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# Evaluation of evapotranspiration from alternative landfill covers at the Rocky Mountain Arsenal

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ABSTRACT: The performance of an alternative evapotranspirative landfill cover is assessed in this study using field monitoring results and numerical modeling of unsaturated water flow. In particular, this study focuses on evaluation of evapotranspiration defined using field monitoring of water balance components and estimated using empirical models. Parameters governing evapotranspiration in physical models are discussed. Modeling results indicate that evapotranspiration recovered 96% of the infiltrated moisture over a 4 year simulation period. Even though significant emphasis was placed in vegetation development at the site, assessment of the monitoring results at the site indicates that evaporation from the cover surface removes 1.5 times more water than plant transpiration. Overall, evapotranspiration was sufficient to elicit satisfactory cover performance.

## 1 INTRODUCTION

The management of waste generated by a growing population is an important topic for government decision makers and engineers. The current trend in waste management is the isolation of waste into protected containment facilities to minimize human and environmental contact. Accordingly, one of the key engineered components in municipal and hazardous waste containment systems is the cover system. The objective of a cover system is to prevent infiltration of rainwater, which is often translated as a design that minimizes basal percolation. If rainwater reaches the waste, it may mobilize contaminants that may eventually reach the groundwater.

One particular cover type, the evapotranspirative cover, is gaining popularity in arid climates (Dwyer 1998; Zornberg et al. 2003). An evapotranspirative cover is a simple system that involves a monolithic soil layer with a vegetative cover. Evapotranspiration and moisture storage play a significant role in the performance of this system. An evapotranspirative cover acts not as a barrier, but as a reservoir that stores moisture during precipitation events and then releases it back to the atmosphere as evapotranspiration, as shown in Figure 1. Evapotranspirative covers have been shown to be less vulnerable to desiccation and cracking during and after installation than compacted clay covers, are relatively simple to construct, require low long-term maintenance, and may provide significant cost savings

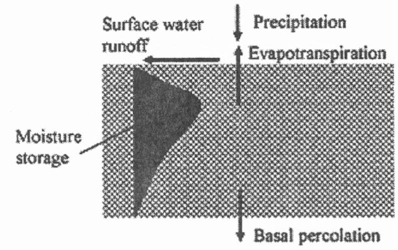


Figure 1. Schematic of an evapotranspirative cover.

(Zornberg et al. 2003). As evapotranspirative covers function with a reasonably broad range of soils, much of the cost savings are because these covers can be typically constructed using local soils.

A site-specific demonstration of adequate performance is still required to evaluate the suitability of the selected soils and climate conditions. Accordingly, a number of field monitoring programs commenced in the late 1990's to evaluate different variables governing the behavior of evapotranspirative cover systems, including precipitation, surface water runoff, water storage, and basal percolation (Albright and Benson 2002). In these monitoring programs, basal percolation measured using zero-tension pan lysimeters has been typically used as the primary performance indicator of the cover performance. However, performance is governed by evapotranspiration from the soil profile. Consequently, quantification of the moisture removal specific to the soils and climatic conditions at the site should be considered during cover design.

The main objective of this paper is to evaluate the contribution of evapotranspiration to the performance of an evapotranspirative cover based on field monitoring data collected from a case study as well as on results from simulations made using REF-ET (Allen 2001) and HYDRUS-1D (Simunek et al. 1998). Monitored meteorological variables are used as input to REF-ET to obtain a measure of the "potential" evapotranspiration for the site, which is the maximum evapotranspiration that can occur for given climatic conditions. The meteorological variables, laboratory measured unsaturated flow parameters, and site-specific agronomic properties are used as input to HYDRUS-1D to assess the "actual" evapotranspiration expected for the cover, which is the evapotranspiration for particular soil and vegetation conditions. The modeling results are compared with evapotranspiration calculated using field monitoring of water balance components.

