Evaluation of Evapotranspirative Covers for Waste Containment in Arid and Semiarid Regions in the Southwestern USA

Bridget R. Scanlon,* Robert C. Reedy, Kelley E. Keese, and Stephen F. Dwyer

ABSTRACT

Performance evaluation of evapotranspirative (ET) covers is critical for waste containment. The purpose of this study was to evaluate ET covers at sites in Texas and New Mexico representative of arid and semiarid regions in the southwestern USA using water balance monitoring during 4- and 5-yr periods and water balance simulations using short-term (1–5 yr) and long-term (25 yr) climate forcing. Estimated drainage at the Texas site was related to irrigation while measured drainage at the New Mexico site was restricted to the first 2 yr of the 5-yr monitoring period. Evapotranspirative covers work extremely well in these regions because of the dominance of summer precipitation (62–80%) that corresponds to periods of highest ET. Strong relationships between decreases in soil water storage and vegetation productivity at both sites underscore the importance of vegetation in controlling the water balance in these systems. Simulations of the Texas site indicate that drainage can occur in response to high precipitation near the end of the growing season, but such drainage can be eliminated with a capillary barrier. Inclusion of a capillary barrier increased available water storage by a factor of about 2.5 at both sites. The capillary barrier effect of drainage lysimeters can result in underestimation of drainage and overestimation of water storage relative to covers not underlain by capillary barriers. The data from this study indicate that a 1-m-thick ET cover underlain by a capillary barrier should be adequate to minimize drainage to $\leq$1 mm yr^{-1} in these arid and semiarid regions. Comprehensive monitoring integrated with modeling is required to assess total system performance to develop a predictive understanding of ET covers.

Engineered surface covers are widely used throughout the USA to contain radioactive, hazardous, mixed, industrial, and municipal solid wastes. There are approximately 4000 active municipal solid waste and hazardous waste landfills in the USA (EPA, 1996, 1997). In addition, surface covers are commonly used alone or in combination with other remediation technologies at contaminated sites, especially those of large areal extent. The growing realization over the past decade that total cleanup of many contaminated sites is infeasible because of cost, technical difficulties, or worker safety has resulted in a shift in emphasis from contaminant removal to containment as a remediation alternative. Engineered covers may also be used as interim covers for waste containment before remediation.

Conventional engineered covers generally consist of multilayered resistive cover systems that are relatively expensive to construct and include the prescribed Resource Conservation and Recovery Act Subtitle C design for hazardous waste and Subtitle D design for municipal solid waste recommended by the USEPA (Koerner and Daniels, 1997). Resistive barriers rely on low hydraulic conductivity to minimize water movement into the underlying waste; however, previous studies have shown that many resistive covers, particularly compacted clay layers, leak because of desiccation, which can occur even in humid settings (Melchior, 1997; Dwyer, 2001; Albrecht and Benson, 2001; Albright et al., 2003). Increasing emphasis is being placed on optimal cover design for arid and semiarid regions because they are generally considered more suitable for waste disposal than humid regions (Reith and Thompson, 1992) and many contaminated sites are located in these regions. A variety of alternative cover designs have been proposed for waste containment in arid and semiarid regions, including monolithic ET covers, capillary barrier ET covers, and anisotropic barrier ET covers, which all rely on increased water storage rather than low hydraulic conductivity to minimize water movement into waste (Albright et al., 2003; Dwyer, 2001; Hauser et al., 2001).

Evapotranspirative covers rely on vegetation to increase the water storage capacity of the cover by removing water through ET so that deep drainage is negligible or zero. In areas where winter precipitation is dominant, the thickness of the cover is designed to store the infiltrated water until vegetation can transpire it in the spring and summer. Evapotranspirative covers generally consist of a single soil type (monolithic) and may constitute the sole barrier in a system or may form a component of more complex barrier systems that include underlying capillary or resistive barriers (Wing and Gee, 1994).

Most studies evaluating the performance of ET covers have been conducted at USDOE sites (Nyhan et al., 1990; Anderson et al., 1992; Waugh et al., 1994; Anderson, 1997; Dwyer, 2001). The Alternative Landfill Cover Demonstration project was established at Kirtland Air Force Base near Albuquerque, NM, to test four alternative cover designs (monolithic ET, capillary barrier ET, anisotropic barrier ET, and geosynthetic clay liner) relative to conventional Subtitle C and D covers (Dwyer, 2001). Long-term studies of the performance of engineered covers and comparison with the natural system were conducted at the USGS Beatty site, Nevada (Andraski, 1997). In addition, the Alternative Cover Assessment Program was established by the USEPA in 1998 to evaluate the performance of various cover designs under different climatic conditions throughout the USA (Albright et al., 2003). A total of 11 field-scale test sections were established, including conventional and alternative covers.

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Abbreviations: AWS, available water storage; CB, capillary barrier; ET, evapotranspirative; GAB, geosynthetic clay layer overlying an asphalt barrier; GCL, geosynthetic clay layer; LAI, leaf area index; PET, potential evapotranspiration; TDR, time domain reflectometry.

Monitoring approaches can be subdivided into performance and process monitoring. Performance monitoring usually focuses on a performance parameter, generally drainage in the case of engineered covers. However, natural drainage is very difficult to monitor because zero pressure (pan) lysimeters used for drainage monitoring behave like capillary barriers and require overlying soils to become almost saturated before drainage will occur. Therefore, water storage is generally overestimated and drainage underestimated relative to covers without capillary barriers. The degree to which lysimeter drainage represents actual drainage beneath a cover depends on whether the interface between the cover and the underlying waste or between the final and interim cover acts as a capillary barrier. Process monitoring includes many parameters related to flow processes in a cover and provides comprehensive information on total system performance, which is considered more robust than simply relying on a single parameter. For example, increases in water storage at the base of a cover profile could provide early warning of incipient drainage.

Numerical modeling can be used to evaluate and optimize monitoring systems, assess different cover designs, and determine critical parameters through sensitivity analyses. To increase confidence in models, it is important to compare model results with detailed field monitoring data. Many previous studies have simulated the water balance of engineered covers and compared the simulation results with the monitoring data (Fayer et al., 1992; Khire et al., 1997). A detailed evaluation of the performance of different codes for simulating the water balance of engineered covers was conducted using data from sites in Texas and Idaho (Scanlon et al., 2002). Recent advances in computer technology, more computationally efficient codes, and availability of input data on climate and hydraulic properties online make long-term simulations of the near-surface water balance much more feasible. Weather generators, such as USCLIMATE and GEM (Richardson, 2000), can be used to develop long-term climate records for simulations. Pedotransfer functions are available for estimating hydraulic parameters from information on soil texture (Schaap and Leij, 1998; Schaap et al., 1998).

The purpose of this study was to evaluate ET covers in arid and semiarid sites in Texas and New Mexico on the basis of monitoring and modeling analysis. The monitoring program provides information on performance of the covers for the duration of the monitoring (4–5 yr), whereas the modeling analysis allows us to evaluate cover performance for much longer (25 yr in this study). Unique aspects of this study include detailed instrumentation of water balance parameters at these two sites, length of monitoring record (4–5 yr), integration of monitoring and modeling analysis, and detailed knowledge of unsaturated flow processes in the natural system for comparison with the ET covers.

MATERIALS AND METHODS

Site Description and Cover Designs

Texas Site

Prototype engineered covers were installed for a proposed low-level radioactive-waste disposal site in the Chihuahuan Desert in West Texas, 10 km east of Sierra Blanca, about 150 km southeast of El Paso (31°8.773′ N, 105°16.237′ W; elevation, 1337 m) (Fig. 1). The potentiometric surface is at a depth of approximately 200 m. Long-term (1962–1990) mean annual precipitation is 311 mm (Sierra Blanca). Approximately 80% of precipitation occurs in June through October (Fig. 2a). Precipitation during the monitoring period was much lower in January through May (33–65%), August (47%), and September (16%) relative to the long-term (29-yr) monthly distribution. Summer precipitation generally occurs as localized convective storms with durations of a few minutes to several hours, whereas winter precipitation is generally associated with larger frontal systems of lower intensity.

Two different engineered cover designs were installed at the site in the summer of 1997: (i) a conductive or capillary barrier (CB) of sand at the 2-m depth and (ii) a resistive or geosynthetic clay layer (GCL) overlying an asphalt barrier (GAB) at the 1.3-m depth (Fig. 1). In this study, we focus on the upper portion of both covers above the barriers because water movement was generally restricted to these zones and, both covers functioned primarily as ET covers. Each cover design was 17 by 34 m (CBET, GABET) and was divided into two 17- by 17-m subplots. Both cover designs consisted of 0.3 m of topsoil (sandy clay loam, bulk density 1.5 Mg m^{-3})

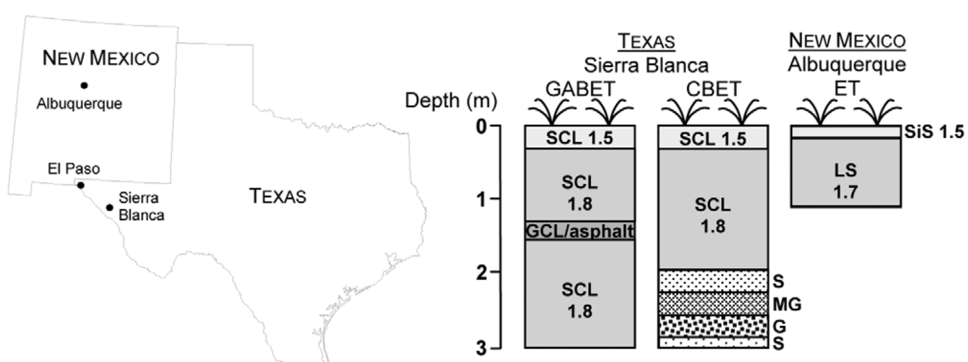

Fig. 1. Location of monitored and engineered cover sites in Texas (Sierra Blanca) and New Mexico (Albuquerque) and vertical profiles of texture and materials for the different cover designs evaluated in the study. GCL, geosynthetic clay liner; GABET, GCL/asphalt barrier ET cover; CBET, capillary barrier ET cover; SCL, sandy clay loam; S, sand; MG, muddy gravel; G, gravel; LS, loamy sand. Numbers following textures indicate soil bulk density (Mg m^{-3}). Texas site consisted of topsoil mixed with gravel (24 wt%); New Mexico site includes a 20- to 40-mm-thick gravel surface layer.

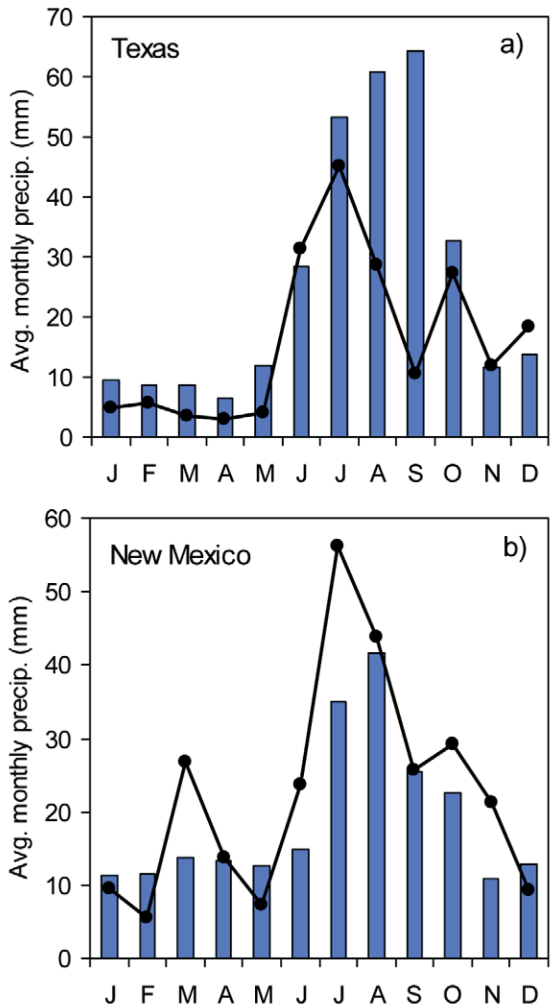

Fig. 2. Average monthly precipitation during monitoring periods (lines) and historical records (columns) for (a) Texas site (Sierra Blanca, 29-yr average annual total = 311 mm) and (b) New Mexico site (Albuquerque, 30-yr average annual total = 226 mm).

underlain by compacted soil (sandy clay loam, bulk density 1.8 Mg m^{-3}) constructed with a 2% surface slope in all layers. Gravel (24% by weight) was added to the upper 0.3 m of the topsoil to reduce erosion.

