and variability in the properties of materials existing in landfills.

C. MULTIMED Model

Introduction

The US Environmental Protection Agency's Multimedia Exposure Assessment Model (MULTIMED) simulates the movement of contaminants leaching from a landfill. The model consists of a number of modules which predict concentrations at a receptor due to transport in the subsurface, surface water, or air. Recent reports describe the theory behind the model (Salhotra et al., 1993) and provide details on how to apply the model to study and design Subtitle D land disposal facilities (Sharp-Hansen et al., 1993). In fact, only some of MULTIMED's capabilities are used to analyze Subtitle D facilities. Although here we provide an overview of the general features of the model, the detailed review is limited to those features needed for modeling Subtitle D facilities. Here we review version 2.0 of MULTIMED, released in September 1993. Our review draws heavily on the information presented in the user's manual for MULTIMED (Sharp-Hansen et al., 1993).

As in any other model, the relevant processes included in MULTIMED are simplified to a certain degree. Some of the complex features not included in the model are, for example, site-specific spatial variability, the shape of the land disposal facility, site-specific boundary conditions, or multiple aquifers and pumping wells. Furthermore, there are a number of processes not included in MULTIMED. Some of these processes, such as flow in fractures, multiphase flow, and chemical reactions between contaminants, can have a significant effect on the concentration of contaminants at a site.

It is the modeler's responsibility to evaluate whether a particular model (e.g., MULTIMED) can be expected to produce meaningful estimates when applied to a particular situation. In making this judgment, the modeler pays special attention to the processes included in the model and the simplifying assumptions used to represent those same processes. The uncertainty in input parameters also has to be considered: an interesting feature of MULTIMED is its ability to perform uncertainty analysis using the Monte Carlo simulation method.

Overview of Modeling Procedure

MULTIMED has been developed as a modular package that can be easily modified by adding modules and/or modifying existing modules. To facilitate the use of the model, two separate interactive preprocessing and postprocessing software packages were developed to create and edit input and to plot model output. However, the pre- and postprocessors, PREMED and POSTMED, have not been integrated with MULTIMED because of the size limitations of PC computers. The three packages are used in sequence, running one at a time. MULTIMED and the pre- and postprocessors were designed primarily for IBM-PC compatible computers. The PC must use either the Intel 386 or 486 technology, have 4 MB of extended memory, a math coprocessor, and approximately 5 MB of free disk space. MULTIMED is also available for workstations running different operating systems: Unix, VMS, and PRIMOS.

MULTIMED can simulate some or all of the following processes: (1) leachate flux from the source, (2) unsaturated zone flow, (3) unsaturated zone transport, (4) saturated zone transport, (5) plume interception by a stream, (6) contaminant emission from the landfill into the atmosphere, and (7) dispersion of the contaminants in the atmosphere. The code is organized as independent modules that correspond to each of the seven processes listed above. The user can choose what processes are relevant at a particular site and select the modules that will be active when running MULTIMED. The conceptual models and the methods of solution used for each process are extensively discussed in Salhotra et al. (1993).

MULTIMED simulates the transport and transformation of contaminants released from a waste disposal facility into the multimedia environment. Although the release to air and streams are included in the model, we focus our attention in the release to soil and the resulting transport on 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 by 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 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, non-linear 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 both 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 now simulate (1) non linear (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 non-linear adsorption and incorporated into the EPA CML model (Geotrans, 1990). The original analytical unsaturated zone transport model is also in version 2.0, such that the user has an option of 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 non-linear adsorption, arbitrary initial conditions, time-varying infiltration rates, or volatilization in the unsaturated zone, then the numerical model must be used.

Non-linear 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 US EPA for applications involving Subtitle D waste facilities.

Application of MULTIMED to the design and analysis of Subtitle D disposal facilities

The US EPA has developed several restrictions for Subtitle D applications of MULTIMED. Since in this project we are only interested in these applications, our review of MULTIMED is limited to the subset of capabilities and limitations defined by the EPA restrictions. These restrictions were made in an effort to develop a conservative approach for simulating leachate migration from Subtitle D facilities. The restrictions are:

- Only the Saturated and/or Unsaturated Modules may be active in Subtitle D applications, because the Surface Water, Landfill and Air Modules have not yet been sufficiently tested.

- Although MULTIMED can simulate either steady-state or transient transport conditions, only steady-state transport simulations are allowed for Subtitle D applications. No decay of the source term is allowed; the concentration of contaminants entering the aquifer system must be constant in time. The contaminant pulse is assumed continuous and constant for the duration of the simulation.

