Field Hydrology of Landfill Final Covers with Composite Barrier Layers

William H. Albright[1]; Craig H. Benson[2]; and Preecha Apiwantragoon[3]

Abstract: A study was conducted at seven sites across the United States to evaluate the field hydrology of final covers with a composite barrier (a geomembrane over a soil barrier or a geosynthetic clay liner) for final closure of landfills. The water balance of each cover was monitored with a large (10×20 m) instrumented drainage lysimeter. With one exception, the covers limited the average annual percolation to < 2.8 mm/year ($< 0.4\%$ of precipitation). The geomembrane barrier at one site (Marina, California) was likely damaged during construction; percolation at this site averaged 30 mm/year (6.9% of precipitation). The annual percolation through the cover at the wettest site (Cedar Rapids, Iowa) ranged between 0.1 and 6.2 mm/year. The annual percolation at arid and semiarid sites was typically no more than a trace (< 0.1 mm/year). Percolation from all test covers generally was coincident with high water storage in the surface soil layer and lateral flow in the drainage layer on the surface of the geomembrane barrier. Water balance predictions were made with the hydrologic evaluation of landfill performance model using site-specific input. Surface runoff was overpredicted and evapotranspiration underpredicted when as-built soil hydraulic properties were used as input. Better agreement was obtained when in-service soil hydraulic properties were used as input. The lateral flow was consistently overpredicted regardless of the hydraulic properties, and no correspondence existed between the predicted and measured percolations. **DOI: 10.1061/(ASCE)GT.1943-5606.0000741.**

CE Database subject headings: Landfills; Geomembranes; Hydrology; Barriers.

Author keywords: Landfill; Final cover; Geomembrane; Hydrology; HELP model; Field scale.

Introduction

Regulations for closure of waste containment facilities in the United States commonly require a hydraulic barrier layer in the final cover to limit ingress of precipitation into underlying waste [U.S. Environmental Protection Agency (USEPA) 1992]. The type of barrier layer required in the cover generally depends on the type of liner beneath the waste. Many modern landfills are constructed with composite liners (a geomembrane over a low-conductivity soil layer). The corresponding conventional final cover profile includes, at a minimum, a layer of low-conductivity soil overlain by a geomembrane (a 1–2-mm-thick plastic sheet), and a vegetated surface layer at least 150-mm thick (USEPA 1992). The soil component of the composite barrier is required to have low saturated hydraulic conductivity ($\leq 1 \times 10^{-5}$ or $\leq 1 \times 10^{-7}$ cm/s, depending on the properties of the liner in the landfill). Covers meeting these requirements are herein referred to as composite barrier covers.

In many cases, a drainage layer is placed directly above the geomembrane. The surface layer also is typically much thicker than 150 mm. Although soils that do not classify as clay can be used for the barrier layer, the clay nomenclature is common in practice and, therefore, is used herein. A geosynthetic clay liner (thin factory manufactured hydraulic barrier consisting of 3.5–6.0 kg/m^2 of bentonite clay sandwiched between two geotextiles) is often substituted as the low-conductivity soil layer.

Despite the prevalence of composite barrier covers in current landfill practice, few studies report the hydrology at the field scale over an extended period. This paper describes the field-scale performance of composite barrier covers at seven locations across the United States with climates ranging from arid to humid. The evaluations were made using test sections that included large instrumented drainage lysimeters constructed as part of the USEPA alternative cover assessment program (ACAP) (Albright et al. 2004). Field data from these test sections are reported for monitoring periods ranging from 3 to 5 years. The hydrology of each test section was predicted with the hydrologic evaluation of landfill performance (HELP) model (Schroeder et al. 1994) using as-built soil hydraulic properties and in-service properties measured after the test sections were decommissioned. The predictions made with the HELP model are compared with the field data.

Previous Field Studies of Composite Landfill Cover Hydrology

Melchior et al. (2008) monitored three composite barrier covers for 17 years at a landfill near Hamburg, Germany, using 10×50-m drainage lysimeters. The composite barrier in each test section consisted of a 1.5-mm high-density polyethylene (HDPE) geomembrane overlying 600 mm of compacted glacial till. Each test section had a 750-mm-thick surface layer and 200 mm of drainage material below the composite barrier. The test sections differed in slope (5 and 20%) and method of installation of the geomembrane (welded or overlapped). The annual precipitation at the site ranged

[1]Research Hydrogeologist, Desert Research Institute, Nevada System of Higher Education, Reno, NV 89512 (corresponding author). E-mail: bill.albright@dri.edu

[2]Wisconsin Distinguished Professor and Director of Sustainability Research and Education, Office of Sustainability, Univ. of Wisconsin, Madison, WI 53706. E-mail: chbenson@wisc.edu

[3]Major and Assistant Professor, Dept. of Civil Engineering, Chulachomklao Royal Military Academy, Nakhon Nayok 26001, Thailand. E-mail: papiwan@yahoo.com

Note. This manuscript was submitted on January 17, 2012; approved on April 5, 2012; published online on April 11, 2012. Discussion period open until June 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Geotechnical and Geoenvironmental Engineering***, Vol. 139, No. 1, January 1, 2013. ©ASCE, ISSN 1090-0241/2013/1-1–12/$25.00.

J. Geotech. Geoenviron. Eng. 2013.139:1-12.

between 740 and 1,032 mm and the average annual percolation ranged from 1.3 to 3.7 mm/year (< 1% of precipitation). The test section with an overlapping geomembrane allowed approximately 2 mm/year more percolation than those with welded geomembranes.

Dwyer (2003) monitored two composite barrier covers for 6 years in semiarid Albuquerque, New Mexico, using 13 × 100-m drainage lysimeters. The covers differed only in the soil portion of the composite barrier; one used a geosynthetic clay liner (GCL), the other used a 600-mm-thick layer of native soil amended with 6% sodium bentonite and compacted to achieve a saturated hydraulic conductivity of $\leq 1 \times 10^{-7}$ cm/s. Both covers included a 1.0-mm-thick linear low-density polyethylene (LLDPE) geomembrane in the composite barrier that was overlain by a 300-mm-thick sand drainage layer and a 600-mm surface layer. During construction, eight 100-mm^2 holes were randomly placed into the LLDPE geomembrane in each test section. Percolation was < 2.5 mm (< 1% of precipitation) for each year throughout the monitoring period for both covers, with no percolation recorded during the final 2 years. Annual precipitation during the 6-year monitoring period ranged between 254 and 300 mm/year and did not exceed the long-term annual average by more than a factor of 1.4.