Both covers were nonvegetated during the first year. Seedlings transplanted in August 1998 consisted of five perennial warm-season bunchgrass species, including blue grama (*Bouteloua gracilis*), plains bristlegrass (*Setaria leucopila*), sand dropseed (*Sporobolus cryptandrus*), green sprangletop (*Leptochloa dubia*), and lehmann lovegrass (*Eragrostis lehmanniana*). However, opportunistic vegetation invaded the covers at different times, including tumbleweed (russian thistle; *Salsola kali*), several salt cedar (*Tamarix ramosissima*), and one mesquite tree (*Prosopsis glandulosa*). A drip irrigation system and mulch pad (20-mm-thick aspen shavings with a UV degradable mesh net) were installed before planting. The mulch pad generally degraded within 1 yr.

New Mexico Site

A monolithic ET cover was installed as part of the Alternative Landfill Cover Demonstration project established at Kirtland Air Force Base near Albuquerque, NM (34°58.473′ N, 106°32.396′ W; elevation, 1652 m) (Dwyer, 2003). Long-term (30-yr) mean annual precipitation is 226 mm, which is based on data from Albuquerque, 11 km northwest of the engineered covers. Approximately 62% of precipitation occurs in June through October (Fig. 2b). Monthly precipitation during the monitoring period differed from the long-term monthly distribution, particularly in March (196%), June (159%), July (161%), and November (196%) (Fig. 2b).

The ET cover was constructed between May and August 1996, and monitoring began in May 1997. The ET cover was divided into two 12.2- by 46-m subplots with east and west slope aspects. The engineered cover design consisted of 0.15 m of topsoil (loamy sand, bulk density 1.5 Mg m^{-3}) underlain by 0.92 m of compacted soil (loamy sand, bulk density 1.7 Mg m^{-3}) constructed with a 5% surface slope in all layers. A thin veneer of gravel (20–40 mm) was placed on the surface after the cover was seeded to enhance establishment of vegetation and minimize erosion (Reith and Thompson, 1992).

The test facility topsoil was drill seeded in fall 1996 with native rangeland vegetation that included various grasses ranging from cool-season, such as Indian ricegrass (*Oryzopsis hymenoides*) and needle-and-thread grass (*Stipa comata*), to warm-season grasses, including blue grama, galleta (*Hilaria jamesii*), and sand dropseed varieties. In addition, various opportunistic plants grew at different times, including russian thistle and fourwing saltbush (*Atriplex canescens*).

Monitoring Systems

Performance of the ET covers was evaluated by monitoring various components of the water balance:

$$ET = P + Irr - R_o - \Delta S - D \qquad [1]$$

where P is precipitation, Irr is irrigation, R_o is runoff, ΔS is change in soil water storage, and D is drainage. Various instruments and measurement systems were used to monitor all of the water balance parameters except ET, which was calculated by difference. Meteorological parameters monitored at both sites included precipitation, solar radiation, air temperature, relative humidity, and wind speed and direction.

Texas Site Monitoring Systems

The covers were irrigated in August and September 1998 to establish vegetation. Vegetation was removed in June 2001 from one of the CBET subplots using herbicide. The CBET subplots were also irrigated in late June through early August 2001. Vegetation coverage was evaluated by making notes during each site visit (approximately monthly) and by photographing the vegetation. In addition, relative variations in leaf area index (LAI, one sided green leaf area per unit ground area) were estimated from surveyed transects at selected times from October 2000 through September 2001 using an AccuPar Ceptometer (Model PAR-80, Decagon Devices, Inc., Pullman, WA).

Surface runoff was collected in trench drains at the base of each subplot and measured to ±0.004 to ±0.06 mm for runoff events ≤2 and ≤400 mm, respectively. Deep drainage was collected by 12- by 12-m pan lysimeters (1.5-mm [60-mil] very flexible polyethylene geomembrane) buried at a depth of 3 m and centered beneath the subplots. Lateral drainage was collected from two 15- by 15-m areas of the asphalt layer. All drainage was collected in subsurface drains located along the down-slope lysimeter edges and measured with infrared drop sensors, tipping bucket rain gauges, and a graduated cylinder in 114-L collection drums. Cumulative measurement errors per event were ≤0.5%.

Soil water storage was monitored on a monthly basis using a neutron probe (Model 503DR Hydroprobe, CPN, Martinez, CA) at 0.15-m depth intervals in 20 vertical neutron probe access tubes (51-mm i.d. PVC) installed in June 1998. Water content in the upper 0.15 m was calculated using an empirical correction factor to adjust for the loss of neutrons at the soil surface (Greacen et al., 1981, after Grant, 1975). The neutron probe was calibrated with water content data from core samples ($r^2 = 0.96$; $\sigma = 0.011$ m^3 m^{-3}). Water content before June 1998 was estimated for the upper 0.3 m from matric potential measurements using heat dissipation sensors and laboratory-measured water retention functions. Electromagnetic induction was also used to monitor water storage (Reedy and Scanlon, 2003) but is not discussed in this paper.

Heat dissipation sensors (model 229, Campbell Scientific Inc., Logan, UT) were installed during site construction to monitor matric potentials that can be used to determine flow direction. These instruments were calibrated individually using pressure plate extractors (-0.1 to -50 m) and by equilibrating the sensors over saturated salt solutions (-450 to -2500 m). Temperature corrections were applied according to procedures outlined in Flint et al. (2002).

A cylindrical instrument silo (3.7-m diameter, 6.1 m high) constructed of welded steel panels was installed in the center of the installation to house data loggers and computers. Eight PVC instrument trees (0.3-m diameter) were installed 12 m from the silo to accommodate heat dissipation sensor installation. A 0.6-m-diameter, 10-mm-thick disk-shaped baffle was installed 0.45 m below the ground surface to inhibit preferential flow along the perimeter of the instrument trees. Instrument cable bundles passed through watertight fittings in the walls of the instrument trees at selected depths and were connected to data loggers in the silo. Instruments were installed in the soil during site construction at 1.0- to 1.5-m offset distances from the trees.

New Mexico Site Monitoring Systems

The west subplot was irrigated in January and February 2002. Vegetation parameters, including plant cover percentage and species count, were measured approximately annually (fall 1997 through 2000 and spring 1998) using point frames (Dwyer, 2003). Surface runoff was collected in a gutter system located along the base of each subplot slope and routed through pipes to tanks with flow meters that quantified runoff with cumulative errors per event ≤0.2%. Deep drainage was measured using pan lysimeters that consisted of a geotextile underlain by a geonet, and then a geomembrane and water was routed to an underdrain collection system that included tipping buckets and measured with cumulative errors per event ≤0.2%.

Changes in water storage were monitored using time domain reflectometry (0.3 m long, three-wire probes; Campbell Scientific Inc. Model 610). Vertical profiles of time domain reflectometry (TDR) probes were installed in 10 locations equally spaced along the center of the plot. Time domain reflectometry probes were installed horizontally at the 0.15-m depth (base of topsoil) and 0.45- and 0.9-m depths within the compacted soil. Water content monitoring with TDR began in May 1997 and continued through September 2002.

Numerical Modeling

The computer code UNSAT-H (Fayer, 2000) was used to simulate water balance of the engineered covers. In this study, we conducted short-term simulations (1–5 yr) of the covers at both sites for comparison with measured water balance parameters. We also conducted long-term simulations on the basis of meteorological data from 1961 through 1990, which were obtained from the GEM database for El Paso and Albuquerque (Hanson et al., 1994). Model results are reported for the last 25 yr of the 30 yr simulated to avoid the impact of initial conditions; therefore, these simulations are termed 25-yr simulations. Nodal spacing ranged from 2 mm at the top and base of the profile and increased by a factor of 1.2 to a maximum of 150 mm within the profile. This grid design resulted in negligible mass balance errors (two to three orders of magnitude less than simulated drainage).

Table 1. Model input parameter values.†

Layer	Z	G, S, Si, C	K_s	θ_s	θ_r	α	n
	m	— wt % —	mm d^{-1}	m^3 m^{-3}		mm^{-1}	
			Texas				
1	0.30	24, 43, 17, 16	410	0.45	0.00	0.0027	1.276
2	1.7	0, 55, 18, 27	199	0.35	0.00	0.0010	1.167
3	0.30	0, 89, 3, 8	6390	0.40	0.00	0.0020	1.464
			New Mexico				
1	0.15	0, 83, 10, 7	873	0.40	0.00	0.0035	1.378
2	0.90	0, 83, 10, 7	38	0.36	0.00	0.0020	1.280
3	0.10	100, 0, 0, 0	302, 400	0.42	0.00	49.30	2.190

† Z, layer thickness; G, gravel; S, sand; Si, silt; C, clay; wt%, weight percent; K_s: saturated hydraulic conductivity; θ_s, saturated water content; θ_r, residual water content; α and n, van Genuchten water retention function parameters.

The upper boundary for UNSAT-H was based on meteorological forcing and included daily precipitation, minimum and maximum air temperature, dew-point temperature, solar radiation, average wind speed, and average cloud cover. Daily precipitation was input to the simulations, and actual intensities were approximated by a default value of 10 mm h^{-1} (Fayer, 2000). Examination of the precipitation records during the monitoring period indicates that this intensity generally represents the median intensity of the precipitation. Plant transpiration is simulated as a sink term in UNSAT-H (Fayer, 2000). The lower boundary was simulated as a seepage face by including a 0.1-m-thick gravel layer at the base of the profile (Scanlon et al., 2002). A seepage face approximates the capillary barrier present beneath the ET cover at the Texas site and approximates the capillary barrier effect of the pan lysimeter at the base of the New Mexico cover. In additional simulations, a unit gradient lower boundary condition was used that allows free drainage at the base. Vegetation was represented using ecosystem LAI where measured transects included vegetated and bare areas, and percentage bare area was set to zero in the model. The growing season was based on visual observations of plant growth and water content and matric potential data over the monitoring period. Maximum root depths were not measured at either site, and estimates used in the models were evaluated using sensitivity analyses. Root length densities for bunchgrass were used (Rockhold et al., 1995).

Texas Site Model Input

Most input data for the Texas site are described in Scanlon et al. (2002). Simulations were conducted of the upper 1.1 m for comparison with the New Mexico profile and of the upper 2 m to represent the CBET system. Hydraulic parameters used in the model are described in Scanlon et al. (2002) and given in Table 1. In this study, simulations were conducted through the vegetated cover for water year 2000 (October 1999–September 2000; WY00) that is generally representative of long-term conditions and provided guidance on vegetation parameters for the 25-yr simulations (Table 2). Drying that occurred in WY99 was not considered representative of long-term conditions.

