TEST-TRENCH STUDIES IN THE AMARGOSA DESERT, SOUTHERN NEVADA: RESULTS AND APPLICATION OF INFORMATION TO LANDFILL COVERS IN ARID ENVIRONMENTS

Brian J. Andraski[1]

ABSTRACT--As arid sites in the western United States are increasingly sought for disposal of the Nation's hazardous wastes and as volumes of locally generated wastes increase, concern about the potential effect of contaminants on environmental quality is being raised. Studies at the U.S. Geological Survey's Amargosa Desert research site near Beatty, Nevada are being done to evaluate mechanisms that can affect waste isolation in an arid environment. Precipitation at the site averages about 108 mm yr^{-1}. Results have shown that, under undisturbed conditions, the naturally stratified soils in combination with native plants are effective in limiting the potential for percolation of precipitation. Under nonvegetated waste-site conditions, data indicated the accumulation and shallow, but continued, penetration of infiltrated water. However, water potentials below the test trenches and below the 2-m depth for nonvegetated soil indicated the persistence of an upward driving force for water flow during the 5-yr test period. General trends in trench-cover subsidence suggested a positive relation with cumulative precipitation, but subsidence did not appear to have a measurable effect on the water balance. Erosion rates were inversely related to near-surface rock-fragment content. Results suggest that the ultimate fate of contaminants buried at properly managed solid-waste sites may be determined largely by the interactions among climate and the surface-cover features of the disposal facility, and how these factors change with time.

Keywords: Soil moisture, water balance, hydraulic properties, erosion, subsidence.

Accumulation and management of waste is a pressing problem facing the United States today. Improper disposal of wastes poses a threat to public health and environmental quality. As arid sites increasingly are sought for disposal of the Nation's radioactive and other hazardous wastes, concerns about the potential effect of contaminants on environmental quality in the arid western United States are being expressed. In addition, volumes of locally generated municipal, industrial, and mining wastes are increasing because of rapid population growth, industrialization, and the importance of mining in the region.

Mechanisms that control the near-surface water balance can strongly influence the suitability of a burial site or landfill for isolating wastes. Precipitation that infiltrates into the surface of a landfill cover and does not return to the atmosphere by evaporation from bare soil and transpiration from plants can percolate downward and come in contact with buried waste. In addition, the loss of structural integrity by erosion and subsidence of landfill covers may increase the likelihood of infiltration and percolation, thereby reducing the effectiveness of the site in isolating waste. Water that contacts the waste can enhance the release of contaminants for subsequent transport by liquid water, water vapor, or other gases.

Deserts are often considered ideal areas for waste isolation (Reith and Thomson 1992). Low precipitation, high potential evapotranspiration, and thick unsaturated zones are characteristics of deserts that make them attractive as waste repositories. A prevalent assumption is that little or no precipitation will percolate to buried waste at an arid site. Not clearly understood, however, is that water flow in desert soils can be affected in dramatic ways by temporal and spatial changes in precipitation, vegetation,

[1]U.S. Geological Survey, Carson City, Nevada 89706

and soils (Gee et al. 1994). Depending on specific but commonly transient conditions, water moves through soil in liquid and vapor form, and the two forms can move simultaneously and interdependently as a consequence of water potential and temperature gradients--from high to low potential; from warm to cool soil. Under dry conditions, vapor flow may dominate over liquid flow and several variables--water content, water potential, and temperature--are needed to define rates and directions of water flow. Quantitative evaluation of flow processes and analysis of the complex interactions controlling water movement at arid sites requires the use of numerical models (Scanlon and Milly 1994).

Few data have been available to test the validity of assumptions about hydrologic processes at sites where precipitation averages less than 150 mm yr^{-1}. The lack of data is the result of (1) the technical complexity of hydraulic characterization and monitoring of dry, often stony soils and (2) insufficient field studies that account for the extreme temporal and spatial variations in precipitation, soils, and plants in arid regions. Regulations governing the licensing of waste sites require an assessment of the potential for water movement through the landfill or burial facility before disposal operations can begin. Numerical models are commonly relied on as tools for such predictive assessments. Although significant advances have been made in the development of flow and transport models, the lack of long-term field data has resulted in these models remaining largely untested as to how well they represent flow systems at arid sites.

In 1976, the U.S. Geological Survey (USGS) began a series of studies at a waste-burial site in the Amargosa Desert, near Beatty, Nevada to further the study and understanding of hydrologic processes in an arid environment where precipitation averages about 100 mm yr^{-1} (Andraski et al. 1995). In 1983, the USGS established a research area adjacent to the waste facility through agreements with the Bureau of Land Management and the State of Nevada. This 16-ha area serves as a field laboratory for multiple-year studies of arid-site processes. The test-trench studies, which began in 1987, were designed to evaluate mechanisms that can affect the potential for waste isolation under natural climatic conditions. Data were collected both under undisturbed conditions and under simulated waste-site conditions. This paper summarizes results from the field and laboratory characterization components of the test-trench studies, and discusses how this information can be applied to the design of landfill covers in arid environments.

Materials and Methods

Site Description

The Amargosa Desert research site is adjacent to the waste-burial facility near Beatty, NV and about 50 km east of Death Valley National Park (Fig. 1). This area is in the northern part of the Mojave Desert, one of the most arid regions of the United States. Precipitation averaged 108 mm yr^{-1} during 1981-92 and ranged from 14 mm during 1989 to 225 mm during 1983. Annual potential (pan) evaporation is about 1900 mm (Nichols 1987). The water table is 85 to 115 m below land surface (Fischer 1992). Sediments in the area are largely fluvial deposits (Nichols 1987). Soils are typically coarse textured and highly stratified (Andraski 1996). Vegetation is sparse; creosote bush [*Larrea tridentata* (DC.) Cov.], an evergreen shrub, is the dominant species. The waste facility has been used for burial of low-level radioactive waste (LLRW) (1962-92) and hazardous chemical waste (1970 to present). Burial-trench construction includes excavation of native soil, emplacement of waste, and backfilling with previously stockpiled soil. The surfaces of completed burial trenches and perimeter areas are kept

