Field Performance of Three Compacted Clay Landfill Covers

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ABSTRACT

A study was conducted at sites in subtropical Georgia, seasonal and humid Iowa, and arid southeastern California to evaluate the field hydrology of compacted clay covers for final closure of landfills. Water balance of the covers was monitored with large (10 by 20 m), instrumented drainage lysimeters for 2 to 4 yr. Initial drainage at the Iowa and California sites was $<$32 mm yr^{-1} (i.e., unit gradient flow for a hydraulic conductivity of 10^{-7} cm s^{-1}, the regulatory standard for the clay barriers in this study); initial drainage rate at the Georgia site was about 80 mm yr^{-1}. The drainage rate at all sites increased by factors ranging from 100 to 750 during the monitoring periods and in each case the drainage rate exceeded 32 mm yr^{-1} by the end of the monitoring period. The drainage rates developed a rapid response to precipitation events, suggesting that increases in drainage rate were the result of preferential flow. Although no direct observations of preferential flow paths were made, field measurements of water content and temperature at all three sites suggested that desiccation or freeze–thaw cycling probably resulted in formation of preferential flow paths through the barrier layers. Data from all three sites showed the effectiveness of all three covers as hydraulic barriers diminished during the 2 to 4 yr monitoring period, which was short compared with the required design life (often 30 yr) of most waste containment facilities.

Regulations for closure of waste containment facilities commonly specify a hydraulic barrier layer in the final cover to limit movement of precipitation into the underlying waste (USEPA, 1992). The type of barrier layer that is required generally depends on the type of liner beneath the waste. For unlined or soil-lined sites, the final cover profile must include a soil hydraulic barrier layer at least 46 cm thick and an overlying surface layer at least 15 cm thick. The saturated hydraulic conductivity of the cover barrier layer must be no greater than that of the liner or the underlying soils (for unlined sites) and must be less than a specified saturated hydraulic conductivity. At the three sites described here, the maximum saturated hydraulic conductivity was 10^{-7} cm s^{-1}. Covers meeting these requirements are referred to as *clay barrier covers.* Although the term *clay* does not accurately describe all soils used for barrier layers, the nomenclature is common in practice and therefore is used here.

The long-term performance of clay barrier covers is predicated on two factors: (i) proper construction of the barrier layer so that the hydraulic conductivity requirement is met at field scale; and (ii) long-term maintenance of the barrier layer so as to maintain the low hydraulic conductivity. Factors contributing to proper construction have been studied in detail and are well understood (see Benson et al. [1999a] for a review). Far less attention has been given to evaluating whether the integrity of clay barriers can be maintained under field conditions. Several laboratory studies have shown that environmental conditions, especially those that result in desiccation and freeze–thaw cycling, cause cracking of the soil and increases in saturated hydraulic conductivity of two or more orders of magnitude (DeJong and Warkentin, 1965; Boynton and Daniel, 1985; Kleppe and Olson, 1985; Chamberlain et al., 1990; Benson and Othman, 1993; Bowders and McClelland, 1994; Othman et al., 1994; Phifer et al., 1994, 2000; Benson et al., 1995; Drumm et al., 1997; Albrecht and Benson, 2001).

There is some evidence from field observations that clay barrier covers may not be performing as intended (Corser and Cranston, 1992; Maine Dep. of Environmental Protection, unpublished data, 2001). Despite the evidence that clay barrier layers may be adversely affected by environmental stresses, only a few studies have measured the hydrology of clay barrier covers at field scale for an extended period. This study investigated the field-scale hydrology of clay barrier covers at three sites located in warm–humid, cool–humid, and warm–arid climates. Test sections that included large, instrumented drainage lysimeters were used for monitoring. Field data for multiple (2–4) years of monitoring are reported.

PREVIOUS FIELD STUDIES OF COMPACTED CLAY COVER HYDROLOGY

Cool–Humid Locations

Montgomery and Parsons (1990) monitored the hydrology of three clay barrier covers at a site near Milwaukee, WI, for nearly 4 yr using 6.1- by 12.2-m drainage lysimeters. Two of the covers consisted of a clay barrier layer 124 cm thick overlain by a surface layer, and differed only in thickness of the surface layer (15 vs. 46 cm). The third cover consisted of two clay barrier layers separated by a layer of sand and overlain by a 15-cm-thick surface layer. The cover profiles and properties of the soils are summarized in Table 1.

Annual precipitation during the monitoring period ranged between 578 and 896 mm. A drought occurred during the summer of the second year. Freezing temperatures were recorded at a depth of 30 cm (15 cm below the interface between the surface layer and the

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Table 1. Summary of cover characteristics and drainage rates from previous field studies on compacted clay barrier final covers.

				Barrier layer					
Location and reference	**Test pad size**	**Test years**	**Annual precipitation**	**Thickness**	**Soil type†**	**Initial K_s‡**	**Final K_s**	**Surface layer thickness**	**Annual drainage**
	m^2		mm	cm		$cm\ s^{-1}$	$cm\ s^{-1}$	cm	mm
				Cool–humid locations					
Milwaukee, WI (Montgomery and Parsons, 1990)	74.4	4	578–896	124	CL	$>1.0 \times 10^{7}$	NA	15	1.5–57
				124				47	6.9–60
				62 (×2)				15	22–41
Hamburg, Germany (Melchior, 1997)	500	8	714–1032	60	SC	2.4×10^{-8}	NA	100 (5% slope)	7.0–174
				60				100 (20% slope)	1.9–150
				40				100 (20% slope)	8.4–201
Kalamazoo, MI (National Council for Air and Stream Improvement, 1997; Benson and Wang, 1998)	65–70	7	795–1109	61	CL	1.9×10^{-8}	8.1×10^{-7}	61	16–70
				61		4.5×10^{-9}	7.0×10^{-6}	61	26–69
Reedsburg, WI (Abichou et al., 1998; Albrecht and Benson, 2001)	85	3	780–929	61	CL	9.8×10^{-9}	6.9×10^{-5}	15	42–299
				61		1.6×10^{-8}	NA	15	87–386
				61		NA	NA	107	17–54
				61		NA	NA	107	28–99
				Warm–humid locations					
Atlanta, GA (Khire et al., 1997)	223	3	1188–1721	92	CH	3.2×10^{-8}	NA	15	30–150
				Semiarid locations					
Albuquerque, NM (Dwyer, 2003)	1300	5	144–300	45	NA	4.9×10^{-7}	NA	15	0.0–3.6
Wenatchee, WA (Khire et al., 1997)	223	3	140–260	60	ML-CL	2.2×10^{-7}	NA	15	2–22

† CL = low to medium plasticity clay, SC = clayey sand, CH = high plasticity clay, ML-CL = silty clay.
‡ K_s = saturated hydraulic conductivity.

clay in the cover with the thinner surface layer), but did not penetrate to temperature probes located at a depth of 92 cm. Annual drainage from the two covers with a single barrier layer increased throughout the monitoring period from <1% of precipitation the first year (1.5 and 6.9 mm) to approximately 7% (57 and 60 mm) during the last full year of monitoring. Drainage through the third test section with an intermediate sand layer was 4 to 5% of precipitation (22–41 mm) each monitoring year.

Two years after construction, test pits were excavated adjacent to the test sections. Observations from the test pits showed weathering with a blocky structure in the upper 25 cm of clay in all three test sections, cracks 8 to10 mm wide to depths of 90 to 100 cm, dense root development in the upper 20 to 25 cm of the clay layer with some roots penetrating as deep as 76 cm into the clay layer, and that the lower clay layer in the multilayered design remained relatively intact throughout the test period. Montgomery and Parsons (1990) concluded that cracks in the clay barrier layers were responsible for the increases in drainage that occurred in the covers with a single barrier layer, that the cracks persisted regardless of soil water status of the clay layer, and that the thickness of the surface layer over the two monolithic clay barriers did not affect the drainage rate.

Melchior (1997) monitored three clay barrier covers at a site near Hamburg, Germany, for 8 yr using 10- by 50-m drainage lysimeters. Two of the test sections had identical profiles (60-cm-thick clay barrier layers overlain by 25-cm sand drainage layers and 75-cm surface layers) and differed only in slope (4 and 20%). The third test section, which was on a 20% slope, had a 40-cm clay layer and included a capillary barrier under the compacted soil layer as a second barrier system. Annual precipitation at the site ranged between 740 and 1032 mm. Annual drainage was similar for all three test sections and was <1% of annual precipitation (1.9–8.4 mm) the first year of monitoring, but increased to as much as 26% of annual precipitation (150–201 mm) in the final year. Seven years after construction, test pits were excavated and a tracer experiment was conducted in the clay barrier covers without a capillary layer. The clay barrier layer was found to be dry, cracked, and invaded with plant roots through the entire depth. The presence of tracer confirmed that preferential flow paths penetrated through the barrier layer.

