Use of Long-Term Lysimeter Data in Support of Shallow Land Waste Disposal Cover Design

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ABSTRACT

Water balance studies using two precision weighing lysimeters have been conducted at the Nevada Test Site in support of low-level radioactive waste disposal since 1994. The lysimeters are located in northern Frenchman Flat approximately 400 meters (m) from the southwest corner of the Area 5 Radioactive Waste Management Site. Frenchman Flat is in the northern Mojave Desert and has an average annual precipitation of 125 millimeters (mm). Each lysimeter consists of a 2 m by 4 m by 2 m deep steel tank filled with native alluvium, supported on a sensitive scale. The scale is instrumented with an electronic loadcell and datalogger for continuous measurement of total soil water storage with a precision of approximately ±800 grams or ±0.1 mm of soil-water storage. Dataloggers are linked to cell phone modems for remote data acquisition. One lysimeter is vegetated with native creosote bush, fourwing salt bush, and annual grass at the approximate density of the surrounding landscape while the other is maintained as bare soil. Since no drainage has been observed from the bottom of the lysimeters and runon/runoff is precluded, the change in soil-water storage is equal to precipitation minus evaporation/evapotranspiration. After equilibration, the bare lysimeter contains approximately 20.2 centimeters (cm) of water (10.1% volumetric water content) and the vegetated lysimeter contains approximately 11.6 cm of water (5.8 % volumetric water content). The finite difference code UNSAT-H was used to simulate the continuous water balance of the lysimeters. Calibrated one-dimensional model simulations were generally in agreement with field data. 30-year model simulations were conducted to evaluate long-term potential transport of radionuclides via the soil water migration pathway. A 30-year climate record was generated by repeating the existing data record. Simulations indicate a 2 m thick closure cover, in conjunction with native vegetation, will essentially eliminate drainage.

INTRODUCTION

The Area 5 Radioactive Waste Management Site (RWMS) is located in northern Frenchman Flat approximately 100 kilometers (km) northwest of Las Vegas, Nevada, within the Nevada Test Site (NTS). The RWMS was established in 1961 and is used primarily for the disposal of defense-generated, low-level radioactive waste from cleanup activities at the NTS and other sites within the U.S. Department of Energy (DOE) complex. Several closure design options for the

Area 5 RWMS have been evaluated [1, 2, 3]. In general, closure cover designs vary greatly in both materials and complexity. Appropriate designs are highly site-specific, and are contingent upon multiple factors including climate, vegetation, and waste characteristics. A key component of landfill cover design is protection of groundwater resources by minimizing leachate.

Extensive physical and chemical characterization of the unsaturated zone at the Area 5 RWMS indicates the natural vegetated system under the current climatic conditions effectively eliminates groundwater recharge [4]. These findings along with performance concerns of conventional Resource Conservation and Recovery Act multi-layer prescriptive covers under subsided waste conditions [3] provided the impetus to evaluate the use of a single layer of native soil with native vegetation as a final closure cover. To further evaluate a monolayer evapotranspiration (ET) cover design, weighing lysimeters were installed near the RWMS to provide detailed measurements of near-surface water balance. This paper presents results from model simulations calibrated using long-term lysimeter data to evaluate a monolayer ET cover design. The use, study, and acceptance of evapotranspiration covers in arid and semi-arid regions have increased significantly in recent years [5, 6, 7, 8].

LYSIMETER DESCRIPTION

Two precision weighing lysimeters were installed in Area 5 in 1994, approximately 400 m from the southwest corner of the RWMS. One lysimeter is vegetated with creosote bush and annual grasses at the approximate density of the surrounding landscape, and the other is maintained as bare soil. Each lysimeter is a 2 m by 4 m by 2m deep steel tank filled with native alluvium at a bulk density of 1.6 grams (g)/cm^3 and supported on a sensitive scale. The alluvium is classified as a well to poorly-graded sand with silt and gravel under the Unified Soil Classification System with approximately 70% sand, 20% gravel and 10% fines. The scale has an electronic loadcell and datalogger for continuous measurement of total soil-water storage with a precision of approximately ± 800 g or ± 0.1 millimeter (mm) of soil-water storage. Dataloggers are linked to cell phone modems for remote data acquisition. Eight small drains are located just above the sealed lysimeter bottom to allow saturated drainage. The soil profile is instrumented with time domain reflectometer probes (Campbell Scientific CS610) for volumetric water content measurements and heat dissipation probes (Campbell Scientific 229-L) for matric potential measurements.