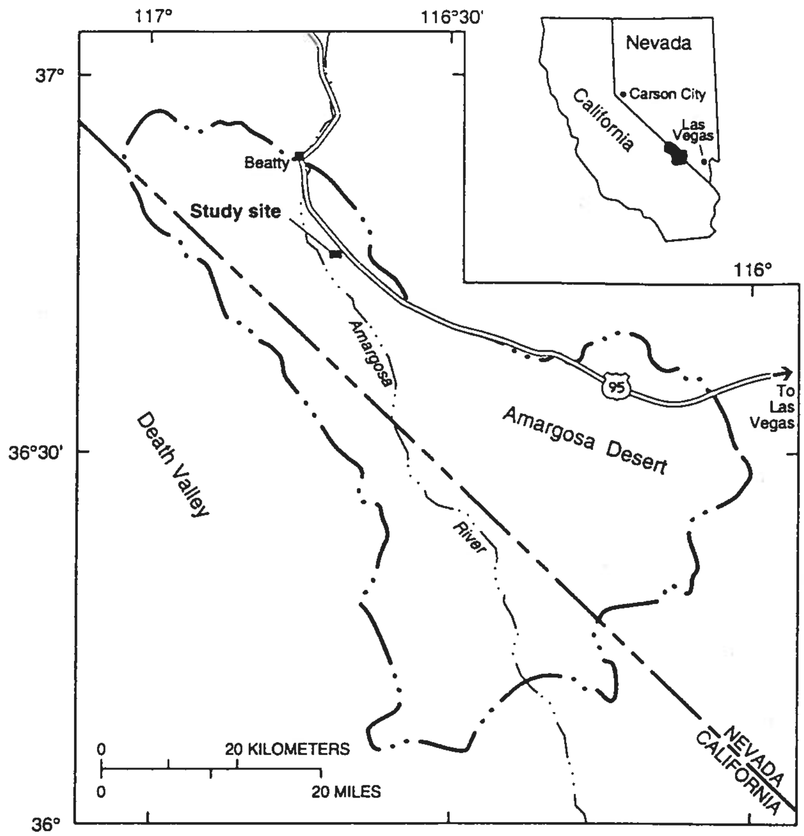

Fig. 1. Location of study site.

free of vegetation. Regulations governing burial of low-level radioactive waste do not require that trenches be lined with low-permeability materials. Prior to 1988, linings were not required for chemical-waste trenches; only the most recently closed hazardous-waste trench (1991) incorporates a synthetic liner in the cover. Liquid LLRW could be shipped to the facility, but the operating license required that liquids be solidified with portland cement before disposal. A 1976 U.S. Nuclear Regulatory Commission (USNRC) investigation, however, indicated that liquid wastes delivered to the site between 1962 and 1975 were disposed directly into the LLRW trenches (USNRC 1976).

Field and Laboratory Experiments

Four experimental field sites were used in the USGS test-trench studies: two nonvegetated test trenches; one undisturbed soil profile where vegetation was removed; and one undisturbed, vegetated soil profile. The three disturbed sites (Fig. 2) were established in 1987 and were designed to simulate solid-LLRW-burial and nonvegetated-surface conditions (Andraski 1990); herbicide was used to keep these sites free of vegetation. The undisturbed, vegetated site was established in 1983, about 40 m from the disturbed sites; boreholes and a vertical shaft (13.7-m long) were used to instrument the soil profile (Fischer 1992). A neutron probe was used to measure water content, and these data were used to calculate the quantity of water stored in a given depth of soil. Thermocouple psychrometers (referred to hereafter as psychrometers) were used to measure water potential and

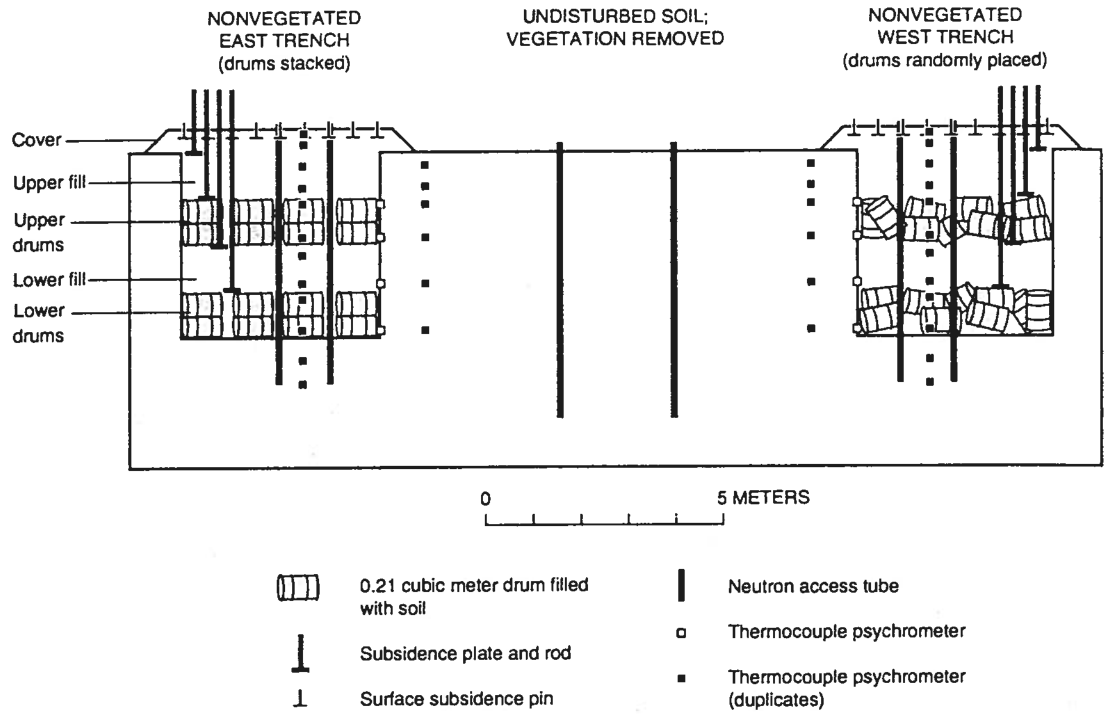

Fig. 2. General design and instrumentation of three disturbed sites.

temperature. Erosion of the trench covers was estimated by measuring the distance between the top of monitoring pins and the trench surface. Subsidence was determined by measuring the elevation of monitoring pins and plates with a rod and level. Meteorological data were collected by an automated weather station (Wood 1996).

