GEOHYDROLOGY OF THE UNSATURATED ZONE AND SIMULATED TIME OF ARRIVAL OF LANDFILL LEACHATE AT THE WATER TABLE, MUNICIPAL SOLID WASTE LANDFILL FACILITY, U.S. ARMY AIR DEFENSE ARTILLERY CENTER AND FORT BLISS, EL PASO COUNTY, TEXAS

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 97-4036

Prepared in cooperation with the

U.S. DEPARTMENT OF THE ARMY,
U.S. ARMY AIR DEFENSE ARTILLERY CENTER AND FORT BLISS

Albuquerque, New Mexico
1999

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PLATE

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch	25.40	millimeter
foot	0.3048	meter
mile	1.609	kilometer
acre	0.4047	hectare
feet per second	30.480	centimeters per second
feet per mile	0.1894	meters per kilometer
ton	907.1848	kilogram
quart	0.9464	liter
gallon	3.785	liter

Temperature in degrees Celsius (°C) or degrees Fahrenheit (°F) can be converted as follows:

$$°F = 1.8\ (°C) + 32$$

$$°C = 5/9\ (°F - 32)$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

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Abstract

The U.S. Air Defense Artillery Center and Fort Bliss Municipal Solid Waste Landfill Facility (MSWLF) is located about 10 miles northeast of downtown El Paso, Texas. The landfill is built on the Hueco Bolson, a deposit that yields water to five public-supply wells within 1.1 miles of the landfill boundary on all sides. The bolson deposits consist of lenses and mixtures of sand, clay, silt, gravel, and caliche. The unsaturated zone at the landfill is about 300 feet thick. The Hydrologic Evaluation of Landfill Performance (HELP) and the Multimedia Exposure Assessment Model for Evaluating the Land Disposal of Wastes (MULTIMED) computer models were used to simulate the time of first arrival of landfill leachate at the water table.

Site-specific data were collected for model input. At five sites on the landfill cover, hydraulic conductivity was measured by an in situ method; in addition, laboratory values were obtained for porosity, moisture content at field capacity, and moisture content at wilting point. Twenty-seven sediment samples were collected from two adjacent boreholes drilled near the southwest corner of the landfill. Of these, 23 samples were assumed to represent the unsaturated zone beneath the landfill. The core samples were analyzed in the laboratory for various characteristics required for the HELP and MULTIMED models: initial moisture content, dry bulk density, porosity, saturated hydraulic conductivity, moisture retention percentages at various suction values, total organic carbon, and pH. Parameters were calculated for the van Genuchten and Brooks-Corey equations that relate hydraulic conductivity to saturation. A reported recharge value of 0.008 inch per year was estimated on the basis of soil-water chloride concentration.

The HELP model was implemented using input values that were based mostly on site-specific data or assumed in a conservative manner. Exceptions were the default values used for waste characteristics. Flow through the landfill was assumed to be at steady state. The HELP-estimated landfill leakage rate was 101.6 millimeters per year, approximately 500 times the estimated recharge rate for the area near the landfill.

The MULTIMED model was implemented using input values that were based mainly on site-specific data and some conservatively assumed values. Landfill leakage was assumed to begin when the landfill was established and to continue at a steady-state rate of 101.6 millimeters per year as estimated by the HELP model. By using an assumed solute concentration in the leachate of 1 milligram per liter and assuming no delay or decay of solute, the solute serves as a tracer to indicate the first arrival of landfill leachate. The simulated first arrival of leachate at the water table was 204 to 210 years after the establishment of the landfill.

INTRODUCTION

The U.S. Army Air Defense Artillery Center and Fort Bliss (USAADACENFB) military reservation is located within the extraterritorial jurisdiction of the City of El Paso and extends into unincorporated portions of El Paso County, Texas, and Doña Ana and Otero Counties, New Mexico (fig. 1). The primary missions of the USAADACENFB are air defense artillery training, senior noncommissioned officers training, administrative and logistical support of tenant activities, and provision of training facilities for reserve components. The USAADACENFB military

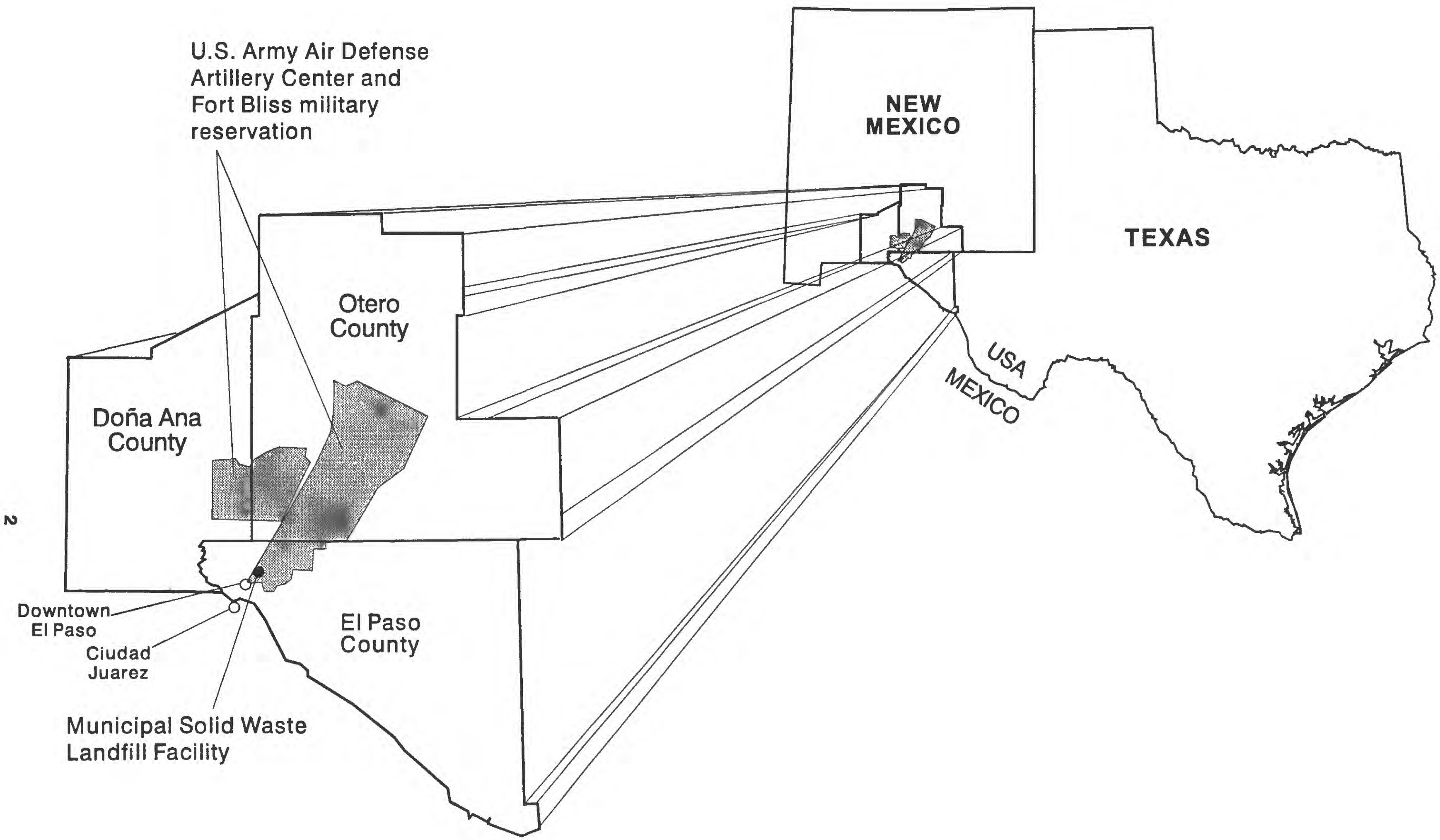


Figure 1.--Location of U.S. Army Air Defense Artillery Center and Fort Bliss military reservation, Texas and New Mexico.

reservation serves a total post population of more than 90,000 (Population Performance Factors, March 1994, U.S. Army Air Defense Artillery Center and Fort Bliss, written commun., April 26, 1994), including military and civilian personnel, on- and off-post family members, and retirees. The population of the El Paso metropolitan area is greater than 600,000. Directly south of El Paso, Ciudad Juarez, Mexico (fig. 1) has a population greater than 1,000,000.

The USAADACENFB Municipal Solid Waste Landfill Facility (hereafter referred to as "MSWLF" or "landfill") was established in January 1974 and is estimated to receive an average of approximately 56 tons of municipal solid waste per day. Types of solid wastes disposed of at the MSWLF include household refuse, administrative solid wastes, bulky items, grass and tree trimmings from family housing, refuse from litter cans, construction debris, classified waste (dry), dead animals, asbestos, and empty oil cans (1-quart and 5-gallon sizes). The landfill area is 106 acres, and the fill rate is 1 to 4 acres per year. The MSWLF is expected to reach its capacity by 2004 at this fill rate; approximately 15 acres of the permitted area will not be filled. The USAADACENFB Directorate of Public Works and Logistics manages contract operation of the MSWLF. The private contractor also provides refuse collection and disposal services.

The MSWLF is located about 10 miles northeast of downtown El Paso, Texas (fig. 1). The MSWLF is about 1,200 feet east of the nearest occupied structure. Most Fort Bliss land within 1 mile of the landfill is vacant (fig. 2).

The USAADACENFB is evaluating hydrogeologic conditions of the MSWLF to implement requirements of Federal and State of Texas regulatory programs. In 1994, the U.S. Geological Survey, in cooperation with the U.S. Army, initiated a study of the MSWLF to identify hydrogeologic conditions at the facility. Thus far, this study has resulted in a geohydrologic site characterization (Abeyta, 1996); design, installation, and monitoring of a methane monitoring network; and design of a ground-water monitoring network. This information is being used by the U.S. Army to aid in fulfilling regulatory requirements at the facility as specified in U.S. Environmental Protection Agency (USEPA) 40 Code of Federal Regulations (CFR) Parts 257 and 258, Subtitle D (U.S. Environmental Protection Agency, 1993) and 30 Texas Administrative Code (TAC) 330 (Texas Natural Resources Conservation Commission, 1993a,b), administered by the Texas Natural Resources Conservation Commission (TNRCC).

In 1995, the U.S. Geological Survey, in cooperation with the U.S. Army, initiated an investigation to determine the potential for migration of leachate from the MSWLF to the uppermost aquifer during the active life and the closure and post-closure care period of the landfill. To conduct this investigation, the TNRCC (Compliance and Enforcement Section, Municipal Solid Waste Division, Texas Natural Resources Conservation Commission, oral commun., October 4, 1994) suggested using two USEPA models: the Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder, Dozier, and others, 1994; Schroeder, Lloyd, and others, 1994) for evaluating the production of leachate by the landfill and the Multimedia Exposure Assessment Model for Evaluating the Land Disposal of Wastes (MULTIMED) model (Salhotra and others, 1993; Sharp-Hansen and others, 1993) for evaluating the transport of solutes from the landfill to the water table.