PRECIPITATION DATA

Site precipitation is highly variable. Long-term (1964-2004) precipitation measurements taken 5.6 kilometers (km) from the lysimeter plots indicate site mean precipitation is 12.5 cm/year (yr). On average, 33.3 days/yr have measurable precipitation with a standard deviation of 10.5 days. February is the wettest month (14.5% of annual total) and June is the driest (3.4% of annual total). An average of 1.9 days/yr have relatively large (>1.27 cm) precipitation totals. Months that tend to have large daily totals include February, August and December.

Annual precipitation measured at the lysimeter facility during the monitoring period (1994-2005) was generally equivalent to the long-term average of 12.5 cm/yr. These annual precipitation totals were quite variable ranging from 24% to 191 % of the long-term average. Winters (December – February) of 1994-1995, 1997-1998, and 2004-2005 had precipitation amounts over twice the long-term winter average (4.5 cm), providing an excellent test of the cover design. Fig. 1 shows the average monthly potential evapotranspiration (PET) and ratio of PET to precipitation for the lysimeter monitoring period. Although the annual average ratio of PET to precipitation is 11.6, the months of December, January and February have a ratio less than 4.

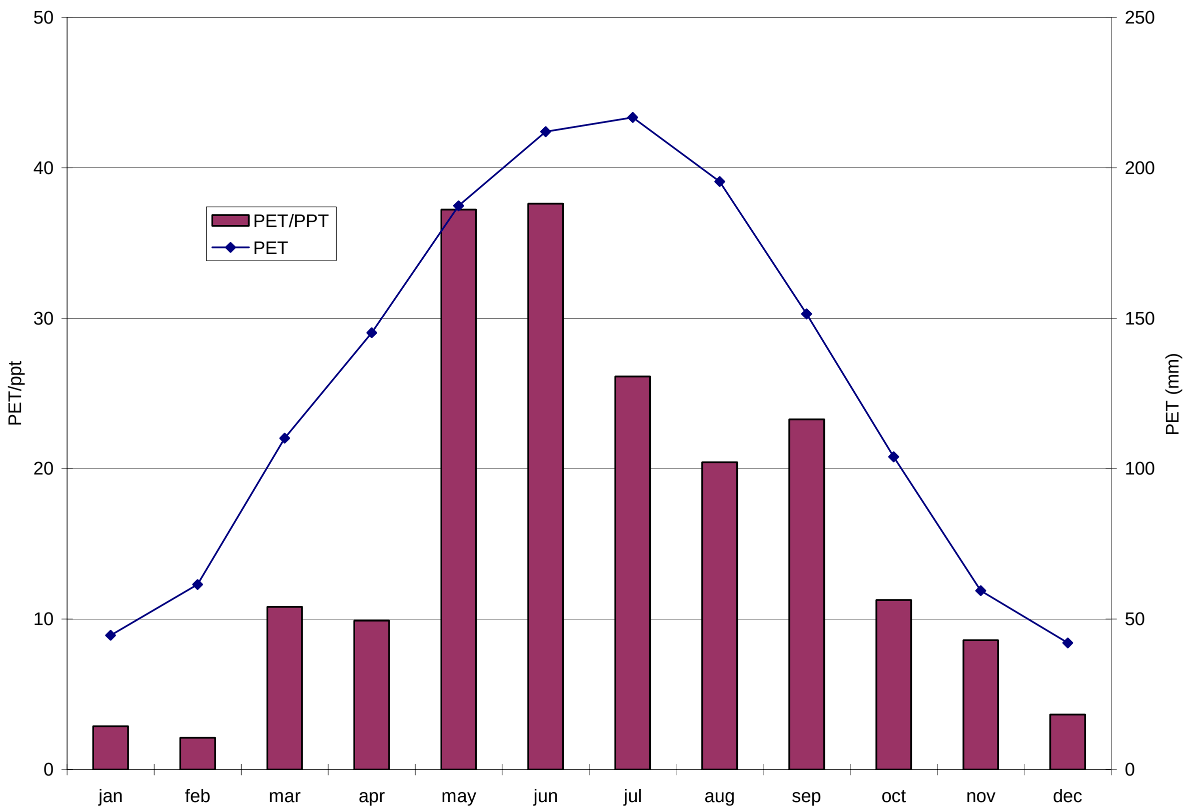