Samples for the analysis of native soil (upper 5 m) and trench fill properties were collected during construction and instrumentation of the disturbed sites (Andraski 1991, 1996). Water-retention measurements were extended to air dryness (about -200 MPa) using a water-activity meter described by Gee et al. (1992). The Rossi and Nimmo (1994) model was used to characterize the water retention relation from saturation to oven dryness. Unsaturated hydraulic conductivity was calculated using the Mualem (1976) model and isothermal vapor conductivity was calculated as described by Fayer et al. (1992).

RESULTS

Deep Water Content Profiles

Variation in water content with depth for selected dates is shown in Fig. 3. The March 1991 data show the maximum water content value (measured at the 0.15-m depth) that was observed for each site; these data were collected in response to 29 mm of precipitation that fell during a 3-day period. Among the four sites, maximum depth to which temporal changes in water content were observed increased in the following order: west trench (0.5 m), east trench and vegetated soil (0.75 m), and nonvegetated soil (1 m). Below these depths, temporal changes in water content were within the accuracy of the neutron-probe measurements.

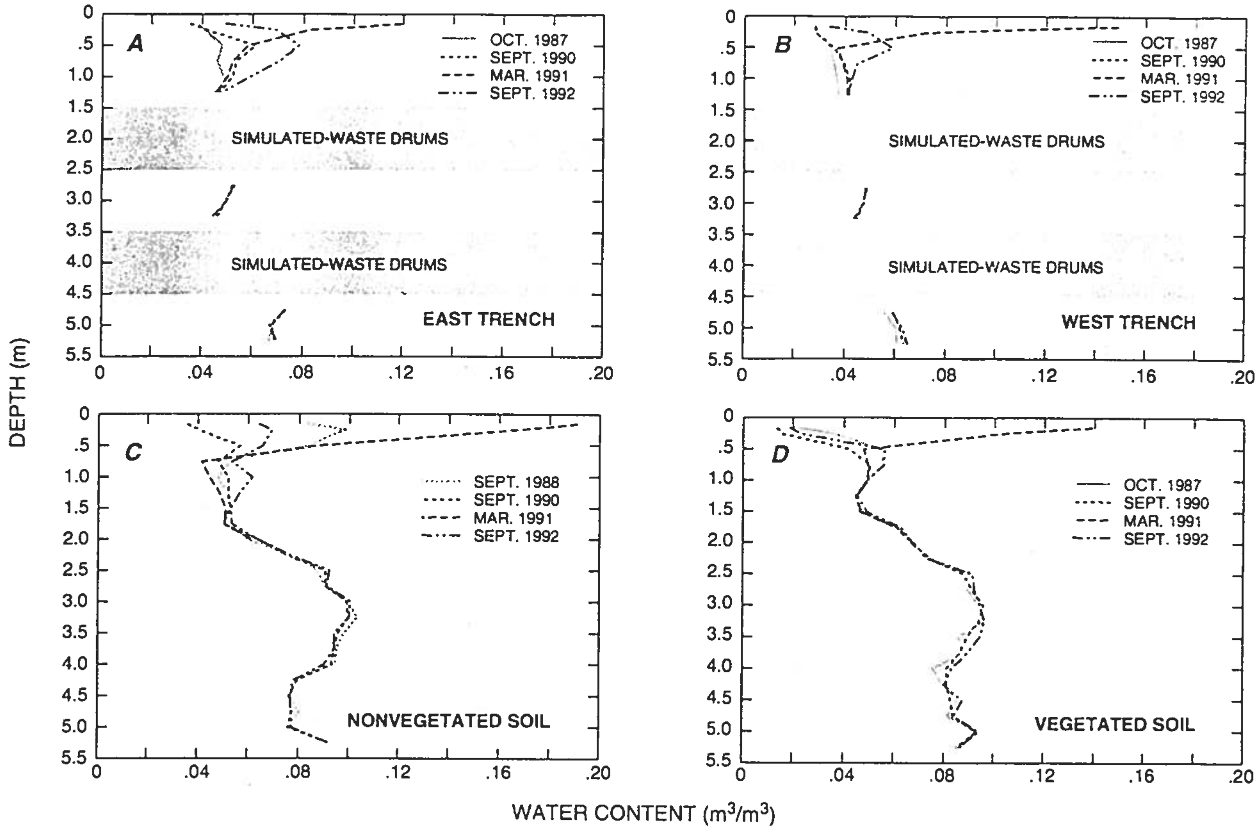

Fig. 3. Water content variations with depth for selected dates at the (A) east trench, (B) west trench, (C) nonvegetated, native soil profile, and (D) vegetated, native soil profile. Water content values for depth intervals from 1.5 to 2.5 m and 3.5 to 4.5 m at the trench sites were not determined because of the influence of simulated-waste drums on neutron-probe readings. Monitoring of nonvegetated soil began in September 1988.

Steps used in the construction of burial trenches (excavation, stockpiling excavated materials, and backfilling) produced a fill material with an initial (Oct. 1987) water content that was low and uniform with depth (Fig. 3A, 3B). The uniformity of initial water content reflects the lack of significant vertical variation in fill properties; textural classification of the fill was gravelly loamy coarse sand (Andraski 1996).

For the nonvegetated- and vegetated-soil sites, vertical variations in water content below a depth of 0.75 to 1 m corresponded with variations in soil texture. Five soil deposits in the upper 5 m of native soil were visually identified by texture, cohesiveness, and color (Andraski 1996). Layers were designated 1 (surface) to 5 (deepest). The thickness of the uppermost layer varied from about 0.75 to 1 m and each of the four underlying layers was about 1 m thick. Textural classification for the five layers was: 1, loamy sand; 2, gravelly coarse sand; and 3, 4, and 5, gravelly coarse sandy loam. Water content values for the gravelly coarse sand were about 40 to 55 percent less than those for the underlying soil (Fig. 3C and 3D).