Long-term (25-yr) simulations were also conducted. The short-term (1-yr) and long-term (25-yr) models were identical

Table 2. Water balance monitoring results (mm) for the GCL/Asphalt evapotranspirative system (GABET) and capillary barrier evapotranspirative (CBET) systems and simulation results for the CBET system at the Texas site.†

							0–1.1 m depth					0–2.0 m depth				
Cover	Water year	P	PET	Irr	R_o	Net I	D	ΔS	ET	S	RMSE	D	ΔS	ET	S	RMSE
		mm										mm				
GABET																
(measured)	1998	202	1644	221	56	367	0.0	59	308	246						
	1999	247	1588	0	5.5	241	0.0	−75	317	171						
	2000	130	1484	0	9.3	121	0.0	−8.7	129	163						
	2001	199	1346	0	12	187	0.0	−4.6	191	158						
	98–01	778	6062	221	83	916	0.0	−29	945	738						
CBET																
(measured)	1998	202	1644	226	60	368	0.9	59	309	246		0.0	61	307	448	
	1999	247	1588	0	5.7	241	0.8	−71	311	174		0.0	−73	314	374	
	2000	130	1484	0	8.2	122	0.0	−9.5	131	164		0.0	−13	135	361	
	2001	199	1346	2340	1866	673	5.0	34	630	198		0.0	43	631	404	
	98–01	778	6062	2566	1940	1404	6.7	12.5	1381	782		0.0	18	1387	1587	
SF‡	2000	130	1484	0	8.1	122	0.0	−8.5	130	165	8.4	0.0	−15	136	357	8.6
UG‡				0	8.1	122	0.2	−8.6	130	165	7.5	2.4	−17	136	359	8.6

† P, precipitation; PET, potential evapotranspiration; Irr, irrigation; R_o, runoff; net I, net infiltration; D, drainage; ΔS, water storage change; ET, evapotranspiration; S, water storage at end of water year; RMSE, root mean square error between simulated and measured (monthly) water storage.
‡ Simulation results for SF, seepage face lower boundary for CBET; and UG, unit gradient lower boundary for CBET.

with the exception of meteorological forcing and a slight increase in ecosystem level LAI from 0.1 to 0.15 because WY00 was a dry year. The long-term simulations were based on daily meteorological data (1961–1990) from El Paso rather than Sierra Blanca because Sierra Blanca had only precipitation data and El Paso included all required meteorological parameters. During the 4-yr monitoring period (1997–2001), precipitation at El Paso was ±25% of annual precipitation at Sierra Blanca and averaged within 5% during the 4 yr. The long-term monthly distributions of precipitation in El Paso and Sierra Blanca are also similar. Initial conditions for the 25-yr simulations were based on linear interpolation of water content on 1 Oct. 1999, which generally represents average conditions for the cover during the monitoring period.

New Mexico Site Model Input

Input data for the New Mexico site are described in Dwyer (2003). Simulations were conducted for 1997 through 2002 for comparison with the measured water balance. Meteorological data for the simulations were based on daily values from the onsite meteorological station. Water retention was measured on disturbed soil samples using hanging water columns and pressure plates. The van Genuchten water retention function was fitted to the laboratory-measured water retention data (Table 1). Saturated hydraulic conductivity of the different materials was measured in the laboratory on disturbed soil samples collected from a borrow pit in the field (Dwyer, 2003). The samples (100-mm diam, 120-mm height) were recompacted to bulk densities ranging from 1.5 to 1.7 Mg m^{-3}. A falling head approach was used with a compaction mold permeameter (ASTM D5856, ASTM, 1995). Initial conditions for the simulations were based on linear interpolation of water contents monitored by TDR on 1 Oct. 1997 converted to matric potentials using water retention functions for the different materials. Long-term (25-yr) simulations were based on the monitoring period and used daily meteorological data from Albuquerque (1961–1990).

RESULTS AND DISCUSSION

Texas Site Monitoring

Precipitation, Irrigation, and Runoff

The 4-yr monitoring period was generally not representative, and precipitation ranged from 42% (WY00) to 79% (WY99) of the long-term (29-yr) average precipitation at Sierra Blanca (311 mm yr^{-1}) (Fig. 3, Table 2). Irrigation in August and September 1998 (221–226 mm) combined with precipitation in that year represented 140% of the long-term average precipitation. Both CBET subplots were also irrigated in summer 2001. A total of 459 mm of water was applied from 18 June through 8 Aug. 2001. Malfunction of the irrigation system in the vegetated CBET subplot resulted in continuous irrigation (1881 mm) during 9 through 11 August.

Total annual runoff ranged from 6 to 1866 mm yr^{-1}, which represented 2 to 73% of annual precipitation + irrigation for WY98 through WY01 (Fig. 3, Table 2). Runoff was highest (1866 mm) in the CBET subplot that was irrigated with 2340 mm of water in summer 2001. Runoff was also high during WY98 (13–14% of P + Irr) because the covers were irrigated and not vegetated. Runoff during the remaining years (WY99 and WY00) ranged from 2 to 7% of precipitation.

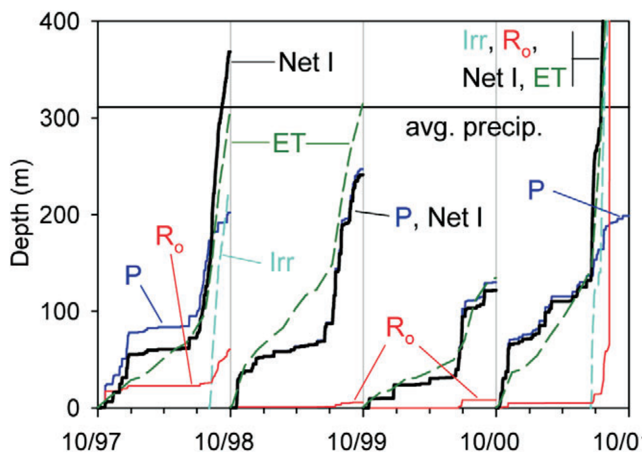

Fig. 3. Measured cumulative precipitation (P), irrigation (Irr), runoff (R_o), and net infiltration (Net $I = P + \mathrm{Irr} - R_o$) and calculated cumulative ET for the CBET cover system for 1998 through 2001 water years at the Texas site. The long-term (1962–1990) average annual precipitation of 311 mm is shown (± 102 mm 1σ). Water year 2001 cumulative values are Irr: 2340 mm, R_o: 1866 mm, net I: 673 mm, and ET: 630 mm.

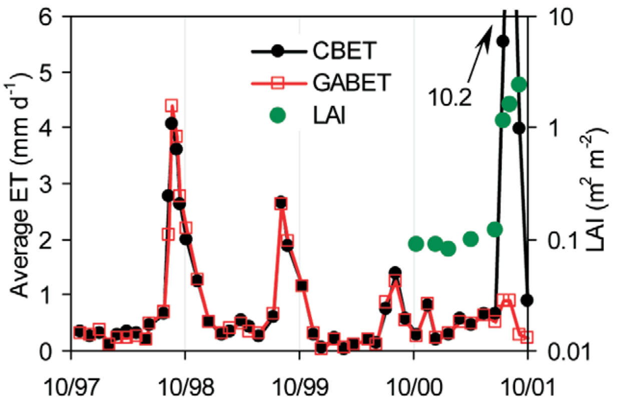

Fig. 4. Daily ET rates to the 1.1-m depth calculated from monthly average values for the GABET and CBET systems and measured leaf area index (LAI) for the CBET system at the Texas site.

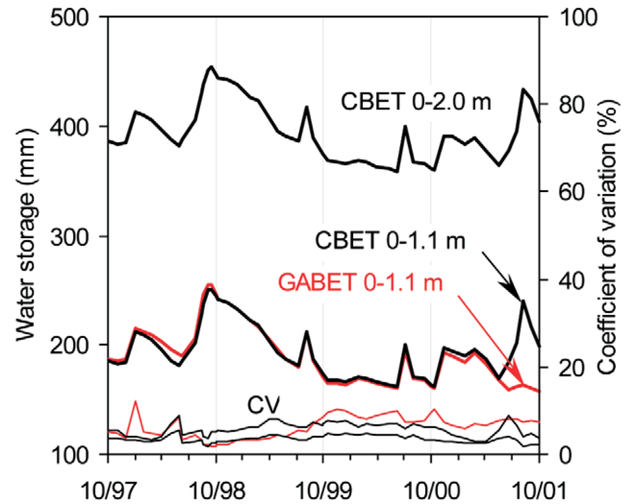

Fig. 6. Average water storage (thick lines) to the 1.1-m depth in the GABET and CBET systems and to the 2.0-m depth in the CBET system at the Texas site. Thin lines represent the coefficient of variation (CV = 100 σ/μ) of water storage from 10 neutron probe access tube measurement locations in each design.

Evapotranspiration, Water Storage, and Matric Potential

The main components of the monitored water budget were ET and water storage change. Cumulative ET was less than net infiltration (P + Irr − R_o) of water to the system in WY98 when the subplots were irrigated to establish vegetation (Fig. 3). During the following year cumulative ET exceeded net infiltration as the cover dried out. Potential evapotranspiration (PET) exceeded actual ET by factors ranging from 5 (WY 98, WY 99) to 11 (WY 00). Average daily ET rates for approximately monthly periods between water content monitoring were initially generally uniform (0.2–0.6 mm d^{-1}; Oct. 1997–Aug. 1998) when the covers were nonvegetated and peaked (≤4.4 mm d^{-1}) after irrigation in September 1998 (Fig. 4). High ET rates during and after irrigation are attributed primarily to evaporation with limited transpiration from opportunistic weeds that grew on the cover. Evapotranspiration rates decreased during the 1998–1999 winter to values of 0.1 to 0.4 mm d^{-1} and increased again in summer 1999 (≤2.6 mm d^{-1}), corresponding to expansion of tumbleweed growth. Highest ET rates (≤10.2 mm d^{-1}) were recorded in summer 2001 after irrigation of the CBET subplots. Periods of high ET generally corresponded to periods of increased water availability and vegetation productivity (Fig. 4, 5). Ecosystem level LAI measurements were low (≈0.1 m^2 m^{-2}) from October 2000 through June 2001 and increased to a maximum value of 2.4 m^2 m^{-2} after irrigation in summer 2001.

The importance of vegetation in controlling water balance is shown by strong relationships between vegetation productivity and soil water storage changes (Fig. 4, 6). Temporal patterns of water storage are similar for the different depth intervals considered, 0 to 1.1 m for the CBET and GABET and 0 to 2 m for the CBET. Water storage was highest after irrigation in September 1998. The large decrease in water storage from October 1998 through June 1999 can be attributed primarily to evaporation and limited transpiration related to weeds and grasses. Sharp increases in water storage (24–40 mm) during July 1999 and 2000 in response to summer monsoon precipitation were reduced rapidly in 1 to 2 mo as a result of increased ET (Fig. 4, 6). Large increases in tumbleweed occurred after high precipitation in July 1999. Monsoonal precipitation results in desert blooms as vegetation quickly responds to increased water availability. In contrast to rapid decreases in water storage in the summer, water storage in winter (e.g., October–November 2000) remained high

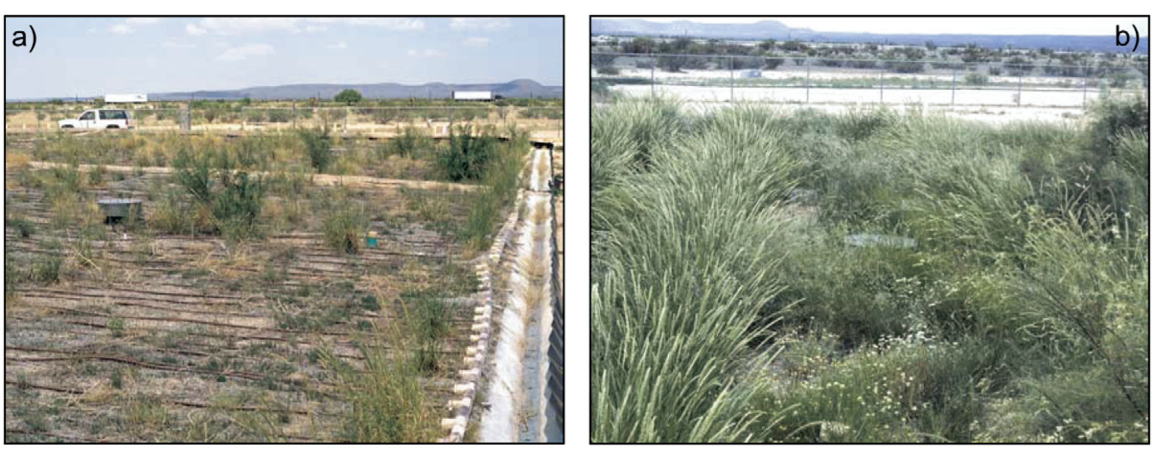

Fig. 5. Texas site vegetation response to (a) natural summer precipitation (Aug. 2000) and (b) irrigation (Aug. 2001).