The National Council for Air and Stream Improvement (NCASI) evaluated two test sections simulating clay barrier covers near Kalamazoo, MI, using drainage lysimeters (~8.5 by 8.5 m) for 8 yr (National Council for Air and Stream Improvement, 1997). The covers consisted of a 61-cm-thick compacted clay barrier layer overlain with a sand drainage layer (46 cm) and 15 cm of topsoil (Table 1). Annual precipitation during the monitoring period ranged between 795 and 1109 mm. The lowest drainage rates (16 and 26 mm, 1.8 and 3.0% of precipitation) were recorded the first year; the highest drainage rates (69 and 70 mm, 8.7 and 6.3% of precipitation) were observed during the third and fourth years. Eight years after construction, the test sections were decommissioned and the barrier layers were examined. In situ hydraulic conductivities were measured with a sealed double ring infiltrometer and two-stage borehole permeameters. The test sections were also excavated and the barrier layers visually examined with the aid of a dye tracer. The hydraulic conductivity of the clay barriers increased by a factor of 40 to 1500 during the 8-yr monitoring period (Table 1). Dye staining indicated that the increase in hydraulic conductivity was probably the result of vertical and horizontal preferential pathways (Benson and Wang, 1996).

Abichou et al. (1998) tested two replicates each of two clay barrier covers using drainage lysimeters (~85 m^2)

for 3 yr near Reedsburg, WI. Both designs had 61-cm-thick compacted clay layers and differed only in the thickness of the surface layer (15 vs. 107 cm, Table 1). Annual precipitation during the monitoring period ranged between 780 and 929 mm yr^{-1}. Drainage from the test section with a thinner surface layer ranged between 5 and 43% of precipitation (42–386 mm), and generally increased during the study period. Drainage from the test section with a thicker surface layer ranged between 2.2 and 11% of precipitation (17–99 mm), and showed little temporal trend during 3 yr of monitoring. Test pits were excavated in the covers to examine the clay barrier layer for structural development and root intrusion. In the test section with a thinner surface layer, the clay barrier layer had vertical cracks extending through the entire depth of the layer and horizontal cracks mostly confined to the upper portion of the layer. Tests on 300-mm-diameter block specimens removed from the clay barrier layer indicated that the hydraulic conductivity of the clay had increased by a factor of 7000 during the 5 yr since construction (Albrecht and Benson, 2001) (Table 1). Roots were found to a depth of 45 cm into the barrier layer. The barrier layer in the test section with the thicker surface layer showed no evidence of frost damage, had few vertical fractures, and had no indication of roots.

Warm–Humid Location

Khire et al. (1997) monitored the performance of a clay barrier design for 3 yr in a 12.2- by 18.3-m drainage lysimeter near Atlanta, GA. The profile consisted of a 92-cm-thick barrier layer of kaolinitic clay overlain by a 15-cm-thick surface layer (Table 1). Annual precipitation during the study ranged between 1188 and 1721 mm. Drainage ranged between 2.5 and 8.7% (30–150 mm) of precipitation, with the greatest drainage during the first year. Test pits excavated in the cover showed no signs of cracking or intrusion of roots in the barrier layer (Khire et al., 1994). Approximately 1 yr following construction, the effective field hydraulic conductivity of the barrier was estimated to be 3.2×10^{-6} cm s^{-1} using the drainage rate measured during periods of steady flow.

Semiarid Locations

Dwyer (2003) monitored a clay barrier cover (Table 1) for 5 yr in semiarid Albuquerque, NM, using a 13- by 100-m drainage lysimeter. The cover consisted of 45 cm of fine-grained soil overlain by a 15-cm-thick surface layer. The first year produced the greatest amount of drainage (3.6 mm, 1.3% of precipitation). Drainage was <1% of precipitation throughout the rest of the monitoring period, with no drainage recorded during 2 yr. While a shallow test pit excavated 5 yr after construction revealed cracks in the top of the barrier layer, the depth of the cracks was not investigated (Dwyer, 2003), and the absence of measurable drainage during the last 2 yr of the study suggests that the cracks had no immediate effect on the cover performance. Annual precipitation during the 5-yr monitoring period did not exceed the long-term annual average by more than a factor of 1.4.

Khire et al. (1997) tested a clay barrier cover for 3 yr in East Wenatchee, WA (Table 1) using an 18.3- by 12.2-m drainage lysimeter. Time-domain reflectometry (TDR) probes were used to monitor the distribution of water content within the cover. The cover consisted of a 60-cm-thick barrier layer overlain by a 15-cm-thick surface layer. Annual precipitation during the 3 yr ranged from 140 to 260 mm. During the first winter, 7.5 mm of drainage (3.0% of precipitation) was transmitted after the TDR data indicated that the wetting front reached the bottom of the cover. More drainage (22 mm, 8.5% of precipitation) was recorded during the third winter. In addition, the TDR data showed that drainage occurred before the wetting front reached the base of the cover, which indicates that preferential flow occurred. Test pits excavated in the barrier revealed vertical desiccation cracks probably responsible for the increase in drainage rate and preferential flow (Khire et al., 1994).

MATERIALS AND METHODS

Site Descriptions

The test facilities for this study were constructed near Albany, GA (March 2000), Cedar Rapids, IA (October 2000), and Apple Valley, CA (April 2002) to evaluate the field hydrology of compacted clay landfill covers across a range of climates (Albright et al., 2004). Albany receives the most precipitation on average (1263 mm yr^{-1}), followed by Cedar Rapids (915 mm yr^{-1}), and Apple Valley (119 mm yr^{-1}) (Table 2). The average monthly rainfall at Albany ranges from 58 to 151 mm, and is >100 mm for the months of January to March and June to August. Cedar Rapids receives 70% of its precipitation between April and September, and is the only site where significant snowfall (715 mm average) is recorded. Apple Valley is dry with only 1 mo (January) receiving at least 25 mm of precipitation on average. Based on the climate definitions described in UNESCO (1979), which is based on the ratio of precipitation (P) to potential evapotranspiration (PET), Albany and Cedar Rapids are humid climates (P/PET > 0.75) and Apple Valley is an arid climate ($0.03 < P$/PET ≤ 0.2). Subfreezing temperatures occur at all three sites, but only at Cedar Rapids do they persist long enough to cause freezing of the soil below the immediate surface.

Table 2. Climate characteristics of the study sites.

Site	Highest monthly avg. max.		Lowest monthly avg. min.		Annual avg.		Annual avg. precipitation/PET†
	Temp.	Precipitation	Temp.	Precipitation	Temp.	Precipitation	
	°C	mm	°C	mm	°C	mm	mm/mm
Albany, GA	33 (July)	151 (July)	8 (Dec.)	58 (Oct.)	19	1263	1.10
Cedar Rapids, IA	23 (July)	112 (June)	−8 (Jan.)	25 (Jan.)	9	915	1.03
Apple Valley, CA	37 (July)	26 (Feb.)	−1 (Jan.)	1.3 (June)	16	119	0.06

† PET = potential evapotranspiration.

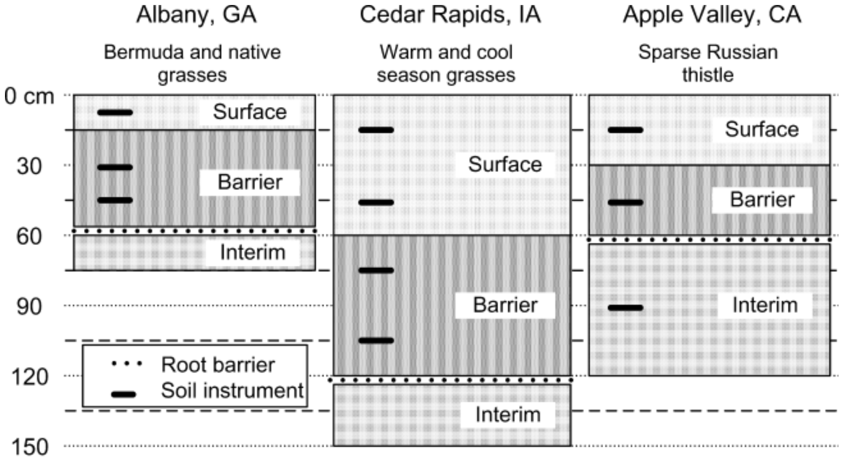

Fig. 1. Cover profiles, vegetation, and locations at which instruments were placed in test sections. Surface grade was 5% at all sites.

Cover Designs

The cover design evaluated at each of the three sites consisted of a compacted clay barrier layer overlain by a surface soil layer. Schematics of the cover profiles are shown in Fig. 1. Each cover profile is consistent with or exceeds the minimum requirements stipulated in the U.S. Resource Conservation and Recovery Act for unlined containment facilities and facilities lined with a compacted clay liner (USEPA, 1993, Ch. 6). In each case, the clay barrier had a saturated hydraulic conductivity $\leq 1 \times 10^{-7}$ cm s^{-1}. The thickness of the clay barrier layer differed from site to site (45 cm at Albany, 60 cm at Cedar Rapids, 30 cm at Apple Valley), as did the thickness of the surface layer (15 cm at Albany, 60 cm at Cedar Rapids, and 30 cm at Apple Valley), depending on local regulatory requirements. At all three sites, the barrier layers were underlain by an additional layer of soil (15 cm at Albany, 30 cm at Cedar Rapids, and 60 cm at Apple Valley) to simulate the existing interim cover at the site. At all three sites, the soils for the interim and surface layers were from the same borrow source. The slope was 5% at all sites.