Precipitation and Near-Surface Water Storage

Temporal variations in near-surface (0- to 1.25-m depth) water storage show site-to-site

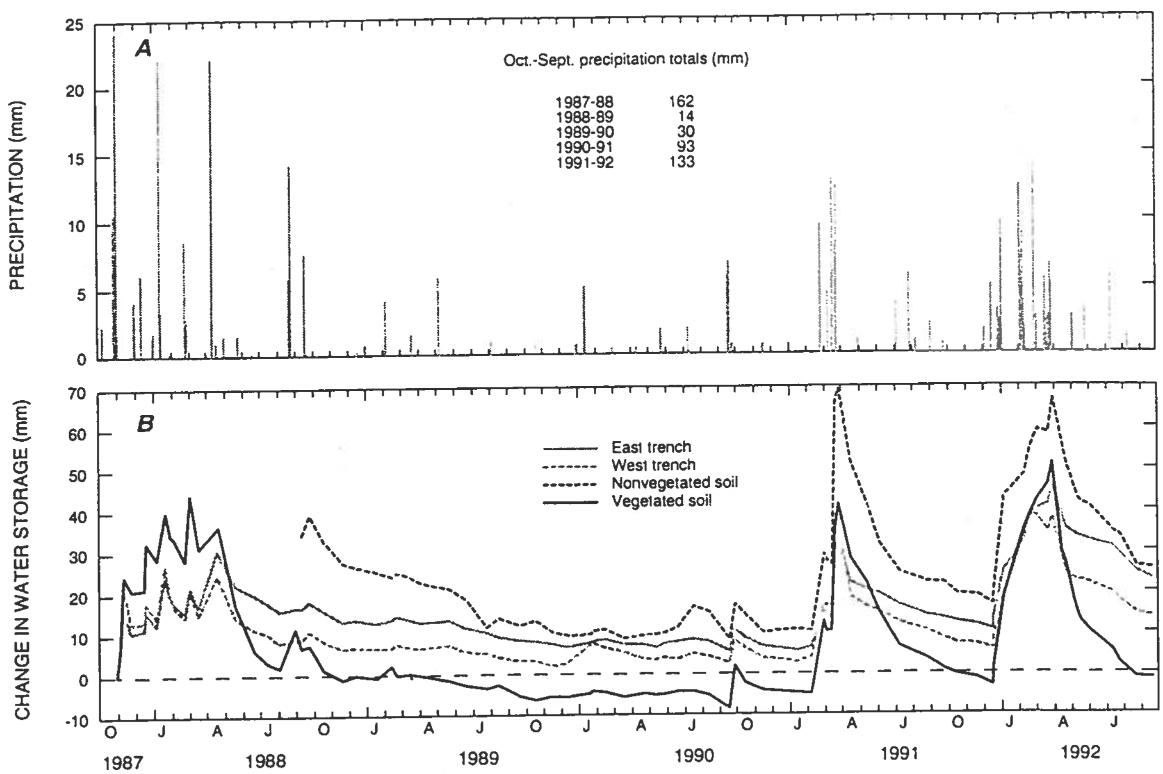

Fig. 4. Daily and annual precipitation (A) and cumulative change in water storage, 0- to 1.25-m depth, measured at four sites (B). Monitoring of nonvegetated soil began in September 1988.

differences in the soil-water response to annual and seasonal changes in precipitation and evaporative demand (Fig. 4). Cumulative changes in water storage showed pronounced increases in response to precipitation from October 1987-January 1988, February-March 1991, and December 1991-March 1992. During these periods, the net increases in storage for the native-soil sites (vegetated and nonvegetated) were greater than those for the trenches. Water that accumulated at the vegetated-soil site, however, was seasonally depleted by evapotranspiration and, by the fall of each year, water storage values were similar to, or less than, those measured initially. In contrast, water storage values for the three nonvegetated sites remained greater than those measured initially.

Plants appeared to have the most substantial effect on the water balance, but site-to-site differences in soil/fill properties also influenced water accumulation and depletion. For example, the structure of the uppermost native-soil layer enhanced water penetration and, concomitantly, reduced evaporation following precipitation. The difference in water accumulation between the two trenches may be related to the quantity of rock fragments in the near-surface cover materials [rock fragments (kg kg^{-1}): east = 0.45, west = 0.23]. A greater quantity of rock fragments in the near surface of the east trench versus that for the west could have retarded evaporation and enhanced internal drainage. The apparent influence of rock-fragments on water accumulation is in general agreement with the results of Waugh et al. (1994).