- The receptor must be located directly downgradient of the facility, so that it intercepts the center of the contaminant plume. In addition, the contaminant concentration must be calculated at the top of aquifer. Therefore, the angle from the plume centerline to the receptor and the vertical distance to the receptor must be specified as zero in Subtitle D applications.

- Only the Gaussian source geometry is allowed in Subtitle D applications.

Thus, MULTIMED can be applied at Subtitle D land disposal facility sites to simulate the transport of contaminants from the source, through the saturated and/or unsaturated zones by groundwater, to a receptor (i.e., a well). When MULTIMED is used in conjunction with a separate source model, such as HELP (Schroeder et al., 1994a, b), it can be used in a variety of applications. These applications include 1) development and comparison of the effects of different facility designs on groundwater quality, 2) prediction of the results of different types of "failure" of the landfill, and 3) if leachate migration into the groundwater below an existing waste disposal facility occurs, prediction of the fate and transport of the contaminants in the subsurface.

Flow and transport in the subsurface typically occurs through the unsaturated zone, to the water table and into the saturated zone. However, in some instances, the water table may be located just below the waste disposal facility, so that only saturated flow and transport away from the facility need to be considered. Therefore, two basic simulation options are allowed for Subtitle D applications of MULTIMED: 1) flow and transport in the unsaturated zone coupled with transport in the saturated zone or 2) saturated transport only.

The design of Subtitle D waste facilities using MULTIMED includes the following steps: (1) Collect site-specific hydrogeologic data, (2) Determine the contaminant to be simulated and the point of compliance, (3) Propose a landfill design and determine the corresponding infiltration rate, (4)Select the active modules in MULTIMED, (5) Run MULTIMED and calculate the dilution attenuation factor (i.e., the factor by which the concentration is expected to decrease between the landfill and the point of compliance), and (6) Based on the resulting dilution attenuation factor (DAF), determine if the design is acceptable.

The EPA-recommended criteria for establishing whether or not a particular design is acceptable is very simple: if the DAF is equal to or greater than 100, the design is acceptable. The threshold DAF of 100 is used to define an acceptable design because the maximum allowable leachate concentration of chemicals expected to exist in a Subtitle D landfill is 100 times the Maximum Contaminant Level (MCL) for each chemical (US EPA, 1990). This approach to determining the expected concentration of constituents in leachate from a Subtitle D landfill is attractive because of its consistency with other regulations and its generic nature. (However, if site-specific conditions permit the use of other approaches which are acceptable to an approved state, these may be used.)

Model Output

MULTIMED computes contaminant concentrations at a certain receptor located a certain distance downgradient from the site. It is assumed that the receptor (i.e., a well) is on the plume centerline and screened at the top of the aquifer. Concentrations are computed at times specified by the user.

Model Input

Only three of the seven modules in MULTIMED can be used for Subtitle D applications of the model: the Saturated Zone Transport Module, the Unsaturated Zone Flow Module, and the Unsaturated Zone Transport Module. The Saturated Zone Transport Module is required for all Subtitle D applications and can be applied independently of the Unsaturated Zone Modules. Depending on site-specific conditions, the Unsaturated Zone Modules may or may not be needed.

The operation of each module requires specific input, which is organized into data groups. The General Data Group, which is required for all simulations, contains flags and data which describe the scenario being modeled. The input parameters needed for the Saturated Zone Transport Module are found in three additional data groups: the Chemical Data Group, the Source Data Group, and the Aquifer Data Group. Use of the Unsaturated Zone Modules requires input found in the same data groups, as well as two others: the Unsaturated Zone Flow Data Group and the Unsaturated Zone Transport Data Group.

We list below the primary parameters used by the three modules, organized by data groups. Other parameters can also be specified by the user, typically when some of the primary parameters are not known and are to be derived by MULTIMED (methods used to derive parameters are described in detail by Salhotra et al., 1993). For example, the overall decay coefficient can be calculated as a function of the biodegradation rate, solid phase decay coefficient, dissolved phase decay coefficient, bulk density, distribution coefficient, and porosity. An exhaustive list of all the possible parameters is not provided here (see instead Sharp-Hansen et al., 1993).

a) Parameters in the Saturated Zone Transport Module. Source parameters are: area of the land disposal facility, leachate concentration at the waste facility, freshwater recharge rate into the aquifer, infiltration rate from the facility, standard deviation (i.e., spread) of the source. Aquifer parameters are: type of source geometry (only Gaussian allowed), porosity, thickness of the aquifer, thickness of source (i.e., mixing zone depth), seepage velocity, dispersivities (longitudinal, transverse, vertical), retardation coefficient, radial distance from the site to the receptor. Chemical parameters are: effective first-order decay coefficient and distribution coefficient.