The test sections were constructed with methods, procedures, and equipment representative of full-scale final cover construction. The clay barrier layers were placed in 15-cm-thick lifts and compacted with padfoot (Albany) and tamping foot (Cedar Rapids) compactors or dump trucks loaded with soil (Apple Valley) as was planned for full-scale construction at each site. Each lift of barrier soil was compacted using a water content–density criterion (Daniel and Benson, 1990) to achieve the target saturated hydraulic conductivity ($<1 \times 10^{-7}$ cm s^{-1}). Methods described by Daniel and Benson (1990) were used to define the acceptable zones. A nuclear density gauge was used to determine the dry unit weight and gravimetric water content at four locations in each lift within the perimeter of the lysimeter following methods described in ASTM (2005).

The surface layers were placed either in a single lift (Apple Valley and Albany) or two lifts (Cedar Rapids) at a dry unit weight of approximately 85 to 90% of standard Proctor maximum dry unit weight. The sites in Albany and Cedar Rapids were seeded with local grasses shortly after construction. Seeding was not conducted at the Apple Valley site, although sparse vegetation consistent with local surroundings (primarily Russian thistle) did become established during the monitoring period. The natural precipitation at Albany was occasionally supplemented with irrigation to maintain the vegetative cover.

Instrumentation

Large (10- by 20-m) instrumented pan-type lysimeters (Fig. 2) constructed with 1.5-mm linear low-density polyethylene geomembrane were used for direct measurement of the water balance of each test section (Benson et al., 2001; Albright et al., 2004). A geocomposite drainage layer consisting of a geonet sandwiched between two nonwoven geotextiles was placed between the lysimeter geomembrane and the interim cover soil to convey drainage from the soil profile to the measurement system and to protect the geomembrane during placement of cover soils. Surface berms were used to delineate

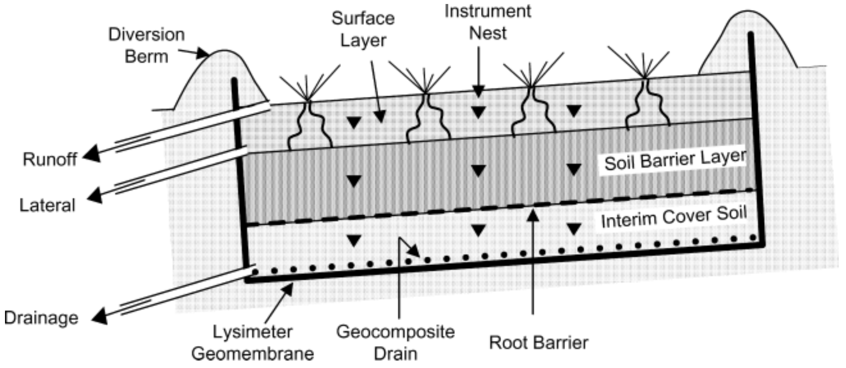

Fig. 2. Schematic of drainage lysimeter. Each test section included an identical soil profile 3 m outside the lysimeter to reduce boundary effects. Termination of the lysimeter side walls within the surface berms eliminated the possibility that a preferential flow path at the geomembrane–soil interface could extend to the surface. Lateral flow was not collected from the test section at Albany, GA.

the test sections, to prevent surface water run-on, and to collect surface water runoff for measurement.

To reduce the formation of preferential flow paths between the cover soil and the vertical membrane forming the sides of the lysimeter, the lysimeter side walls were terminated within the surface berms and the interface between each soil lift and the membrane was sealed with bentonite and compacted by hand with a jumping-jack compactor. Lateral flow over the clay barrier layer was also collected at the lower end of the lysimeter (lateral flow was not collected at Albany). Polyvinyl chloride pipes conveyed drainage, lateral flow, and surface runoff from collection points at the center of the low end of the lysimeters to measurement basins equipped with a dosing siphon (a self-priming siphon activated by addition of a known quantity of water) (Benson et al., 2001) equipped with a float switch and a pressure transducer. The entrances of all pipes were screened to prevent clogging and were inspected periodically to ensure that no blockage existed. For the drainage system, the basin was also equipped with a tipping bucket gauge. The collection systems permit resolution of lateral flow and runoff to better than 1 mm yr^{-1} and drainage to $<$0.1 mm yr^{-1} (Benson et al., 2001).

Volumetric soil water content was monitored with water content reflectometers (WCR) (Model 615, Campbell Scientific, Logan, UT) installed in three nests located at the quarter points along the center line of the lysimeters (Fig. 2). Each nest consisted of three to four probes located at multiple depths (Fig. 1). Soil water storage was determined by integrating the average (of the three nests) point measurements of volumetric water content throughout the soil depth represented by individual probes. Five-point calibration curves were used for the WCRs and soil-specific temperature corrections were applied (Kim and Benson, 2002). The WCRs were not calibrated to report frozen water content. Thus, when subfreezing temperatures were encountered, the volumetric water content reported by the WCRs was set to the volumetric water content recorded immediately before freezing occurred.

Methods used to install the lysimeters were described in Benson et al. (1999b) and details specific to the installation at the three sites were described in Bolen et al. (2001). The cover profiles constructed within the lysimeters were also placed in a 3-m-wide buffer area around the perimeter of the lysimeter to reduce boundary effects and to provide an area for sampling of soil.

The interface between the cover soils and the geocomposite drainage layer at the base of the lysimeters forms a capillary break that can affect the amount of measured drainage. The capillary break limits drainage into the lysimeter until soil at the soil–drainage layer interface is nearly saturated. Drainage occurred early in the monitoring periods at Albany and Cedar Rapids, suggesting that the capillary break effect at those sites was negligible. The root barrier (Biobarrier, Reemay, Old Hickory, TN) between the interim cover soil and the overlying layers (a porous, nonwoven geotextile studded with nodules containing trifluralin [2,6-dinitro-*N,N*-dipropyl-4-(trifluoromethyl)benzenamine], a root inhibitor) also prevented roots from accessing water in the interim soil adjacent to the drainage layer without affecting the movement of water. Thus, the soil at the bottom of the profile remained wet, minimizing the capillary barrier effect. Moreover, a capillary break normally exists at the interface between the interim cover soil and waste in a solid waste landfill because solid waste has low air-entry suction (~0.1 kPa) and desaturates readily at suctions exceeding the air-entry suction (Benson and Wang, 1998). Further discussion of the importance of the capillary break effect and details of lysimeter design to minimize those effects can be found in Albright et al. (2004).

Measurements of precipitation, temperature, relative humidity, solar radiation, and wind speed and direction were made with a weather station located adjacent to each test section. Precipitation gauges were 2 m above the ground and were fitted with snow adapters where appropriate. No estimates of sublimation were made. All data were collected and recorded by a datalogger every 15 min and were normally stored at 1-h intervals. The exception was during periods of heavy precipitation, when the sampling and recording was conducted at intervals as short as 0.25 min. Periods of missing meteorological data from the Apple Valley and Cedar Rapids sites were replaced with data from nearby U.S. National Oceanographic and Atmospheric Administration (NOAA) stations.

Soil Characterization

Soils used during construction of the test sections were tested to determine the particle size distribution (D 422, ASTM, 2005), Atterberg limits (D 4318, ASTM, 2005), and compaction behavior (D 698, ASTM, 2005) by testing four disturbed samples (20-L buckets) collected from each lift. A summary of these index properties is given in Table 3. Saturated hydraulic conductivity of each clay barrier layer was determined by testing samples collected in thin-wall (75-mm-diameter) sampling tubes and as hand-carved blocks (200-mm diameter and length) in flexible-wall permeameters using ASTM D 5084 (ASTM, 2005). The hydraulic gradient was set at 10 and the effective stress was set at 15 kPa for the hydraulic conductivity tests. Results of the hydraulic conductivity tests are summarized in Table 3.

RESULTS AND DISCUSSION

Water balance quantities (precipitation, drainage, surface runoff, soil water storage, soil volumetric water content, and lateral flow where measured) for the three sites are shown graphically in Fig. 3 through 5 and are summarized in Table 4. Figure 3 also includes soil temperature for the cover at Cedar Rapids to illustrate periods when frozen soil occurred. Precipitation and drainage for each site are shown for individual days and as cumulative quantities. Data for complete years are reported from 1 July through 30 June in Table 4. The long-term annual average precipitation for each site, obtained from nearby NOAA stations, is also given in Table 2.

Albany, Georgia

Monitoring data were collected at the Albany site from 19 Apr. 2000 to 31 July 2002 (Fig. 3; Table 4). The annual on-site precipitation for the two complete years of monitoring (1 July 2000–30 June 2002) was 909 mm (2000/2001) and 763 mm (2001/2002) (81 and 105% of that recorded at the nearby NOAA station), both of which are less (89 and 60%) than the 1273-mm long-term average annual precipitation. Precipitation events were frequent through the monitoring period and showed little seasonality (Fig. 3a). The precipitation reported in Table 4 for 2001/2002 includes supplemental irrigation, which brought the total applied water (precipitation plus irrigation) during the second complete year to 996 mm (79% of the long-term average). The cover at Albany transmitted 609 mm of drainage

(24% of applied water) during the monitoring period (Table 4, Fig. 3b). Surface runoff was 223 mm, or 9.4% of applied water. Lateral flow was not collected. Subfreezing temperatures were not recorded in the soil at Albany and thus temperature data are not included in Fig. 3.