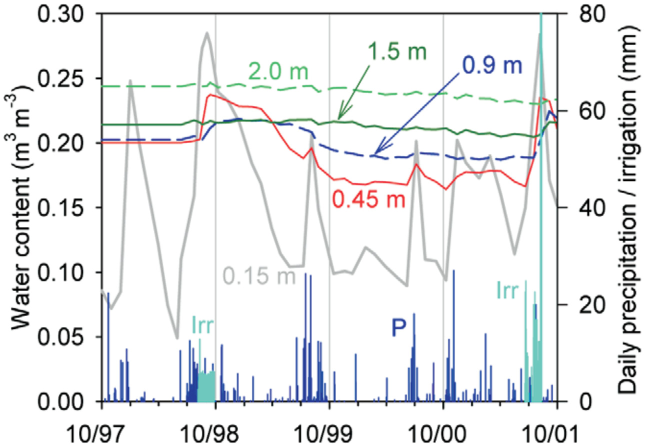

Fig. 7. Average water content based on data from 10 neutron probe access tubes at selected depths in the CBET system and daily precipitation and irrigation at the Texas site.

for several months when vegetation was dormant because evaporation was insufficient to remove the infiltrated water. Water storage was reduced in the following spring 2001 when vegetation began actively transpiring. The opportunistic response of vegetation to soil water storage is shown by the large increase in vegetation after irrigation of 422 mm (July and August 2001) and resulted in monthly ET values of 144 to 214 mm, which equaled PET in July and exceeded PET by a factor of 2 in August 2001.

Measured water content was highly variable with time at different depths in the CBET system (Fig. 7); similar patterns were seen in the GABET system (data not shown). Temporal variability in water content was greatest near the surface (0.15-m depth) and decreased with depth. Water content ranged from 0.05 $m^3\ m^{-3}$ (May 1998) to a maximum value of 0.28 $m^3\ m^{-3}$ (September 1998) after the plot had been irrigated to establish vegetation. Minimum water content during the remaining time was about 0.1 $m^3\ m^{-3}$ and increased in July and August 1999 and 2000 to a maximum value of 0.2 $m^3\ m^{-3}$. Progressively smaller water content changes occurred with increasing depth (0.23 $m^3\ m^{-3}$, 0.15 m; 0.08 $m^3\ m^{-3}$, 0.45 m; 0.03 $m^3\ m^{-3}$, 0.9 m; 0.02 $m^3\ m^{-3}$, 1.5 m). Increases in average water content following the 1998 irrigation penetrated to depths between 0.9 and 1.5 m, whereas the 2001 irrigation penetrated to the 1.5-m depth. Successive increases in water content with depth, as seen after the 1998 irrigation, indicate predominantly piston-type flow, as the wetting front moved progressively deeper with time. Water content generally increased with depth from a low value (≈0.10 $m^3\ m^{-3}$) at the 0.15-m depth when the soils were dry to a high value of 0.24 $m^3\ m^{-3}$ at the 2-m depth. The high water content at depth is attributed to heavy precipitation during construction of the deeper parts of the cover. There was no uniform trend in average water content for the top of slope vs. the base of slope, which may reflect in part the low slope of the cover (2%). Initially, water contents were higher at the base of the slope relative to the top; however, vegetation concentrated in this region and resulted in lower water contents at the base relative to the top of the slope.

Representative time series of monitored matric potentials indicate predominantly upward water movement, except after infiltration events, as shown by low matric potentials near the surface (0.3-m depth) and increasing with depth (Fig. 8b, 8c). Information on flow processes derived from matric potential data was similar to that from water content data: piston-type flow following irrigation, matric potential spikes to 0.3-m depth in the summer in response to monsoon precipitation followed by high ET, and persistent high matric potential in response to winter precipitation (2000–2001). Two time series representing different types of vegetation after October 1999, grasses and salt cedar (Fig. 8b) and grasses only (Fig. 8c), indicate that salt cedar was more effective in drying out the soil, as shown by lower matric potentials from summer 2000 through mid summer 2001. The matric potential data during fall 2001 following irrigation recorded progressive downward movement of a drying front. Matric potentials stopped decreasing in mid November 2001 because vegetation was dormant and started decreasing again in April and May 2002 when vegetation became active. Matric potentials at all depths started decreasing at the same time, indicating that roots at different depths were active in the spring. These data provide very valuable information on the time scales at which vegetation actively dries out the cover. The matric potential data suggest generally deeper water penetration at the locations of the heat dissipation sensors relative to the neutron probe access tubes, which showed penetration to 1.4 to 2 m at different locations. Focused flow may have occurred because of less compaction around the instrument trees where heat dissipation sensors were installed.

Drainage

Measured drainage was zero at the base of the capillary barrier (3-m depth) (Table 2). Even after addition of 1883 mm of irrigation in August 2001, there was no measured drainage at the base of the profile in 2001 through 2002. Ideally, evaluation of the performance of the ET portion of the cover would require drainage measurements at the 2-m depth. However, the capillary break at the 2-m depth precludes drainage until the overlying material becomes almost saturated. Calculated drainage at the 1.1-m depth in the CBET profile for comparison with the New Mexico profile was based on increases in water content over time below this depth and ranged from 0.00 (WY00) to 5.0 mm yr^{-1} (WY01). Calculated drainage at the 1.1-m depth in the CBET subplots followed 1998 and 2001 irrigations.

Measured lateral drainage from the GCL/asphalt layer in the GABET cover ranged from 0.00 mm yr^{-1} in one subplot to 0.14 mm yr^{-1} in the other for WY98 through WY01. The measured lateral drainage from one subplot may be attributed to localized fluxes because there was no evidence of increased water contents or matric potentials in any of the instrument locations.

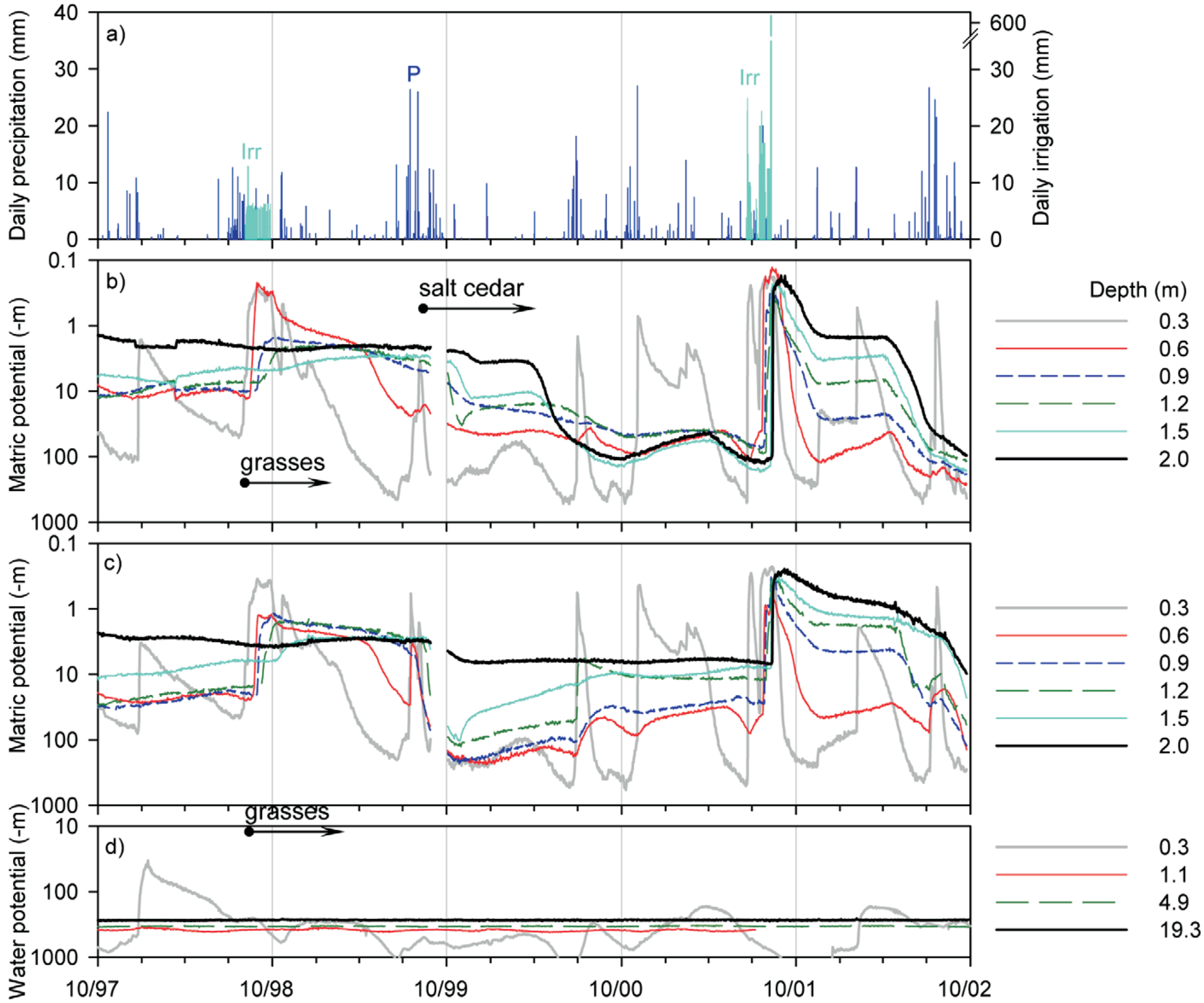

Fig. 8. (a) Daily precipitation (*P*) and irrigation (Irr) depths, (b) and (c) matric potential at selected depths at two locations in the CBET cover system at the Texas site, and (d) water potential monitored with thermocouple psychrometers in the adjacent natural setting at the Texas site.

New Mexico Site Monitoring

Precipitation, Irrigation, and Runoff

The monitored period was representative and precipitation ranged from 80% (WY02) to 151% (WY01) of the long-term (30-yr) average precipitation at Albuquerque (226 mm yr^{-1}) (Table 3, Fig. 9). The west subplot was irrigated in late January through early February 2002, with a total of 110 mm of water. Total annual runoff ranged from 0.2 to 22.0 mm. The highest runoff (14 mm on 26 July 1998) occurred in response to heavy precipitation (24.2 mm) the previous day. Runoff was also relatively high in WY97 in the west subplot (6.4 mm yr^{-1}). Annual runoff was generally low during the remaining time (0.2–0.8 mm yr^{-1}).

Evapotranspiration, Water Storage, and Drainage

Cumulative ET was greater than net infiltration to the cover in WY98 and similar to net infiltration on an annual basis during the remaining time (Fig. 9). Net infiltration generally exceeded ET during November through June in WY01. Potential evapotranspiration exceeded actual ET by factors ranging from 5 (WY01) to 11 (WY02) (Table 3).