Site Descriptions

The seven test facilities in this study were constructed at the locations shown in Fig. 1 (Albright et al. 2004). The long-term average precipitation at these sites ranges from 119 mm/year at Apple Valley to 915 mm/year at Cedar Rapids (Table 1). The climate definitions, based on the ratio of precipitation (P) to potential evapotranspiration [United Nations Educational, Scientific and Cultural Organization (UNESCO) 1979], describe Cedar Rapids and Omaha as humid; Polson as subhumid; Altamont, Boardman, and Marina as semiarid; and Apple Valley as arid. Snowfall occurs at Cedar Rapids, Omaha, Polson, and Boardman. The seasonality of the precipitation varies between the sites, with most precipitation occurring during the winter months at Marina, Apple Valley, and Altamont and a more even distribution of precipitation at the other sites. Subfreezing temperatures have been recorded at all sites, which persisted long enough to cause freezing of the soil below the immediate surface only at Cedar Rapids, Omaha, Polson, and Boardman.

Cover Designs

A schematic of the cover profile at each site is shown in Fig. 2. Each site included a composite barrier overlain by a surface soil layer and underlain by an additional layer of soil to simulate the existing interim cover at the site. The test sections were constructed with methods, procedures, and equipment representative of the full-scale final cover construction anticipated at each site (Bolen et al. 2001). Either LLDPE or HDPE geomembranes (1.0- or 1.5-mm thick) were used, depending on the anticipated practice at the site (Table 1). The geomembranes were placed directly on top of the soil barrier. At Altamont, Boardman, Cedar Rapids, and Polson, a geocomposite drainage layer (GDL) consisting of a geonet heat bonded between two nonwoven geotextiles was placed between the geomembrane and the overlying soil to transmit lateral flow over the geomembrane. The GCLs, geomembranes, and GDLs were installed following the methods described in the manufacturer installation guides and ASTM D6102 (ASTM 2007b).

The soil barrier portion of the composite barrier consisted of compacted clay (Altamont, Cedar Rapids, Marina, Omaha, and Polson) or a GCL (Apple Valley and Boardman). The clay barriers were compacted within an acceptable zone of dry unit weight and water content selected to achieve a target saturated hydraulic conductivity required by local regulations (Table 1) following the methods described by Daniel and Benson (1990). The clay layers were either 305- or 460-mm thick (Table 1 and Fig. 2) and were placed in 150-mm-thick lifts compacted with padfoot or tamping foot compactors or dump trucks loaded with soil, as was planned for full-scale construction at each site. A nuclear density gauge was used to ensure the soil barrier was compacted within the acceptable zone.

Surface layers were constructed in 1–3 lifts and had a total thickness of 305–910 mm (Table 1 and Fig. 2), depending on local requirements. Surface layers were compacted to 80–90% of standard maximum dry unit weight (ASTM D698; ASTM 2007c) at the existing water content. All sites were seeded shortly after construction except Apple Valley, where sparse vegetation consistent with the surroundings was established naturally during the monitoring period.

Instrumentation

Each test section was 20 × 30 m and contained a large (10 × 20-m) instrumented pantype lysimeter (Fig. 3) constructed with a 1.5-mm LLDPE geomembrane for direct measurement of percolation through the cover (Benson et al. 2001; Albright et al. 2004). A GDL was placed directly on the lysimeter geomembrane for rapid transmission of percolation from the soil profile to the measurement system. The GDL also protected the geomembrane during placement of the overlying cover soils. The sidewalls of the lysimeter extended to the surface. The geomembrane portion of the composite

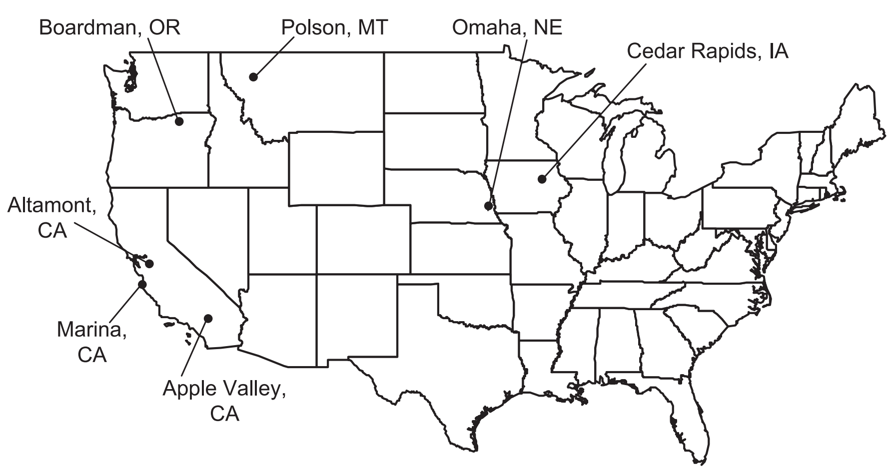

Fig. 1. Locations of ACAP field sites where composite covers were tested

J. Geotech. Geoenviron. Eng. 2013.139:1-12.

Table 1. Precipitation, Barrier Layer, and Surface Layer Properties of the ACAP Test Sections

				Composite barrier layer						Surface soil layer	
				Geomembrane		Soil barrier layer					
								Saturated hydraulic conductivity (m/s)			
Site	Year constructed	Year decommissioned	Average annual precipitaion (mm)	Type	Thickness (mm)	Material	Thickness (mm)	Required	Range in as-built	Thickness (mm)	USCS classification
Altamont, California	November 2000	March 2007	358	Smooth HDPE	1.5	CL	305	$\leq 1 \times 10^{-8}$	1.9×10^{-9} to 2.3×10^{-9}	305	CL-CH
Apple Valley, California	April 2002	March 2007	119	Smooth HDPE	1.0	GCL	NA	$\leq 1 \times 10^{-8}$	1.2×10^{-11} to 1.7×10^{-11}	305	SM
Boardman, Oregon	December 2000	September 2007	225	Textured HDPE	1.0	GCL	NA	$\leq 1 \times 10^{-8}$	2.1×10^{-11} to 4.2×10^{-11}	910	ML
Cedar Rapids, Iowa	October 2000	June 2006	915	Textured LLDPE	1.0	CL	460	$\leq 1 \times 10^{-9}$	5.1×10^{-11} to 3.5×10^{-10}	305	CL
Marina, California	May 2000	NA	466	Textured LLDPE	1.5	CH	305	$\leq 1 \times 10^{-9}$	1.2×10^{-10} to 6.3×10^{-10}	305	SC
Omaha, Nebraska	October 2000	July 2008	760	Smooth HDPE	1.0	CL	460	$\leq 1 \times 10^{-7}$	4.5×10^{-9} to 9.4×10^{-8}	460	CL
Polson, Montana	November 1999	August 2008	380	Textured LLDPE	1.5	CL-ML	460	$\leq 1 \times 10^{-8}$	6.4×10^{-9} to 8.7×10^{-9}	610	SM

Note: CL = low plasticity clay; GCL = geosynthetic clay liner; CH = high plasticity clay as defined by USCS; CL-ML = clayey silt; SM = silty sand; SC = clayey sand; NA = not available [as defined by Unified Soil Classification System (USCS)].

barrier was welded to the sidewall around the circumference of the lysimeter, and lateral flow on the barrier geomembrane was collected via a sump for measurement (Fig. 3).