A noticeable change in response of drainage to precipitation occurred ~8 mo following construction of the test section (Fig. 3b). A 7-wk drought (23 Sept.–15 Nov. 2000) resulted in a decrease in soil water storage to the lowest recorded level in all soil layers since construction (Fig. 3c). Early in November, desiccation cracks were observed in the surface of the test section (Albright and Benson, 2003). When precipitation resumed in mid-November, drainage increased from 8.9% (44 mm) of applied water before the drought to 29.5% (564 mm) of applied water after the drought. Surface runoff (Fig. 3d) increased slightly from 8.1% (40 mm) of applied water before the drought to 9.9% (190 mm) of applied water after the drought.

The temporal response of drainage to precipitation changed as well. In the summer of 2000, before the drought, a fairly constant drainage rate showed only moderate response to precipitation events (Fig. 6). Precipitation events the following summer (after the drought) resulted in large increases in the drainage rate, often within 1 h, which returned to near-zero following a few days without precipitation. The increased drainage rate and temporal response of drainage to precipitation suggest preferential flow paths developed in the cover as a result of the drought in the fall of 2000. Water storage at all depths in the cover soils fluctuated with infiltration from the frequent precipitation events, which resulted in the barrier layer being subjected to several wet–dry cycles. Periods of relatively low precipitation (for example, October–November 2000, April 2001, and November 2001) corresponded to reduced volumetric water contents at all depths, probably due to evaporation and root water uptake.

Cedar Rapids, Iowa

Monitoring data were collected at the Cedar Rapids site for 4 yr (3 Oct. 2000–4 Oct. 2004) (Fig. 4; Table 4). All data from the site were lost from 16 Oct. 2001 through 4 May 2002. In addition, on-site precipitation data were lost from 1 Oct. 2003 through 30 Apr. 2004. Daily precipitation records from the nearby NOAA station were substituted for the missing precipitation data. For the 3 yr beginning 1 July 2001, precipitation at the NOAA station was 789, 975, and 1025 mm, compared with the long-term annual average of 925 mm. During the 2002/2003 yr (the only complete year when precipitation data were collected at the study site), the on-site precipitation was 80% of that recorded at the NOAA station.

The cover at Cedar Rapids transmitted 287 mm of drainage, or 8.8% of precipitation during monitoring (the period with drainage data) (Table 4). Surface runoff was 123 mm (4.0% of precipitation) and lateral flow

Table 3. Alternative Cover Assessment Program test section soil properties.

										Compaction			
			Atterberg limits‡		Particle size distribution§					Standard Proctor		During construction	
Site	Layer	K_s†	LL	PI	Clay	Silt	Sand	Gravel	Soil type¶	Optimum water content	Max. dry density#	Water content	Dry density#
		cm s^{-1}			%					%	Mg/m^3	%	Mg/m^3
Albany, GA	Barrier	4.0×10^{-8} (1.4×10^{-8}–1.1×10^{-7})	28	14	24	5	63	8	SC (sandy clay loam)	15.6	1.85 (18.1)	15.8	1.71 (16.8)
	Surface	2.1×10^{-5} (3.5×10^{-6}–1.3×10^{-4})	26	12	19	3	74	4	SC (sandy loam)	13.9	1.90 (18.6)	15.6	1.71 (16.8)
	Interim	3.1×10^{-7} (2.5×10^{-7}–3.8×10^{-7})	28	13	31	4	61	4	SC (sandy clay loam)	14.6	1.87 (18.3)	19.3	1.69 (16.6)
Cedar Rapids, IA	Barrier	1.6×10^{-8} (5.1×10^{-9}–5.1×10^{-8})	34	20	22	23	52	3	CL (sandy clay loam)	12.3	1.95 (19.1)	14–16	2.02 (≥ 19.8)
	Surface	2.1×10^{-6} (1.8×10^{-7}–9.4×10^{-6})	53	18	28	48	23	1	CH (clay loam)	31.1	1.34 (13.1)	34.6	1.20 (11.8)
	Interim	2.2×10^{-7} (2.7×10^{-8}–1.0×10^{-5})	31	17	18	17	56	9	SC (sandy loam)	10.2	2.00 (19.6)	14.7	1.77 (17.4)
Apple Valley, CA	Barrier	1.7×10^{-8} (2.7×10^{-9}–1.5×10^{-7})	29	10	27	66	5	2	CL (silty clay)	12.5	1.97 (19.3)	NA	NA
	Surface††	1.1×10^{-5}	NA	NA	3	7	42	48	SM (silty sand)	9.9	2.10 (20.65)	NA	NA
	Interim††	2.0×10^{-6}											

† Saturated hydraulic conductivity; values are the geometric mean of samples measured in the laboratory using Method D 5084 (ASTM, 2005) on undisturbed samples collected during construction.

‡ LL = liquid limit, PI = plasticity index.

§ Particle size ranges are the USDA classification: clay (<0.002 mm), silt (0.002–0.05 mm), sand (0.05–2.0 mm), and gravel (>2.0 mm).

¶ SC = clayey sand, CL = low to medium plasticity clay.

Numbers in parentheses are dry unit weight in kN/m^3.

†† Soil classification and compaction behavior for the surface and interim layers at Apple Valley were based on a single sample, NA = not available.

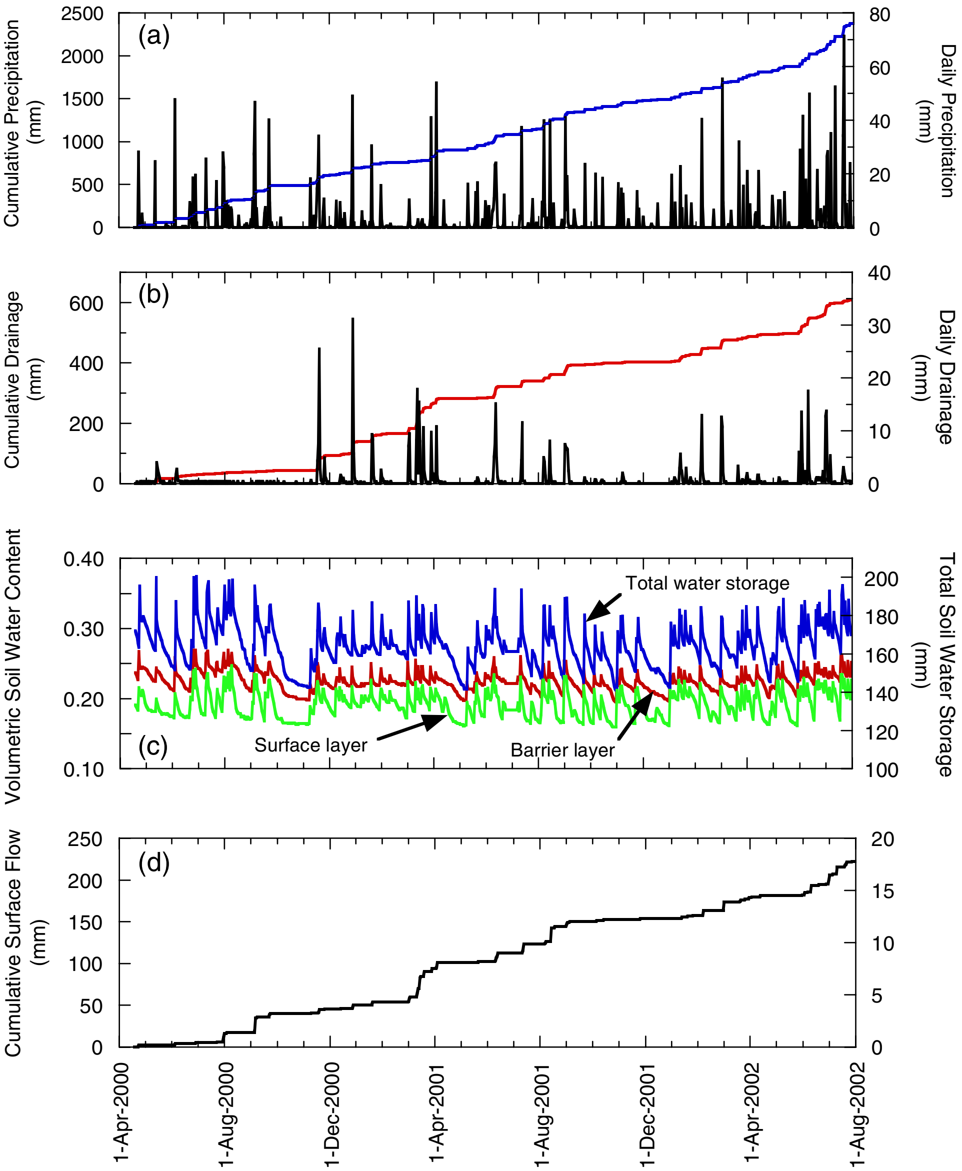

Fig. 3. (a) Precipitation, (b) drainage, (c) volumetric soil water content, and (d) surface flow data from the test section at Albany, GA.