Fig. 1. Average monthly PET and PET-to-precipitation ratio for lysimeter monitoring period

LYSIMETER DATA

The lysimeter design prevents runon/runoff and no drainage has been observed. Therefore the change in lysimeter soil-water storage is equal to precipitation minus evaporation (E) or ET. Fig. 2 presents the daily total storage data for the vegetated and bare lysimeters. Early (1994-1995) vegetated lysimeter storage data are influenced by irrigation added to establish transplanted vegetation. After equilibration the integrated volumetric water content is 10.1 % for the bare lysimeter and 5.8 % for the vegetated lysimeter. As transplanted vegetation becomes established in the spring of 1995, the storage in the vegetated lysimeter diverges from bare lysimeter storage.

Fig. 2 illustrates a pattern of peak winter storage due to high precipitation and low PET followed by a return to baseline values as evaporation or evapotranspiration returns stored water to the atmosphere. The return to baseline storage values is significantly faster for the vegetated lysimeter due to plant transpiration. Following the wet winter season of 1997-1998, spring vegetated lysimeter ET rates (1.7 mm/day) exceeded E from the bare lysimeter by a factor of 2.7 over a 56 day period.

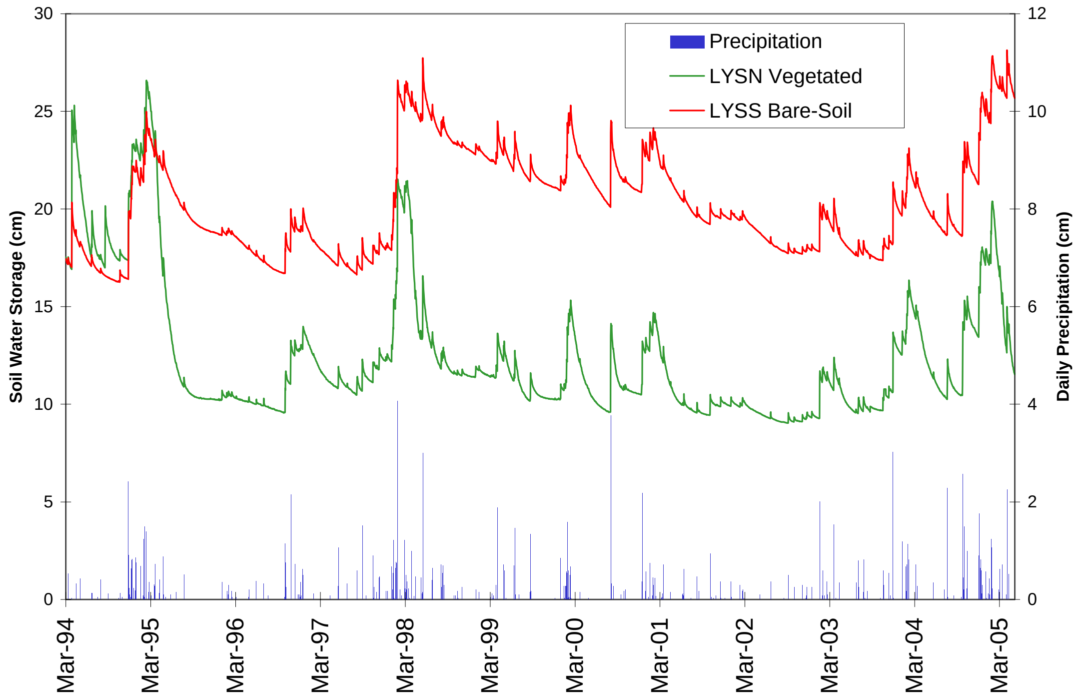

Fig. 2. Daily observed precipitation and total storage for vegetated and bare lysimeters