The methods used to install the lysimeters are described in Benson et al. (1999) and details specific to the installation at the sites are described in Bolen et al. (2001). Extreme care was employed to ensure the geomembrane forming the lysimeter was leak free. All welds were evaluated by pressure testing (ASTM D5820; ASTM 2007e) and vacuum testing (ASTM D5641; ASTM 2007d). The lysimeters were filled with water to ensure the sumps and plumbing were free of leaks, and a sump test pipe was included to permit testing of the sump.

Surface berms were used to delineate the perimeter of the lysimeter, to prevent surface water run-on, and to collect surface water runoff for measurement. Pipes conveyed surface runoff, lateral flow, and percolation from the collection points to the measurement basins equipped with a pressure transducer, float switch, and self-priming siphon to empty the basin when full (Benson et al. 2001). For the percolation system, the basin was also equipped with a tipping bucket gauge. The collection systems permitted resolution of runoff to less than 0.4 mm/year and percolation to less than 0.1 mm/year (Benson et al. 2001). Percolation rates less than 0.1 mm/year are reported herein as trace.

The soil-water content was monitored with water content reflectometers (WCRs) (Model CS 615, Campbell Scientific Inc., Logan, Utah) installed in three nests located at the quarter points along the centerline of the lysimeters (Fig. 3). Each nest consisted of 3–5 WCRs located at multiple depths (Fig. 3), both above and below the barrier geomembrane. A five-point calibration with site-specific soils and temperature compensation was used for the WCRs (Kim and Benson 2002). The soil-water storage was determined by integrating the point measurements of the water content over the soil volume represented by individual probes (Meyer and Gee 1999).

The 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. All data were collected and recorded by a data logger every 15 min and were normally stored on 1-h intervals. During periods of heavier precipitation, sampling and recording were conducted in intervals as short as 15 s. Data were retrieved from the data logger each day and subjected to screening quality assurance (QA) protocols. A detailed QA evaluation of all measurements was conducted quarterly.

Soil Characterization

Soils used during construction of the test sections were tested to determine the particle-size distribution (ASTM D422; ASTM 2007a), Atterberg limits (ASTM D4318; ASTM 2007f), and compaction behavior (ASTM D698; ASTM 2007c) by testing four disturbed samples (20-L buckets) collected from each lift. The 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 D5084 (ASTM 2007g). The hydraulic gradient was set at 10 and the effective stress was set at 15 kPa when conducting the hydraulic conductivity tests. The range of saturated hydraulic conductivity for each barrier layer is summarized in Table 1 along with the soil classification (ASTM D2487; ASTM 2007h) for the soil barrier determined from the index properties. A compilation of all as-built soil properties is given in Gurdal et al. (2003).

The ACAP sites were decommissioned after 4–9 years of service (Table 1). During decommissioning, a series of field tests was used to evaluate the saturated hydraulic conductivity of the barrier layer, and large intact soil samples were collected from the soil layers for laboratory testing. The objective was to define the in-service properties of the cover materials so that comparisons could be made with the

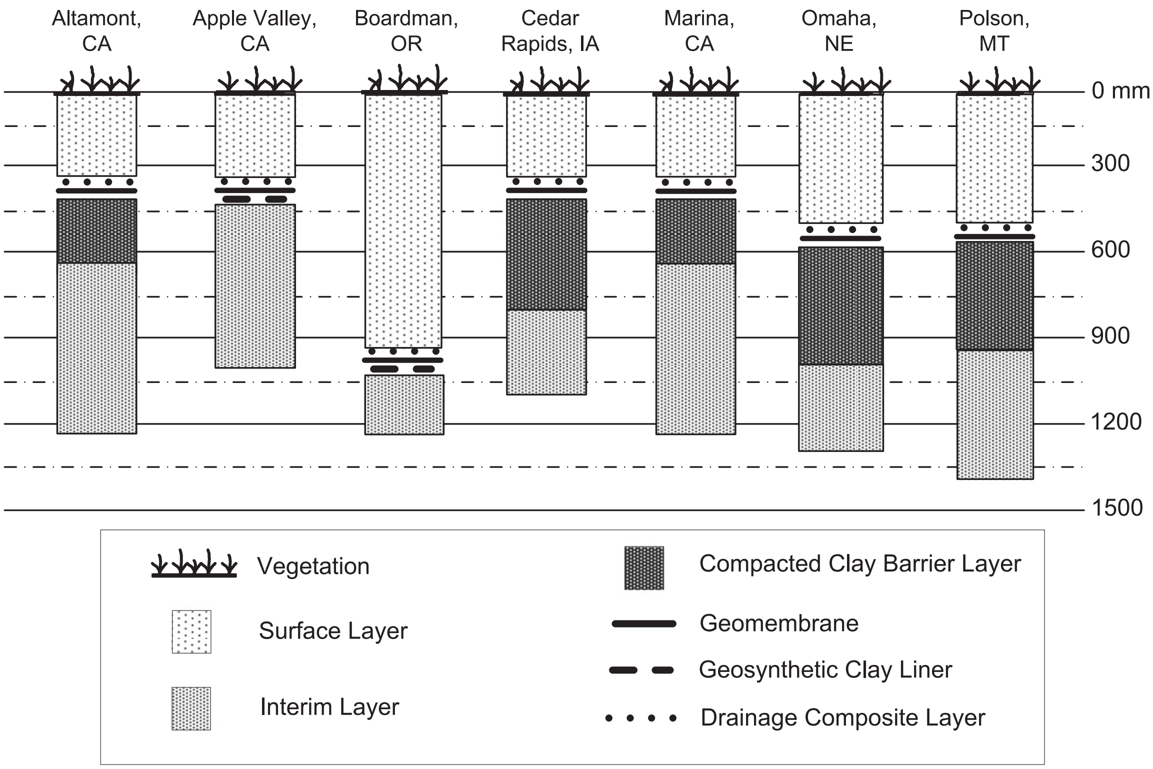

Fig. 2. Profiles of ACAP composite covers

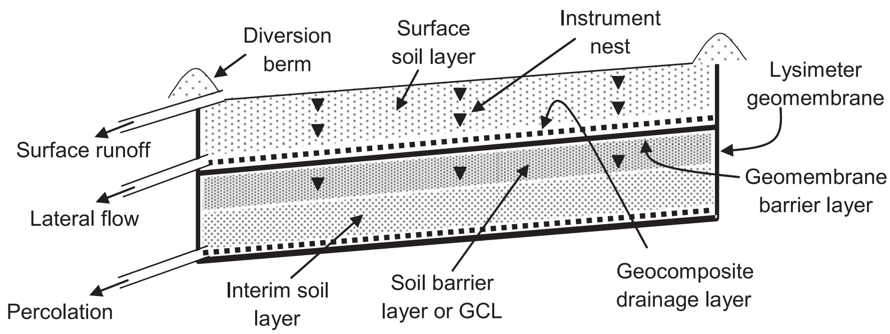

Fig. 3. Schematic of ACAP lysimeter for composite covers

as-built condition in the context of the site conditions and material types. The results of these analyses are discussed subsequently in the section on prediction. A detailed discussion of the decommissioning activities and testing is given in Benson et al. (2011).