(transmitted through the soil directly above the compacted clay barrier) was 117 mm (3.6% of precipitation). Performance of the cover during the first year following construction was marked by low drainage (3.1 mm) and little temporal sensitivity to precipitation events (Fig. 4a and 4b). This early period (3 Oct. 2000–18 Oct. 2001), and the following 6.5-mo gap in the data, preceded a period (4 May 2002–4 Oct. 2004) characterized by higher drainage rates and increased temporal response to precipitation events (Fig. 4a and 4b).

Less than 1% of precipitation passed through the cover as drainage during the early period. During the later period, 2498 mm of precipitation was received (Fig. 4a), of which 11% (283 mm) was transmitted as drainage (Fig. 4b). Precipitation events in the later period also were often accompanied by a rapid increase in drainage rate (Fig. 4b), a pattern indicative of preferential flow, whereas the early period was characterized by a relatively steady drainage rate that is consistent with matrix flow. Annual surface runoff ranged from 15 to 43 mm and increased from 2.0% of precipitation during the early period to 4.3% later. Annual lateral flow ranged from 0.3 to 88 mm and increased from <1% of precipitation during the early period to 4.7% after. Reasons for the changes in surface runoff and lateral flow are not clear.

Soil water content and soil temperature data show that conditions were present in the cover soils that can result in the development of preferential flow paths in the barrier layer. Although subfreezing temperatures were not recorded in the barrier layer, the overlying soils did freeze during the winters to a depth of at least 45 cm (i.e., 15 cm above the barrier layer, see Fig. 1 for location of temperature probes), as shown in Fig. 4d. During freezing, water is drawn to the freezing zone from underlying soils, which results in desiccation of the soil below. Benson and Othman (1993) indicated that desiccation can occur to a depth of ~30 cm below the

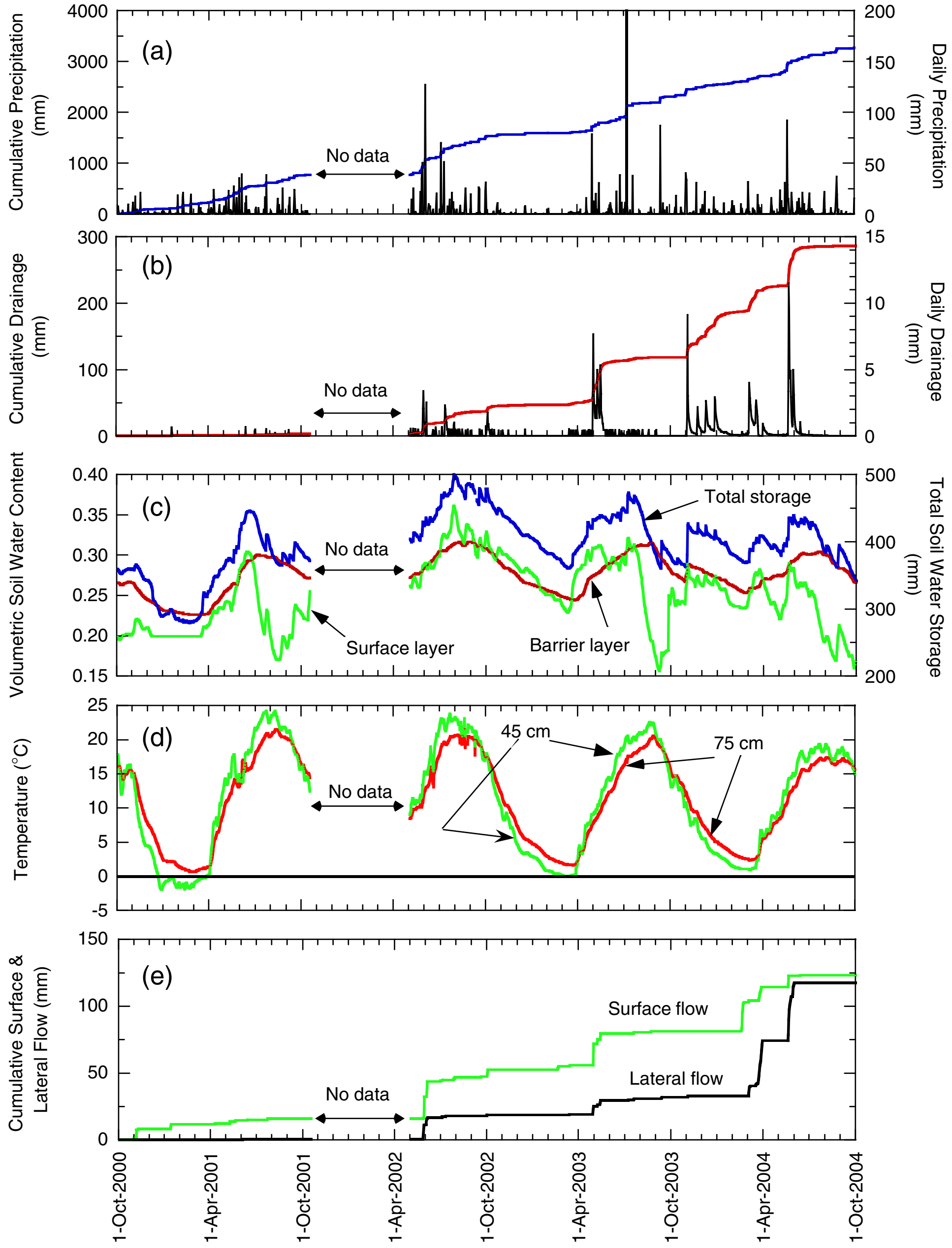

Fig. 4. (a) Precipitation, (b) drainage, (c) volumetric soil water content, (d) soil temperature, and (e) surface and lateral flow data from the test section at Cedar Rapids, IA. The indicated depths of the temperature data are the bottom of the surface soil layer (45 cm) and the top of the soil barrier layer (75 cm).

frost depth and result in severe cracking and large increases in hydraulic conductivity in the unfrozen soil. Thus, freezing conditions at Cedar Rapids may have caused desiccation and cracking of the barrier layer even though the clay barrier was below the maximum frost depth recorded during the monitoring period.

Most of the drainage during the first 2 yr (through early October 2002) occurred at a relatively uniform rate when the volumetric water content of the clay barrier was >0.29 (saturated volumetric water content of the clay barrier measured in the laboratory ranged between 0.29 and 0.31) regardless of the volumetric water content of the surface layer, which fluctuated between 0.17 and 0.30 (Fig. 4b and 4c). This steady flow suggests that the barrier was intact and that flow was through the soil matrix and not through preferential flow paths for the period up to October 2002. In contrast, most of the drainage during the remainder of the monitoring period was more closely associated with individual precipitation and snowmelt events, and less dependent on water content of the clay layer (Fig. 4a–4c). For example, in the spring of 2003 and 2004 and in late fall 2003, high rates of drainage occurred in response to heavy precipitation events. Similarly, during snow melt events in February and March 2004 (illustrated by abrupt increases in surface runoff and lateral flow), sharp increases in drainage rate occurred. Moreover, during each of these periods, the volumetric