Trends in water storage were similar in the west and east subplots; however, water storage was generally lower in the west subplot, except after irrigation in WY02 (Fig. 10). Mean water storage showed large seasonal and interannual variability. High initial water storage may be attributed to precipitation exceeding the long-term average by 70% in summer 1997 (April–September) and by 57% in winter 1997-1998 (October–March), corresponding to the strong 1997-1998 El Niño period. Large decreases in water storage in spring and summer 1998 corresponded to substantial increases in plant cover from about 1% in fall 1997 to between 30 and 60% in 1998 (Fig. 10). Interannual variability in water storage generally reflected variability in precipitation: low water

Table 3. Water balance monitoring (west and east subplots) and simulation results (east subplot) (mm) for the New Mexico site.†

Subplot	Water year	P	PET	Irr	R_o	Net I	D	ΔS	ET	S	RMSE
		mm									
West (meas.)	1997‡	227	–	0	6.4	221	0.1	−23.2	244	162	
	1998	299	1772	0	22.0	277	0.4	−66.4	343	95	
	1999	280	1851	0	0.8	279	0.0	−0.9	280	95	
	2000	189	1908	0	0.2	189	0.0	35.1	153	130	
	2001	341	1786	0	0.6	341	0.0	−44.1	385	86	
	2002	181	2012	110	0.6	290	0.0	20.3	270	106	
	1997–2002	1517	9329	110	30.6	1597	0.5	−79.2	1675	674	
East (meas.)	1997‡	227	–	0	1.5	226	0.0	31.5	194	182	
	1998	299	1772	0	0.8	298	0.0	−73.6	372	108	
	1999	280	1851	0	0.6	279	0.0	−8.6	288	99	
	2000	189	1908	0	0.2	189	0.0	16.2	172	116	
	2001	341	1786	0	0.8	340	0.0	−4.3	345	111	
	2002	181	2012	0	0.4	180	0.0	3.5	177	114	
	1997–2002	1517	9329	0	4.3	1512	0.0	−35.3	1548	730	
East (simul. SF)§	1998	299	1772	0	0.0	299	0.0	−76	375	106	37
	1999	280	1851	0	0.0	280	0.0	−14	294	94	17
	2000	189	1908	0	0.0	189	0.0	−8.2	197	91	17
	2001	341	1786	0	0.0	341	0.0	−1.6	343	115	37
	2002	181	2012	0	0.0	181	0.0	13	167	124	19
	1998–2002	1290	9329	0	0.0	1290	0.0	−86.8	1376	530	
East (simul. UG)§	1998	299	1772	0	0.0	299	0.3	−76	375	106	32
	1999	280	1851	0	0.0	280	0.1	−14	294	94	17
	2000	189	1908	0	0.0	189	0.0	−8.1	197	91	17
	2001	341	1786	0	0.0	341	0.0	−1.5	343	114	37
	2002	181	2012	0	0.0	181	0.0	13	167	124	18
	1998–2002	1290	9329	0	0.0	1290	0.4	−86.6	1376	529	

† P, precipitation; PET, potential evapotranspiration; Irr, irrigation; R_o, runoff; net I, net infiltration; D, drainage; ΔS, water storage change; ET, evapotranspiration; S, water storage at end of water year; RMSE, root mean square error between simulated and measured (daily) water storage.
‡ 1 May through 30 Sept.
§ Simulation results for SF, seepage face lower boundary; and UG, unit gradient lower boundary.

storage in WY99 and WY00 when precipitation was low and higher water storage in WY01 when precipitation was higher. Temporal variability in water storage at shorter time scales generally reflected variability in precipitation and plant growth. Large increases in water storage occurred on 15 Mar. 1998, in response to high precipitation (48 mm in 2 d). Summer precipitation in 1999 was effective in increasing water storage. The large increase in water storage recorded in summer 2000 through spring 2001 was attributed to high precipitation during this time. Decreases in water storage in some years (1998 and 2002) can be related to vegetation growth and ET in the spring and summer. However, there was

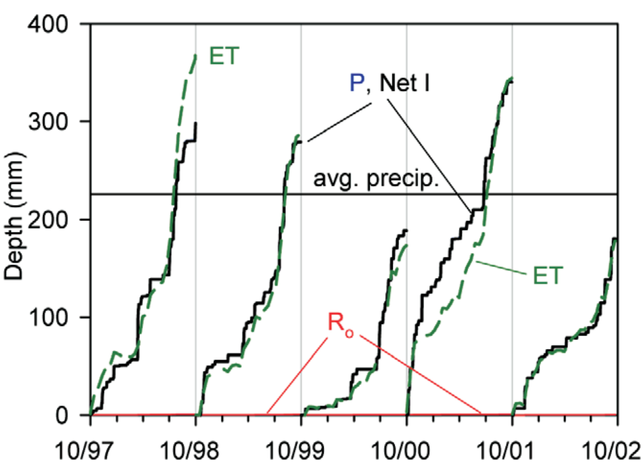

Fig. 9. Measured cumulative precipitation (P), runoff (R_o), and net infiltration (net $I = P - R_o$) and calculated cumulative evapotranspiration (ET) for the ET engineered cover to the 1.1-m depth for water years 1998 through 2002 at the New Mexico site. The long-term (1961–1990) average annual precipitation of 226 mm is shown (±55 mm 1 σ).

no definite seasonal variability in water storage because water storage increases and decreases occurred in both winter and summer. The much larger coefficient of variation (100 σ/μ) in measured water storage (≤ about 35%) relative to that for the Texas data (≤ about 10%) may reflect the smaller sampling volume of the TDR probes relative to the neutron probe and lower number of sample points in each average (15 in New Mexico vs. 70 in Texas data). The CV in water storage also reflects spatial variability in measured water content: lower water contents in the upland areas and higher water contents toward the base of the slopes (Fig. 11a).

Temporal variability in water content measured at different depths was greatest near the surface and decreased with depth (Fig. 11b). Water content was generally high at 0.15 m during winter periods, with the exception of 1999, and generally decreased in March and April of each year when vegetation became active. Water redistributed to depths of 0.45 and 0.90 m after infiltration in winter 1997–1998 and winter and spring 2000–2001. Drying also propagated with depth (e.g., for 1998: 0.15 m in March, 0.45 m in June, 0.9 m in August).

Measured drainage at the base of the ET cover was 0.0 mm yr^{-1} in the east subplot and ranged from 0.0 to 0.4 mm yr^{-1} in the west subplot. Drainage occurred during the first 2 yr of the 5-yr monitoring period. Low drainage during 1997 extended over several months and was attributed to wet initial conditions (average water content 0.18 m^3 m^{-3}) from construction water in the profile and summer precipitation events (10 July 1997, 24.4 mm; 18 July 1997, 20.6 mm; 22 Aug. 1997, 23.6 mm; 21 Sept. 1997, 50.8 mm). Drainage in 1998 generally occurred during a short time period (0.39 mm; 18 July 1998 to 20 Sept. 1998) and was attributed to a sequence

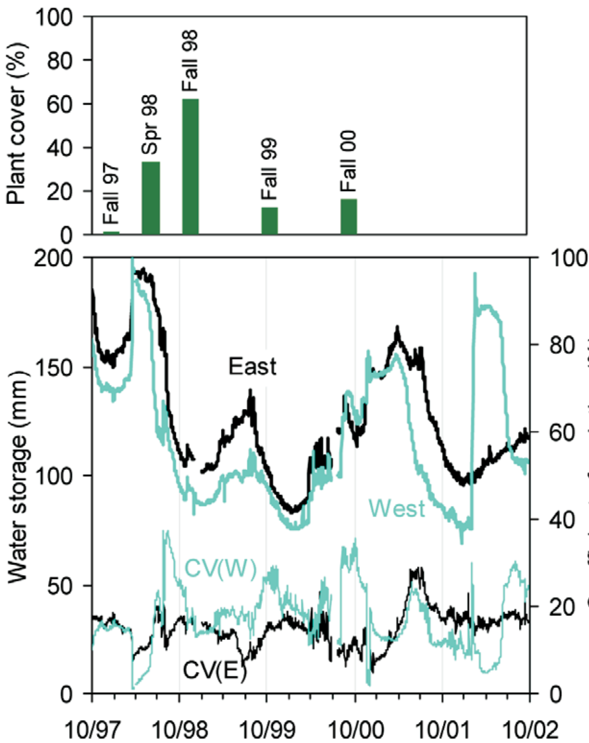

Fig. 10. Average plant cover (columns) and average water storage (thick lines) to the 1.1-m depth in the west and east subplots at the New Mexico site. Thin lines represent the coefficients of variation of five TDR measurement locations for both the west and east subplots.

of large discrete precipitation events (16 July 1998, 24.6 mm; 25 July 1998, 24.4 mm; and 1 Aug. 1998, 18.5 mm). Drainage may have been spatially focused also, as shown by lack of drainage in the east subplot.

Comparison with the Natural System

The natural system surrounding the ET covers in West Texas was characterized for a proposed low-level radioactive waste disposal facility (Scanlon et al., 1999). Water content monitored with a neutron probe in an access tube installed 20 m from the covers did not change below 0.6 m during the 4-yr monitoring period. Long-term water potential monitoring using thermocouple psychrometers 30 m from the covers showed that maximum depth of the wetting front was <0.3 m (Fig. 8d; Scanlon et al., 2003). Water potential includes matric and osmotic potentials; however, estimated osmotic potentials from pore water Cl^- data are generally ≤10% of measured water potentials (Scanlon et al., 2003); therefore, water potential and matric potential can be considered approximately equivalent. Matric potentials in the engineered cover were much higher than water potentials monitored in the natural system (Fig. 8d). Wetter conditions in the engineered covers can be attributed partly to precipitation, addition of water for compaction during construction, and irrigation of the subplots to establish vegetation. Measurement and modeling of matric potential and Cl^- profiles in the natural system indicate that it has been in a long-term drying trend since the Pleistocene (≈10 000–15 000 yr ago) and that water has been moving upward since that time (Scanlon et al., 2003). Chloride moves into the subsurface with infiltrating precipitation and builds up in the subsurface as water is evapotranspired because Cl^- is not volatile and plant uptake is negligible. This comparison of engineered covers and the surrounding natural system indicates that the two are not directly comparable. Soils in the natural system have been developing for very long times and are characterized by thick caliche development. It is questionable whether the water balance of the covers will approach that of the natural system in the near future.

Numerical Simulation Results

Texas Site Water Balance Simulations

Previous studies indicate that simulated and measured water balance generally compare favorably for the first year of monitoring (WY98) when the system was nonvegetated; however, simulated runoff was underestimated (Scanlon et al., 2002). Simulated water balance of the vegetated cover for WY00 was similar to the

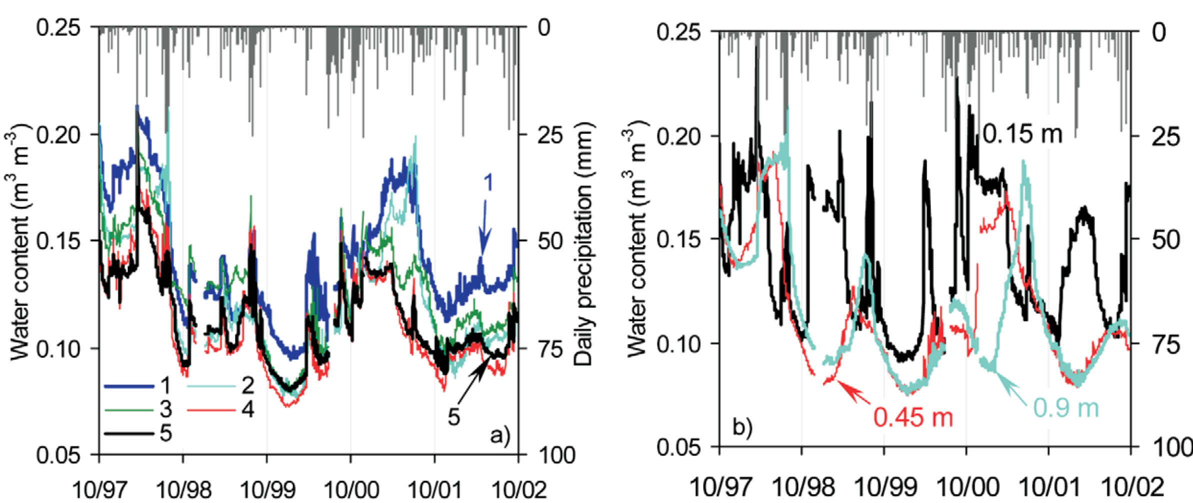

Fig. 11. Average measured water content for (a) all monitored depths within a given slope position (1: base of slope, 5: top of slope) and (b) all slope positions at a given monitored depth in the east subplot at the New Mexico site.