## 2 EVAPOTRANSPIRATIVE TEST COVER, SOIL DATA, AND EQUIPMENT

A series of instrumented test plots were constructed at the Rocky Mountain Arsenal, located near Denver, Colorado, USA, in Summer 1998 (Kiel et al. 2002; Zornberg and McCartney 2003). The climate in Denver is semiarid, with an average annual precipitation of 396 mm and an average pan evaporation of 1,394 mm (quantified from 1948 to 1998). The wettest months of the year (April to October) are also the months with the highest pan evaporation; which are optimal conditions for an evapotranspirative cover. The test cover analyzed in this study was constructed by placing a 1168 mm layer of low-PI clay soil atop a large pan lysimeter (9.1 m by 15.2 m). The soil was placed at 70% relative compaction with respect to standard proctor maximum dry density (1960 kg/m$^3$). The lysimeter consists of a geocomposite for water collection (consisting of a geonet for in-plane drainage sandwiched between two geotextiles) underlain by a geomembrane. The lysimeter was placed on a 3 percent grade, which allows gravity drainage through the geocomposite. The soil used was a low plasticity clay (CL), with an average fines content of 43%, and an average PI of 15.4. The cover and surrounding buffer zone were vegetated with local grasses and shrubs, such as Cheatgrass.

The pressure plate, hanging column and dew point potentiometer methods (Klute 1986) were used to define site-specific relationships between soil suction $\psi$ and volumetric moisture content $\theta$ (the characteristic curve). For use in the numerical models, the

Table 1. Characteristic curve and K-function parameters.

| Parameter | Value | Units |
|---|---|---|
| $\alpha$ | 0.00332 | 1/mm |
| N | 1.3348 | |
| $\theta_r$ | 2.5 | % |
| $\theta_s$ | 47 | % |
| $K_{sat}$ | 4.7E–08 | m/s |

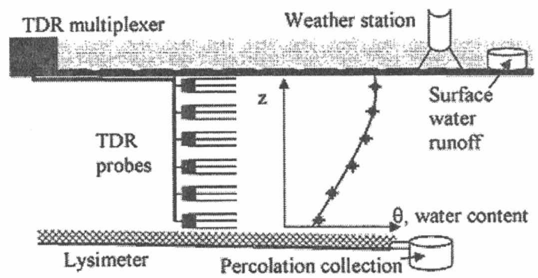


Figure 2. Monitoring system layout.

characteristic curve was fitted using the van Genuchten model, while the relationship between the hydraulic conductivity and suction (the K-function) was defined using the van Genuchten-Mualem model (van Genuchten 1980). Table 1 summarizes the van Genuchten model parameters: $\alpha$, $n$, $\theta_s$, and $\theta_r$ as well as the saturated hydraulic conductivity $K_s$ for the soil in this cover.

Basal percolation, precipitation, changes in soil moisture storage, and surface water runoff were monitored on a daily basis. In addition, solar radiation, wind speed and direction, and percentage cloud cover were also measured. Figure 2 shows a schematic of the monitoring layout used at the site.

Considering the conservation of mass of water into and out of the cover, the evapotranspiration may be obtained as follows:

$$ET = P - G - \Delta S - R \quad (1)$$

where $ET$ is the evapotranspiration, $P$ is the precipitation, $G$ is the basal percolation, $\Delta S$ is the change in moisture storage, and $R$ is the surface water runoff. Rain and snow were measured using an all season gauge. Percolation was channeled from the lysimeter by gravity and measured in a sump using a tipping-bucket rain gauge. The moisture content profile was measured in the center of the lysimeter using an array of six wave content reflectometer (WCR) sensors spaced evenly with depth. Surface water runoff was collected in geomembrane swales around the cover perimeter.

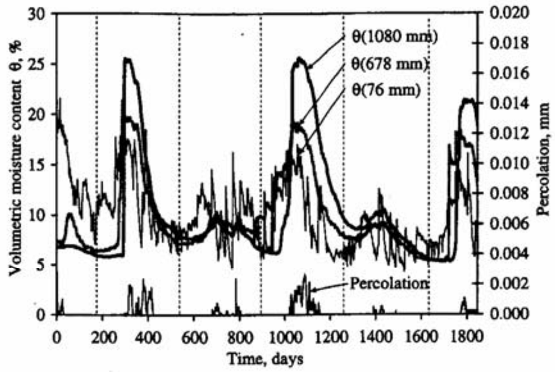


Figure 3. Percolation and volumetric moisture content at three depths (76 mm, 678 mm, and 1080 mm).