Site-specific data were collected for use with the HELP and MULTIMED models. In April and May 1995, two boreholes were drilled to collect soil samples, cores, and geophysical data. The drill site is located near the southwest corner of the landfill (fig. 3). Borehole BH-3 was drilled with a hollow-stemmed auger to a depth of 55 feet. Borehole MSWLF03 was drilled adjacent to borehole BH-3, using mud-rotary drilling techniques, to a depth of 351 feet and was completed as a ground-water monitoring well. Soil samples were collected during the drilling process for analysis of physical properties, soil moisture, chloride concentration, and soil chemistry. Physical-property data were used as input for the HELP and MULTIMED models. Geophysical and lithologic logs were used to generalize physical properties of the unsampled parts of the unsaturated zone. Soil-moisture and chloride data were used to estimate ground-water recharge in the vicinity of the MSWLF (P.F. Frenzel, Hydrologist, U.S. Geological Survey, written commun., 1997) and indirectly to evaluate results of the HELP model. Soil chemistry data were reported to characterize the soil chemistry, but were not directly related to the HELP or MULTIMED models. During October 1995, in situ measurements of hydraulic conductivity of the landfill cover were made; landfill-cover samples also were collected and analyzed for moisture retention characteristics. These data were used in the HELP model and are reported in Abeyta and Frenzel (1999a).

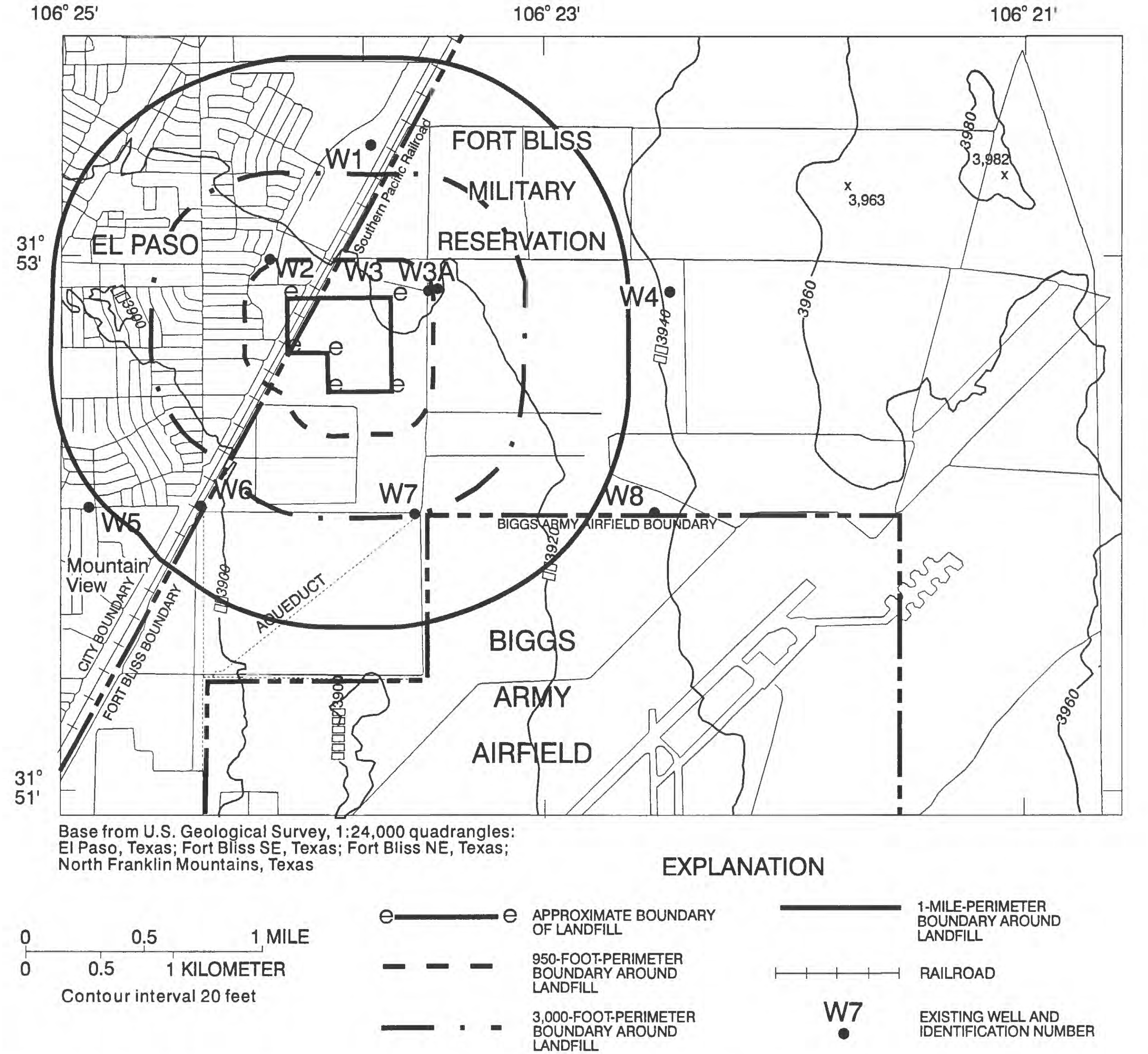
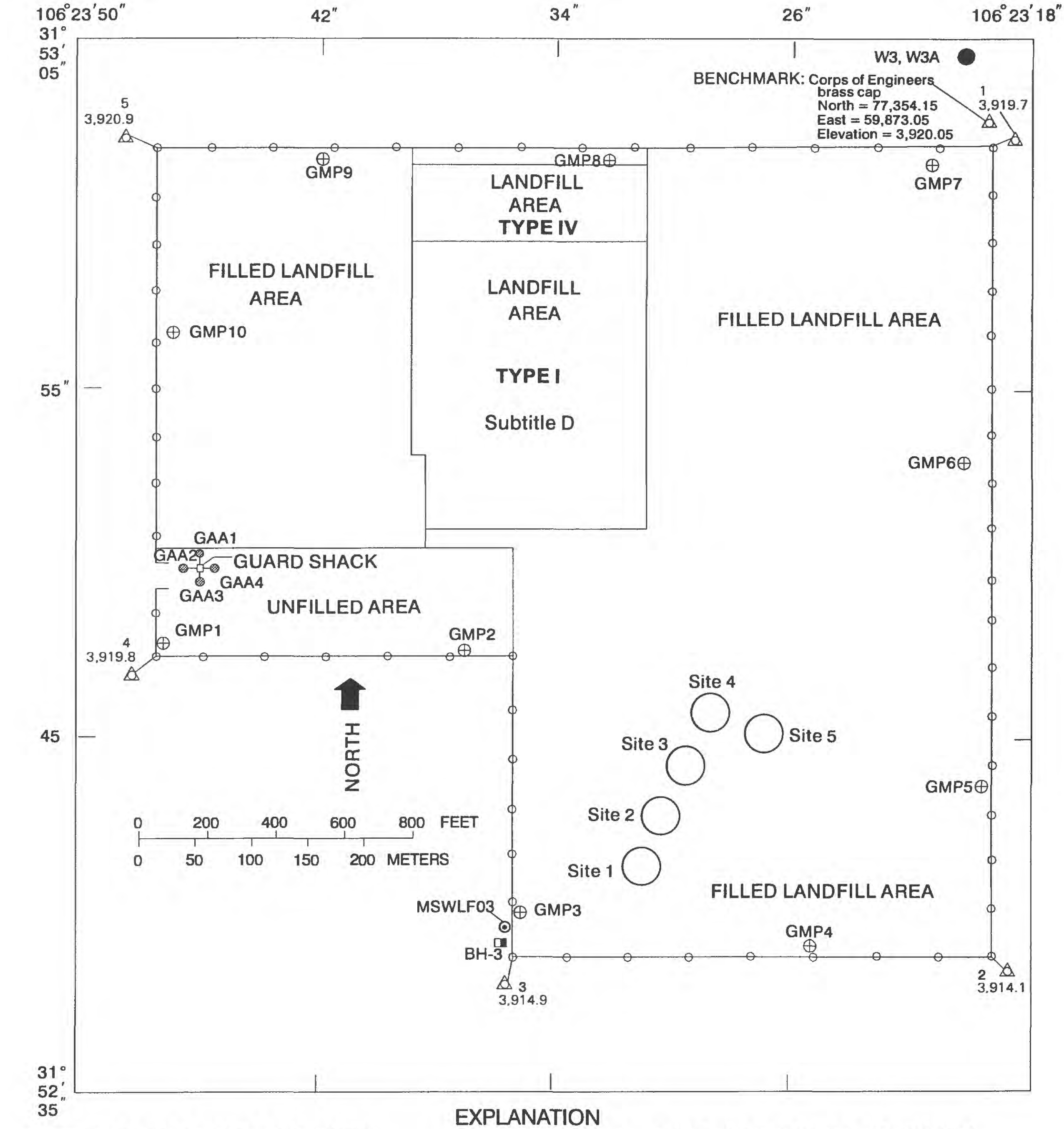


Figure 2.--Location of U.S. Army Air Defense Artillery Center and Fort Bliss Municipal Solid Waste Landfill Facility, Texas.



EXPLANATION

FENCE/LANDFILL BOUNDARY

4 3,919.8 CONTROL POINT -- Identification number and elevation, in feet above sea level

W3, W3A GROUND-WATER PRODUCTION WELL AND IDENTIFICATION NUMBER

MSWLF03 GROUND-WATER MONITORING WELL AND IDENTIFICATION NUMBER

BH-3 BOREHOLE AND IDENTIFICATION NUMBER

GMP1 METHANE-MONITORING WELL AND IDENTIFICATION NUMBER

GAA4 AMBIENT-AIR METHANE-MONITORING SITE AND IDENTIFICATION NUMBER

Site 1 LANDFILL-COVER SAMPLING SITE AND IDENTIFICATION NUMBER

TYPE I STANDARD LANDFILL FACILITY FOR DISPOSAL OF MUNICIPAL SOLID WASTE

TYPE IV FACILITY AUTHORIZED FOR DISPOSAL OF BRUSH, CONSTRUCTION-DEMOLITION WASTE, AND RUBBISH THAT ARE FREE OF PUTRESCIBLE AND HOUSEHOLD WASTES

Figure 3.--Ground-water production and monitoring wells, borehole BH-3, methane-monitoring locations, and boundary conditions at and adjacent to the U.S. Army Air Defense Artillery Center and Fort Bliss Municipal Solid Waste Landfill Facility.