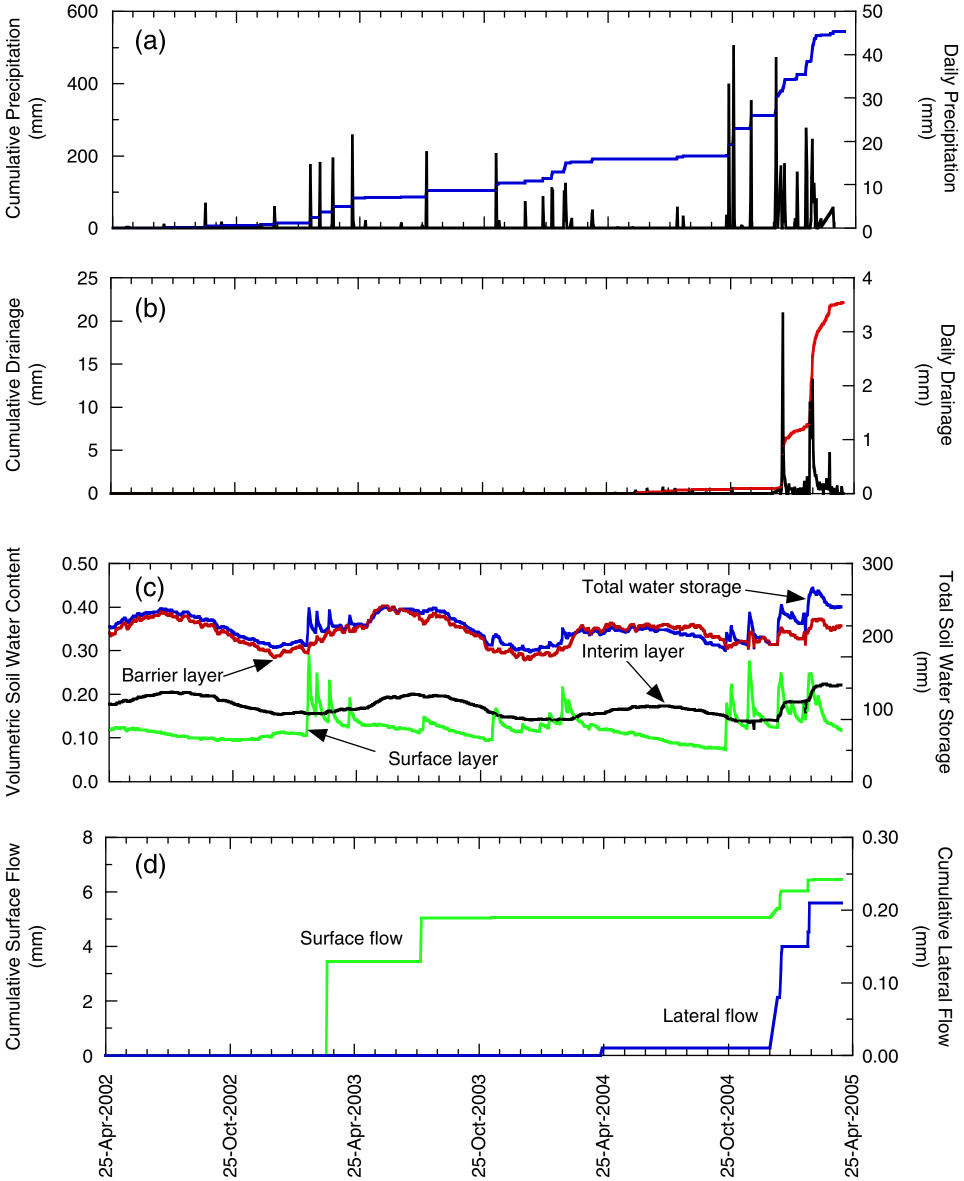

Fig. 5. (a) Precipitation, (b) drainage, (c) volumetric soil water content, and (d) surface flow and lateral flow data from the test section at Apple Valley, CA.

water content of the clay barrier was <0.29, and in some cases was near the lowest value of year (Fig. 4c). The occurrence of drainage soon after these precipitation or snowmelt events, and when the water content of the barrier layer was relatively low, suggests that preferential flow was occurring.

Drainage was muted at times by storage in the surface layer. For example, during the final summer (2004), the drainage rate was near zero when the clay layer was at the annual peak volumetric water content (0.28–0.30), but the volumetric water content of the surface layer soil was low (0.16–0.25) (Fig. 4b and 4c). There was probably sufficient water storage capacity in the relatively dry surface layer to store summer infiltration, thereby limiting water transmitted to the barrier layer. The large precipitation events of early July 2003, for example, resulted in significant, but short-term, increases in the water content of the surface soil layer, but had little effect on drainage or the water content of the clay layer.

Apple Valley, California

Monitoring data were collected at the Apple Valley, CA, site for three full years (25 Apr. 2002–9 Apr. 2005) (Fig. 5; Table 4). Much of the precipitation record is from the NOAA station at Victorville, CA (15 km from the field site) due to frequent failure of the precipitation gauge at the site. Annual precipitation totals for the three full monitoring years were 61, 132, and 251% (86, 106, and 351 mm) of the long-term annual average of 140 mm yr^{-1}. Precipitation at Apple Valley was seasonal and, with the exception of a few summer thunderstorms, most rain events were recorded during winter and early spring (Fig. 5a). A large storm in late October 2004 initiated an unusually wet season,

Table 4. Summary of water balance data from the three test sections. Drainage as a percentage of precipitation is given in parentheses.

Site	Monitoring period	Precipitation	Surface runoff	Lateral flow	Drainage
		mm			
Albany, GA	**19 Apr.–30 June 2000**	**173**	**5.0**	**Not measured**	**30 (17)**
	1 July 2000–30 June 2001	**909**	**108**		**292 (32)**
	1 July 2001–30 June 2002	**996†**	**83**		**238 (24)**
	1–31 July 2002	**298**	**27**		**49 (16)**
	Total	**2376**	**223**		**609 (26)**
Cedar Rapids, IA	**3 Oct. 2000–30 June 2001**	**534**	**15**	**0.3**	**1.4 (<1)**
	1 July 2001–30 June 2002	**581‡**	**29§**	**16§**	**19§ (3.3)**
	1 July 2002–30 June 2003	**784**	**36**	**13**	**94 (12)**
	1 July 2003–30 June 2004	**1182‡**	**43**	**88**	**171 (14)**
	1 July–4 Oct. 2004	**181**	**0.0**	**0.0**	**1.3 (<1)**
	Total	**3262**	**123**	**117**	**287 (8.8)**
Apple Valley, CA	**25 Apr.–30 June 2002**	**0.5¶**	**0.0**	**0.0**	**0.0 (0.0)**
	1 July 2002–30 June 2003	**86¶**	**3.4**	**0.0**	**0.0 (0.0)**
	1 July 2003–30 June 2004	**106¶**	**1.6**	**0.0**	**0.2 (<1)**
	1 July 2004–9 Apr. 2005	**351¶**	**1.4**	**0.2**	**22 (6.3)**
	Total	**544¶**	**6.4**	**0.2**	**22.2 (4.1)**

† At Albany, the precipitation total during the 2001/2002 yr includes 231 mm of supplemental irrigation.
‡ Precipitation data for Cedar Rapids for 2001/2002 and 2003/2004 are partially from a NOAA station 25 km from the site.
§ All data were lost at Cedar Rapids between 16 Oct. 2001 and 4 Apr. 2002.
¶ Most of the precipitation data at Apple Valley are from the nearby NOAA station at Victorville, CA (15 km from the site).

during which 344 mm of precipitation (2.5 times the average annual) was received during 5 mo.

The cover at Apple Valley transmitted 22 mm of drainage (4.1% of precipitation). Surface runoff was 6.4 mm (1.2% of precipitation) and a trace amount (0.2 mm) of lateral flow was recorded. No drainage was transmitted for the first 20 mo of monitoring; nearly all of the drainage occurred during the first 3 mo of 2005 (Fig. 5b).

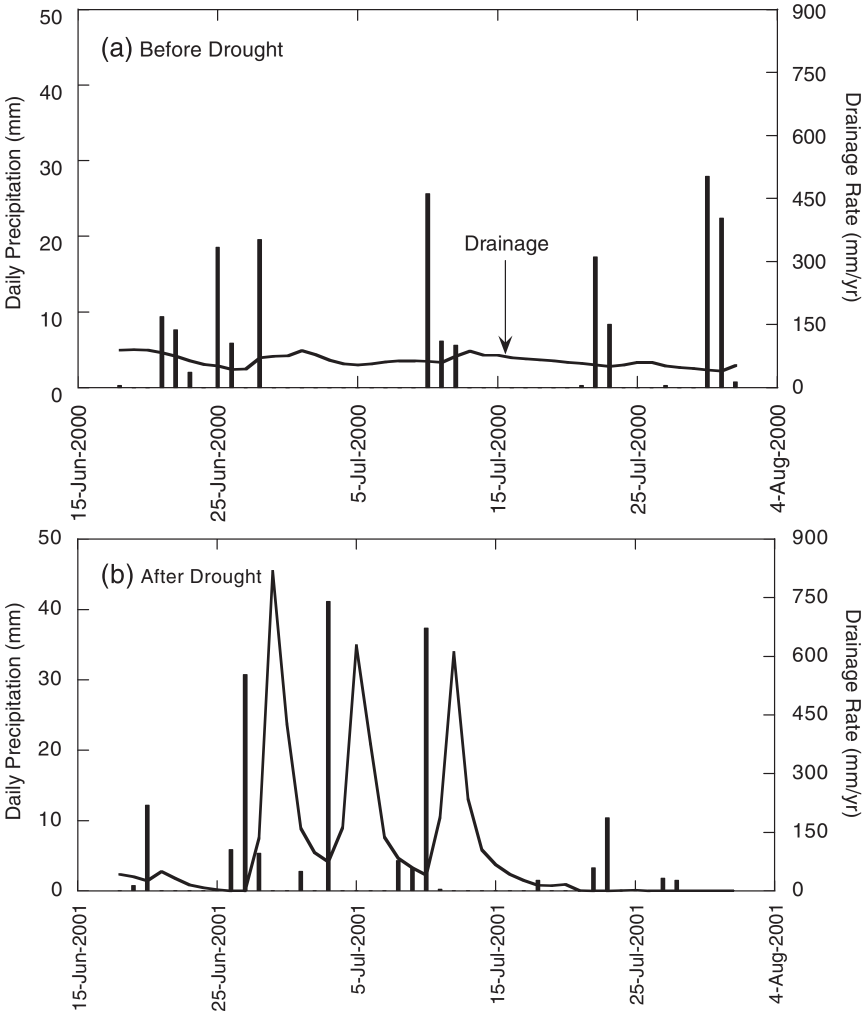

Fig. 6. Daily precipitation and resulting drainage rate for periods (a) before and after (b) the fall 2000 drought at Albany, GA. Daily precipitation is shown as vertical bars, drainage rate as a continuous line.