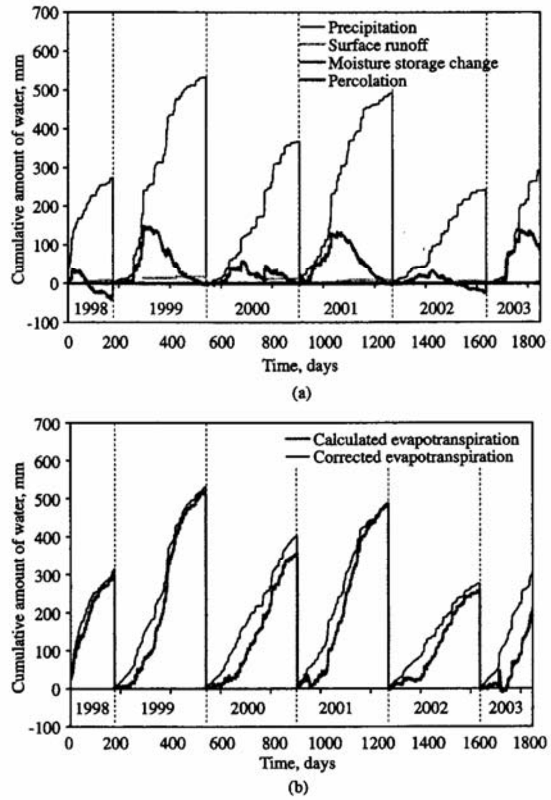


Figure 4. Water balance variables: (a) Measured values; (b) Calculated values.

## 3 FIELD MONITORING RESULTS

This section presents the measurements obtained for water balance components in the evapotranspirative cover at the Rocky Mountain Arsenal. These results are used for defining numerical model input parameters as well as for comparison with simulation results. Monitoring commenced on July 10, 1998 (day 1), and continued until July 31, 2003. Figure 3 shows the variation in moisture content with time at three depths in the test cover along with the percolation collected from the lysimeter. The vertical dashed lines in the figures denote January 1st of each monitoring year.

This figure indicates that the time periods when was percolation collected in the lysimeter correspond with the periods of increased moisture within the cover. The surface moisture content fluctuates on a daily basis (see θ at depth of 76 mm), while the basal moisture content changes in response to significant wetting events (see θ at depth of 1080 mm). The basal moisture content was observed to show higher moisture contents than that at the surface because of the boundary effect induced by the lysimeter: the geotextile component must become saturated before it will conduct water at an appreciable rate (McCartney and Zornberg 2004). This causes water to accumulate at the base of the cover instead of flowing into the lysimeter. Nonetheless, the small volume of percolation collected by the lysimeter indicates that upward gradients due to evapotranspiration may have removed a substantial amount of the stored water.

The moisture content was integrated over the cover depth to calculate the cover moisture storage. Figure 4(a) shows the cumulative values for the measured water balance. Above average amounts of precipitation occurred in 1999 and 2001, which corresponds with the periods of increased moisture content observed in Figure 3. The cover moisture storage increases in the early portion of each year in response to higher precipitation in the spring, while it decreases in response to high evapotranspiration in the summer and fall. Runoff was minimal, but was observed to follow the pattern of precipitation and was greatest in the spring during heavy storms. Little runoff was collected from melting snow. The percolation was a comparatively small component of the water balance, typically less than 0.02% of the precipitation.

Figure 4(b) shows the cumulative ET calculated on a daily basis using Equation (1). On some days, the sum of the change in moisture storage, runoff, and percolation was greater than the precipitation, resulting in a negative value of ET. This is physically unrealistic, as ET is a strictly positive quantity. This occurred on days when no precipitation was measured but an increase in moisture storage was calculated (due to the discretization of $S$). To account for the discretization error, it was assumed that every ET calculation had the same average daily error. The average daily error was defined by taking the average of the negative calculated ET values. The average daily error calculated to be $-1.03$ mm. On days with a negative calculated ET, the corrected ET was assumed to be the average error. On the days with a positive calculated ET, the average error was subtracted from this value to obtain the corrected ET. Figure 4(b) shows that the major differences between the calculated and corrected values of ET occur in the early days of each year. The corrected ET generally exceeds the precipitation, indicating good cover performance.

## 4 NUMERICAL MODEL REQUIREMENTS

### 4.1 *Modeling goals*

The error in the water balance evaluation led to difficulties in using the monitoring results to accurately assess the effects of evapotranspiration on cover performance. Accordingly, estimation of the contribution of evapotranspiration to cover performance can be made using numerical models. For instance, HYDRUS-1D uses the finite element method to solve Richards' equation, which governs unsaturated water flow through porous media in response to atmospheric boundary conditions. However, the input parameters needed for HYDRUS-1D (e.g. initial conditions, boundary conditions, soil properties, model geometry and discretization, plant root properties) are often poorly defined and may lead to uncertain results. In addition, empirical models are often required to estimate input parameters. The focus of this section is to justify the selection of the input parameters used in the subsequent numerical simulations.