Vegetated lysimeter storage typically returns to baseline values by the end of May. Average winter (December-February) ET for the bare and vegetated lysimeters is 0.29 and 0.24 mm/day, respectively. These values are quite similar due to low plant transpiration during winter. ET for the bare lysimeter exceeded the vegetated lysimeter due to the higher volumetric water content in the bare lysimeter. Segregation of ET from the vegetated lysimeter into components of transpiration and evaporation could be accomplished by assuming evaporation from the vegetated lysimeter is equal to the evaporation of the bare lysimeter. However, the greater volumetric water content in the bare lysimeter should result in higher evaporation and therefore an underestimation of transpiration.

Soil-moisture profile data prior to 2001 are generally unreliable for the bare lysimeter and could only be evaluated qualitatively for the vegetated lysimeter. Data collected after 2001 indicate that wetting fronts in the bare lysimeter reached the deepest sensor (180 cm) during March 2005. Calibrated model simulations (presented in the subsequent section) indicate similar wetting fronts occurred in the bare lysimeter during the winter of 1997-1998. All data collected for the vegetated lysimeter indicate that wetting fronts have never reached 1.5 m deep.

WATER BALANCE MODEL

The UNSAT-H [9] finite difference numerical model was used to simulate the continuous water balance of the lysimeters. UNSAT-H is a one-dimensional unsaturated soil-water and heat flow model. UNSAT-H is a widely used public domain code that includes a range of hydraulic functions, a transpiration model and thermal and isothermal vapor flow. A total of 64 nodes was used to simulate the 2 m lysimeter soil column. Node spacing varied from 0.1 cm near the surface to 10 cm in the middle of the column and decreased to 1 cm at the lower boundary.

The upper boundary was modeled using the atmospheric boundary condition from UNSAT-H. Hourly average meteorological parameters (air temperature, relative humidity, wind speed and solar radiation) measured 1.2 km from the lysimeters were used to calculate PET using a radiation based equation [10]. A no-flux condition was used to model the lower boundary, consistent with observed data.

HYDRAULIC AND VEGETATION PROPERTIES

Eighteen core samples were collected from the lysimeters in 10 cm increments from 0 m to 2 m [11]. Saturated hydraulic conductivity and water retention relationships were measured. Water retention data were collected using hanging water columns, pressure chambers, and a water activity meter. Water-retention data were fit to the van Genuchten relationship [12] using RETC [13]. Fit van Genuchten parameters are presented in Table I. The geometric mean of constant head saturated hydraulic conductivity measurements is 14.0 cm/hr.

Table I. Fit van Genuchten Soil-Water Parameters

α (cm^{-1})	**N**	**θ_r**	**θ_s**
0.0328	1.57	0.04	0.357

Maximum rooting depth (140 cm) and root density were assigned based on statistical analysis of site vegetation data [14]. The remainder of the transpiration parameters were adjusted to match observed total storage data. PET is partitioned into PE and PT using the Ritchie and Burnett model [15] and a constant assigned leaf area index of 0.1. Transpiration was modeled from March through September for each year. The root water uptake parameters used in model simulations are given in Table II.