Water content of the barrier layer fluctuated between 0.30 and 0.40 and was higher than that of the coarser soils used for the interim and surface layers throughout the monitoring period (Fig. 5c). This was due to the relatively high compaction water content during construction (Table 3), the ability of the fine-grained soil to retain water, and the presence of capillary breaks afforded by the coarser textured soils placed above and below the barrier layer. The barrier layer went through three wet and dry cycles during the monitoring period. The water content of the surface layer responded quickly to precipitation events and generally dried during the warmer months; the deeper layers showed a more seasonal response with higher water content during late spring and diminishing through summer. A notable exception to this pattern was in response to heavy precipitation during the period December 2004 through February 2005, when the water content of all three layers increased and resulted in peaks in total water storage.

Most of the drainage in early 2005 occurred when the water content of the barrier layer was between 0.31 and 0.37, levels reached or exceeded during two of the previous 3 yr. The water content of the interim layer increased to the highest point during this period, but much of the drainage occurred before the peak water content in the interim layer. The absence of drainage during times of elevated water content of the barrier layer in prior years and the quick response of drainage to precipitation in early 2005 suggests that preferential flow paths developed in the cover in response to desiccation of the barrier layer.

Preferential Flow as a Function of Soil Water Content

Absence of a strong correlation between drainage rate and water content of a clay barrier is a good indication that preferential flow is occurring. Thus, the field data were analyzed to determine if the episodic drainage rates observed later in the monitoring period at each site were correlated to the water content of the barrier layer. The relation between daily drainage and barrier–soil water content measured the day before precipitation is shown in Fig. 7. Since preferential flow was more likely to occur as a result of larger precipitation events, only the drainage corresponding to larger (>10 mm) precipitation events were included in this analysis. An *F* test was performed to test significance of trend; results are shown in Fig. 7. For the Albany and Cedar Rapids sites, the drainage rate does not correlate well with the water content of the clay barrier at the start of a precipitation event. Figure 7b indicates a correlation between high (>1 mm d^{-1}) drainage rates and high (>0.34) barrier layer volumetric water content at Apple Valley; however, the 4 d with high drainage shown in Fig. 7b were in a span of 5 d in February, 2005, when water content was high in all layers of the cover due to several weeks of unusually high precipitation. Figure 4b shows that drainage for those days was closely linked in time with large precipitation events. This general lack of correspondence, and the "stair-step" pattern of drainage (Fig. 3b, 4b, and 5b), suggest that preferential flow was occurring at all three sites. The high rates of drainage even when the water content was high also suggests that preferential flow paths do not seal as the water content of a clay barrier increases.

Effective Field Hydraulic Conductivity

The effective field hydraulic conductivity (K_{ef}) was estimated to evaluate the as-built condition of the cover for comparison to the design specification (saturated hydraulic conductivity $K_s \leq 1 \times 10^{-7}$ cm s^{-1} at all three sites), to laboratory measurements of K_s made on intact samples collected during construction, and to evaluate changes to the cover throughout the monitoring period. The value of K_{ef} was calculated by dividing the drainage volume for a specified period by the area of the test section and the time period during which the drainage was recorded. Steady-state flow and a unit hydraulic gradient were assumed. These assumptions are simplistic, but the K_{ef} obtained in this manner provides an indication of the in-service hydraulic conductivity of the barrier layer. Specifically, in the absence of ponded conditions, the K_s must be $>10^{-7}$ cm s^{-1} if $K_{ef} > 10^{-7}$ cm s^{-1}. For the as-built (early-time) conditions, which were characterized by fairly steady drainage rates at Albany and Cedar Rapids (at Apple Valley there was no drainage for the first 20 mo), K_{ef} was calculated from steady flows recorded during periods of several weeks. For the later periods when drainage rates were highly variable at all three sites, K_{ef} was calculated for a single day. A summary of the K_{ef} is given in Table 5.

At Albany, for the 5-mo period before the drought when drainage was fairly constant, the total drainage (43.9 mm) divided by the elapsed time (150 d) resulted in a K_{ef} of 3.4×10^{-7} cm s^{-1}. This is a factor of 8.5 higher than the geometric mean saturated conductivity value from all undisturbed block samples taken during construction (4.0×10^{-8} cm s^{-1}) and 3.4 times higher than the design specification (1.0×10^{-7} cm s^{-1}) for the clay barrier layer. After the drought, K_{ef} was computed using the highest daily drainage rate (31.1 mm on 28 Dec. 2000), which corresponds to $K_{ef} = 3.6 \times 10^{-5}$ cm s^{-1}. This K_{ef} is more than two orders of magnitude higher than the design criterion, the as-built $K_{ef,}$ and the geometric mean hydraulic conductivity of the block samples.

The as-built K_{ef} of the cover at Cedar Rapids was evaluated for the period between 15 June and 16 Oct. 2001, when 1.7 mm of drainage was recorded with little variation in rate. The K_{ef} for that period was 1.7×10^{-8} cm s^{-1}, which is comparable to the geometric mean hydraulic conductivity (1.6×10^{-8} cm s^{-1}) of the nine specimens collected from the barrier layer during construction and lower by nearly an order of magnitude than the regulatory criterion (1.0×10^{-7} cm s^{-1}). Periods of increased drainage later in the monitoring period included a single day (22 May 2004) when 11.5 mm of drainage was recorded ($K_{ef} = 1.3 \times 10^{-5}$ cm s^{-1}). The K_{ef} during this period is 765 times higher than the as-built K_{ef}.

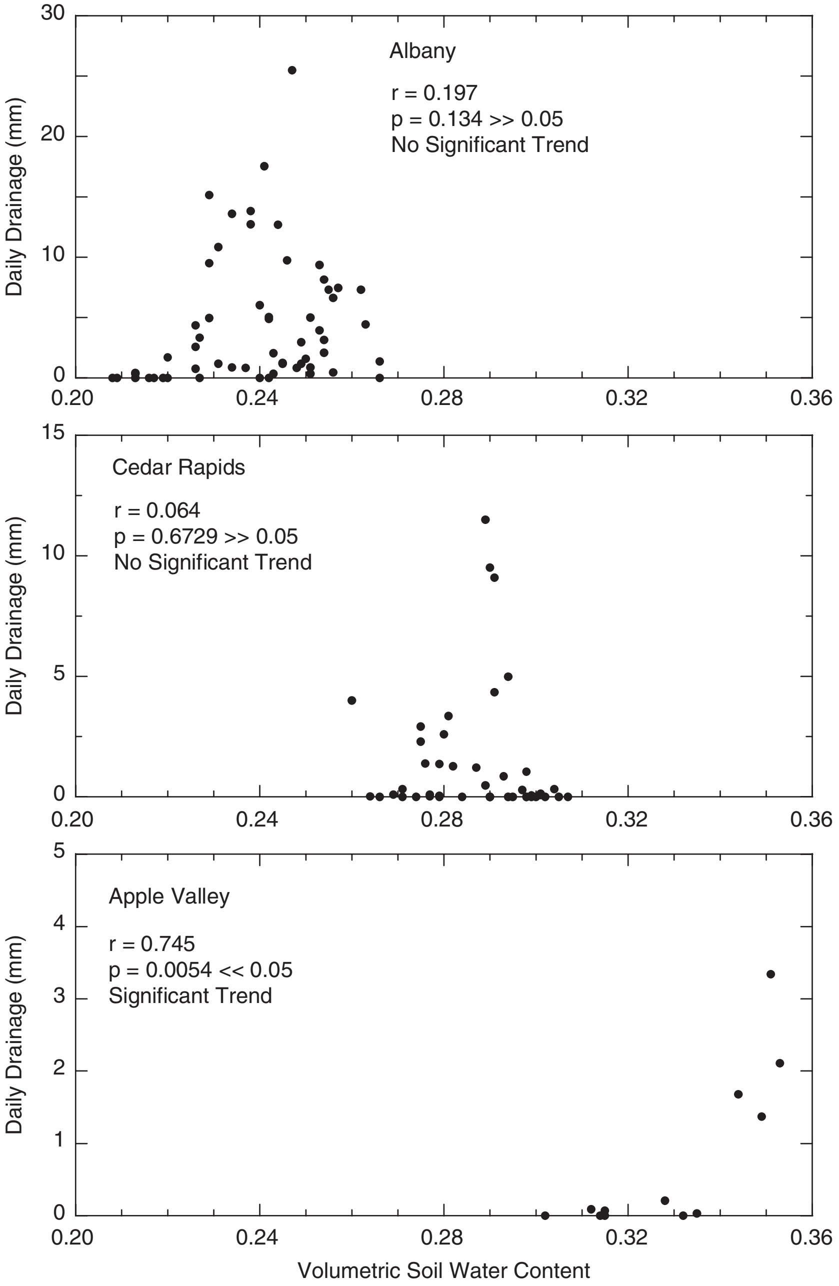

Fig. 7. Daily drainage as a function of the volumetric water content of the clay barrier for Albany, Cedar Rapids, and Apple Valley. Data are shown only for those days with >10 mm of precipitation. Water content data are from measurements made near the bottom of the clay barrier on the day before precipitation. Saturated volumetric water contents of the clay barrier layers were 0.31 (Albany), 0.30 (Cedar Rapids), and 0.39 (Apple Valley). An *F* test was used to evaluate the correlation between volumetric soil water content and daily drainage, and the resulting *P* values are shown in each graph. A trend is significant when $P < 0.05$.