In this report, the uppermost aquifer underlying the MSWLF is defined as the water table. The active life of the landfill is approximately 30 years; filling at the MSWLF started in 1974 and is projected to end by 2004. Closure was assumed to take no longer than about 4 or 5 years. The period of post-closure monitoring was assumed to be 30 years, the same as that established by regulation for Subtitle D landfills (30 TAC 330.254b). The active life, closure, and post-closure period total about 65 years. The potential usefulness of ground-water monitoring depends on the likelihood of ground water being contaminated during the period of monitoring. Thus, the time before the first arrival at the water table of leachate from the MSWLF needs to be estimated. The HELP model was used to estimate the leakage from the landfill, and the MULTIMED model was used to estimate the delay between the first introduction of landfill leakage at the top of the unsaturated zone and the first arrival of leachate at the water table, assuming no delay or decay of solutes in the landfill or unsaturated zone. This estimate is relevant only for contaminants potentially carried as leachate solutes and does not apply to other possible mechanisms of contaminant movement.

Purpose and Scope

This report describes the use and results of the HELP and MULTIMED models in the estimation of the time of first arrival at the water table of leachate from the MSWLF. A brief discussion of the climate, physiography, Hueco Bolson, water development in the vicinity of the landfill, and the geohydrology of the landfill and unsaturated zone is provided. Because the end point of the flow system that was studied is at the water table, the hydrology of the saturated zone is not included. The description of the implementation of the HELP and MULTIMED models is organized around the model input, which is discussed item by item. A geohydrologic site characterization of the MSWLF, which was based mostly on existing information, is presented in a report by Abeyta (1996).

Climate

The climate of the MSWLF and vicinity is classified as arid continental and is characterized by an abundance of sunny days, high summer temperatures, relatively cool winters typical of arid areas, scanty rainfall, and very low humidity throughout the year. Temperature and precipitation data are recorded at the El Paso International Airport by the National Weather Service and reported in monthly and annual reports by the National Oceanic and Atmospheric Administration. The El Paso International Airport is located approximately 4.5 miles southeast of the MSWLF.

Mean annual precipitation in the El Paso area is 7.8 inches (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 1992). Average monthly precipitation ranges from less than 1 inch during October through June to more than 1.2 inches in July, August, and September. Winter months are typically dry, and monthly snowfalls seldom exceed 3 inches (approximately 0.25 inch of water). Snow rarely lasts longer than 24 hours in the nonmountainous areas. Typically the rainy months receive almost half the annual precipitation in the form of brief but locally heavy thunderstorms. Prolonged periods of continuous precipitation are rare.

The average annual temperature at the El Paso International Airport is 63.3 °F, ranging from a mean monthly low of 44.2 °F in January to a mean monthly high of 82.5 °F in July (U.S. Department of Commerce, National Oceanic and Atmospheric Administration, 1992). Summer daytime temperatures are frequently above 90 °F and occasionally rise above 100 °F. Summer night minimum temperatures are usually 60 to 65 °F. Winter days are cool and mild, and temperatures rise to 55 to 60 °F. Winter night temperatures drop to below freezing during several nights in December and January.

The prevailing wind direction in the winter months is from the north. In the summer months, the prevailing wind direction is from the south. Dust and wind storms are frequent in March and April, and wind speeds occasionally exceed 35 miles per hour.

Mean annual pan evaporation for 1985-92 was about 93 inches. Sixty-one percent of the evaporation occurred during April through August. Actual evapotranspiration, almost always less than pan evaporation, depends on the availability of moisture in the soil and on other conditions such as vegetation. Relative humidity in the Fort Bliss/El Paso area is generally low, ranging from an average 31 percent during the second quarter of the year to an average 51 percent during the fourth quarter.

Physiography

The MSWLF and most of Fort Bliss military reservation lie in an intermontane valley. The Franklin Mountains are about 4 miles west of the MSWLF, and the Hueco Mountains are about 25 miles east (Abeyta, 1996, fig. 5). The land surface is gently sloping near the mountains and nearly flat near the north-to-south axis of the valley. In the area west of the MSWLF, moderately defined arroyos extend from the Franklin Mountains and drain into the ground 2 or more miles west of the MSWLF. The arroyos flow only in response to intense precipitation during thunderstorms. Although the south end of the valley is drained by the Rio Grande, there is no defined surface drainage on the hummocky land surface around the MSWLF. The Franklin Mountains have peaks from 4,600 feet to greater than 7,000 feet above sea level. Elevations of the terrain around the MSWLF range from about 3,912 feet on the south side to about 3,921 feet above sea level on the north side. The land surface near the MSWLF generally slopes about 20 feet per mile toward the south-southwest. The landfill surface rises to about 10 to 15 feet above the surrounding terrain.

Description of the Hueco Bolson

The MSWLF is underlain by Hueco Bolson deposits of locally derived materials. "Bolson" is a Spanish word meaning "big purse" and, in this context, means "basin" or "graben." The Hueco Bolson is a clastic-filled graben extending from a few miles north of the New Mexico-Texas border to several miles south into Mexico. Hueco Bolson deposits are of Tertiary age and primarily include fluvial and lacustrine deposits, although alluvial-fan material and eolian sediments also are present (Cliett, 1969). Hueco Bolson deposits are reported to have a maximum thickness of about 9,000 feet within a deep structural trough paralleling the east base of the Franklin Mountains (Mattick 1967, p. 85-91; Abeyta, 1996, fig. 9).

Hueco Bolson deposits typically are composed of unconsolidated to slightly consolidated, fine- to medium-grained sand with interbedded lenses of clay, silt, gravel, and caliche. Sand fragments are composed primarily of chert, granite, and porphyry. Individual beds are not well defined and range in thickness from a fraction of an inch to about 100 feet.

Consolidated igneous and sedimentary rocks ranging in age from Precambrian to Tertiary are exposed in the Franklin and Hueco Mountains. Igneous rocks are predominantly granitic and are composed of coarse grains of quartz and feldspar. These granitic rocks are easily weathered and are a primary source material of the bolson deposits.

Near-surface soils on the MSWLF, of the Hueco-Wink association, are nearly level to gently sloping, have a fine sandy loam subsoil, and are moderately deep over caliche (Jaco, 1971). Loam denotes a mixture of clay (7 to 27 percent), silt (28 to 50 percent), and sand (less than 52 percent). Surficial soils are described to a depth of about 5 feet; these descriptions generally are not applicable to the deeper part of the unsaturated zone through which landfill leachate may migrate toward the water table. To a depth of about 14 feet, however, the soil at borehole BH-3 was very similar to that at land surface.

Water Development in the Vicinity of the Landfill

Wells completed in the unconsolidated and slightly consolidated sedimentary deposits of the Hueco Bolson supply water for the City of El Paso, Ciudad Juarez, Fort Bliss military reservation, private industries, and agriculture. Wells yielding large amounts of water usually are drilled at least 200 feet into saturated material. The municipal water system of the City of El Paso and Fort Bliss is supplied by wells ranging in depth from about 600 to greater than 1,200 feet. Water pumped from wells in the vicinity of the MSWLF is mostly for municipal use.

The nearest public supply wells are located about 350 feet north of the MSWLF. Well W3, which is now plugged and abandoned, was in operation for several years; well W3A is a newly completed well located adjacent to W3 (fig. 2). These wells are owned by the U.S. Army. Five other wells are within 1.1 miles of the landfill on all sides (fig. 2). Well W6 is used for observation, and the others are used for public supply.

Depth to water in the vicinity of the MSWLF is greater than 300 feet and has been increasing. Water levels declined 55.65 feet from November 1958 to December 1987 in well W3 (well JL-49-05-904; Abeyta, 1996, table 4), an average of more than 1.8 feet per year. At the new production well W3A, near the northeast corner of the landfill, the water level was 325.8 feet below land surface on July 26, 1994. These production wells are completed at least 250 feet below the water table (Abeyta, 1996, table 4). At monitoring well MSWLF03 (fig. 3), which is completed at the water table near the southwest corner of the landfill, the water level in the open, uncased hole (based on geophysical logs) was 305 feet below land surface on May 4, 1995; this water level was used for the model analysis. After completion, development, and recovery of well MSWLF03, water levels in the well, in feet below land surface, were 310.21 on May 15; 312.84 on October 20; and 313.18 on November 28, 1995. Although these water levels were measured during a high water-use season of the year, they may indicate that the water table was falling faster in 1995 than the average decline indicated above for the production zone. The rate of water-table decline in an observation well generally can be expected to lag behind and to be somewhat steadier than that in production wells. Because of pumping of production wells surrounding the MSWLF, the direction of horizontal ground-water flow at the water table cannot be inferred with certainty; horizontal flow direction, however, is not relevant to estimating the first arrival of leachate at the water table.

Acknowledgments

The authors acknowledge Joe Vinson, Mark Ankeny, and Mark Prieksat, of Daniel B. Stephens and Associates, Inc., for their consultation on theory and approaches to this study. Paul Schroeder, U.S. Army Corps of Engineers, provided information regarding the HELP model, and Gerry Laniak, USEPA, provided information regarding the MULTIMED model.

DESCRIPTION OF THE MUNICIPAL SOLID WASTE LANDFILL FACILITY

Landfill Construction

The MSWLF consists of excavated trenches 40 feet wide by 30 feet deep. The method of land filling is progressive trench, where excavation and filling are done simultaneously (Abeyta, 1996, p. 4). Refuse is dumped at the end of the trench, then spread and covered by a crawler tractor. Daily cover of a minimum of 6 inches of compacted earth and a final landfill cover of 2 to 3 feet are provided. The TNRCC approved a permit modification to construct landfill cells within the MSWLF (labeled Subtitle D in fig. 3), complying with 1993 Federal requirements. Each Subtitle D landfill cell was designed to contain a soil and geomembrane liner engineered to restrict leakage from the bottom of the landfill cell and a leachate recovery system; a cover engineered to restrict infiltration will be provided when the landfill cell is full. The fill area outside the Subtitle D area, in compliance with previous regulations, has no engineered liner, and the cover consists of 2 to 3 feet of locally available soil. For the purposes of this leakage study, the landfill areas outside the Subtitle D area are considered to be the most likely contributors to the first arrival of leachate at the water table. Therefore, no further consideration is given to the Subtitle D area.

Features of the MSWLF are shown in figure 3. A 10-foot-high chain link fence with barbed wire outriggers surrounds the entire perimeter of the facility. A 6- by 12-foot guard shack is located on the facility near the entrance. No utilities are within the perimeter of the MSWLF. The filled area extends to within about 50 feet of the perimeter fence, leaving an unfilled border around the landfill (not shown). Within this border area are 10 methane-monitoring wells, which are about 30 feet deep. Bladed access roads (not shown) surround the landfill both inside and outside the perimeter fence.