Results and Discussion

The annual water-balance quantities (precipitation, surface runoff, lateral flow, and percolation) for all sites are summarized in Table 2. Data for the complete years in Table 2 are reported from July 1 to June 30 of each year.

Precipitation

The annual precipitation at the study sites during the monitoring periods ranged between 116 mm (Apple Valley) and 1,028 mm (Cedar Rapids) (Table 2). The annual precipitation at the nearby National Weather Service stations during the monitoring periods ranged between 72% (Polson 2003−2004) and 396% (Apple Valley, 2004−2005) of the long-term mean annual precipitation for those stations; the annual precipitation for the other five sites was within 15% of the long-term mean. The maximum daily precipitation ranged from 13.5 mm (Boardman) to 202 mm (Cedar Rapids). When Cedar Rapids was excluded, the largest maximum daily precipitation was 61.2 mm (Marina).

Surface Runoff

The average annual surface runoff generally was a small fraction of the water balance (Table 2), ranging from 0.4 mm/year (Boardman) to 32 mm/year (Cedar Rapids). The annual surface runoff ranged from 0.0 to 57 mm. At Cedar Rapids and Omaha, the highest surface runoff was recorded during the first (partial) year of monitoring prior to establishment of significant surface vegetation. At Altamont, Cedar Rapids, Marina, and Polson, there was a general trend of decreasing annual surface runoff during the monitoring period

J. Geotech. Geoenviron. Eng. 2013.139:1-12.

Table 2. Water Balance Data from ACAP Composite Cover Test Sections

Year	Number of days	Precipitation (mm)	Surface runoff (mm)	Lateral flow (mm)	Percolation (mm)	
					Measured	Scaled
Site: Altamont (long-term average precipitation = 358 mm/year)						
2000–2001	233	226	0.9 (0.4)	0.0 (0.0)	0.0	0.0 (0.0)
2001–2002	365	287	30 (10.5)	1.1 (0.4)	0.0	0.0 (0.0)
2002–2003	365	425	28 (6.6)	2.4 (0.6)	4.0	0.4 (< 0.1)
2003–2004	366	325	1.5 (0.5)	90 (28)	0.2	Trace (< 0.1)
2004–2005	365	499	0.1 (0.0)	0.4 (0.1)	0.3	Trace (< 0.1)
Average (mm/year)		379	13 (3.9)	20 (6.2)	1.0	0.1 (< 0.1)
Site: Apple Valley (long-term average precipitation = 119 mm/year)						
2001–2002	67	0	0.0 (0.0)	0.0 (0.0)	0.0	0.0 (0.0)
2002–2003	365	177	6.8 (3.9)	0.0 (0.0)	0.0	0.0 (0.0)
2003–2004	366	116	3.9 (3.3)	0.0 (0.0)	Trace	Trace (0.0)
2004–2005	365	272	12 (4.4)	1.0 (0.4)	0.0	0.0 (0.0)
2005–2006	338	131	5.5 (4.2)	0.0 (0.0)	0.1	Trace (< 0.1)
Average (mm/year)		169	6.8 (3.8)	0.3 (0.1)	Trace	Trace (< 0.1)
Site: Boardman (long-term average precipitation = 225 mm/year)						
2000–2001	204	75	0.0 (0.0)	0.0 (0.0)	0.0	0.0 (0.0)
2001–2002	365	164	0.0 (0.0)	0.0 (0.0)	0.0	0.0 (0.0)
2002–2003	365	185	0.0 (0.0)	0.4 (0.2)	0.0	0.0 (0.0)
2003–2004	366	211	1.7 (0.8)	0.0 (0.0)	0.0	0.0 (0.0)
2004–2005	365	169	0.0 (0.0)	0.0 (0.0)	0.0	0.0 (0.0)
Average (mm/year)		177	0.4 (0.2)	0.1 (0.1)	0.0	0.0 (0.0)
Site: Cedar Rapids (long-term average precipitation = 915 mm/year)						
2000–2001	271	664	24 (3.5)	0.7 (0.1)	1.0	0.1 (< 0.1)
2001–2002	168	603	17 (2.8)	26 (4.3)	4.3	0.4 (< 0.1)
2002–2003	365	843	14 (1.6)	70 (8.3)	21.6	2.2 (0.3)
2003–2004	366	1028	50 (4.8)	240 (23)	63.7	6.4 (1.0)
Average (mm/year)		981	32 (4.0)	105 (11)	28.3	2.8 (0.3)
Site: Marina (long-term average precipitation = 466 mm/year)						
1999–2000	35	2	0.0 (0.0)	0.0 (0.0)	0.0	NA
2000–2001	365	493	49 (9.9)	19 (3.9)	9.0	NA
2001–2002	365	401	39 (9.7)	1.4 (0.4)	25.8	NA
2002–2003	359	467	11 (2.4)	27 (5.7)	36.2	NA
2003–2004	275	409	18 (4.4)	47 (12)	44.7	NA
Average (mm/year)		433	29 (6.5)	23 (5.2)	28.3	NA
Site: Omaha (long-term average precipitation = 760 mm/year)						
2000–2001	269	612	57 (9.3)	29 (4.7)	6.3	0.6 (0.1)
2001–2002	365	552	3.0 (0.6)	0.0 (0.0)	1.0	0.1 (< 0.1)
2002–2003	365	721	27 (3.7)	15 (2.0)	9.2	0.9 (0.2)
2003–2004	366	725	0.0 (0.0)	20 (2.7)	10.9	1.1 (0.2)
2004–2005	95	313	0.0 (0.0)	0.0 (0.0)	0.0	0.0 (0.0)
Average (mm/year)		731	22 (3.4)	16 (2.4)	6.9	0.7 (0.1)
Site: Polson (long-term average precipitation = 380 mm/year)						
1999–2000	225	216	7.8 (3.6)	3.9 (1.8)	0.3	Trace (< 0.1)
2000–2001	365	358	7.0 (2.0)	23 (6.4)	1.2	0.1 (< 0.1)
2001–2002	365	308	0.0 (0.0)	5.1 (1.6)	0.0	0.0 (0.0)
2002–2003	365	326	2.9 (0.9)	4.3 (1.3)	0.0	0.0 (0.0)
2003–2004	298	273	0.0 (0.0)	1.2 (0.4)	0.5	Trace (< 0.1)
2004–2005	96	117	0.0 (0.0)	0.0 (0.0)	0.3	Trace (< 0.1)
Average (mm/year)		341	3.8 (1.4)	8.0 (2.5)	0.5	Trace (< 0.1)

Note: Numbers in parentheses are percentages of precipitation; trace = < 0.1 mm; and percolation for Marina is not scaled because of assumed damage to the geomembrane; NA = not appropriate.