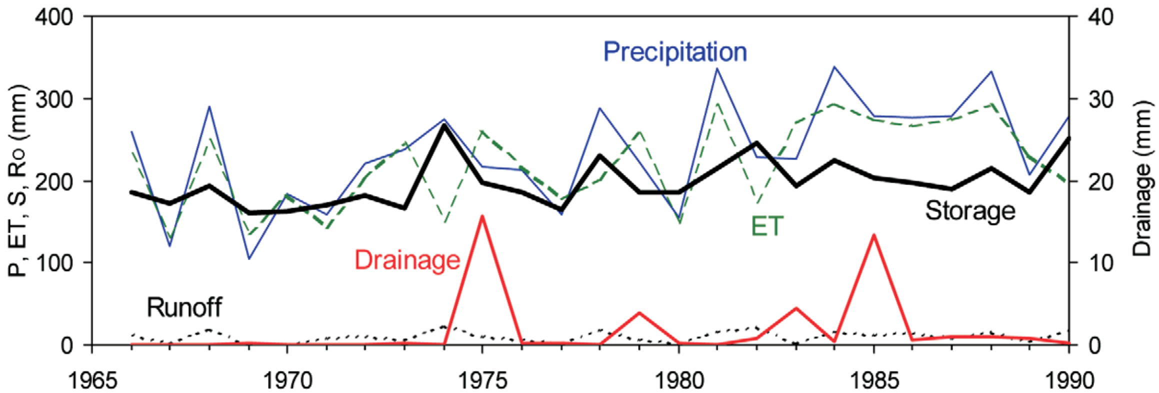

Fig. 12. Simulated annual water balance results for the 1.1-m Texas profile with a unit gradient lower boundary condition.

measured water balance also (Table 2). Vegetation parameters included maximum ecosystem level LAI of 0.1 m^2 m^{-2}. The growing season extended from mid March to the end of September, with maximum LAI from late May through mid-August. The maximum rooting depth was set at 0.75 m and was evaluated using sensitivity analyses. To better simulate runoff, a 50-mm crust with 44% lower hydraulic conductivity was included in the simulation profile. Crusts often form in these regions. The saturated hydraulic conductivity of the crust can be considered a calibration parameter to better simulate runoff. Simulated drainage was 0.0 mm for the 2-m profile using a seepage face lower boundary condition that reflects the underlying capillary barrier. In contrast, simulations using a unit gradient lower boundary condition, which allows free drainage, resulted in 0.2 mm of drainage at the 1.1-m depth and 2.4 mm of drainage at the 2-m depth. The higher drainage at the 2-m depth reflects the wetter initial conditions between 1 and 2 m because of heavy rain during construction (Fig. 7). Simulated drainage at the 1.1-m depth is similar to zero drainage estimated at this depth.

The main components of the water balance were ET and water storage change because runoff and drainage were low. Simulated and measured annual ET values were within 1%, and water storage changes were within 12%. Calculated root mean square errors based on measured and simulated water storage were low (≤10 mm), indicating that the simulations generally reproduced the temporal variability in water storage.

Although there are no measured data for comparison with the 25-yr simulations, these simulations provide information on how the cover might perform in response to long-term climate forcing (Fig. 12). The results for the 1.1-m profile are described and are similar to those for the 2-m profile. Simulated runoff ranged from 0.0 to 22.7 mm yr^{-1} and averaged 9.5 mm yr^{-1}, which is similar to measured values during the monitoring period (Table 2). Simulated drainage was 0.0 mm yr^{-1} for the 1.1- and 2-m profiles using a seepage face lower boundary condition. In contrast, a unit gradient lower boundary resulted in simulated drainage ranging from 0.0 to 1.0 mm yr^{-1}, with the exception of 4 yr when drainage was higher: 1975 (16.7 mm yr^{-1}), 1979 (4.5 mm yr^{-1}), 1983 (4.9 mm yr^{-1}), and 1985 (14.1 mm yr^{-1}) (Fig. 12). The highest drainage occurred in 1975 after above-normal precipitation in September 1974. A total of 163 mm of precipitation occurred in 9 d in September, with daily precipitation up to 57 mm. Precipitation during 1974 before September was low (112 mm), and low simulated ET is consistent with the low precipitation before September. High precipitation near the end of the growing season resulted in insufficient time for the vegetation to remove the infiltrated water and resulted in a large increase in water storage (100 mm) in 1974 followed by drainage in 1975 (16.7 mm) (Fig. 12). Similar processes occurred in 1984 (131 mm precipitation 4–13 Aug.; 68 mm, 23–26 Oct.) that resulted in 14.1 mm of drainage in 1985. Dominant parameters in the water balance were ET and water storage changes. Temporal variability in water storage was low. The highest water storage increase (100 mm) was recorded in 1974, which corresponded to above-normal precipitation in September. These simulations indicate that cover performance in response to long-term climatic forcing should be similar to that shown by the shorter term monitoring record; however, drainage may occur in response to intense precipitation toward the end of the growing season that can be eliminated with a capillary barrier.

New Mexico Site Water Balance Simulations

The 5-yr water balance of the east subplot was simulated to determine how well simulations would match measured values. The vegetation parameters included maximum ecosystem level LAI of 0.3 m^2 m^{-2} (Dwyer, 2003). The growing season extended from mid-March to the end of September, with maximum LAI from mid-May through early September. Maximum rooting depth was set at 0.75 m, and sensitivity of model results to this parameter was tested. Zero runoff was simulated, which is generally consistent with very low measured runoff values (Table 3). Simulated drainage of zero for the seepage face lower boundary condition is consistent with zero measured drainage. Replacement of the seepage face with a unit gradient resulted in small amounts of drainage that decreased with time (0.1–0.3 mm yr^{-1}; Table 3). Interannual trends and variability in both ET and water storage were generally reproduced by the simulations; however, magnitudes differed. Simulated and measured annual ET values were within 15%. The greatest discrepancy in simulated and measured water

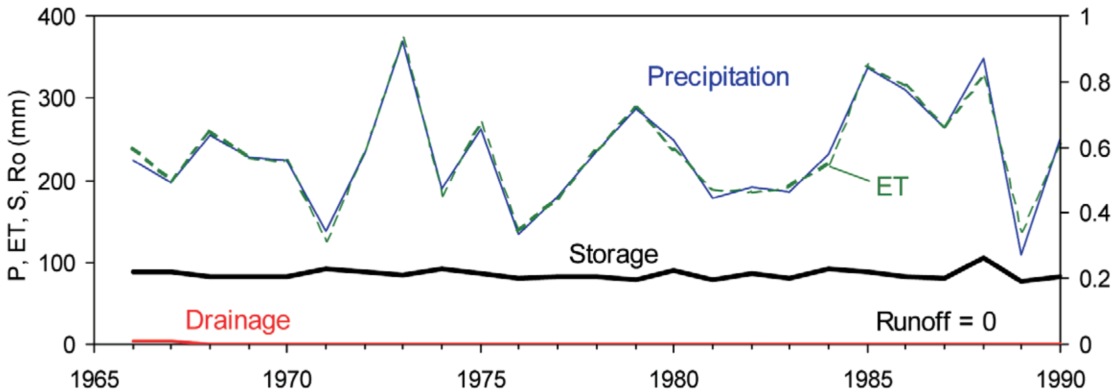

Fig. 13. Simulated annual water balance results for the 1.1-m New Mexico profile with a unit gradient lower boundary condition.

storage was for WY00, when measured storage increased and simulated storage decreased.

The 25-yr simulations resulted in zero runoff and drainage, which is consistent with the monitoring data (Fig. 13). The largest increase in water storage occurred in 1988 (24 mm) and may be attributed to precipitation being about 60 to 70% above average in April through September 1987 and October through March 1997-1998 related to El Nino. Increases in water storage of about 10 mm also occurred in 1964, 1965, 1971, 1974, 1980, and 1984. Annual precipitation and ET were highly correlated ($r = 0.99$). Similar results were obtained for seepage face and unit gradient lower boundary conditions.

Sensitivity Analysis

The simulations provide information on the sensitivity of the simulated water balance to variations in meteorological forcing, profile thickness, and lower-boundary condition. Additional simulations were conducted to assess sensitivity of simulations to variations in PET, vegetation parameters (including root depth, root-length density, vegetation type, and LAI), and hydraulic parameters (Fig. 14, Table 4). Parameters were generally varied from a factor of 0.5 to 1.5 times the values used in the base case. The sensitivity analyses were conducted on the 25-yr simulations.

Results of sensitivity analyses for the Texas site are described for the 1.1-m-deep profiles because results from the 2-m profiles were similar (Fig. 14; Table 4). Simulations were based on a unit gradient lower boundary condition. Simulated water balance was most sensitive to the presence or absence of vegetation. Simulating the extreme case of no vegetation resulted in increased drainage by 27.7 mm yr^{-1} and was balanced by reduced ET. The model was not very sensitive to variations in individual vegetation parameters, such as LAI, root depth, or root-length density. Varying root distribution from bunchgrass (base case) to cheat grass (higher root density at shallower depths; Rockhold et al., 1995) increased drainage by 3.6 mm yr^{-1} and was generally balanced by reduced ET. Decreasing PET by a factor of 2 increased drainage by 7.7 mm yr^{-1} and was generally balanced by reduced ET, whereas increasing PET by a factor of 1.5 decreased drainage and increased ET. However, temporal variability in annual PET is low (CV 0.06–0.08), and PET is generally not highly uncertain. Simulated water balance was more sensitive to variations in hydraulic parameters than in vegetation parameters. Previous studies at the Texas site showed that laboratory and field measured K_s values underestimated the effective K_s of the cover as shown by the monitoring data (Scanlon et al., 2002). Simulations are sensitive to variations in K_s. Increasing K_s by an order of magnitude increased drainage by 7.5 mm yr^{-1} that was balanced by reduced ET, whereas

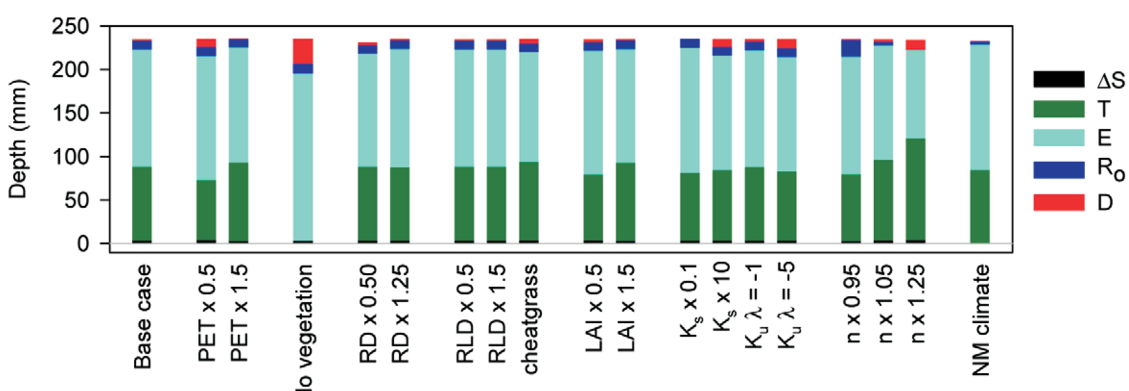

Fig. 14. Sensitivity analysis for the Texas site simulation: 25-yr average annual values are shown for the base case simulation and for simulations with a single parameter altered as indicated. PET, potential evapotranspiration; RD, root depth; RLD, root length density; LAI, leaf area index; *K*$_s$, saturated hydraulic conductivity; *K*$_u$ λ, unsaturated hydraulic conductivity function parameter; *n*, van Genuchten soil water retention function parameter; NM climate, simulation using New Mexico site climate forcing. Water balance parameters are ΔS, water storage change; *T*, transpiration; *E*, evaporation; *R*$_o$, runoff; *D*, drainage.