Surface Drainage

From the outside boundary, the surface of the MSWLF slopes upward at about 3 percent, then near the middle of the landfill slopes more gradually to elevations of about 10 to 15 feet above the surrounding terrain (Directorate of Public Works and Logistics, U.S. Army Air Defense Artillery Center and Fort Bliss, 1994 landfill surface-contour map, written commun., 1994). A berm at the boundary fence is generally about 1.5 feet above land surface inside the fence and about 2 feet above land surface outside the fence. Therefore, surface-water inflow to the landfill from the surrounding terrain is very unlikely. Drainage is generally from the middle of the landfill toward the outside; in the southern part of the landfill (south of the west-to-east jog in the west perimeter fence, fig. 3), however, some of the trenches have sunk, resulting in local ponding areas that intercept drainage from higher slopes. Most of the northern part of the landfill slopes toward the outside of the landfill except for the Subtitle D area, which is open. For the purposes of this leakage study, drainage from the southern part of the landfill is considered to represent that of the entire landfill.

Evapotranspiration

The rate of evapotranspiration depends on surface drainage, climate, soil, and plant conditions. Surface drainage, climate, and soil were discussed previously in this report. Most of the northern part of the landfill has no plant cover. Small mesquite, less than 2 feet high, and a multitude of grasses and forbs grow in clusters about 6 to 12 inches high on the southern part of the landfill. Between the clusters is bare ground. The terrain outside the landfill is covered with similar vegetation except that the mesquite is 6 to 8 feet high and the next most visible plant is yucca.

P.F. Frenzel (written commun., 1997) estimated recharge in the vicinity of the MSWLF, using a soil-water chloride method (Allison and Hughes, 1978), to be about one-thousandth of precipitation, or an average of about 0.008 inch per year. Stephens and Coons (1994) estimated approximately the same rate of recharge using the same method for a site in Doña Ana County, New Mexico, 13 miles southwest of the MSWLF. The remainder, or about 99.9 percent of precipitation, is taken up by evapotranspiration. Therefore, evapotranspiration accounts for almost all precipitation because of the climate and natural vegetation in the vicinity of the MSWLF. On the landfill, evapotranspiration may vary somewhat because of less mature vegetation, runoff from the sloping landfill surface, disturbance of soils, and soils intermixed with waste materials. However, the estimated recharge for the surrounding land indicates how low landfill leakage could be in this climatic setting. For the purpose of estimating leakage from the landfill, evapotranspiration was calculated by the HELP model on the basis of simulated surface drainage and climate, specified soils, and vegetative cover.

Hydrologic Properties of the Landfill Cover

Hydrologic properties of the landfill cover were determined mainly from in situ measurements made on the landfill cover and from cored soil samples collected from five sites on the landfill cover (fig. 3). Ten soil samples were analyzed for hydrologic properties (Abeyta and Frenzel, 1999a). The saturated hydraulic conductivity of the surface of the landfill cover was determined by an infiltrometer technique (Ankeny, 1992); other properties of the cover were determined from near-surface soil-core samples. Hydrologic properties of the waste material were not determined and are assumed to be average values as reported by Schroeder, Lloyd, and others (1994).

The landfill cover is approximately 2 to 3 feet thick (Abeyta, 1996, p. 4). The cover of the filled area, outside the Subtitle D area, is a mixture of soils excavated from the trenches and consists mainly of sand, silt, and lesser fractions of clay and pulverized caliche. Hydrologic properties of the northern part of the landfill cover, outside the Subtitle D area, were not determined because at the time of measurement (October 24, 1995) the area east of the Subtitle D area was covered with rubble and the area to the west had loose, coarse sand or fine gravel at the surface. Hydrologic properties of the southern part of the landfill cover were measured at five sites (fig. 3). At each site, in situ infiltration was measured at two places about 50 feet apart. Values of saturated hydraulic conductivity, calculated using measured infiltration rates, ranged from 0.00091 to 0.0041 centimeter per second (cm/s). After each infiltration measurement was made, a soil core was collected by forcing a brass ring into the moistened soil. The brass rings filled with soil were capped, taken to the laboratory, and tested for porosity and for percentage of water retained at "field capacity" and "wilting point." These values were necessary for the HELP model. Field capacity is defined for the purposes of the HELP model as the moisture content at a suction of 1/3 bar (Schroeder, Lloyd, and others, 1994, p. 32). Similarly, wilting point is defined as the moisture content at 15 bars of suction (one bar is a pressure equivalent to that exerted by a 1,022.7-cm head of water at 21 °C). Calculated porosity values (Abeyta and Frenzel, 1999a, table 14) ranged from 32.5 to 38.4 percent. Approximate field capacity (337-cm suction) moisture values (Abeyta and Frenzel, 1999a, table 15) ranged from 12.0 to 29.1 percent. Interpolated wilting point values ranged from 7.0 to 14.3 percent moisture (table 1) (Abeyta and Frenzel, 1999a, table 15).

Table 1.--Percent moisture content at wilting point for 10 landfill-cover samples

[Sampling sites shown in fig. 3]

Sample identifier	Moisture (percent)
Site1, rep1	13.8
Site1, rep2	11.2
Site2, rep1	13.6
Site2, rep2	9.6
Site3, rep1	14.3
Site3, rep2	10.7
Site4, rep1	9.9
Site4, rep2	8.1
Site5, rep1	9.0
Site5, rep2	7.0

GEOHYDROLOGY OF THE UNSATURATED ZONE BETWEEN THE LANDFILL AND THE WATER TABLE

Hydrologic properties between the MSWLF and the water table were determined mainly from cored sediment samples collected adjacent to the landfill. Samples collected as part of this investigation included cored sediment samples collected from borehole BH-3 and borehole MSWLF03, which was completed as a ground-water monitoring well (fig. 3). A total of 27 sediment samples were analyzed for hydrologic properties (Abeyta and Frenzel, 1999a). Hydrologic properties of 23 cored sediment samples from boreholes BH-3 and monitoring well MSWLF03 (fig. 3), assumed to represent the unsaturated zone between the landfill and the water table, were analyzed as required by the HELP and MULTIMED models.

For this study, the unsaturated zone was considered to be the 283-foot interval between the bottom of the landfill, at an elevation equivalent to a depth of 22 feet in monitoring well MSWLF03, and the 305-foot water level identified after drilling the borehole for monitoring well MSWLF03. Although the water table continues to drop at well MSWLF03 and depth to the water table at a different location could be somewhat different, conditions at well MSWLF03 were considered to represent the entire unsaturated zone below the landfill. Soils in depths shallower than 22 feet were assumed to have been incorporated into the landfill. Abeyta and Frenzel (1999a) described 43 sand zones totaling 129.5 feet and 20 clay zones totaling 21.3 feet in the unsaturated zone between the depths of 22 and 305 feet at borehole BH-3 and monitoring well MSWLF03. The total footage described (total core recovery) was 150.8 feet, or 53 percent of the 283-foot interval. Cores were not recovered from the remaining footage within that zone.

Core samples were collected to a depth of 55 feet below land surface using hollow-stemmed auger drilling techniques and a 5-foot long, 4-inch-diameter split-spoon sampler. Core samples below 55 feet were collected using mud-rotary drilling techniques and a 10-foot long, 3.5-inch-diameter split-spoon core barrel with a diamond button core bit attached to the bottom of the core barrel. Twenty-three samples representative of the recovered cores within the 283-foot unsaturated zone were collected and analyzed in the laboratory for the following characteristics: initial moisture content, dry bulk density, porosity, saturated hydraulic conductivity, moisture retention percentages at various suction values, total organic carbon, pH, and calculated parameters for the van Genuchten (van Genuchten, 1980) and Brooks-Corey (Brooks and Corey, 1966) equations that relate hydraulic conductivity to saturation. Laboratory results (Abeyta and Frenzel, 1999a, tables 20 and 22) include those for two samples from below the water table and two samples from above the level of the bottom of the landfill, which are not considered in this discussion.

The 23 values of saturated hydraulic conductivity for the unsaturated zone between the bottom of the landfill and the water table range from 8.4 x 10^{-10} to 2.5 x 10^{-2} cm/s. The median of 2.5 x 10^{-6} cm/s indicates that more than half the values are less than the minimum value for silty sand shown by Freeze and Cherry (1979, table 2.2). Although the lithologic description indicates mostly sand, most of the sand zones have modifiers indicating the presence of finer materials, for example "clayey, silty sand." These sands display hydraulic characteristics that are strongly affected by the clay and silt that are often included as thin lenses. Plate 1 shows lithologic and geophysical logs and values of saturated hydraulic conductivity. Geophysical logs were used to extrapolate information from the zones of recovered cores to the zones where cores were not recovered.

SIMULATED TIME OF ARRIVAL OF LANDFILL LEACHATE AT THE WATER TABLE USING HELP AND MULTIMED MODELS

The time of first arrival of landfill leachate at the water table below the MSWLF was estimated using the HELP model (Schroeder, Dozier, and others, 1994) and the unsaturated-zone flow and transport modules of the MULTIMED model (Salhotra and others, 1993). HELP was used to approximate the rate of steady-state leakage from the landfill. MULTIMED was used in transient mode to estimate the time of first arrival of a solute at the water table. The solute was simulated as nondecaying and nonreactive and thus served as a conservative tracer to indicate the first arrival of landfill leachate.

Description of HELP Model Code

The HELP model code, documented by Schroeder, Dozier, and others (1994), describes theoretical considerations. The HELP user's manual (Schroeder, Lloyd, and others, 1994) provides guidance for determination of model-input values and contains the software.

Considered "quasi-two-dimensional" by its authors, the HELP model simulates vertical flow through the landfill and estimates a water balance. HELP simulates daily water movement into, through, and out of the landfill, generally hydrologic surface and subsurface processes. Surface processes include snowmelt, interception of rainfall by vegetation, surface runoff, and evaporation from the surface. A surface-water balance indirectly determines daily infiltration into the landfill. The model does not allow surface evaporation to exceed the sum of surface snow storage and intercepted rainfall and assumes that snowmelt and rainfall that do not run off or evaporate infiltrate into the landfill. Subsurface processes include evaporation of water from the soil, plant transpiration, vertical unsaturated drainage, liner leakage and percolation, and lateral saturated drainage (Schroeder, Lloyd, and others, 1994, p. 29). HELP uses solution techniques that account for surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil-moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through liners constructed of geomembrane, soil, or composite materials. The model accepts weather, soil, and design data.