b) Parameters in the Unsaturated Zone Flow Module. The only source parameter is the infiltration rate from the facility. Unsaturated zone parameters are: number of physical flow layers, number of porous materials, thickness of each layer, material associated with each layer, and a number of properties of each material (air entry pressure head, porosity, saturated hydraulic conductivity, residual saturation (water content), van Genuchten alpha and beta coefficients, and - if desired - Brooks and Corey exponent).

c) Parameters in the Unsaturated Zone Transport Module. Parameters required in the unsaturated zone transport module for Subtitle D applications of MULTIMED. Although there is actually a choice of two modules to model transport in the unsaturated zone, the parameters required are the same, with the exception of the Freundlich coefficient and Freundlich exponent, which are required in the numerical but not in the analytical module. The only source parameter is the source concentration at top of unsaturated zone. Unsaturated zone transport parameters are the control parameters related to the evaluation schemes used in the module, the number of materials used to simulate transport (this value was input for the flow module), and the characteristics of each material (longitudinal dispersivity, bulk density of the soil, biodegradation rate, and percent organic matter; if the numerical solution is selected, the Freundlich coefficient and Freundlich exponent are also required). The only unsaturated zone flow parameter is the porosity of the unsaturated zone. Aquifer parameters are the temperature and pH of the aquifer. Chemical parameters are the normalized distribution coefficient (i.e., Koc), reference temperature, acid and base hydrolysis rates at reference temperature, and neutral hydrolysis rate at reference temperature.

d) Additional Parameters. Although many more parameters are required to run MULTIMED, we have only listed those that correspond to the primary physical variables of the flow and transport processes. For the sake of brevity we do not list here the control parameters that affect the type of output, the numerical solution, or the Monte Carlo simulations. Most of the parameters (e.g., those related to material properties and functional relationships) are assigned default values which can be used in the absence of site-specific data. The MULTIMED manual (Sharp-Hansen et al., 1993) provides all the details necessary to run MULTIMED, as well as a number of examples and guidance on selecting appropriate parameter values..

e) Parameters of Monte Carlo Simulation. When MULTIMED is run in Monte Carlo mode (see Uncertainty Analysis section), input parameters selected by the user are represented with a probability distribution instead of a constant value. The user defines the distribution with a small number of parameters, like the mean, variance, minimum, and maximum. For this reason, the number of parameters - and the supporting data - is always larger for Monte Carlo simulations than for deterministic runs of MULTIMED.

Uncertainty Analysis

The fate of contaminants critically depends on a number of media-specific parameters. Typically many of these parameters exhibit spatial and temporal variability (as well as variability due to measurement errors). We may consider some of these parameters to be uncertain when they have a significant amount of variability, or when we are unable to assess their variability because of insufficient data. Uncertainty in model predictions results from our inability to characterize a site in terms of the boundary conditions or the key parameters describing the important flow and transport processes (National Research Council, 1990). Uncertainty analysis is a way of quantifying the uncertainty in the model output resulting from uncertain inputs. MULTIMED can be used to perform Monte Carlo simulations, one of the most versatile techniques of uncertainty analysis.

MULTIMED may be run in either a deterministic or a Monte Carlo framework. In a deterministic simulation, exactly one model result is determined for a given set of input values. All of the input variables are assumed to have a fixed mathematical relationship with each other, which completely define the system. On the other hand, in a Monte Carlo simulation the user has to quantify uncertain input parameters in terms of a probability distribution rather than a single deterministic value. When using the Monte Carlo option, MULTIMED generates input values according to the probability distributions specified, calculates the output values for each set of inputs, and performs statistical analyses of the output to evaluate their uncertainty. This technique involves running a model a large number of times with different values of input parameters. The user/modeler has to determine which input parameters are uncertain at a particular site.

However, the Monte Carlo option requires more data than a deterministic run of the model. Defining a probability distribution for a parameter requires additional information, for example the minimum and maximum values, the mean and standard deviation. And statistical measures such as mean and standard deviation may require large amounts of data to be accurately determined.