Table 4. Sensitivity analysis results for 25-yr simulations using a unit-gradient lower boundary condition. Base case represents the model average annual total values. All other values represent *changes* relative to the base case in average annual total values resulting from the indicated parameter modification.†

Parameter	Texas site 1.1-m profile						New Mexico site 1.1-m profile					
	T	E	ET	R_o	D	ΔS	T	E	ET	R_o	D	ΔS
	mm											
Base case	85.8	134.9	220.7	9.5	1.9	3.2	93.6	139.8	233.4	0.0	0.0	−0.8
PET × 0.5	−16.7	7.7	−9.0	0.8	7.7	0.9	−11.2	13.6	2.5	0.0	0.0	0.3
PET × 1.5	5.1	−2.7	2.3	−0.3	−1.1	−0.5	9.0	−6.7	2.3	0.0	0.0	0.5
No vegetation	−85.8	57.4	−28.4	1.0	27.7	−0.3	−93.6	90.8	−2.8	0.0	1.8	1.0
RD × 0.5	1.9	−4.3	−2.4	−0.1	2.6	0.0	16.0	−17.2	−0.3	0.0	0.1	0.2
RD × 1.25	−1.2	1.5	0.3	0.1	−0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RLD × 0.5	0.0	0.0	0.0	0.0	0.0	0.0	1.4	−1.3	0.0	0.0	0.0	−0.1
RLD × 1.5	−0.3	0.2	−0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cheat grass	4.8	−8.5	−3.8	−0.2	3.6	0.3	21.0	−20.9	0.2	0.0	0.0	−0.2
LAI × 0.5	−9.3	7.4	−1.9	0.1	1.5	0.3	−9.6	9.3	−0.3	0.0	0.0	0.3
LAI × 1.5	4.9	−4.1	0.8	−0.1	−0.5	−0.2	6.3	−6.3	0.0	0.0	0.0	0.0
K_s × 0.1	−6.6	8.6	2.0	0.2	−1.9	−0.3	−11.5	11.4	−0.1	0.0	0.0	0.1
K_s × 10	−4.1	−3.2	−7.4	−0.1	7.5	0.0	14.6	−14.7	−0.1	0.0	0.0	0.1
K_u $\lambda = -1$	−0.1	−1.1	−1.2	0.0	1.2	0.0	7.3	−7.4	−0.1	0.0	0.0	0.1
K_u $\lambda = -5$	−6.0	−3.0	−8.9	0.1	8.9	0.0	20.6	−24.0	−3.5	0.0	3.3	0.1
n × 0.95	−8.5	0.3	−8.2	9.6	−0.9	−0.5	−7.5	7.5	0.0	0.0	0.0	0.0
n × 1.05	7.3	−3.4	3.9	−5.5	1.2	0.4	7.5	−7.5	0.0	0.0	0.0	0.0
n × 1.25	32.1	−34.2	−2.1	−9.5	10.7	1.0	41.3	−41.2	0.1	0.0	0.0	−0.1
Climate	−0.8	9.2	8.4	−5.7	−1.7	−3.8	0.6	−2.8	−2.2	2.1	0.0	2.9

† T, transpiration; E, evaporation; ET, evapotranspiration; R_o, runoff; D, drainage; ΔS, water storage change; PET, potential evapotranspiration; RD, root depth; RLD, root length density; LAI, leaf area index; K_s, saturated hydraulic conductivity; K_u λ, unsaturated hydraulic conductivity function parameter; n, van Genuchten water retention function parameter; Climate, climate forcing exchanged between the Texas and New Mexico sites.

decreasing K_s by an order of magnitude decreased drainage by 1.9 mm yr^{-1}. The unsaturated hydraulic conductivity (K_u) can also be varied by changing the λ parameter in the van Genuchten–Mualem K_u function. Mualem (1976) suggested a value of 0.5 for λ. Decreasing λ to values of −1 to −5 increased the K_u and increased drainage by 1.2 and 8.9 mm yr^{-1}, respectively, balanced by reduced ET. The van Genuchten n parameter in the water retention function represents the range in pore sizes in the soil: high n indicates low pore-size distribution, typical of coarser material, and low n indicates high pore-size distribution, typical of finer material. The typical range in parameters (factor of 0.5–1.5) could not be considered for n because it resulted in unrealistic values ($n \leq 1.0$). Increasing n by a factor of 1.25 increased drainage by 10.7 mm yr^{-1} and was balanced by reduced runoff. Decreasing n by a factor of 0.95 generally reduced drainage slightly. Replacing the unit gradient lower boundary condition with a seepage face to simulate a capillary barrier resulted in zero drainage for all sensitivity cases.

Simulated water balance of the New Mexico site was much less sensitive to the parameter variations considered in the sensitivity analyses than that of the Texas site (Fig. 15, Table 4). The following results are based on a unit gradient lower boundary condition. Varying PET by factors of 0.5 and 2 changed ET by only 1%. Simulating nonvegetated conditions increased water storage by 1.0 mm yr^{-1} and increased drainage by 1.8 mm yr^{-1} and was balanced by reduced ET. Simulation results were insensitive to variations in vegetation parameters. Varying hydraulic parameters, such as K_s and van Genuchten n, had little impact on the simulated water balance. Reducing the Mualem λ parameter to −5 increased drainage by 3.3 mm yr^{-1} balanced by reduced ET. Results for a seepage face lower boundary condition were similar to those for unit gradient condition, except that simulated drainage was zero for all sensitivity cases with a seepage face. The general insensitivity of simulated water balance to many of the parameters evaluated suggests that it may be difficult to estimate parameters using inverse modeling.

To evaluate causes of differences in simulated long-term water balances between Texas and New Mexico, we interchanged climate forcing between sites. Simulating Texas soils with New Mexico climate forcing resulted in reduced drainage, runoff, and water storage change, balanced by increased ET relative to the Texas base case simulation. These changes may be attributed to the lack of large precipitation events occurring near the end of the growing season (August–October) that are present in the Texas climate forcing. Simulating New Mexico soils with Texas climate forcing resulted in zero drainage (i.e., no change) and increased runoff and water storage change balanced by decreased ET relative to the New Mexico base case simulation. The changes may be attributed the 80% lower K_s in New Mexico subsoil relative to Texas subsoil, which reduced the impact of the late growing season precipitation events present in the Texas climate forcing. These comparisons indicate that low K_s in New Mexico subsoil plays an important role in minimizing drainage; however, as with traditional resistive covers, it may be difficult to determine the optimal K_s that can be achieved without developing cracks and preferential pathways. The above comparisons indicate that both climate forcing and hydraulic properties contribute to differences in simulated water balances between the sites.

Implications for Future Studies

Monitoring and modeling results from these studies have important implications for future studies of engineered covers. Major implications for the monitoring program include (i) limitations of relying on a single param-

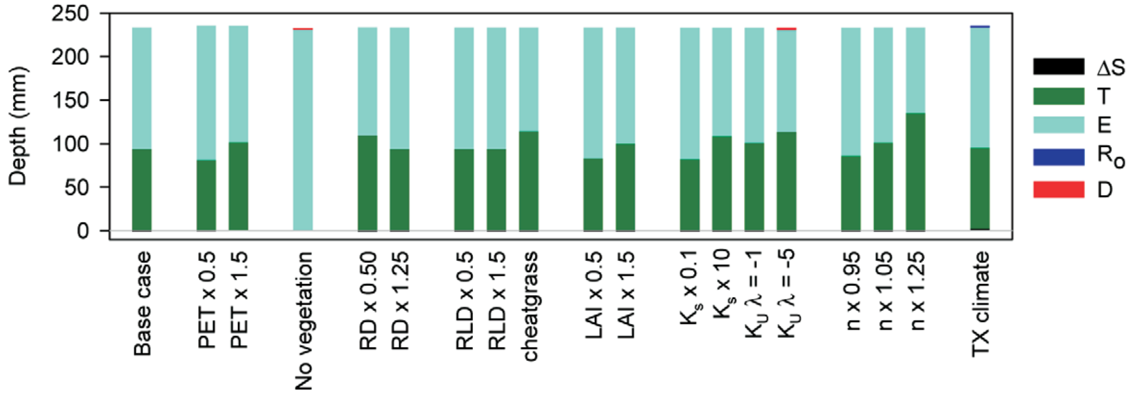

Fig. 15. Sensitivity analysis for the New Mexico site simulation: 25-yr average annual values are shown for the base case simulation and for simulations with a single parameter altered as indicated. PET, potential evapotranspiration; RD, root depth; RLD, root length density; LAI, leaf area index; K_s, saturated hydraulic conductivity; K_u λ, unsaturated hydraulic conductivity function parameter; *n*, van Genuchten soil water retention function parameter; TX climate, simulation using Texas site climate forcing. Water balance parameters are ΔS, water storage change; *T*, transpiration; *E*, evaporation; R_o, runoff; *D*, drainage.

eter such as drainage, (ii) length of the monitoring record, and (iii) spatial variability in water balance parameters.

Drainage is the most critical water balance parameter for performance of engineered covers; however, it is difficult to measure natural drainage in these systems because most pan lysimeters create a capillary barrier effect. The applicability of the lysimeter drainage measurements to actual cover system performance depends on whether the interface between the cover and the underlying waste also acts as a capillary barrier. Although the measurement systems used with pan lysimeters (e.g., tipping bucket rain gauges) can precisely measure drainage, the problem is that water cannot reach these measurement devices and builds up above the lysimeter. Therefore, these systems can underestimate drainage and overestimate soil water storage relative to systems that do not contain a capillary barrier. The impact of the lower-boundary condition was shown by monitoring and modeling at the Texas site. The lack of drainage in the CBET subplot that was irrigated with 2340 mm of water in summer 2001 is attributed to the capillary barrier. In addition, simulated drainage at the Texas site was higher for the unit gradient vs. the seepage face boundary condition, indicating that measured drainage using lysimeters underestimates natural drainage and overestimates water storage for systems without a capillary barrier at this site. The low K_s subsoil in the New Mexico profile resulted in zero drainage for both seepage face and unit gradient conditions. The studies described here emphasize the importance of monitoring multiple parameters to understand total system performance, including water storage, matric potential, and plant parameters.

Engineered covers should be monitored for at least 10 to 20 yr because short-term monitoring may be dominated by construction effects and by disequilibrium between cover parameters and climate forcing. The representativeness of climate forcing during the monitoring period is also very important.

Spatial variability in water balance parameters is important in assessing cover performance. Spatial variability in water content was particularly evident in the New Mexico site (slope 5%) with lower water content in upland areas and higher water content at the base of the slope (Fig. 11a). Monitoring of future covers, particularly those with steeper slopes, should not rely on a single vertical profile for monitoring water storage.