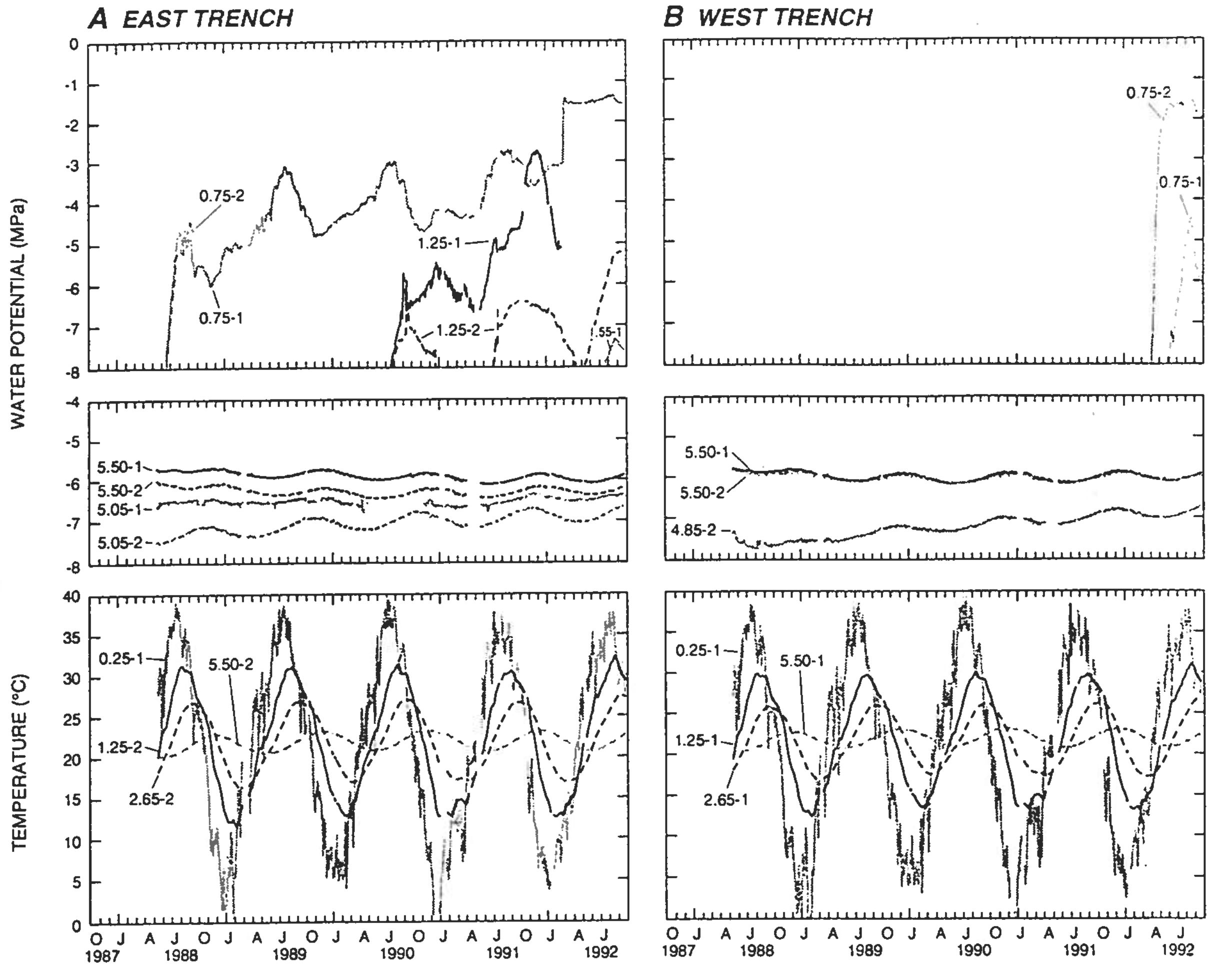

Fig. 5. Daily water potentials and temperatures at the (A) east trench and (B) west trench. Monitoring began in April 1988. Water potentials for east trench fill between the 1.55- and 4.5-m depths and for west trench fill between the 0.75- and 4.5-m depths remained < -8 MPa. Lines are identified by psychrometer depth (in meters) and duplicate number.

Water Potential and Temperature

In contrast with neutron-probe data, the greater sensitivity of psychrometer measurements in the dry range allowed for better definition of the actual extent of water movement and provided much more information about the dynamics and complexities of the soil-water system under disturbed, waste-site conditions and under undisturbed, natural-site conditions. For the trenches, faster penetration of water into the initially dry (< -8 MPa) fill for the east versus west trench was shown by the timing of water potential increases at the 0.75-m depth: east trench, 1988; west trench, 1992 (Figs. 5A, 5B). Rapid percolation in the uppermost layer of undisturbed soil was reflected by the high water potentials at the 0.6- to 0.75-m depths for nonvegetated and vegetated soil during the spring of 1988 and by the large, rapid increases in water potential for the vegetated soil during 1991 and 1992 (Figs. 6A, 6B). In terms of water depletion, the persistence of elevated water potentials at the 0.75-m depth for the three nonvegetated sites

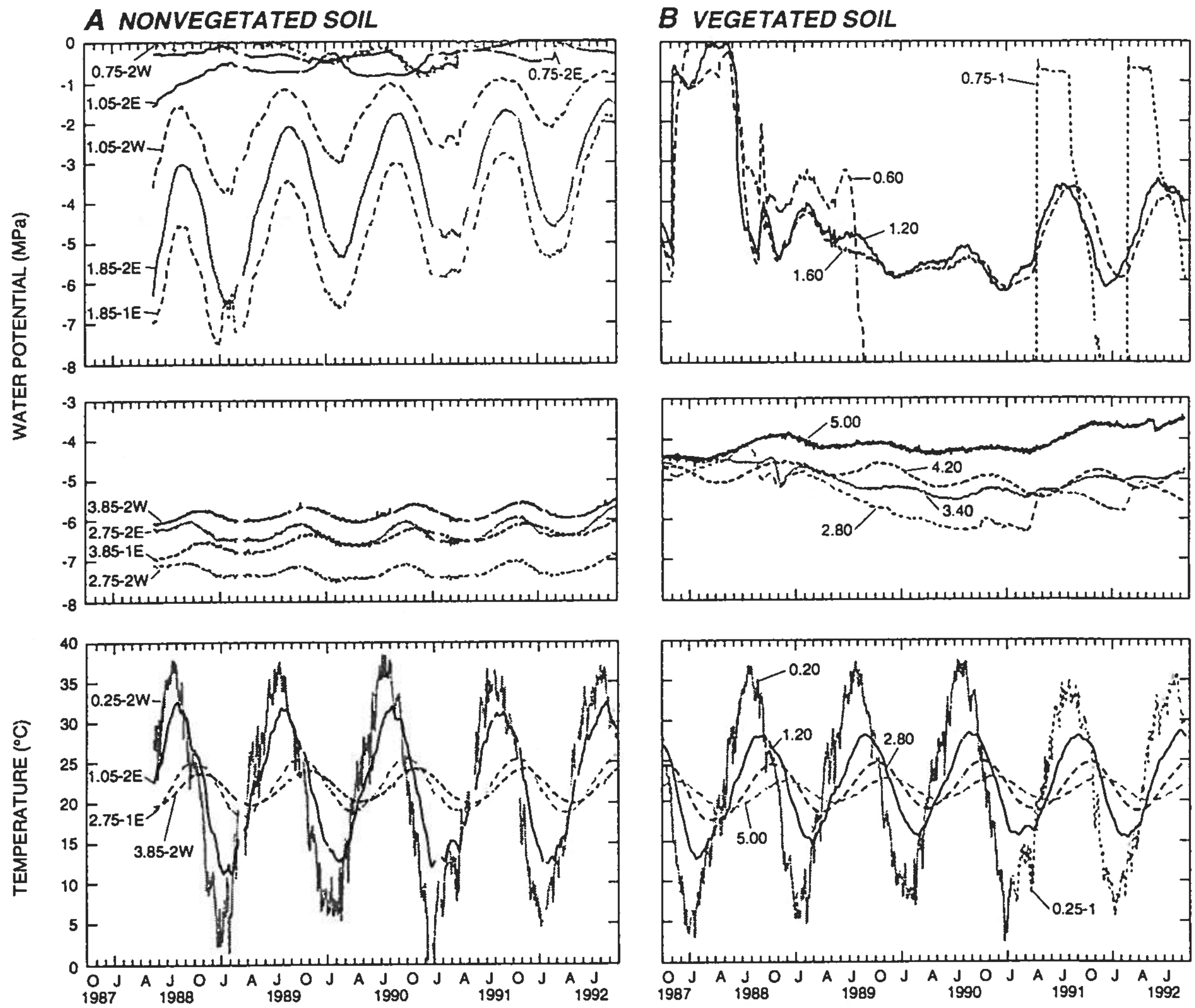

Fig. 6. Daily water potentials and temperatures at the (A) nonvegetated, native soil profile and (B) vegetated, native soil profile. Concurrent monitoring began in April 1988. Lines are identified by psychrometer depth (in meters) and, where applicable, duplicate number.

indicated water that penetrated to a relatively shallow depth was not removed by evaporation. In contrast, the efficiency of root-zone water depletion by native plants was illustrated by the substantial decreases in water potentials at the 0.6- and 0.75-m depths for vegetated soil. Odening et al. (1974) have shown creosote bush to be capable of extracting soil water and maintaining small, positive net photosynthesis when xylem-sap pressures, measured at dawn, were as low as -7.8 MPa.