The HELP model assumes that soil-moisture retention properties and unsaturated hydraulic conductivity can be calculated from saturated hydraulic conductivity, porosity, field capacity, and wilting point, and that the soil-moisture retention properties fit a Brooks-Corey relation (Brooks and Corey, 1964) defined by the three soil-moisture retention properties of porosity, field capacity, and wilting point. Upon obtaining the Brooks-Corey parameters, the model assumes that the unsaturated hydraulic-conductivity/soil-moisture relation is described by an equation reported by Campbell (1974). The model does not explicitly compute flow driven by differences in suction, thus it does not simulate a capillary barrier or upward flow of water due to drying at land surface. The soil drainage rate is equal to the unsaturated hydraulic conductivity calculated as a function of moisture content. The removal of water by evapotranspiration is simulated as an extraction, given a specified evaporative-zone depth.

Runoff is computed using the Soil Conservation Service (SCS) (now the Natural Resources Conservation Service) curve method based on daily rainfall, daily snowmelt, and soil type (U.S. Department of Agriculture, Soil Conservation Service, 1985). Additionally, the procedure for computing SCS-runoff curve numbers accounts for steepness and length of slope. Adjacent areas are assumed not to drain onto the landfill.

Vegetative growth and decay are assumed to be characterized by a vegetative growth model that was developed for crops and perennial grasses. In addition, the vegetation is assumed to transpire water, shade the land surface, intercept rainfall, and reduce runoff in quantities similar to grasses or to an adjusted equivalence expressed as a "leaf area index." A leaf area index is the ratio of leaf area to land-surface area, which ranges from 0 for bare ground to 5 for heavy growth (Arnold and others, 1989).

HELP Model Implementation

The HELP model was used to estimate the rate of leakage out of the MSWLF. Preliminary runs made with the MULTIMED model indicated that the time of arrival of leachate at the water table is earlier as landfill leakage is increased. Thus, the assumptions made for the HELP model tend to err on the side of overestimating the leakage and are termed "conservative." Conservative assumptions result in an earlier estimated first arrival time of leachate at the water table. The assumptions discussed below relate to the general implementation of the HELP model; assumptions concerning specific parameters are described in the discussion of model input.

One of the general assumptions is that leakage from the waste is at steady state, implying that for each unit of moisture that flows into the waste, a unit of moisture immediately leaks out of the waste. Although waste could conceivably have initial moisture contents greater than that of the steady-state model, reported initial moisture contents for municipal solid waste range from about 8 to 20 percent by volume and average 12 percent (Schroeder, Lloyd, and others, 1994, p. 33). A true steady-state condition was not achieved with the HELP model; rather an initial moisture content was specified such that the simulated average annual flow to storage was approximately zero during a 100-year period of simulation. Because the assumed moisture-content values for municipal solid waste are less than the steady-state model value (field capacity), this assumption is conservative.

A simple landfill design that approximates the older part of the MSWLF was assumed. The assumed landfill has a 2-foot cover, 30 feet of waste, and no liner. The cover consists of a mixture of soils that were excavated from the trenches. The sediment beneath the landfill was assumed to be represented by the sample collected at the 29-foot depth in borehole BH-3. These assumptions are true for most of the landfill except the Subtitle D area (fig. 3). The Subtitle D area was assumed not to contribute to the first arrival of leachate at the water table because it is the newest part of the landfill, is equipped with an engineered liner and leachate collection system to restrict leakage, and when filled to capacity will be equipped with a cover engineered to restrict infiltration. This assumption is conservative to the extent that the improvements made to the Subtitle D area are not accounted for and the older design is assumed to apply to the entire landfill.

Description of Model Input

The HELP input data are in standard ASCII format on an IBM PC-compatible 3.5-inch disk (Abeyta and Frenzel, 1999b). Table 2 is a summary of model-input data and remarks. The rationale for the assignment of each value is explained in table 2 or in the following discussion.

Weather data were HELP default values or HELP synthetically generated values specifically for El Paso. Because the default values are for the locality of the landfill (El Paso), they were considered sufficient. The synthetically generated daily values for precipitation, temperature, and solar radiation were considered to be sufficient because they have the same statistical characteristics as local weather data (Schroeder, Lloyd, and others, 1994, p. 14-24).

For estimating evapotranspiration the maximum leaf area index was assumed to be zero--that is, the model simulated no vegetative cover. The maximum leaf area index is any value between 0 for bare ground and 5 for heavy grass cover; a 1 represents a total leaf area equal to land-surface area (Schroeder, Dozier, and others, 1994, p. 26). Although a realistic maximum leaf area index that was determined on the basis of casual observation would have been greater than zero, the assumption of zero is conservative.

Deep-rooted vegetation that might withdraw moisture from the waste and result in deep root channels extending from the surface into the waste was assumed not to exist. Therefore, the depth of the evaporative zone was not allowed to exceed the cover thickness of 2 feet. This is a relatively shallow depth for the El Paso area (Schroeder, Dozier, and others, 1994, p. 27) and could result in an overestimate of deep percolation of moisture. The shallower the depth of the evaporative zone, the less moisture-holding capacity this zone will have and the greater the likelihood of simulation of moisture percolating deeper than the evaporative zone during periods of high precipitation.

The specification of vegetation and soil texture used to determine an SCS runoff curve number is different than that for similar parameters used to simulate evapotranspiration and flow through the cover. For curve generation, the specification is restricted to the integers of 1 through 5; 1 represents bare ground and 5 represents excellent grass cover (Schroeder, Lloyd, and others, 1994, p. 36). A value of 2 was selected, which represents a poor grass cover and some resistance to runoff. The soil texture number for curve generation must be one of a selection of numbers for predefined textures (Schroeder, Dozier, and others, 1994, p. 19). Texture number 3, which represents a "fine sand," was chosen because it represents characteristics closest to those of the cover soil on the MSWLF.

The specification of surface slope, slope length, and fraction of the landfill allowing runoff was based on observation of the MSWLF and a contour map of the 1994 landfill surface (Directorate of Public Works and Logistics, U.S. Army Air Defense Artillery Center and Fort Bliss, written commun., 1994). Although slope lengths were estimated to be as great as 300 feet, drainage from only about 20 percent of the landfill was estimated to be able to reach the perimeter without being trapped in sunken trenches. The middle part of the landfill was assumed to have no runoff.

The minimum reported cover thickness of 2 feet was assumed to apply to the entire landfill. The soil cover found at cover sampling site 5 (fig. 3), characterized by large values of saturated hydraulic conductivity and small differences between moisture retention values, was considered representative of the entire landfill cover. The difference between moisture retention at field capacity and at wilting point is a measure of the capacity of the soil to retain moisture between precipitation events, leaving this moisture available for evapotranspiration. These assumptions would tend to overestimate cover leakage.

Table 2.--Hydrologic Evaluation of Landfill Performance (HELP) model-input data summary

[--, not applicable]

Feature	Unit[1]	Assigned value	Remarks
Weather and evapotranspiration data			
Start of growing season	Julian date	66	Default for El Paso (Schroeder, Lloyd, and others, 1994, p. 14).
End of growing season	Julian date	315	Do.
Average annual wind speed	Miles per hour	9.2	Do.
Average relative humidity:	Percent		Do.
First quarter		40	
Second quarter		27	
Third quarter		46	
Fourth quarter		48	
Precipitation	Inches	Synthetically generated daily values for 100-year period	Data generated by the HELP model specifically for the El Paso area (Schroeder, Lloyd, and others, 1994, p. 14-24).
Temperature	Degrees Fahrenheit	do.	Do.
Solar radiation	Langleys	do.	Do.
Maximum leaf area index	--	0	Assuming no vegetative cover.
Evaporative zone depth	Inches	24	Thickness of cover.
Data for simulation of runoff on landfill cover			
Vegetation for Soil Conservation Service curve generation	--	2	Restricted to a selection of the integers between 1 and 5; 2 simulates a "poor stand of grass" (Schroeder, Lloyd, and others, 1994, p. 36).
Soil surface for Soil Conservation Service curve generation	Texture number	3	Restricted to default soil textures; texture 3 simulates a "fine sand" and has characteristics closest to those of the observed soil (Schroeder, Dozier, and others, 1994, p. 19).
Surface slope	Percent	3	Estimated from contour map for area near perimeter of landfill.
Slope length	Feet	300	Do.
Fraction of area allowing runoff	Percent	20	Assumed runoff is from only a strip around the perimeter of the landfill.
Data for simulation of flow through landfill cover			
Thickness	Inches	24	Thinnest reported value.
Saturated hydraulic conductivity	Centimeters per second	4.1×10^{-3}	Maximum of 10 in situ measurements.

Table 2.--Hydrologic Evaluation of Landfill Performance (HELP) model-input data summary--Concluded

Feature	Unit[1]	Assigned value	Remarks
Data for simulation of flow through landfill cover--Continued			
Porosity	Percent	36.8	Value was selected from in situ measurements that had the minimum difference between field capacity and wilting point.
Field capacity	Percent	12.0	Do.
Wilting point	Percent	9.0	Do.
Initial moisture content	Percent	9.0	Adjusted to minimize change in storage.
Number of model layers	--	6	Each layer is 4 inches thick; all layers have identical hydrologic characteristics.
Data for simulation of flow through landfill waste			
Thickness	Feet	30	As reported (Abeyta, 1996, p. 4).
Saturated hydraulic conductivity	Centimeters per second	1×10^{-3}	Default value for municipal waste (Schroeder, Dozier, and others, 1994, p. 30).
Porosity	Percent	67.1	Do.
Field capacity	Percent	29.2	Do.
Wilting point	Percent	7.7	Do.
Initial moisture content	Percent	29.2	Adjusted to minimize change in storage.
Number of model layers	--	6	Thicknesses, in inches, starting from top: 6, 12, 24, 48, 96, and 174. Identical hydrologic characteristics.
Data for simulation of flow through basal layer (natural soil)			
Thickness	Feet	8	Arbitrary value.
Saturated hydraulic conductivity	Centimeters per second	2.3×10^{-2}	As measured in core from 29-foot depth in borehole BH-3.
Porosity	Percent	43.7	Do.
Field capacity	Percent	5.6	Do.
Wilting point	Percent	1.6	As measured in core from 29-foot depth in borehole BH-3.
Initial moisture content	Percent	7.62	Adjusted to minimize change in storage.
Number of layers	--	1	--

1. A combination of inch-pound and international units was used as input as required by the HELP model.

Six model layers were used to simulate flow through the cover, an arbitrary number. The sum of layer thicknesses equals the cover thickness. The waste thickness was 30 feet, as reported by Abeyta (1996). All hydraulic characteristics were default values for waste (soil texture number 18 of Schroeder, Lloyd, and others, 1994, p. 30). The waste interval was arbitrarily divided into six model layers of increasing thickness downward, adding up to 30 feet.

A basal layer of arbitrary thickness was specified with water-yielding characteristics equal to those found at the 29-foot depth in borehole BH-3, located near the southwest corner of the landfill (fig. 3). Because the initial moisture capacity was selected to simulate near steady-state conditions, the thickness of this layer is immaterial.