J. Geotech. Geoenviron. Eng. 2013.139:1-12.

(Table 2). This trend may reflect development of vegetation on the test sections and changes in soil hydraulic properties from pedogenesis (Benson et al. 2007, 2011).

Lateral Flow

The average annual lateral flow over the geomembrane for all sites ranged from 0.1 mm/year (Boardman) to 105 mm/year (Cedar Rapids) (0.3−11% of precipitation), with annual flows between 0.0 and 240 mm (Table 2). The maximum daily lateral flow ranged from < 1 mm (0.2 mm at Apple Valley; 0.4 mm at Boardman) to 14.2 mm at Cedar Rapids.

Lateral flow is expected when the maximum soil-water storage capacity of the surface layer is exceeded, or under conditions of preferential flow in the surface layer. An example of the interaction of the water-balance components is shown in Fig. 4 for the test section at Cedar Rapids during April to May 2003. Lateral flow began on April 30 when 79 mm of precipitation increased the soil-water storage in the vegetated surface layer. Lateral flow initiated when the soil-water storage of the surface layer reached 84 mm and continued until the soil-water storage diminished. Between April 30 and May 18, 148 mm of precipitation maintained high soil-water storage in the surface layer, which resulted in 60 mm of lateral flow.

The maximum daily lateral flows at the ACAP sites were 7.2 mm (Altamont), 0.2 mm (Apple Valley), 14.2 mm (Cedar Rapids), 0.4 mm (Boardman), 6.0 mm (Marina), 2.1 mm (Omaha), and 1.8 mm (Polson). On the days with lateral flow, there was no correlation between the lateral flow and the precipitation.

Maximum daily lateral flow increases with maximum annual precipitation and with maximum daily precipitation, as shown in Fig. 5. The maximum daily lateral flow (L_{md}), in mm, may be estimated from either the maximum annual precipitation (P_{ma}) or the maximum daily precipitation (P_{md}) (P_{ma} and P_{md}), in mm, as follows:

$$L_{\mathrm{md}} = 0.18(P_{\mathrm{md}} - 20\,\mathrm{mm}) \tag{1}$$

$$L_{\mathrm{md}} = 0.015(P_{\mathrm{ma}} - 200\,\mathrm{mm}) \tag{2}$$

where P_{md} or $P_{\mathrm{ma}} > 200$ mm. The annual lateral flow as a function of annual precipitation for the ACAP sites is shown in Fig. 6. The lateral flows recorded by ACAP were consistent with—but lower than—those measured in other studies when the annual precipitation exceeds 400 mm/year (Melchior et al. 2008; Dwyer 2003). With few exceptions, the data showed little lateral flow when the annual precipitation was less than 500 mm and showed a trend of increased lateral flow with increased precipitation when the annual precipitation was more than 500 mm. An upper bound on the annual lateral flow (L_{a}), in mm, can be estimated as

$$L_a = 0.75(P_a - 400) \tag{3}$$

where P_a = annual precipitation in mm ($P_a \geq 400\,\mathrm{mm}$).

The data from Marina are not included in Fig. 6 because the geomembrane at Marina was damaged during construction. A geotextile or sand layer was not placed over the geomembrane prior to placement of the overlying soils, which contained construction and demolition debris including concrete rubble and steel reinforcing bars. The relatively high percolation rates at Marina (Table 2) likely included water that would have been recorded as lateral flow if the geomembrane had not been damaged.

Percolation

The percolation rates are summarized in Table 2. Also given in Table 2 are the scaled percolation rates, which are the measured rates divided by a factor of 10. Many designers assume that the defect frequency for carefully constructed geomembranes is 5 holes/ha, with each hole having an area of approximately 100 mm^2 (e.g., see Giroud and Bonaparte 1989). In the ACAP test sections, a single 100-mm^2 hole was intentionally placed in the center of the barrier geomembrane, which corresponded to a defect frequency that is 10 times higher than normally assumed. The scaled percolation

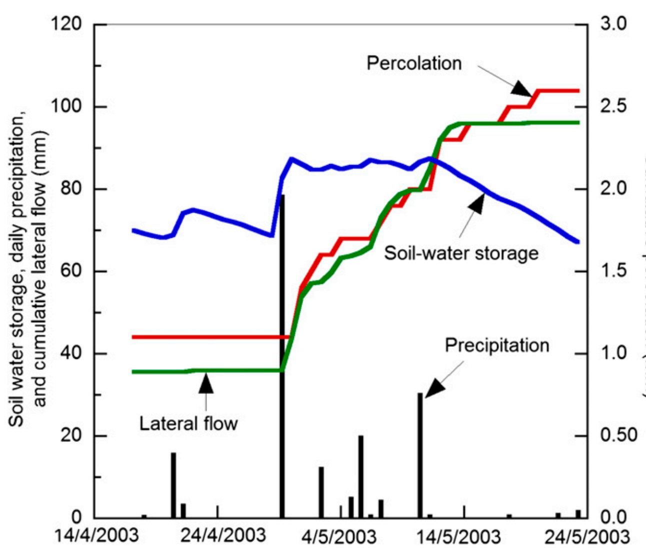

Fig. 4. (Color) Water balance of the composite cover test section at the Cedar Rapids, Iowa, ACAP site during April and May 2003