Although the neutron-probe data (Fig. 3) indicated no measurable change in water content with time below depths of 0.5 to 1 m at the four sites during the monitoring period, psychrometer data collected below the 1-m depth showed distinct seasonal and long-term changes. The seasonal pattern of temperature change with depth was similar for all sites and the resultant gradients suggested that the thermal driving force for vapor flow was predominantly downward during the summer and upward during the winter (Figs. 5, 6). Changes in water potential with time and depth differed from site to site. In contrast with vegetated soil, long-term increases in water potential between the 1- and 2-m depths for the east trench and nonvegetated soil showed that water which accumulated under simulated waste-site conditions continued to move downward (Figs. 5A, 6). For vegetated soil, seasonal trends in water potential between the 1- and 2-m depths were most obvious during 1991 and 1992; potentials were greatest during the summer and least during the winter (Fig. 6B). This seasonal trend is the opposite of what one would expect if plant-water uptake was actively occurring in the coarse soil layer because evaporative demand is greatest during summer. Wallace and Romney (1972) stated that the rooting depth for creosote bush closely corresponds with the depth of penetrating moisture. Thus, the water potential data for vegetated soil implied that the coarse soil layer not only impeded percolation of liquid water out of the uppermost soil layer, but in so doing, may also have limited the depth of root penetration.

Water potentials measured below the 2-m depth showed marked differences in the soil-water response to year-to-year changes in precipitation under waste-site and natural-site conditions. For the soil below the trenches and below the 2-m depth at the nonvegetated-soil site, water potentials remained < -5.5 MPa, showed little long-term change, and indicated driving forces for water flow were generally upward (Figs. 5A, 5B, 6A). For vegetated soil, however, during the 2-year period with below average precipitation (1988-90), water potentials for all depths below 2 m showed a measurable decrease and the resultant gradients between the depths of 2.8 and 5 m provided a consistently upward driving force for water flow (Fig. 6B). Results suggest that the upper boundary conditions imposed by plant activity in the uppermost soil layer provided for the imposition of a second control on subsurface water flow that resulted in deep, episodic drying during periods of below-average precipitation. A comparison of water potentials measured at comparable depths below 2 m also showed that values for vegetated soil were, on average, about 1 to 2 MPa greater than those for the other sites (Fig. 5 and 6). The reason for this difference cannot be readily explained, but may be related to spatial and(or) instrument-installation differences between the sites.

Hydraulic Properties

Results from the field investigations indicated that differences in soil/fill properties influenced the water balance and water movement. To characterize these features, hydraulic properties and their vertical variations were evaluated using laboratory data measured across a moisture range that is representative of arid conditions, but is seldom studied (Andraski 1996). To better approximate the water content-water potential relation from saturation to oven dryness, the Rossi and Nimmo (1994) modifications to the Brooks and Corey (1964) model were applied in this study (Fig. 7). Andraski (1996) found that the Rossi-Nimmo model described the laboratory-measured water retention values well and predicted water potential values were consistent with field values. The -1.5 MPa pressure-plate data were omitted from the analysis because these data introduced a significant error in the description of hydraulic properties in the dry range (i.e., low water content; high negative water potential).

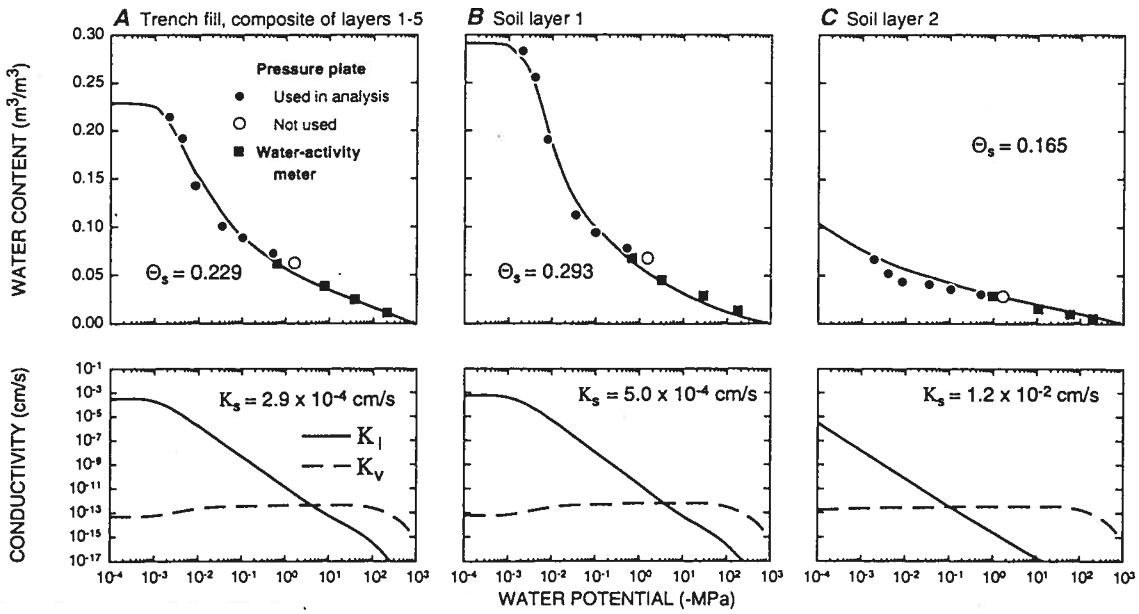

Fig. 7. Hydraulic properties of trench fill (A) and soil layer 1 (B) and 2 (C). Greek symbol theta, subscript s, is saturated water content; Ks, K1, and Kv are saturated-, unsaturated-, and isothermal-vapor conductivity.