Several of these assigned values are conservative: the assumption of no vegetative cover for the purpose of calculating evapotranspiration and the evaporative zone depth as compared to natural vegetation for the vicinity. The maximum measured value of saturated hydraulic conductivity was used for the landfill cover, which is conservative compared to the average measured value. Also conservative are values selected for field capacity and wilting point to minimize moisture storage capacity of the evaporative zone and the simulation of near steady-state conditions. Other parameters, though not conservative, are appropriate for the reasons given.

Results

With the data discussed above, the HELP model simulated the following average annual rates rounded to the nearest tenth of a millimeter per year (mm/yr):

Inflow:	
Precipitation	196.2
Outflow:	
Runoff	0.0
Evapotranspiration	94.6
Leakage	101.6
Flow to storage	0.0

Because the leakage rate, more than half of precipitation, is about 500 times the estimated recharge in the vicinity (P.F. Frenzel, written commun., 1997), it could possibly be substantially reduced if lesser hydraulic conductivity and greater moisture retention in the cover material and more runoff from the landfill surface were simulated.

Description of MULTIMED Model Code

The MULTIMED model, documented by Salhotra and others (1993), describes the theory upon which the model is based. The MULTIMED user's manual (Sharp-Hansen and others, 1993) provides guidance for determination of model-input values. The MULTIMED version 2 (beta), dated July 1994, was used for this report. This version includes the preprocessor "Premed," which allows the user to easily create an input file for use in MULTIMED. The model code and documentation can be obtained electronically from the EPA Center for Exposure Assessment Modeling, Athens, Georgia. Paper copies of MULTIMED documents can also be purchased from the National Technical Information Service.

The MULTIMED model simulates the fate and transport of contaminants leaching from a waste-disposal facility into the environment. The model includes two options for simulating leachate flux: the infiltration rate can be specified directly or a landfill module can be used to estimate the infiltration rate. An unsaturated-zone flow module simulates steady-state, one-dimensional (downward) flow in the unsaturated zone by a "semianalytical" method. The output from this module, water saturation as a function of depth, is used as model input to the unsaturated-zone transport module. The unsaturated-zone transport module simulates steady-state or transient, one-dimensional (vertical) transport in the unsaturated zone and includes the effects of longitudinal dispersion, linear adsorption, and first-order decay. When the thickness of the unsaturated zone is specified as a constant, as many as 20 model layers having unique flow properties can be simulated. Van Genuchten parameters (van Genuchten, 1980) are required by the model to describe the relation between pressure head and water saturation. Output from the unsaturated-zone transport module, contaminant concentrations at the water table (either steady state or time series), is used to join the unsaturated-zone transport module with the steady-state or transient, semianalytical saturated-zone transport module. The saturated-zone transport module simulates one-dimensional (horizontal) uniform flow, three-dimensional dispersion, linear adsorption, first-order decay, and dilution resulting from direct infiltration into the ground-water plume.

MULTIMED does not simulate processes such as flow in fractures and chemical reactions between contaminants. A preferential pathway could exist. The MULTIMED transport modules essentially assume piston flow (continuous, spatially distributed diffuse recharge through the entire unsaturated zone). The possible transient-concentrated recharge that penetrates the unsaturated zone and bypasses most of its volume (Gee and Hillel, 1988) is not considered. Although piston flow is not considered a conservative assumption, recharge along preferential pathways would not be amenable to simulation.

MULTIMED Model Implementation

The use of the MULTIMED model is limited to estimating the time of first arrival of landfill leachate at the water table, assuming no delay or decay of solutes in the landfill or unsaturated zone. Sediments in the unsaturated zone at monitoring well MSWLF03 and borehole BH-3 were assumed to represent those under the entire landfill.

Description of Model Input

Input for the MULTIMED model was based on site-specific data or was conservative. The MULTIMED input data are in standard ASCII format on an IBM PC-compatible 3.5-inch disk (Abeyta and Frenzel, 1999b). The description of MULTIMED model input is organized to approximately match the order of input required by the Premed model-input software. Options that limit the scope of model input are the first input required. Specifications relating to the modules that were selected (unsaturated-zone flow module, unsaturated-zone transport module, and saturated-zone module) are discussed in the following sections.

MULTIMED Options

The following options satisfied the needs of this study:

(1) The application type was "generic" because the other option, "Subtitle D," does not allow the transient-mode option.

(2) The unsaturated-zone and saturated-zone modules were used.

(3) The model was run in deterministic mode (Sharp-Hansen and others, 1993, p. 62) because not enough site-specific data were available to determine statistical distributions for the Monte Carlo option (Salhotra and others, 1993, Section 9).

(4) The model was run in transient mode to satisfy the study objective.

(5) Infiltration from the landfill was user specified equal to the leakage value determined by the HELP model.

(6) The analytical solution was assumed to be sufficient for the unsaturated-zone model.

Although the MULTIMED model requires that the saturated-zone module be used in combination with the unsaturated-zone module, in this implementation the distance from the landfill to the point of compliance was set to a small value (0.107 meter) to reduce the effect of the saturated-zone module. The point of compliance is defined as "a vertical surface located no more than 500 feet from the hydraulically downgradient limit of the waste management unit boundary, extending down through the uppermost aquifer underlying the regulated units, and located on land owned by the owner of the permitted facility" (Texas Natural Resources Conservation Commission, 1993a, p. 5). The modules for landfill leakage simulation, air emissions, and surface stream contamination were not used.

Unsaturated-Zone Flow Module

The unsaturated zone between the bottom of the landfill and the water table was divided into 18 layers (pl. 1). The unsaturated zone was assumed to be represented by the interval between the depths of 22 and 305 feet in borehole BH-3 and monitoring well MSWLF03. The 18 layers were delineated on the basis of lithologic and geophysical log data (pl. 1) and the availability of laboratory core analyses for determining hydraulic and physical characteristics (Abeyta and Frenzel, 1999a). The distinction between clay and coarser materials generally was based on a gamma count of 80 counts per second. Greater than 80 counts per second was considered clay; less than 80 counts per second was considered coarser material. This was generally consistent with the lithologic log data and laboratory analyses of cores. Most layers have at least one representative laboratory core analysis, and mean values were specified for those layers represented by more than one laboratory core analysis. Also, the layers were delineated in such a way that the range of laboratory values used for any given layer generally was restricted to avoid to some degree the skew of the mean toward extreme values. An exception was layer 15, where values of saturated hydraulic conductivity were 1.1×10^{-7} cm/s and 9.5×10^{-10} cm/s and the average was approximately equal to the larger value. The smaller value for layer 15 was not determined until after the model layering was established. The addition of a layer to accommodate the smaller value would have reduced the simulated rate of flow through the system.

The model layer number, depth interval, core sample numbers associated with each material, and material property number associated with each layer are listed in table 3. Layer thickness, in feet, was converted to meters for model input. The depth intervals, in feet, correspond to the lithologic column and geophysical logs shown on plate 1. Core sample numbers show which core samples were used to obtain the properties (table 4), functional coefficients (table 5), and unsaturated-zone transport properties (table 6) for each material property number. For example, properties of core samples 29 and 45 were averaged to obtain values assigned to material property number 1 (layer 1), and properties of core sample 72 were assigned to material property number 2 (layer 2). Core sample numbers (table 3) indicate depth, in feet, for all samples except numbers 81, 318, and 318.5, which were collected from depths of 79, 316, and 316.5 feet, respectively. Because samples 318 and 318.5 (not shown in table 3) were collected from the saturated zone, they were not used in the unsaturated-zone model. Material property numbering allows a given material to be associated with various layers. Most material properties, however, were defined individually for each layer except for layers 7, 8, and 10, for which properties were the same as those for 9, 6, and 12, respectively. Material property numbers 7, 8, and 10 were not used.

Material properties and functional coefficients (tables 4 and 5) required for the unsaturated-zone flow module are used for determining the relation between pressure head (suction), degree of saturation, and unsaturated hydraulic conductivity. Material properties and functional coefficients are laboratory values (Abeyta and Frenzel, 1999a) for materials represented by a single core sample or are averages of laboratory values for materials represented by more than one sample. Residual water content is the minimum laboratory-measured value for each sample, generally measured at a suction of about 800,000 cm, and is the same value used in the calculation of the other functional coefficients. The Brooks-Corey and van Genuchten functional coefficients in table 5 were calculated by Daniel B. Stephens and Associates, Inc. (Abeyta and Frenzel, 1999a, tables 16 and 18), for core samples or are averages thereof. The van Genuchten beta is the value "N" of Daniel B. Stephens and Associates, Inc. Also included as material property input data is the thickness of the unsaturated zone; a uniform value of 86.3 meters (m) was specified for all materials.

Unsaturated-Zone Transport Module

The unsaturated-zone transport module uses chemical specifications and material properties. (Chemical specifications are also used by the saturated-zone module.) No chemical specifications were tabulated because all were given a value of zero to simulate no decay or attenuation of any kind. The material properties required as input data for the unsaturated-zone transport module, listed in table 6, are laboratory values (Abeyta and Frenzel, 1999a) or derivatives thereof. Percentage of organic matter was calculated as 172.4 times the fractional organic carbon content (Sharp-Hansen and others, 1993, p. 94), which was taken as 10^{-6} times the laboratory values for total organic carbon. For two properties not listed in table 6, the value was the same for all materials: longitudinal dispersivity was 1 m, following Sharp-Hansen and others (1993, p. 92), and the biological decay coefficient was 0, simulating no biological decay.