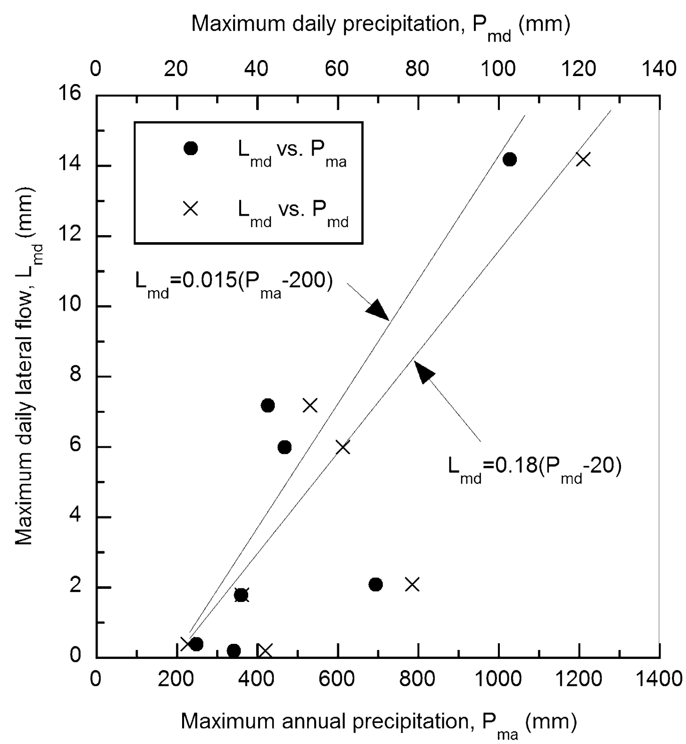

Fig. 5. Maximum daily lateral flow (L_{md}) as a function of the maximum annual precipitation (P_{ma}) and maximum daily precipitation (P_{md}) for the period of record for each of the seven ACAP sites

rates are used in the following discussion to reflect the conditions anticipated at the full scale. The percolation rates from Marina were not scaled because the geomembrane was assumed to be damaged and the actual number of defects was unknown.

The annual percolation for the ACAP sites ranged from 0.0 to 456.4 mm (Table 2). The average annual percolation was < 1 mm/year, except at Cedar Rapids (2.8 mm/year) and Marina (30 mm/year). The highest percolation rates, recorded at Marina, likely were caused by punctures in the geomembrane as described previously.

The percolation rates for the ACAP sites (except Marina) were consistent with those reported by Dwyer (2003) for semiarid New Mexico and by Melchior et al. (2008) for more humid Germany (Fig. 7). Little percolation (< 1 mm/year) occurred when the precipitation was less than 400 mm/year. The highest observed annual percolation (6.2 mm) at the ACAP sites was at Cedar Rapids during a year with 1,027 mm of precipitation. In more humid Hamburg, Germany, where the annual precipitation ranged from 520 to 1,150 mm, Melchior et al. (2008) reported annual percolation rates as high as 5.3 mm. The trend in Fig. 7 shows a consistent increase in the percolation rate with increasing precipitation when the precipitation is greater than 400 mm/year. The upper bounding line in Fig. 8 corresponds to

$$P_r = 0.01(P_a - 400) \quad (4)$$

where P_r = annual percolation in mm. Eq. (4) provides an upper-bound estimate for the annual percolation rate for the ACAP covers with composite barriers.

Most percolation was seasonal and occurred when the climate conditions (precipitation and evapotranspiration) resulted in high water storage in the vegetated surface layer and lateral flow in the drainage layer, as illustrated in Fig. 8 for the sites with a high degree of seasonality in precipitation (e.g., Marina) and less seasonality (e.g., Omaha). Winter precipitation at Marina [Fig. 8(a)] resulted in an annual peak in water storage of the vegetated layer and an annual pulse of percolation. The maximum soil-water storage capacity of the vegetated surface layer (i.e., the field capacity) at Marina was about 50 mm, which was exceeded each year [Fig. 8(a)]. With the surface layer at capacity, additional precipitation resulted in water impinging on the lateral drainage layer and lateral flow on the surface of the geomembrane. Percolation was coincident with lateral flow, except during the winter of 2001–2002. Percolation at Marina was exaggerated because of the higher frequency of defects in the geomembrane. However, this example demonstrates the conditions under which percolation occurs through a composite cover.

Percolation at Omaha [Fig. 8(b)] was also seasonal, with an annual pulse in April to May that coincided with heavy precipitation and a peak in water storage of the vegetated surface layer. Unlike Marina, precipitation at Omaha occurred frequently throughout the year. However, outside of the April-to-May period, precipitation events generally did not cause water storage in the vegetated layer to exceed the maximum storage capacity. Consequently, lateral flow and percolation only occurred in the April-to-May period.

A similar correspondence between the lateral flow in the drainage layer and the percolation was observed at all sites, as shown in Fig. 9. There was little percolation (≤ 1 mm) when the lateral flow was less than about 50 mm. At annual lateral flow rates greater than 100 mm, percolation increased dramatically. The highest percolation rates (> 3 mm/year) occurred when the lateral flow rates were in excess of 250 mm/year.

Prediction

The hydrology of the composite covers was predicted with the HELP model (Schroeder et al. 1994), which was developed by USEPA for hydrologic modeling of landfills. HELP is commonly used by engineers to predict the hydrologic performance of landfills. The meteorological data, soil properties, and vegetative parameters measured

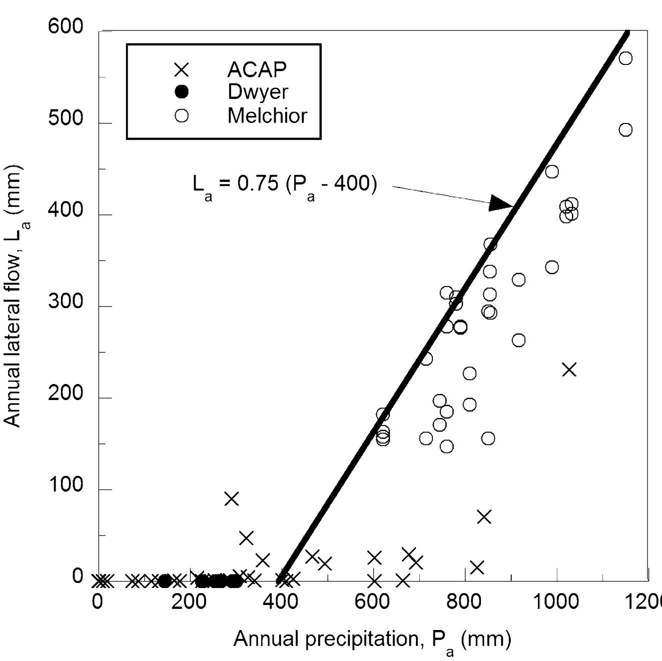

Fig. 6. Annual lateral flow (L_a) as a function of annual precipitation (P_a) for the seven ACAP test sections and past studies (Melchior et al. 2008; Dwyer 2003); data from the Marina site are not included because of likely damage to the geomembrane