Assumptions and Limitations

By definition all models are simplified versions of reality, incorporating relatively few processes and a limited number of parameters (often required to be constant in space and time). MULTIMED is no exception; the representation of the system simulated by the model is simple, and little or no spatial or temporal variability is allowed for the parameters in the system. In addition, the analytical models included in MULTIMED require simplifying assumptions about the system which are not necessary for numerical models. The modeler first determines which conditions and processes are important at a specific site, compares them to the features of a particular model, and determines the degree of confidence to be assigned to the model results. In many cases, simple but comprehensive models such as MULTIMED can be used as tools to qualitatively understand the behavior of complex systems. In this section we examine the main assumptions made in MULTIMED and the associated limitations; both should be carefully considered when applying MULTIMED to a waste disposal site.

a) Processes not Included in the Model. MULTIMED cannot simulate processes such as flow in fractures and chemical reactions between contaminants, which can have a significant effect on the concentration of contaminants at a site. Another example is the assumption of equilibrium adsorption (either linear or non-linear), which may not be valid in some systems. Since a host of other processes are not included, perhaps is easier for the user to keep in mind those processes that are included (reviewed in a previous section).

b) Solution Methods. MULTIMED utilizes analytical, semi-analytical, and numerical solution techniques to solve the mathematical equations describing flow and transport. The analytical and semi-analytical solution techniques have advantages and disadvantages over fully numerical models. Analytical solutions are computationally more efficient than numerical simulations and are more conductive to uncertainty analysis (i.e., Monte Carlo techniques). Typically, input data for analytical models are simple and they do not require detailed familiarity with the code or extensive modeling experience. Analytical solutions are typically the most efficient alternative when data necessary for the characterization of the system are sparse (Javandel et al., 1984). The limited data available in most field situations may not justify the use of a detailed numerical model; in some cases, results from simple analytical models may be just as meaningful (Huyakorn et al., 1986).

c) Source Representation. MULTIMED uses a simple representation of the source of groundwater contamination. The source geometry can be simulated either as a patch source (not allowed for Subtitle D applications) or as a Gaussian-distributed source. If the actual source has to be described with more complicated distributions, the impact on contaminant transport can be significant.

d) Heterogeneity of Hydrogeologic System. A highly complex hydrogeological system cannot be accurately represented with MULTIMED. Heterogeneous or anisotropic aquifer properties, multiple aquifers and complicated boundary conditions cannot be simulated using this model. Bond and Hwang (1988) present guidelines for determining whether the assumption of uniform aquifer properties is justified at a particular site.

e) One-Dimensional Modeling. Although actual landfills and groundwater systems are three-dimensional, it is common to model them as two- or even one-dimensional, as in MULTIMED. Tradeoffs include model simplicity, amount of data available, and computational requirements. There are no simple rules to guide this choice. Often times the migration of contaminant plumes is subject to three-dimensional effects and using a one-dimensional model may produce inaccurate results. But in some instances, a one-dimensional model may adequately represent the system. MULTIMED models flow and transport processes as one-dimensional; vertical in the unsaturated zone and horizontal in the saturated zone (although dispersion in the saturated zone has lateral and vertical components as well). The assumption of flow only in the vertical direction may not be valid in facilities where surface soils (covers or daily backfill) or surface slopes result in an increase of runoff in certain areas of the facility and ponding of precipitation in others (Kirkham et al., 1986). The simulation of one-dimensional, horizontal flow in the saturated zone in turn requires several assumptions: the saturated zone is treated as a single, horizontal aquifer with uniform properties, so that the effects of pumping or discharging wells on the groundwater flow system cannot be considered.

f) Steady-State Versus Transient Modeling. MULTIMED generally assumes steady-state flow in all applications; this assumption simplifies the mathematical equations and reduces the amount of input data. However, some input variables such as precipitation may have strong seasonal components, invalidating the assumption of constant recharge of the groundwater system. In general, this assumption will cause underestimation of contaminant concentrations in the subsurface, since steady-state models can not simulate the effects of individual storms, which can provide a substantial driving force for contaminant transport. Although MULTIMED can simulate either steady-state or transient transport conditions, the US EPA has recommended that the contaminant source be assumed continuous and constant. If these assumptions can not be made at a particular site, modeling results will be inaccurate, although on the conservative side. Steady-state models are also inappropriate when the simulation includes chemicals which sorb or transform significantly (Mulkey et al., 1989).

g) Data Requirements of Monte Carlo Simulations. Although the Monte Carlo method can be a useful tool for quantitatively evaluating uncertainty in a model, it is not without problems. Determining the cumulative probability distribution for a given parameter requires large amounts of data, which may not be available. And assuming a parameter probability distribution when the distribution is unknown does not help to reduce uncertainty, as the certainty of the output is then a function of the assumed certainty of the input parameter (US EPA, 1988).

D. Concluding Statement

The two models reviewed are not alternatives but complement each other. HELP is a water budget model of the landfill itself and 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. When this module is tested and approved, MULTIMED will become a self-contained model for source evaluation and contaminant transport.

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