The Stehfest analytical solution scheme (Salhotra and others, 1993, p. 30) was used for the unsaturated-zone transport module as advised in the Premed documentation for ratios of layer thickness to longitudinal dispersivity less than 20. Default values for the parameters ISOL, N, NTEL, NGPTS, and NIT (Sharp-Hansen and others, 1993, p. 79) (defined below) were used for the solution. The unsaturated-zone transport solution was calculated 100 times (number of time steps (NTSTPS) = 100) and was reported 100 times in 6-year time increments. The following defaults were used for the unsaturated zone-transport model:

ISOL	Type of scheme used in unsaturated zone	1
N	Stehfest terms or number of increments	18
NTEL	Points in Lagrangian interpolation	3
NGPTS	Number of Gauss points	104
NIT	Convolution integral segments	2
IBOUND	Type of boundary condition	2
ITSGEN	Time values generated or input	1
TMAX	Maximum simulation time	0.0
WTFUN	Weighting factor	1.2

Table 3.--Multimedia Exposure Assessment (MULTIMED) model-input data summary and sample information

Layer number[1] (pl. 1)	Depth interval (feet)	Core sample number(s)[2]	Material property number[1]	Layer thickness (meters)[1]
1	22-64	29, 45	1	12.80
2	64-69	72	2	1.52
3	69-82	81 (depth is 79 feet)	3	3.96
4	82-141	92, 93, 109, 140	4	18.00
5	141-149	147	5	2.44
6	149-158	151	6	2.74
7	158-160	164	9	0.61
8	160-164	151	6	1.22
9	164-172	164	9	2.44
10	172-180	199	12	2.44
11	180-190	180	11	3.05
12	190-219	199	12	8.84
13	219-229	220	13	3.05
14	229-244	233, 236	14	4.57
15	244-265	245	15	6.40
16	265-291	284, 289	16	7.92
17	291-297	294	17	1.83
18	297-305	298	18	2.44

1. MULTIMED model input.
2. Values correspond to sample depth except where noted.

Table 4.--Material property input data for the Multimedia Exposure Assessment (MULTIMED) unsaturated-zone flow module

Material property number	Saturated hydraulic conductivity (centimeters per hour)	Porosity	Air entry pressure head (meters)
1	86.4	0.402	0.270
2	4.39×10^{-6}	0.401	34.5
3	5.80×10^{-4}	0.319	13.2
4	6.10×10^{-2}	0.350	0.990
5	2.70×10^{-4}	0.359	111
6	5.80×10^{-3}	0.301	1.21
9	1.00×10^{-5}	0.384	25.6
11	6.48×10^{-5}	0.421	21.7
12	16.0	0.410	0.390
13	1.70×10^{-5}	0.445	167
14	1.40	0.512	0.690
15	2.00×10^{-4}	0.368	10.2
16	4.60	0.377	0.360
17	1.50×10^{-3}	0.419	5.99
18	9.70	0.428	0.460

Table 5.--Functional coefficient input data for the Multimedia Exposure Assessment (MULTIMED) unsaturated-zone flow module

Material property number	Residual water content (fractions)	Brooks and Corey exponent (dimensionless)	van Genuchten alpha (centimeters^{-1})	van Genuchten beta (dimensionless)
1	0.00800	1.94	3.65×10^{-2}	2.94
2	0.127	0.414	2.90×10^{-4}	1.41
3	0.0700	0.321	7.60×10^{-4}	1.32
4	0.0345	0.308	0.24×10^{-2}	1.31
5	0.0980	0.778	9.00×10^{-5}	1.78
6	0.0420	0.247	8.28×10^{-3}	1.25
9	0.0700	0.449	3.90×10^{-4}	1.45
11	0.0810	0.445	4.60×10^{-4}	1.44
12	0.0170	0.589	2.57×10^{-2}	1.59
13	0.121	0.793	6.00×10^{-5}	1.79
14	0.0190	0.401	1.63×10^{-2}	1.40
15	0.0940	0.354	9.80×10^{-4}	1.35
16	0.0120	1.89	3.56×10^{-2}	2.89
17	0.121	0.242	1.67×10^{-3}	1.24
18	0.00900	1.05	2.17×10^{-2}	2.05

Table 6.--Material property input data for the Multimedia Exposure Assessment (MULTIMED) unsaturated-zone transport module

Material property number	Organic matter (percent)	Bulk density (grams per cubic centimeters)
1	0.055	1.59
2	0.114	1.59
3	0.123	1.80
4	0.133	1.73
5	0.102	1.70
6	0.093	1.85
9	0.064	1.63
11	0.157	1.53
12	0.086	1.56
13	0.090	1.47
14	0.055	1.30
15	0.0104	1.68
16	0.055	1.66
17	0.092	1.54
18	0.0680	1.52

Saturated-Zone Module

The saturated-zone module uses aquifer specifications, source-specific variables, and, as previously noted, chemical-specific parameters that were set to zero. Aquifer specifications are listed in table 7. The particle diameter used was the 50th-percentile value for core samples 318 and 318.5--that is, 50 percent of the soil volume is filled with particles smaller than 2.00×10^{-2} cm (table 7). Values of aquifer porosity, bulk density, hydraulic conductivity, organic carbon content, and pH content were averages for the same core samples. Aquifer thickness was an arbitrary value needed to avoid the warning "near field mixing factor greater than 1." Increasing the aquifer thickness avoided this warning but did not change the simulated time of first arrival of leachate at the water table. The well distance from the MSWLF was specified as a small value to prevent substantial effects of the saturated-zone module on dilution and time of first arrival of leachate. Hydraulic gradient was estimated on the basis of water levels measured in monitoring well MSWLF03 and production well W3A (fig. 3). Retardation coefficient was set to 1 to simulate no retardation. Longitudinal-, transverse-, and vertical-dispersivity values were estimated by formulas given by Sharp-Hansen and others (1993, p. 105). Water temperature of the aquifer was estimated from a temperature log at production well W3A. Angle off center and vertical distance of well were set to zero, placing the simulated monitoring point (point of compliance) in the middle of the simulated leachate plume and at the water table, following Subtitle D requirements (Sharp-Hansen and others, 1993, p. 108).

A Gaussian source (Salhotra and others, 1993, p. 40) was used in the saturated-zone model, as required for simulation of a Subtitle D landfill. The model calculated mixing zone depth and seepage velocity.

Source-specific variables for the MULTIMED model are given in table 8. The infiltration rate was derived using the HELP model. The recharge rate on land surrounding the landfill was derived from the soil-moisture chloride study (P.F. Frenzel, written commun., 1997) conducted at borehole BH-3. The duration of pulse was specified as a time period long enough to show the simulated first arrival of leachate at the water table. The source decay constant was specified as zero, simulating no decay of the source. Initial concentration of solute at the landfill arbitrarily was specified as unity so that any effects of dilution could be easily determined; the actual concentration of solutes in landfill leachate is unknown. Realistic values of area and length were specified assuming the direction of flow is from the southwest toward production well W3A, although the direction of flow at the water table is actually not known. The width scale was specified as area divided by length. If the direction of flow was from the northeast toward monitoring well MSWLF03, consistent with regional flow paths (Abeyta, 1996), the dimensions would be the same. The specification of chemical parameters, biological decay, and retardation factors was conservative.

Results

A plot of the estimated cumulative fraction of leachate concentration of solute at the water table and elapsed time from the beginning of the simulation, and time of arrival of leachate at the water table, assuming a 1-milligram-per-liter (mg/L) concentration of solute in leachate, is shown in figure 4. Because no solute delay or degradation was simulated, the first arrival of landfill leachate at the water table occurs at the time as shown in figure 4. The first arrival of leachate at the current level of the water table is 204 to 210 years after the beginning of the simulation, which was considered to be 1974 when the landfill was first established. The first arrival time of leachate exceeds the active life, closure, and post-closure period of the landfill by more than 139 years. The average travel time is about 1.5 feet per year, which is similar to the 1.8-foot-per-year rate of water-level decline in production well W3. The time of first arrival is approximately inversely proportional to the rate of leachate infiltration (landfill leakage in HELP); thus, the first arrival time would increase by a factor of approximately 10 if the infiltration could be reduced by a factor of 0.1.

Because laboratory-measured hydraulic-conductivity values, particularly of finer grained materials, commonly are orders of magnitude lower than those determined from in situ tests (Weeks, 1978, table 4), sensitivity analyses were performed on the MULTIMED model results. The analyses included simulating the time of arrival of landfill leachate at the water table assuming hydraulic-conductivity values larger than the laboratory-measured values of saturated hydraulic conductivity by factors of 10 and 100. The results are:

Table 7.--Aquifer specifications for the Multimedia Exposure Assessment (MULTIMED) saturated-zone module

[--, not applicable]

Variable name	Unit	Specified value	Remarks
Particle diameter	Centimeters	2.00×10^{-2}	Laboratory values for core sample numbers 318 and 318.5.
Aquifer porosity	--	0.381	Do.
Bulk density	Grams per cubic centimeter	1.64	Do.
Hydraulic conductivity	Meters per year	400	Do.
Organic carbon content	Fraction	4.40×10^{-4}	Do.
pH	Standard units	8.30	Do.
Aquifer thickness	Meters	80	Arbitrary.
Well distance from landfill	Meters	0.107	Small value selected (for Subtitle D application) to prevent dilution effects or delay of first arrival (Sharp-Hansen and others, 1993, p. 108).
Hydraulic gradient	--	5.00×10^{-3}	From well MSWLF3 to well W3A.
Retardation coefficient	--	1.00	No retardation.
Longitudinal dispersivity	Meters	1.00×10^{-2}	Dispersivity values estimated by formulas (Sharp-Hansen and others, 1993).
Transverse dispersivity	Meters	3.30×10^{-3}	Do.
Vertical dispersivity	Meters	1.00×10^{-3}	Do.
Water temperature of aquifer	Degrees Celsius	25.0	From log at well W3A.
Angle of well off center of plume	Degrees	0.000	Assumed (for Subtitle D application) to place simulated monitoring point at water table in the center of the plume (Sharp-Hanson and others, 1993, p. 108).
Vertical distance of well from top of aquifer	Fraction of aquifer thickness	0.000	Do.

Table 8.--Source-specific variables for the Multimedia Exposure Assessment (MULTIMED) model

Variable name	Unit	Specified value	Remarks
Infiltration rate	Meters per year	0.1016	From HELP model.
Recharge rate	Meters per year	2.00×10^{-4}	Chloride method.
Duration of pulse	Year	600	Entire simulation time.
Source decay constant	Per year	0.000	No decay.
Initial concentration of solute at landfill	Milligrams per liter	1.00	Arbitrary.
Area of waste disposal unit	Square meter	429,200	Reported (Abeyta, 1996, p. 4).
Length scale of facility	Meter	580	Approximate distance across landfill from well W3A to well MSWLF3.
Width scale of facility	Meter	740	Area divided by length.