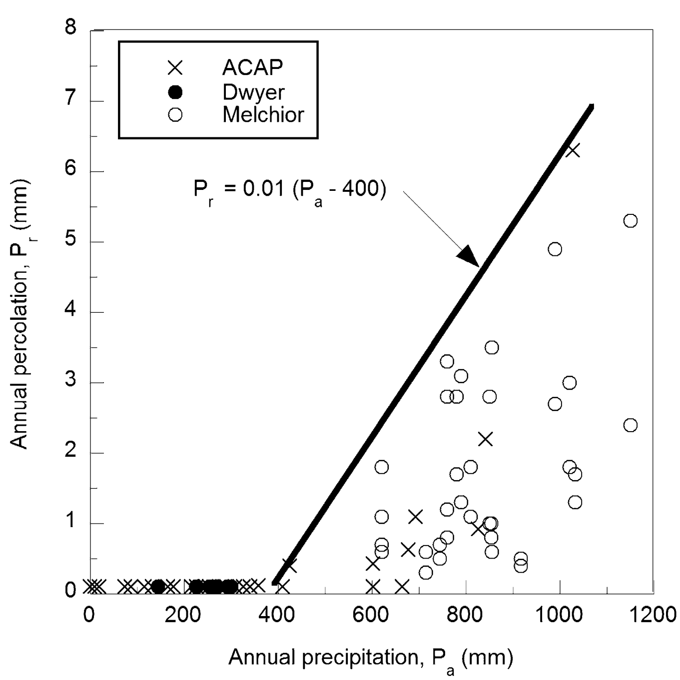

Fig. 7. Annual percolation as a function of annual precipitation for the ACAP test sections and past studies (Melchior et al. 2008; Dwyer 2003); data from Marina not included

J. Geotech. Geoenviron. Eng. 2013.139:1-12.

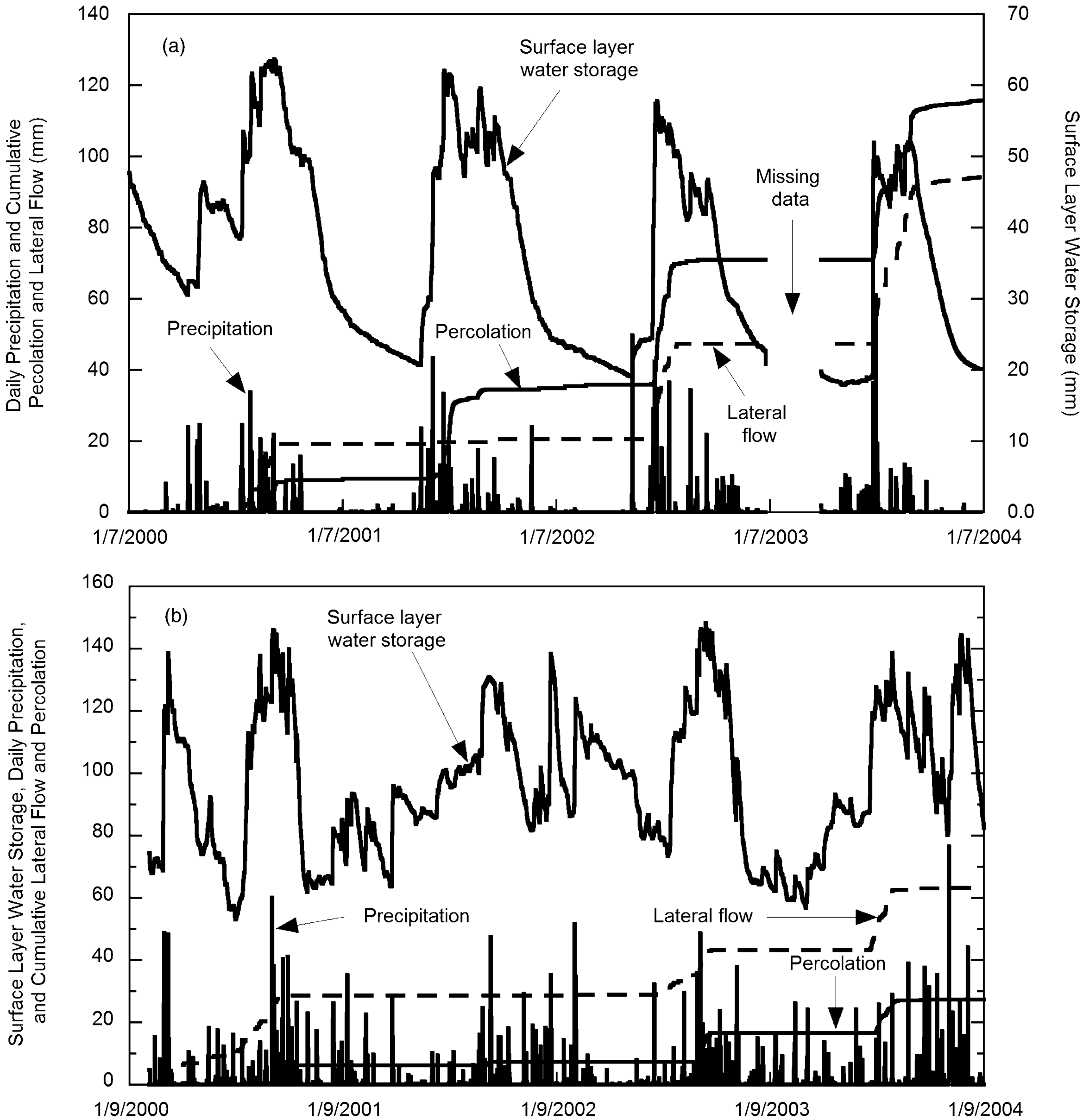

Fig. 8. Water balance components for the test sections at (a) Marina, California, and (b) Omaha, Nebraska (percolation coincides with increased water storage in the surface soil layer and lateral flow on the barrier geomembrane; the very high rate of percolation at Marina is probably a result of damage to the geomembrane during installation)

on site were used as input to HELP. The as-built and in-service hydraulic properties of the soils and GCLs were used as input (Table 3). The as-built soil properties corresponded to conditions at the time of construction (Gurdal et al. 2003), whereas the in-service hydraulic properties were determined when the ACAP test sections were decommissioned 4–9 years after construction (Benson et al. 2011). The default hydraulic properties available in the HELP model were used for the geocomposite drainage layers. For the geomembrane, a density of 50 holes/ha was used to simulate the as-built condition in the test sections (i.e., a single 100 mm^2 in an ACAP test section corresponds to 50 holes/ha). Good quality of the geomembrane installation and zero pinhole density were assumed in all simulations. The runoff curve numbers were predicted by HELP based on the surface slope, slope length, surface layer soil, and vegetation.

The annual surface runoff, lateral flow, and percolation predicted by HELP using the as-built and in-service properties for each site are summarized in Table 4. The water-balance quantities predicted by HELP are compared with the measured water-balance quantities (surface runoff, evapotranspiration, lateral flow, and percolation) for the as-built conditions and in-service conditions for each site in Figs. 10 and 11, where water-balance quantities equal to zero are plotted as 0.01 mm when a logarithmic scale was used.