Table II. Root Water Uptake Parameters used in UNSAT-H

Parameter	Soil Water Tension (cm)
HW	30,000
HD	600
HN	25

WATER BALANCE SIMULATIONS

Initial conditions for the bare lysimeter simulations were set to a uniform matric potential of 800 cm tension based on the total soil-water storage and the fit van Genutchen parameters. Model simulations include isothermal vapor flow. Initial model simulations over predicted evaporation during the winter months. Reducing winter PET by 50% resulted in a better reproduction of observed (typically peak annual) storage for these months. Final simulated and observed total storage values are presented in Fig. 3. Simulations for the period of March 15, 1994, through May 31, 2005, are generally in agreement with field data. Comparison of simulated versus measured daily total storage yielded a root mean squared error of 1.2 cm.

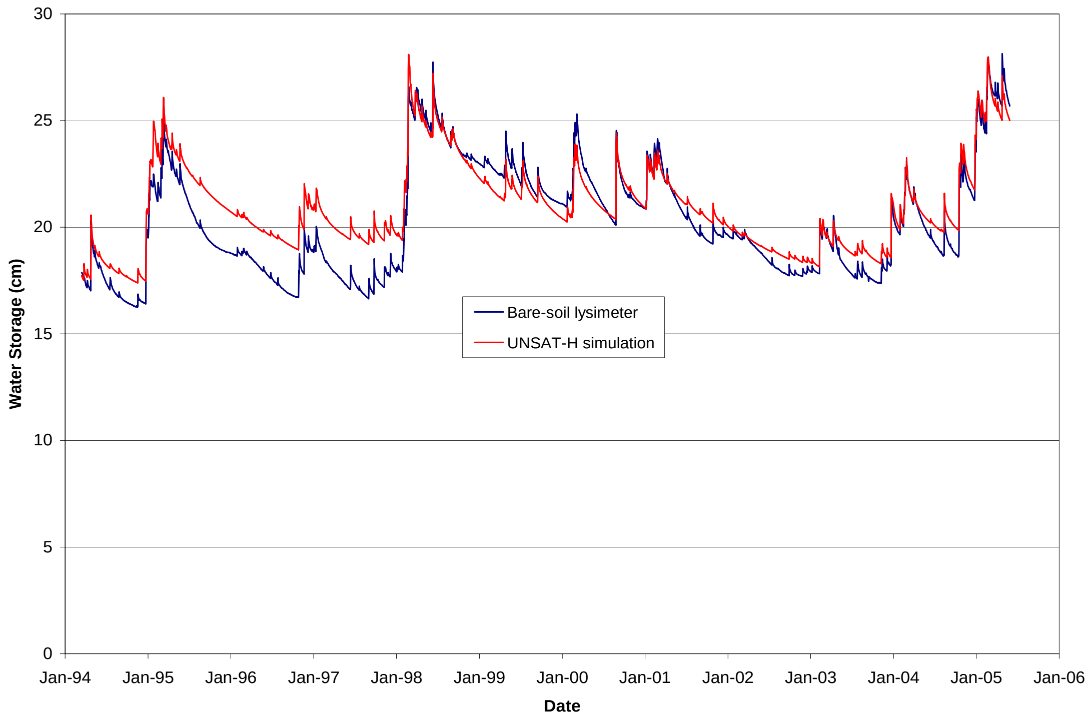

Fig. 3. Simulated and observed bare lysimeter storage

Vegetated lysimeter simulations started January 1996 when vegetation was established. Initial conditions were set to a uniform matric potential of 10,000 cm tension. Boundary conditions were identical to final bare lysimeter simulations. Simulated and observed total storage values are presented in Fig. 4. Simulations were generally in agreement with field data with a root mean squared error of 0.4 cm for total daily storage. Simulated storage is over predicted for the spring of 2005 which followed a wet winter. A similar over prediction of storage would likely have occurred for the spring of 1998 if simulated storage had not been under predicted prior to the wet winter of 1997-1998. Over prediction of storage following wet winters is likely caused by using the prescribed leaf-area index approach which does not capture the dynamic response of plant growth to increased soil-water storage.