Textural differences between the homogeneous trench fill and the two uppermost soil layers (layer 1 and 2, respectively) are reflected by their hydraulic properties (Fig. 7). Water retention data show that soil layer 1, the material with the finest texture, retained the greatest volume of water and soil layer 2, the material with the coarsest texture, retained the least water. For the undisturbed soil, a comparison of the unsaturated hydraulic conductivity (Kl) functions for the two soil layers illustrates how the textural discontinuity between these layers provided a natural capillary break that impeded downward flow of liquid water: Kl values for soil layer 2 typically were 10,000 times less than those for layer 1; therefore, under unsaturated conditions, the lower Kl for layer 2 impeded liquid flow out of layer 1. The shape of the Kl functions for the trench fill and soil layer 1 was similar; however, across a water potential range of 0 to -1 MPa, Kl values for the fill were less than those for soil layer 1.

The water potential value at which isothermal vapor conductivity (Kv) began to exceed Kl was about -4 MPa for the trench fill and soil layer 1, and was about -0.1 MPa for soil layer 2 (Fig. 7). For soil layers 3, 4, and 5, this crossover value was about -6 MPa (Andraski 1996). In combination with the field data shown in Figs. 5 and 6, these results imply that both liquid and vapor flow may be important mechanisms of water transport at the field sites. Quantitative evaluation of these complex, coupled flow processes, however, requires the use of numerical models.

Erosion and Subsidence of Trench Covers

Changes in the structural integrity of trench covers through erosion or subsidence can reduce the waste isolation potential of a burial site. No measurable soil loss was observed for the east trench and soil loss for the west trench totaled about 9 mm during the 5-yr monitoring period (Fig. 8A). Greater soil loss for the west trench may be attributed to fewer

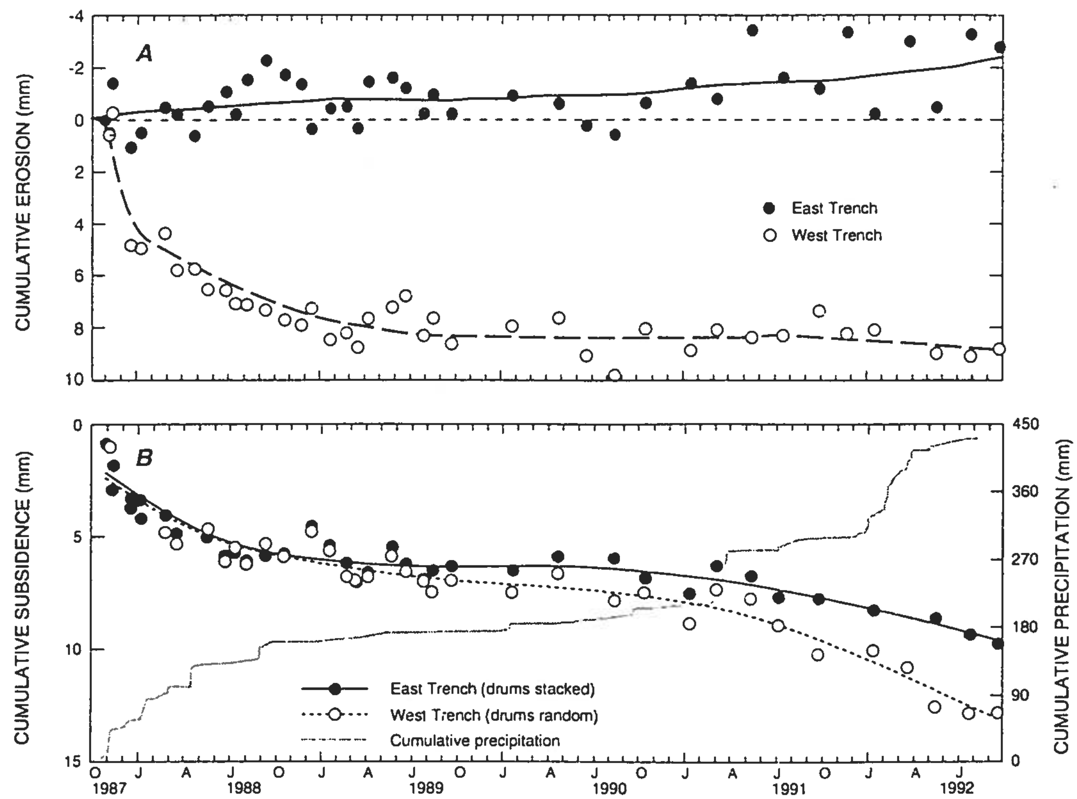

Fig. 8. Cumulative erosion (A) and subsidence (B) of trench covers and cumulative precipitation (B).

rock fragments in the near surface. Most of the soil loss appeared to be due to deflation. During November and December 1987, two periods of high winds occurred during which hourly average windspeeds of 8 to 14 m s^{-1} persisted for 16 h or more (Andraski 1990). Nearly 55 percent of total soil loss for the west trench occurred during this time. The decreased rate of soil loss with time for the west trench may have been due to increased surface armoring by rock fragments and to surface crusting in response to wetting and drying cycles. Data for the east trench indicated a general trend of increased surface elevation with time. This trend may have been due to deposition of eolian material (McFadden et al. 1987) or to the development of vesicular soil structure induced by wetting and drying cycles (Miller 1971).

Subsidence totaled about 10 mm for the east trench and 13 mm for the west trench (Fig. 8B). About 50 percent of the subsidence occurred during the first year following trench construction. Subsidence measured during the first year was probably due to settling of the uncompacted fill material in response to precipitation and freeze-thaw cycles. During 1990 to 1992, the effects of drum placement became evident, with greater subsidence being observed for the trench where drums were randomly placed. General trends in subsidence were similar for the two test trenches and the rates of subsidence appeared to be correlated with cumulative precipitation.

Discussion

Results from the test-trench studies at the Amargosa Desert research site show the relative influence of soils, plants, and structural changes on water movement under natural climatic conditions. This information provides insight into the factors and processes that can influence the performance of a waste-cover system in an arid environment.