### 4.2 *Meteorological and agricultural inputs*

The program REF-ET was used to calculate the potential evapotranspiration (PET) for the years 1999 to 2002 (Allen 2001). This program solves for the PET using the Penman-Montieth equation. Required input information includes the daily minimum and maximum temperatures $t_{min}$ and $t_{max}$, the daily dew-point temperature, the daily solar radiation, the average wind speed at a height of 6 meters above the surface, and the fractional cloud cover. The dew point temperature $t_d$ is given by:

$$t_d = \frac{5}{9}\left(\frac{t_{max} - t_{min}}{2} - 32\right) \tag{2}$$

This information was recorded at a weather station within 10 miles of the evapotranspirative test cover. Figure 5 shows the annual calculated cumulative PET. Evaluation of the daily PET data used to form this graph indicates that PET is greatest in the summer, and lowest in the winter. The calculated PET is over 2 times greater than the measured evapotranspiration shown in Figure 4(b).

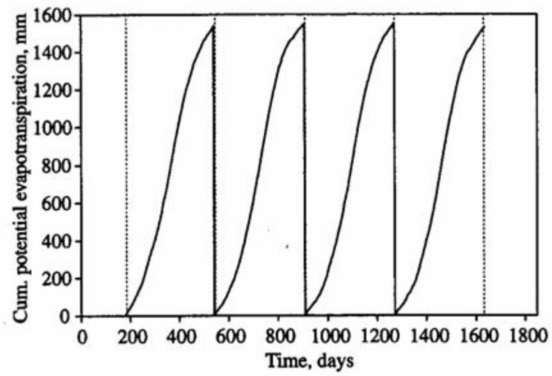


Figure 5. Potential evapotranspiration from REF-ET.

The potential evapotranspiration from REF-ET must be partitioned into the potential transpiration $T_p$ and the potential evapotranspiration $E_p$ for use with HYDRUS-1D. The Ritchie model (Ritchie and Burnett 1971) was used to correlate the variation in the leaf area index $I_{LA}$ with the partitioned evapotranspiration PET, as follows:

$$T_p = PET\left[a + b\left(I_{LA}\right)^c\right] \quad d \le I_{LA} \le e \tag{3}$$

where a, b, c, d, and e are model parameters. The leaf area index is an empirical measure typically used to quantify the health and moisture requirements of a leafy plant. The Ritchie model assumes that the potential transpiration increases proportionally to the square root of the leaf area index. The leaf area index was calculated for the growing season of local Cheatgrass, and is shown in Figure 6(a). The partitioning of the potential evapotranspiration into potential transpiration and the potential evaporation is shown in Figure 6(b). The Ritchie model parameters used in the analysis are indicated in the figure.

Transpiration by root uptake is modeled using a sink term in the Richards' equation at each node. The Feddes model was used to calculate the actual root uptake based on the available moisture at each node and the capacity of the plants (Feddes et al. 1978). The model requires a distribution of root length density with depth, and an estimation of the range of water contents at which plants will transpire. An exponential root length density distribution with depth was used, as follows:

$$\rho_{RL}(Z) = Z[a \exp(-bz) + c] \tag{4}$$

where z is the depth from the surface, $\rho_{RL}$ is the root length density (units of mm roots/mm soil), and $a$, $b$ and $c$ are model parameters equal to 0.875, 0.150 and 0.000, respectively. The three parameters for the root

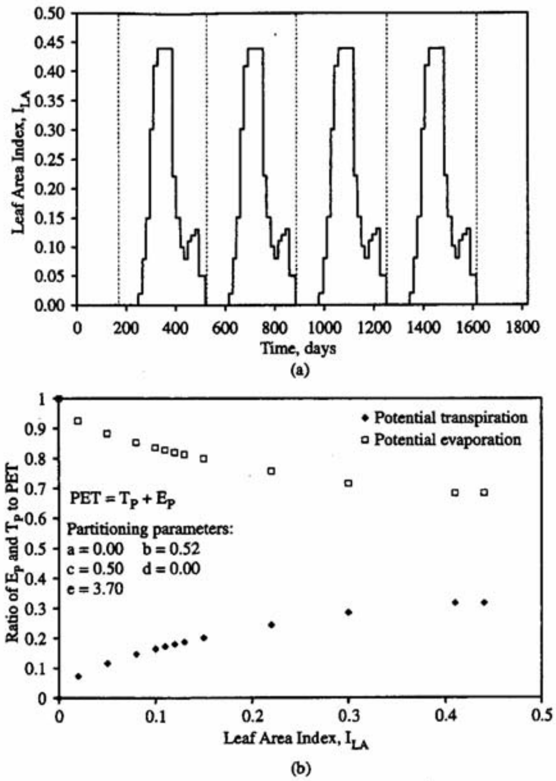


Figure 6. Agricultural data for partitioning PET into $T_p$ and $E_p$: (a) Annual variation in leaf area index, (b) Ritchie model for partitioning $E_p$ and $T_p$ from PET.