The lack of recorded drainage at Apple Valley during the first 20 mo prevented calculation of K_{ef} for the as-built condition. Most of the drainage recorded at the site occurred during the first 3 mo of 2005, about 3 yr following construction. The highest 1-d drainage total was 3.34 mm (10 Jan. 2005), which corresponds to $K_{ef} = 3.9 \times 10^{-6}$ cm s^{-1}. This K_{ef} is 229 times higher than the geometric mean K_s of the eight undisturbed samples removed from the clay barrier layer during construction (1.7×10^{-8} cm s^{-1}) and 39 times higher than the design criterion (1.0×10^{-7} cm s^{-1}) for the cover.

These estimates of K_{ef} are consistent with the K_s of clay barriers reported by others (Table 1). For example, a test conducted by Albrecht and Benson (2001) on one of the clay barriers in Reedsburg, WI, showed that the K_s was 6.9×10^{-5} cm s^{-1} after 4 yr of service. Similarly, tests conducted by Benson and Wang (1998) on the clay barriers in the NCASI landfill cover test sections showed that K_s was between 8.1×10^{-7} and 7.0×10^{-6} cm s^{-1} after 8 yr of service. The reasonable correspondence between the K_{ef} computed in this study and the K_s measurements made by others suggests that large increases

Table 5. Summary of effective hydraulic conductivities (K_{ef}).

Site	K_{ef}		Ratio of K_{ef} from later period to other measures		
	Early period	Later period	K_{ef} in early period	As-built K_s† (laboratory)	Design standard
	cm s^{-1}				
Albany, GA	3.4×10^{-7}	3.6×10^{-5}	106	900	360
Cedar Rapids, IA	1.7×10^{-8}	1.3×10^{-5}	765	812	130
Apple Valley, CA	No drainage‡	3.9×10^{-6}	NA‡	229	39

† Saturated hydraulic conductivity.

‡ There was no drainage during the early period at Apple Valley, thus K_{ef} was not determined.

in the hydraulic conductivity of clay barriers with time are not uncommon.

Practical Implications

Performance of clay barrier covers is predicated on maintaining the low saturated hydraulic conductivity of the barrier layer during the design life of the waste containment facility. Under steady unit gradient conditions, an intact soil barrier at a K_s of 1×10^{-7} cm s^{-1} will transmit 32 mm of drainage per year. Consistently saturated conditions are unlikely in field applications, and in most cases a downward gradient will exist for only short periods (Khire et al., 1997). Thus, annual drainage should be $<$32 mm yr^{-1}. Annual drainage exceeding 32 mm has been recorded in 54% of the cases in this study and previous studies (Fig. 8). This suggests that the design objective probably is not being met for many clay barrier covers.

The use of clay barriers in arid and semiarid climates is often regarded as problematic due to the propensity of clay compacted wet of optimum to develop preferential flow paths through desiccation cracking (e.g., Dwyer, 2003). Annual drainage is shown in Fig. 8 as a function of annual precipitation for the sites evaluated in this study and in previous studies. Drainage rates exceeding 32 mm yr^{-1} occur only when the annual precipitation is $>$750 mm yr^{-1}. Thus, despite commonly held beliefs, the existing field data indicate that, on an annual basis, clay barrier covers perform reasonably well in drier locations. As an example, the clay barrier cover tested by Dwyer (2003) at Albuquerque, NM, transmitted $<$9 mm of total drainage during a 5-yr study and $<$1 mm yr^{-1} during the last 3 yr of monitoring. Similarly, Khire et al. (1997) reported an average drainage rate of 10.5 mm and a maximum annual drainage rate of 22 mm for their clay barrier cover in semiarid Wenatchee, WA. Thus, while cracking of clay barriers may occur in drier climates, the data to date do not support the often-held belief that this necessarily precludes reasonable average performance or that degraded performance (i.e., increased drainage) will rapidly follow; however, the drainage rate from clay barriers is discontinuous and closely linked in time and magnitude with precipitation, making annual drainage rates lower (sometimes much lower) than drainage rates during wetter periods. In some cases, the episodic high rates of drainage characteristic of clay barrier covers may be unacceptable even if the annual drainage rate is low. Additionally, the time scales to develop deep cracking may be longer in arid climates, where wetting and drying cycles are less frequent and may range across smaller magnitudes and depths.

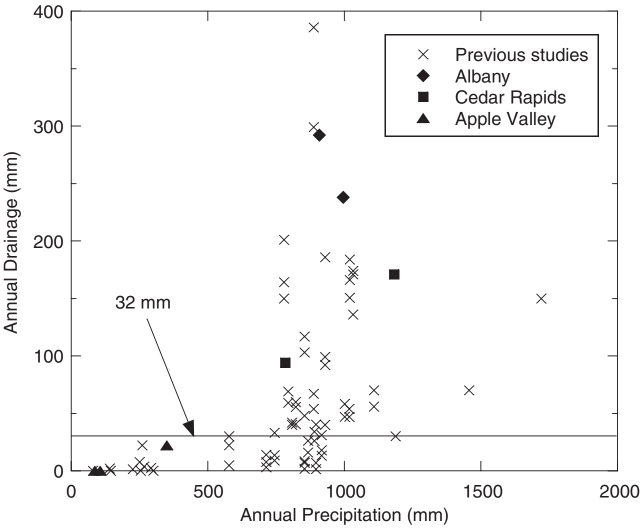

Fig. 8. Annual drainage as a function of annual precipitation for the three sites in this study as well as past studies described in the literature. The annual drainage from a soil with saturated hydraulic conductivity (K_s) = 1×10^{-7} cm s^{-1} at saturation and unit gradient conditions is 32 mm.

All three of the covers described here showed a trend of increasing drainage rate over 2 to 5 yr following construction. A similar trend is evident in 10 of the 15 covers evaluated in the past studies discussed above. Data from these sites indicate that detrimental changes to the barrier layer can occur in a time frame much less than the typical design life of waste containment facilities. Of the five covers from past studies that did not show increased drainage rates, one was a multilayered design in which two clay layers were separated by a sand layer (Montgomery and Parsons, 1990), two had very thick (107 cm) surface layers over the barrier layer (Abichou et al., 1998), one was in semiarid Albuquerque, NM, with relatively little precipitation (Dwyer, 2003), and one was constructed with a kaolinitic clay with low shrink–swell potential (Khire et al., 1997). Thus, some methods exist to protect clay barriers using all-earthen designs, although they have not been proven effective in a broad range of climates or during very long periods of time. An alternative is to cover the clay barrier with a geomembrane to form a composite barrier layer. Field data from Melchior (1997) and Albright et al. (2004) indicate that this strategy can be effective.

CONCLUSIONS

Data describing the water balance from three 10- by 20-m test sections simulating clay barrier landfill covers have been presented from sites in warm–humid, cool–humid, and warm–arid locations. The early performance at the warm–arid and cool–humid sites was consistent with the design criteria (drainage at saturated, unit gradient conditions and $K_s \leq 1 \times 10^{-7}$ cm s^{-1}); drainage at the warm–humid site early in the monitoring period exceeded the design criterion by a factor of 3.2. Drainage at all three sites increased significantly with time. The increase in drainage is attributed to weathering of the barrier layer in response to wet–dry or freeze–thaw cycling and biotic activity, which are known to result in cracks that can act as preferential flow paths and cause corresponding increases in hydraulic conductivity. Soil temperature and water content data collected from the test sections support this inference. Drainage at the warm–arid site was negligible until the final 3 mo of monitoring, when high drainage rates coincided with an exceptionally wet winter.

Calculations of effective field hydraulic conductivity near the end of the monitoring periods (3.6×10^{-5} cm s^{-1} at warm–humid Albany, 1.3×10^{-5} cm s^{-1} at cool–humid Cedar Rapids, and 3.9×10^{-6} cm s^{-1} at warm–arid Apple Valley) demonstrate that the hydraulic conductivity of the barrier layers increased by factors of at least 106 to 765 relative to the as-built hydraulic conductivity. At the two humid sites, the pattern of drainage changed within several months after construction from steady flow relatively independent of the timing of precipitation to variable and intermittent flows closely related to precipitation events and independent of the water content of the barrier layers. Drainage was negligible through the cover at the arid site for 21 mo following construction but increased with heavy precipitation in the last 5 mo of monitoring. Drainage at the arid site was also intermittent and closely related to the timing of precipitation events. These observations suggest that weathering processes affect the integrity of clay barrier covers during a relatively short period of time and that preferential flow can be expected within a relatively short service life.

Clay barrier covers are often recommended for closure of municipal landfills that are unlined or lined with clay. The intent is to provide a hydraulic barrier that limits drainage into the underlying waste so long as the waste poses a threat to groundwater. The field data presented here, along with other data from field and laboratory data in the literature, show that drainage rates from clay barrier covers can increase significantly within periods of time (several months to a few years) considerably shorter than the expected design life of modern waste containment facilities (often 30 yr). These findings cast considerable doubt on the effectiveness of clay barrier covers for long-term waste containment. Designers and regulators considering the use of clay barrier covers are encouraged to carefully assess whether the clay barrier will continue to function as intended during the design life, given the conditions to which the barrier will be exposed.

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