Results of the study suggest that, under nonvegetated conditions, precipitation can accumulate and penetrate downward, thereby increasing the potential for water to come in contact with and enhance the release of contaminants for subsequent transport by liquid water, water vapor, or other gases. For the duration of the experiment, however, water penetration was limited to the upper 1 to 2 m. The method of drum placement (stacked versus random) and associated differences in trench-cover subsidence showed no measurable influence on the water balance of the trenches. The rates of water accumulation and penetration at the trench sites appeared to be controlled by the hydraulic properties and initial dryness of the fill ahead of the advancing moisture front. For the nonvegetated soil, the natural capillary break (loamy sand over gravelly coarse sand) impeded rapid percolation of liquid water out of the uppermost soil layer, but accumulated water did continue to penetrate into the underlying coarse layer. Below the test trenches, water potential gradients provided an upward driving force for water flow that persisted during the 5-yr monitoring period. To reverse the flow direction, sufficient water would have to accumulate in the bottom of the trenches. The potential for such accumulation at a waste-burial site will be enhanced if precipitation and runoff are allowed to collect in open trenches or if liquids are disposed directly into burial trenches. Under such conditions, the effectiveness of the positive surface and subsurface waste-isolation features that were identified under the objectives of this study would be diminished. In relation to this, another study is presently investigating the distribution of contaminants in the unsaturated zone at the Amargosa Desert research site and initial analyses have suggested that liquid wastes disposed into the LLRW trenches during 1962-75 contributed to the observed contamination (Striegl et al. 1996).

Data collected at the undisturbed, vegetated-soil site identify two important features that may be incorporated into the design of a waste-cover system--stratified soils and native plants. Results suggest that the naturally stratified soils, in combination with native plants, provided for (1) rapid infiltration, which reduced runoff, (2) high storage capacity for infiltrated water, (3) limited percolation depth and, apparently, plant-root depth, (4) effective seasonal depletion of water accumulated in the root zone, and (5) episodic, deep drying of the unsaturated zone. These results support the indirect evidence for negligible deep percolation of precipitation that has been inferred from other studies done under undisturbed, vegetated conditions at the site. For example, studies of chloride concentration profiles estimated that percolation below a depth of 10 m has been minimal or nonexistent for at least 6000 yr (Fouty 1989) to 15,000 yr (Prudic 1994). Recent field measurements also indicated that water potential gradients and a geothermal gradient of 0.06°C m^{-1} provide upward driving forces for water movement between depths of 10 and 50 m (Andraski and Prudic *in press*).

Although the natural soil-plant system appears to provide an excellent conceptual model for the design of a waste-cover system, the establishment of such a system may be difficult and will depend on the availability of appropriate soil materials and the restoration of native vegetation. Disturbance caused by construction of a waste-burial facility will not only remove plants, but also will destroy the fragile "fertile-islands" that have formed underneath desert shrubs over long periods of time. Natural revegetation of disturbed land in some arid areas, such as the Mojave Desert, may require decades or centuries; more rapid revegetation may be possible, but only through the use of extensive soil manipulation and plant husbandry techniques that can help, but do not guarantee, restoration of a disturbed site (Wallace et al. 1980). Thus, additional work is needed to evaluate and develop cost- effective revegetation strategies if plants are to be successfully incorporated into waste-cover systems in such areas. Further study also is needed to define the soil-plant-atmosphere interactions that caused the deep drying observed at the vegetated-soil site and to evaluate how such interactions could affect the potential for release of contaminants to the terrestrial environment as well as to groundwater.

Data collected during this study illustrated (1) the extreme range in soil moisture conditions that may be observed at a desert site [from near 0 (saturation) to < -8 MPa (lower limit of psychrometer measurements)], (2) the lower limit to which hydraulic characterization data normally are measured (i.e., -1.5 MPa, referred to as the permanent wilting point for crops) is not adequate for nonirrigated, desert soils and plants, and (3) field instrumentation that is well established in agricultural soils is of limited use under these dry conditions (e.g., tensiometers, have a lower measurement limit of about 0.1 MPa). The field and laboratory results also suggest that both liquid and vapor flow may be important mechanisms of water transport at the field sites. Thus, the hydrologic assessment and the design of arid-site waste-cover and monitoring systems need to consider and evaluate the potential risks associated with liquid- and vapor-phase transport of contaminants to ground water and to the terrestrial environment. Accurate and complete descriptions of hydraulic properties are essential to such predictive assessments. In addition to the Rossi and Nimmo (1994) water retention model that was applied in this study, Fayer and Simmons (1995) have recently proposed modifications to the Brooks and Corey (1964) and van Genuchten (1980) models that provide good descriptions of the water retention relation across the entire range of moisture that may be observed in an arid setting.

Greater rock-fragment concentration in the near surface of trench covers resulted in greater accumulation of infiltrated water and decreased erosion. Incorporation of this factor into cover design may enhance vegetation establishment and control erosion.

Subsidence was greater for the trench where drums were randomly placed than for the trench with stacked drums. Although the method of drum placement and associated effects on subsidence did not appear to have a measurable influence on the water balance for the trenches during the monitoring period, general trends in subsidence rates did indicate a positive relation with cumulative precipitation. This suggests that subsidence could become a factor in the long-term water balance of waste-burial trenches, particularly if the subsidence were to result in localized ponding and the development of preferential flow paths.

In summary, results from the laboratory and multiple-year field components of the test-trench studies at the Amargosa Desert research site provided information about soil, plant, and structural features that can influence the performance of a waste-cover system and the potential for release of contaminants from landfills and waste-burial sites in an arid environment. Results suggest that the ultimate fate of contaminants buried at properly managed solid-waste sites may be determined largely by the interactions among climate and surface-cover features of the disposal facility, and how these factors change with time. The third component of the test-trench studies is designed to combine the laboratory and multiple-year field data with numerical simulations to further evaluate the mechanisms affecting unsaturated flow at the experimental sites. Work on this component is in progress.

The data base and facilities developed at the partially contaminated Amargosa Desert research site also provide a foundation upon which to build collaborative efforts to further the study and understanding of arid-site processes. Additional work is needed to analyze and evaluate the interactive physical, chemical, and biological mechanisms controlling water movement and the transport and fate of contaminants under arid conditions. Such information is important to the development of effective waste-burial systems, monitoring systems, and remedial strategies that are intended to limit contaminant releases to the environment.

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