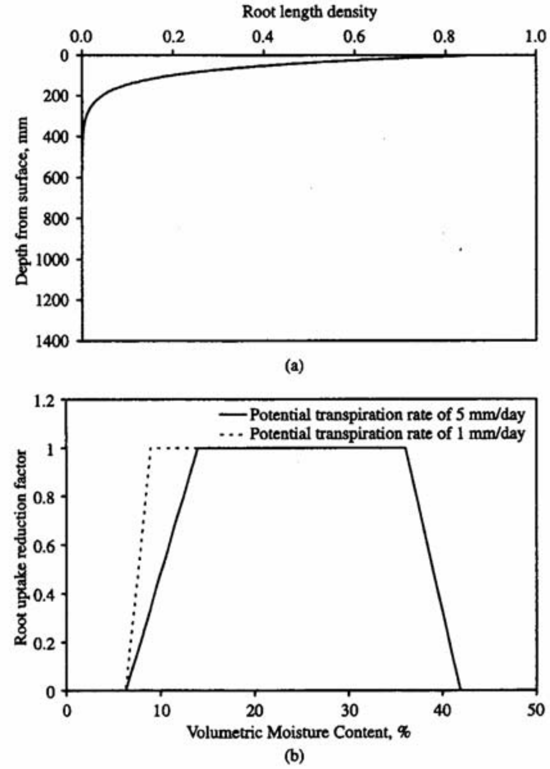


Figure 7. Root uptake information: (1) Root length distribution, (b) Root uptake reduction factor.

density function were selected from a HYDRUS-1D plant database for grass with a maximum rooting depth of 400 mm. The root length distribution with depth is shown in Figure 7(a). A rooting depth of 400 mm was selected to conservatively represent the condition of the roots after a single growing season or recovery after a prolonged drought period. Both situations occurred during the monitoring program.

Cheatgrass has a wilting point corresponding to a moisture content of 6%, and will not transpire at moisture contents near saturation due to anaerobic conditions. Figure 7(b) shows the variation in the uptake correction factor for the local Cheatgrass.

### 4.3 *Geometry input and initial conditions*

A soil profile 1168 mm in depth with a uniform soil type was selected for modeling. A total of 501 nodes were selected, necessary due to the nonlinear soil properties. Observation points were selected in the model at the same depths as the TDR probes in the actual evapotranspirative cover. The initial conditions were selected to be the suction profile corresponding to the moisture content profile on the first day of modeling (day 176). A seepage face boundary condition was used to simulate the lysimeter, implying that drainage occurs only under zero suction. The surface boundary condition was an atmospheric boundary condition with runoff. For this condition, surface water runoff will only occur if the infiltration rate is greater that the saturated hydraulic conductivity of the soil.

## 5 MODELING RESULTS

Figure 8(a) shows the calculated the change in moisture content at three depths. The results shown in this figure indicate that HYDRUS-1D yields similar results to those observed in Figure 3. However, the wetting front does not reach the base of the cover (1080 mm) until 2003. This may be due to preferential flow in the field, or to difficulties in modeling the boundary condition representative of a lysimeter. Regardless, the HYDRUS-1D results are useful for comparison with the calculated ET from the monitored water balance components.