Using the calibrated model, simulations may be conducted to evaluate alternate cover designs. The primary design parameter for a monolayer ET cover is thickness. To model the water balance of a cover, the bottom boundary condition was changed to a unit gradient to simulate field conditions. All other parameters were unchanged from previous simulations. 30-year model simulations were conducted for both vegetated and bare covers by repeating the existing meteorological (1995-2004) record starting with 1996 conditions to avoid partial year simulations and allow for soil-water system equilibration. Vegetated cover simulations, indicate drainage using a 2 m cover is essentially zero, well below the suggested performance goal of 1 mm/yr for covers in arid and semi-arid regions [5]. Simulations indicate drainage using a 2 m bare cover is 1.02 cm/yr or approximately 8.2% of precipitation. Increasing bare cover thickness only slightly delays drainage onset.

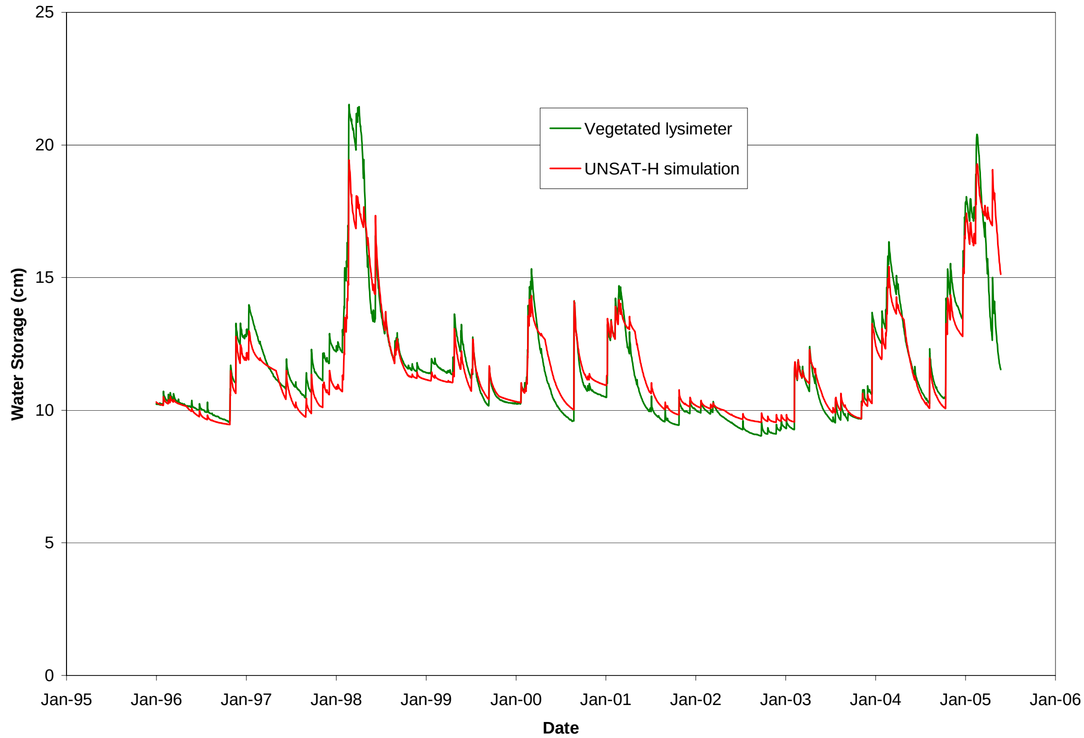

Fig. 4. Simulated and observed vegetated lysimeter storage

CONCLUSION

Long-term weighing lysimeter data were used to calibrate an unsaturated flow model under bare and vegetated cover conditions. Bare cover simulations indicate drainage is relatively insensitive to thickness, with approximately 8% of precipitation draining through the cover. When vegetation is included, simulations indicate drainage is essentially eliminated. These simulations illustrate the dominant role vegetation plays in near surface water balance and indicate a 2 m thick monolayer ET cover will effectively protect groundwater resources by eliminating leachate generation.

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This manuscript has been authored by Bechtel Nevada under Contract No. DE-AC08-96NV11718 with the U.S. Department of Energy.