Many limitations associated with modeling are described in an intercode comparison study (Scanlon et al., 2003), such as difficulties in simulating runoff, accurate representation of precipitation intensity, upper boundary condition during precipitation, and variations in simulated water balance related to hydraulic parameterization. One of the most critical parameters in ET covers is vegetation and how it controls water balance. Most models simulate vegetation by externally prescribing time series in vegetation parameters such as LAI and root depth (Simunek et al., 1998; Fayer, 2000). However, this approach precludes any feedback between soil water storage changes and vegetation and fails to simulate the dynamic two-way interaction between vegetation and water balance. The opportunistic behavior of vegetation is clearly shown in the monitoring data. Vegetative response to water storage changes should be simulated internally rather than prescribed in the input data set. All available data, including monitoring and modeling, should be combined to develop a comprehensive conceptual model of total system performance.

Implications for Cover Design

The monitoring and modeling studies described in this work provide valuable information that can be used to optimize the design of ET covers in arid and semiarid regions. One of the basic design issues is cover thickness. A variety of approaches can be used to estimate cover thickness. Traditional approaches estimate available water storage (AWS) from water content at field capacity and wilting point. However, Meyer and Gee (1999) showed that a head-based approach for estimating AWS may not be valid because field capacity may correspond to unacceptably large water fluxes; they proposed a flux-based approach to estimate AWS. Using the Texas profile as an example, field capacity (h = −3.3 m) corresponds to a flux of 67 mm yr^{-1} under unit gradient

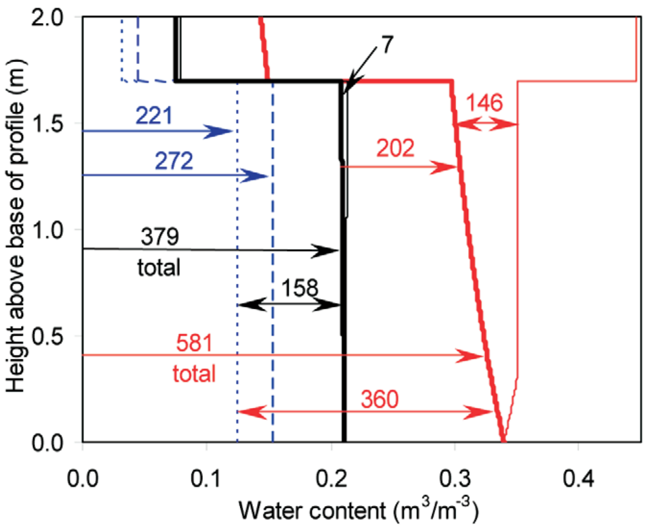

Fig. 16. Calculated water content profiles for the Texas CBET system. All values shown are in millimeters and represent total water storage values over the intervals indicated by associated arrows. Heavy and thin solid line pairs converging at the zero height represent water content profiles for zero and unit downward total head gradient conditions, respectively. The pair of lines converging at 0.34 m^3 m^{-3} water content represent profiles with a capillary barrier located at the zero height having a breakthrough water content equating to −0.3-m head. The two lines converging at 0.21 m^3 m^{-3} water content represent profiles without a capillary barrier and water content at the zero height equating to a prescribed flux of 1 mm yr^{-1}. Dashed lines represent wilting point water content profiles for uniform head conditions ranging from −150 m (long dash) to −500 m (short dash). Abrupt shift in water content near the top of each profile indicates transition from topsoil to subsoil.

conditions (free drainage, no capillary barrier). A flux of 67 mm yr^{-1} is considered excessive. A reasonable performance goal for covers in arid and semiarid regions would be a flux of 1 mm yr^{-1} which corresponds to a head at the base of the profile of −21 m. The maximum water that can be stored in the profile before drainage occurs corresponds to equilibrium or no flow conditions, which corresponds to a total head (H) gradient of zero (i.e., $H = h + z$, unit downward gravitational potential head, z, gradient balanced by unit upward matric potential head, h, gradient). Under equilibrium conditions, a head of −21 m corresponds to 379 mm total water storage in a 2-m profile (Fig. 16) and 191 mm in a 1.1-m profile (Table 5). Under drainage conditions, a unit downward total head gradient is more appropriate, which corresponds to a zero matric potential head gradient and unit downward gravitational potential head gradient. However, the difference in water storage between equilibrium and a downward gradient is small (7 mm) (Fig. 16). To calculate the AWS, water storage associated with the wilting point should be subtracted from storage calculated for the 1 mm yr^{-1} flux. The AWS ranges from 158 mm for a 2-m profile to 82 mm for a 1.1-m profile using a wilting point head of −500 m, which is typical of arid and semiarid conditions (Table 5). The choice of wilting point head impacts the AWS estimate. Use of a wilting point head of −500 vs. −150 m (typical of more humid settings) results in 1.5 times greater AWS.

Stormont and Morris (1998) and Khire et al. (2000) assessed increased storage provided by an underlying capillary barrier. A similar approach was used in this study to evaluate the impact of a capillary barrier. The Texas profile was used as an example. Similar results were found for the New Mexico profile (Table 5). A water entry pressure of −0.3 m was used for the capillary barrier. This analysis indicated that addition of a capillary barrier increases the AWS by 202 mm (2 m profile) and 121 mm (1.1 m profile) for zero total head gradient (equilibrium) and by 348 mm (2 m profile) and 221 mm (1.1 m profile) for unit downward total head gradient (drainage). Stormont and Morris (1998) indicated that unit downward gradients are generally observed during capillary breakthrough conditions. The calculated AWS was not very sensitive to variations in water entry pressure of the capillary break material. Varying water entry pressure from −1.0 m to −3.0 mm only changed the AWS in the 2-m profile by 45 mm. Average water storage at the Texas site exceeded water storage corresponding to the calculated 1 mm yr^{-1} downward water flux 70% of the time; therefore, a capillary barrier was required to minimize drainage in this system (Fig. 17).

The required AWS of a cover is difficult to determine. The dominance of summer precipitation in the Texas and New Mexico regions studied, which corresponds to periods of high ET, reduces the required AWS. However, critical events may result from periods of above-normal summer precipitation followed by high winter precipitation, as in the 1997–1998 El Niño period in New Mexico. Examining the long-term simulations of the Texas site using a unit gradient lower boundary condition (free drainage), total water storage increased from 167 to 282 mm for a 1.1-m profile, and drainage

Table 5. Total water storage (WS_T) and available water storage (AWS) estimates for the Texas and New Mexico cover systems. Both unit gradient (UG) (equivalent to free drainage) and seepage face (SF) (equivalent to capillary barrier) lower boundary conditions are shown using water content profiles corresponding to both zero total head (Equil. = equilibrium conditions) and downward (↓) UG total head conditions within the cover system profiles. AWS was estimated as the difference between WS_T and the water storage corresponding to a uniform −500 m wilting point matric potential. Also shown is the benefit related to a capillary barrier (SF lower boundary condition) expressed as the ratio of SF to UG water storage capacity.

	UG lower boundary condition				SF lower boundary condition				SF/UG ratio			
	Equil. profile		↓ UG profile		Equil. profile		↓ UG profile		WS_T		AWS	
Profile	WS_T	AWS	WS_T	AWS	WS_T	AWS	WST	AWS	Equil	↓	Equil	↓
	mm											
TX 2.0 m	379	158	386	165	581	360	727	506	1.5	1.9	2.3	3.1
TX 1.1 m	191	82	193	84	312	203	412	303	1.6	2.1	2.5	3.6
NM 1.1 m	181	130	194	143	303	252	390	339	1.7	2.0	1.9	2.4

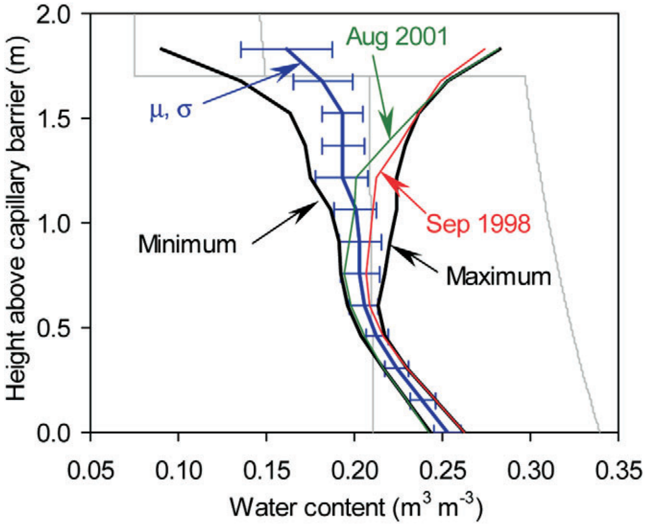

Fig. 17. Temporal variability of measured water content with depth in the Texas site CBET system. Calculated water content profiles for zero total head gradient conditions from Fig. 16 are shown in the background for reference. Average water content throughout the monitored period (μ) is shown with error bars, indicating the temporal standard deviation (σ) at the monitored depths. Also shown are water content temporal minimum and maximum values at each depth. The two wettest measured water content profiles are shown (Sept. 1998 and Aug. 2001).

later occurred following a large precipitation event in September 1974 (Fig. 12). Simulated total water storage increased above the total water storage corresponding to 1 mm yr^{-1} flux without a capillary barrier (191 mm) but remained below that corresponding to a capillary barrier (zero total head gradient, 312 mm; unit downward total head gradient, 412 mm). Monitoring and modeling analyses indicate that a 1-m-thick ET cover underlain by a capillary barrier should be adequate to minimize drainage to ≤1 mm yr^{-1} in these arid and semiarid settings.

CONCLUSIONS

- Estimated drainage from water content data at the Texas site (0.4–5.0 mm yr^{-1}) corresponded to irrigation (226–2340 mm). Low drainage at the New Mexico site (0.1–0.4 mm yr^{-1}) was restricted to the first 2 yr of the 5-yr monitoring period.
- Vegetation plays a critical role in controlling the water balance of ET covers, as shown by the correspondence between rapid water storage decreases and enhanced vegetation productivity at both sites.
- Climate at the Texas and New Mexico sites is particularly suitable for ET covers because of the dominance of monsoonal precipitation in June through October (62–80% of annual precipitation) when ET rates are highest.
- Modeling analysis indicates that the measured water balance can generally be reproduced with the models. Simulating runoff is difficult and required calibration of surface saturated hydraulic conductivity at the Texas site.
- Extension of these models to 25-yr periods indicates that there were critical precipitation events toward the end of the growing season in 1974 and 1984 at the Texas site that resulted in simulated drainage.
- Differences in long-term simulations between the Texas and New Mexico sites indicate that both climate forcing and hydraulic conductivity impact the simulated water balance. Low K_s in New Mexico subsoil was important in resulting in zero simulated drainage at this site.
- Sensitivity analyses indicated that simulated water balance was most sensitive to the presence or absence of vegetation and variations in hydraulic parameters at the Texas site but was much less sensitive to all parameters considered at the New Mexico site.
- Much wetter conditions in the ET covers relative to the natural system at the Texas site are attributed to addition of water for compaction and precipitation during construction of the covers.
- Monitoring and modeling analyses indicate that capillary barrier effects of the drainage lysimeters underestimate free drainage and overestimate water storage in the covers at the Texas site relative to systems that do not contain a capillary barrier. The reliability of the drainage estimates depends on how well the lysimeter capillary barrier replicates the actual system over the waste.
- Capillary barriers increased AWS at both sites by a factor of approximately 2.5 and precluded drainage for all simulated conditions, suggesting that a capillary barrier can provide a significant safety factor and should be considered in cover designs where technically and economically feasible.
- Limitations associated with monitoring drainage in systems without a capillary barrier underscore the need to monitor multiple parameters and integrate modeling to develop a predictive understanding of total system performance.
- Various limitations associated with monitoring and modeling, particularly drainage monitoring and vegetation modeling, should be addressed in future studies. The opportunistic behavior of vegetation would be simulated more realistically using two-way feedback between soil water storage and vegetation.

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