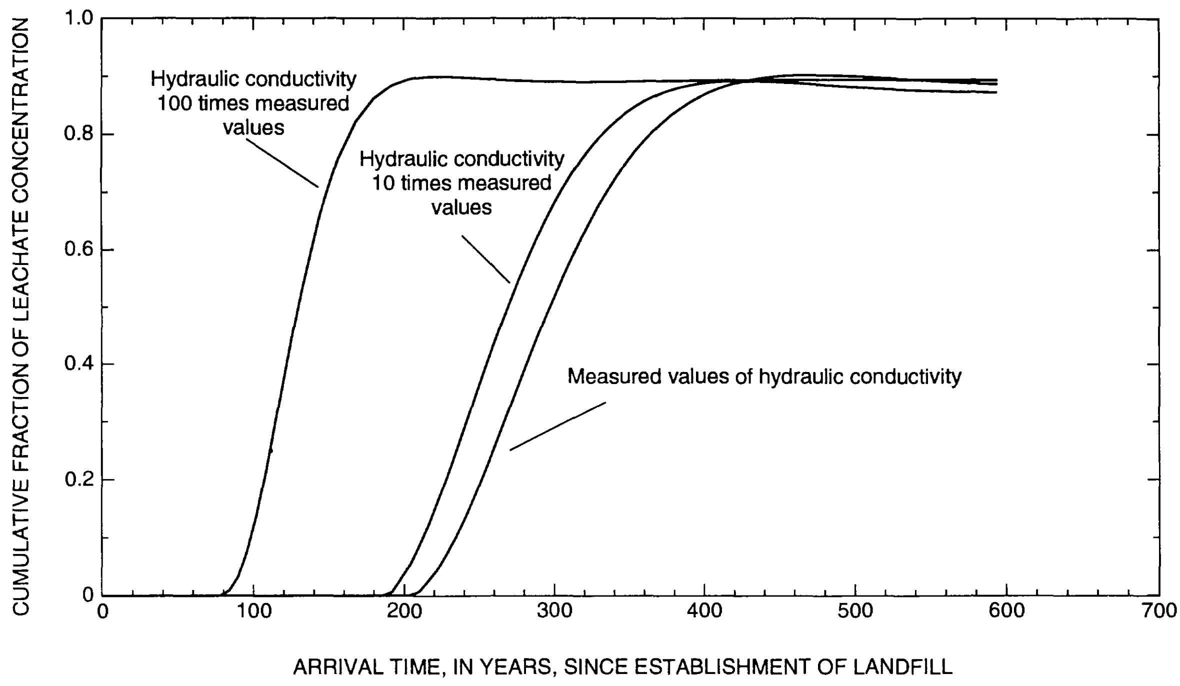


Figure 4.--Estimated cumulative fraction of leachate concentration and time of arrival at the water table.

Saturated hydraulic-conductivity factor:	First arrival time of leachate at the water table 305 feet below land surface:	Fraction of leachate concentration at first arrival time:
1	204 to 210 years	Less than 0.0070
10	186 to 192 years	Less than 0.0063
100	78 to 84 years	Less than 0.0089

The combined active life of the USAADACENFB MSWLF (approximately 30 years) and the post-closure care period (35 years including closure period) is about 65 years. The estimated arrival time of landfill leachate at the water table indicated by the most conservative model result (78 to 84 years) (fig. 4) exceeds the active life and post-closure care period of the landfill.

SUMMARY AND CONCLUSIONS

The MSWLF is located on the USAADACENFB military reservation in El Paso County, about 10 miles northeast of downtown El Paso, Texas. The landfill is built on the Hueco Bolson, a deposit that yields water to five public-supply wells within 1.1 miles of the landfill boundary on all sides. The bolson deposits consist of lenses of sand, clay, silt, gravel, caliche, and various mixtures thereof. The unsaturated zone at the landfill is about 300 feet thick. The arrival time of landfill leakage at the water table was simulated by the U.S. Geological Survey in cooperation with the U.S Department of the Army.

As suggested by the TNRCC, the HELP and MULTIMED models were used to simulate the time of the first arrival of landfill leachate at the water table. The HELP model was used to estimate a landfill leakage rate, which was input to the MULTIMED model. The MULTIMED model was used in transient mode to estimate the concentration of a nonreactive, nondecaying solute at the water table.

For these models to have credibility, site-specific data needed to be collected for model input. At five sites on the landfill cover, hydraulic conductivity was measured using an in situ method; in addition, laboratory values were obtained for porosity, moisture content at field capacity, and moisture content at wilting point. Twenty-seven sediment samples were collected from two boreholes located near the southwest corner of the landfill: borehole BH-3 and adjacent borehole MSWLF03, which was completed as a ground-water monitoring well. Of these, 23 samples were assumed to represent the unsaturated zone beneath the entire landfill. The core samples were analyzed in the laboratory for initial moisture content, dry bulk density, porosity, saturated hydraulic conductivity, moisture retention percentages at various suction values, total organic carbon, and pH. As required for the HELP and MULTIMED models, parameters were calculated for the van Genuchten and Brooks-Corey equations relating hydraulic conductivity to saturation.

Recharge, estimated on the basis of soil-water chloride concentration, was reported to be 0.008 inch per year, approximately the same value as that estimated for a site 13 miles southwest of the MSWLF. This value indicates how low landfill leakage could be in this climatic setting.

The oldest part of the landfill was assumed to contribute the first arrival of leachate at the water table because it was not engineered to restrict infiltration and leakage and has no liner. It consists of about 30 feet of waste and a 2- to 3-foot-thick cover. This design was assumed for the entire landfill.

The HELP model was implemented using input values that were based mostly on site-specific data or assumed in a conservative manner. Exceptions were default values used for waste characteristics. Flow through the landfill was assumed to be at steady state. The HELP-simulated landfill leakage rate was 101.6 mm/yr, approximately 500 times the estimated recharge rate for the area near the landfill.

The MULTIMED model was implemented using input values that were based on site-specific data and some conservatively assumed values. Landfill leakage was assumed to begin when the landfill was established and to continue at a steady-state rate of 101.6 mm/yr as estimated by the HELP model. By using an assumed solute concentration in the leachate of 1 mg/L and assuming no delay or degradation of solute, the solute serves as a tracer to indicate the first arrival of landfill leachate. The simulated first arrival of leachate at the water table would be 204 to 210 years after the 1974 establishment of the landfill.

REFERENCES

Abeyta, C.G., 1996, Geohydrologic site characterization of the Municipal Solid Waste Landfill Facility, U.S. Army Air Defense Artillery Center and Fort Bliss, El Paso County, Texas: U.S. Geological Survey Water-Resources Investigations Report 95-4217, 36 p.

Abeyta, C.G., and Frenzel, P.F., 1999a, Geologic and hydrologic data for the Municipal Solid Waste Landfill Facility, U.S. Army Air Defense Artillery Center and Fort Bliss, El Paso, Texas: U.S. Geological Survey Open-File Report 99-271, 76 p., 1 pl.

———1999b, Model input and output files for the simulation of time of arrival of landfill leachate at the water table, Municipal Solid Waste Landfill Facility, U.S. Army Air Defense Artillery Center and Fort Bliss, El Paso, Texas (supplement to U.S. Geological Survey Water-Resources Investigations Report 97-4036): U.S. Geological Survey Open-File Report 98-397, 4 p., 1 diskette.

Allison, G.B., and Hughes, M.W., 1978, The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer: Australian Journal of Soil Research, v. 16, p. 181-195.

Ankeny, M.D., 1992, Methods and theory for unconfined infiltration measurements, *in* Advances in measurement of soil physical properties--Bringing theory into practice: Soil Science Society of America Special Publication 30, p. 123-141.

Arnold, J.G., Williams, J.R., Nicks, A.D., and Sammons, N.B., 1989, SWRRB, a simulator for water resources in rural basins: College Station, Tex., Agricultural Research Service, U.S. Department of Agriculture, Texas A&M University Press.

Brooks, R.H., and Corey, A.T., 1964, Hydraulic properties of porous media: Fort Collins, Colorado State University Hydrology Paper no. 3, 27 p.

Brooks, R.H., and Corey, A.T., 1966, Properties of porous media affecting fluid flow, *in* Journal of the Irrigation and Drainage Division: Proceedings of the American Society of Civil Engineers, v. 92, no. IR2, June 1966, p. 61-88.

Campbell, G.S., 1974, A simple method for determining unsaturated hydraulic conductivity from moisture retention data: Soil Science, v. 117, no. 6, p. 311-314.

Cliett, Tom, 1969, Groundwater occurrence of the El Paso area and its related geology, *in* Guidebook of the Border Region: Socorro, New Mexico Geological Society, 20th Field Conference, October 23, 24, and 25, 1969, p. 209-213.

Freeze, A.R., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice-Hall, 604 p.

Gee, G.W., and Hillel, D., 1988, Groundwater recharge in arid regions--Review and critique of estimation methods: Hydrologic Processes, v. 2, p. 255-266.

Jaco, H.B., 1971, Soil survey of El Paso County, Texas: U.S. Department of Agriculture, Soil Conservation Service, November 1971, 59 p., 62 sheets, and explanation page.

Mattick, R.E., 1967, A seismic and gravity profile across the Hueco Bolson, Texas: U.S. Geological Survey Professional Paper 575-D.

Salhotra, A.M., Mineart, Phil, Sharp-Hansen, Susan, and Allison, T.L., 1993, MULTIMED, the multimedia exposure assessment model for evaluating the land disposal of wastes--Model theory: U.S. Environmental Protection Agency, EPA/600/R-93/081, May 1993, 122 p.

Schroeder, P.R., Dozier, T.S., Zappi, P.A., McEnroe, B.M., Sjostrom, J.W., and Peyton, R.L., 1994, The hydrologic evaluation of landfill performance (HELP) model, Engineering documentation for version 3: Cincinnati, U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory, EPA/600/R-94/168b, September 1994, 116 p.

Schroeder, P.R., Lloyd, C.M., Zappi, P.A., and Aziz, N.M., 1994, The hydrologic evaluation of landfill performance (HELP) model, User's guide for version 3: U.S. Environmental Protection Agency, EPA/600/R-94/168a, September 1994, 94 p., 1 diskette.

Sharp-Hansen, Susan, Travers, Constance, Hummel, Paul, and Allison, Terry, 1993, A Subtitle D landfill application manual for the multimedia exposure assessment model (MULTIMED): U.S. Environmental Protection Agency, EPA/600/R-93/82, 212 p.

Stephens, D.B., and Coons, L.M., 1994, Landfill performance assessment at a semiarid site--Modeling and validation, *in* Ground Water Monitoring and Remediation, Winter 1994, 9 p.

Texas Natural Resources Conservation Commission, 1993a, 30 TAC 330, Municipal solid waste: Austin, Texas Register, 194 p. plus updates through December 1993.

_____1993b, Texas Water Commission alternate liner design handbook, A performance standard as authorized by 30 Texas Administrative Code Section 330.202: Texas Natural Resources Conservation Commission, version 1, 99 p.

U.S. Department of Agriculture, Soil Conservation Service, 1985, National engineering handbook, section 4, Hydrology: Washington, D.C., U.S. Government Printing Office.

U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data Service, 1992, Annual summary, Texas: National Oceanic and Atmospheric Administration, v. 97, no. 13, 80 p.

U.S. Environmental Protection Agency, 1993, 40 Code of Federal Regulations, Parts 257 and 258: Washington, D.C., U.S. Government Printing Office.

van Genuchten, M.T., 1980, A closed-form equation for predicting the hydraulic conductivity of unsaturated soils: Soil Science Society of America Journal, v. 44, p. 892-898.

Weeks, E.P., 1978, Field determination of vertical permeability to air in the unsaturated zone: U.S. Geological Survey Professional Paper 1051, 41 p.