Figure 8(b) shows a comparison between the simulated surface evaporation and transpiration values. This figure indicates that the surface evaporation contributes approximately 1.5 times more to the removal

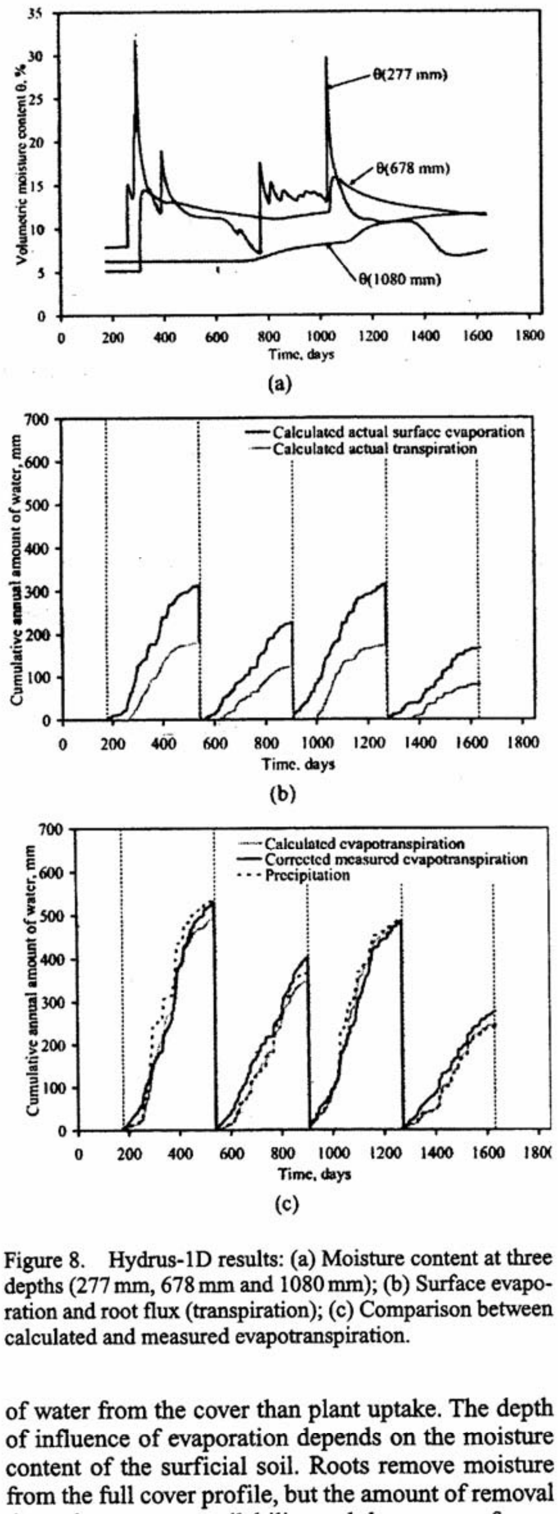


Figure 8. Hydrus-1D results: (a) Moisture content at three depths (277 mm, 678 mm and 1080 mm); (b) Surface evaporation and root flux (transpiration); (c) Comparison between calculated and measured evapotranspiration.

of water from the cover than plant uptake. The depth of influence of evaporation depends on the moisture content of the surficial soil. Roots remove moisture from the full cover profile, but the amount of removal depends on water availability and the season of year. Evaporation occurs throughout the year, while transpiration occurs mostly during the vegetation growing season.

Figure 8(c) shows a comparison between the simulated and the corrected measured evapotranspiration. The two quantities compare quite well. The corrected measured ET typically is slightly greater than the calculated ET. The simulated ET is approximately 30% of the potential evapotranspiration (Figure 5). The simulated ET corresponded well with the precipitation each simulation year. Over the four year monitoring period, ET removed 96% of the precipitation (1565 mm out of 1626 mm). Negligible runoff was collected. Although Figure 8(a) indicates an increase in moisture content on several occasions, ET led to relatively low moisture contents throughout the soil profile at the end of the simulation. Also, the percolation throughout the four year simulation period was less than 0.1 mm (0.02% of the precipitation), indicating that the ET adequate enough to lead to satisfactory cover performance.

## 6 CONCLUSIONS

This paper summarizes the evaluation of ET in an evapotranspirative landfill cover at the Rocky Mountain Arsenal in Denver, Colorado, USA. Specifically, the contribution of site-specific evapotranspiration to the water balance of the cover is identified. Calculation of the evapotranspiration using measured water balance components was prone to error. Prediction of the potential evapotranspiration for the site using REF-ET is significantly greater than the applied precipitation. However, prediction using HYDRUS-1D indicated that the actual evapotranspiration about 30% of the potential evapotranspiration. Numerical modeling using HYDRUS-1D was found to be a useful tool to complement water balance calculations of evapotranspiration. Modeling results indicate that the surface evaporation removes 1.5 times more water from the cover than plant transpiration, and that the evapotranspiration was capable of removing 96% of the precipitation over a 4 year simulation period.


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