When as-built hydraulic properties were used as input, runoff was generally overpredicted (by as much as 615 mm/year) and evapotranspiration was largely underpredicted (by as much as 580 mm/year) at Altamont, Cedar Rapids, Marina, and Omaha. The relatively large overprediction of runoff using as-built soil properties is attributed to the low saturated hydraulic conductivities assigned to the surface layer (10^{-6} to 10^{-8} cm/s), combined with high runoff curve numbers (81.9–88.9) predicted by HELP. Overprediction of runoff results in reduced infiltration and, therefore, less water available for evapotranspiration (Khire et al. 1997).

J. Geotech. Geoenviron. Eng. 2013.139:1-12.

Consequently, evapotranspiration was underpredicted. The much smaller difference between predicted and measured runoff and evapotranspiration at the other sites is attributed to the higher saturated hydraulic conductivity of the surface layer (10^{-5} cm/s) and the lower runoff curve numbers (65.6–82.2) in the as-built condition at these sites.

The predicted runoff and evapotranspiration were much closer to the actual runoff and evapotranspiration when the in-service properties were used as input (Fig. 10). The maximum overprediction of runoff decreased from 615 to 102 mm/year and the mean difference between the predicted and measured runoff decreased from 183 to 11 mm/year using the in-service properties. Similarly, the underprediction of evapotranspiration decreased from −164 mm/year on average (median of −121 mm/year) using the as-built properties to −61 mm/year on average (median of −56 mm/year) using the in-service hydraulic properties.

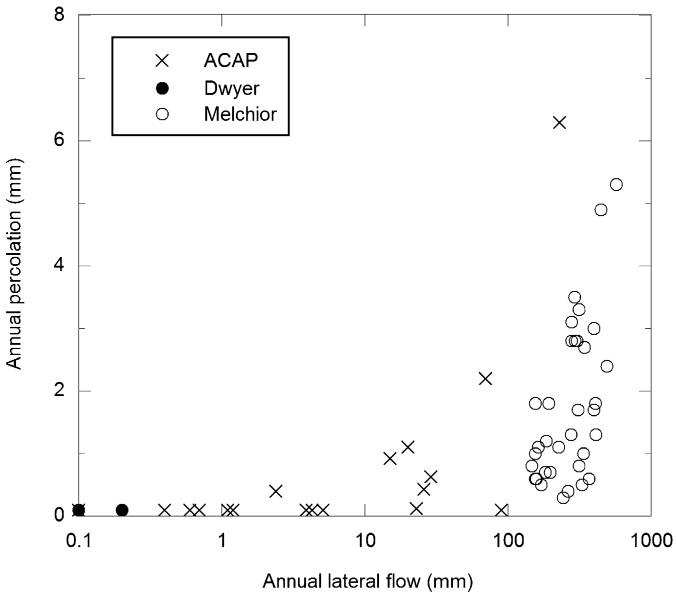

Fig. 9. Annual percolation as a function of annual lateral flow for the ACAP test sections (except Marina) and past studies (Melchior et al. 2008; Dwyer 2003)

The lateral flow was overpredicted in most cases using the as-built hydraulic properties (as much as 74.5 mm/year) or in-service soil properties (as much as 230.4 mm/year) [Fig. 11(a)]. Exceptions included cases where the predicted lateral flow was nil as a result of overprediction of surface runoff. Higher lateral flows were predicted with the in-service hydraulic properties because the higher hydraulic conductivities associated with in-service conditions permit more infiltration. However, the difference between the predicted and measured lateral flow is also attributed to the unit gradient method used by HELP to route water from the surface layer into the drainage layer. In an actual cover, a capillary break may form between the surface layer and the drainage layer as a result of the contrast in hydraulic properties at the interface of the two layers. This capillary break limits flow into the drainage layer until nearly saturated conditions exist in the surface layer (Khire et al. 2000).

The predicted and measured percolation rates are shown in Fig. 11(b). There was no trend between the predicted and measured percolation rates when the as-built hydraulic properties were used as input. Using the in-service hydraulic properties as input did not result in better agreement between the predicted and measured percolation rates, although higher percolation rates were predicted in most cases because of an increase in saturated hydraulic conductivity. Except at Marina where the geomembrane was damaged, the measured and predicted percolation rates were within ± 10 mm/year in all but one case.

Table 3. Input Soil Parameters for HELP Simulations of the ACAP Test Sections

			Field capacity		Wilting point		Saturated hydraulic conductivity (m/s)	
Site	Layer	Porosity	As-built	In-service	As-built	In-service	As-built	In-service
Altamont	Surface	0.380	0.361	0.357	0.120	0.110	5.3×10^{-9}	2.5×10^{-7}
	Clay barrier	0.400	0.397	0.356	0.121	0.145	1.6×10^{-9}	7.0×10^{-8}
	Foundation	0.370	0.345	0.356	0.080	0.145	4.5×10^{-9}	7.0×10^{-8}
	Interim	0.378	0.339	0.356	0.098	0.145	3.0×10^{-8}	7.0×10^{-8}
Apple Valley	Surface	0.350	0.202	0.186	0.072	0.063	3.1×10^{-7}	7.1×10^{-6}
	GCL	0.750	0.747	0.747	0.400	0.400	3.0×10^{-11}	1.2×10^{-11}
	Foundation	0.280	0.215	0.215	0.023	0.023	2.0×10^{-8}	7.1×10^{-6}
	Interim	0.280	0.215	0.215	0.023	0.023	2.0×10^{-8}	7.1×10^{-6}
Boardman	Surface	0.450	0.350	0.320	0.050	0.035	1.2×10^{-7}	5.8×10^{-7}
	GCL	0.750	0.747	0.747	0.400	0.400	3.0×10^{-11}	8.1×10^{-9}
	Interim	0.460	0.370	0.379	0.060	0.051	9.3×10^{-8}	1.9×10^{-7}
Cedar Rapids	Surface	0.530	0.364	0.348	0.131	0.140	3.3×10^{-8}	3.6×10^{-6}
	Clay barrier	0.360	0.332	0.299	0.164	0.196	1.5×10^{-10}	8.4×10^{-8}
	Interim	0.378	0.332	0.332	0.173	0.173	2.5×10^{-9}	8.4×10^{-8}
Marina	Surface	0.400	0.315	0.300	0.065	0.001	8.6×10^{-10}	2.3×10^{-6}
	Clay barrier	0.450	0.419	0.443	0.076	0.117	1.9×10^{-10}	1.9×10^{-7}
	Interim	0.460	0.120	0.120	0.115	0.115	3.2×10^{-5}	5.4×10^{-5}
Omaha	Surface	0.420	0.388	0.404	0.030	0.083	6.4×10^{-9}	3.5×10^{-6}
	Clay barrier	0.450	0.384	0.436	0.080	0.133	1.5×10^{-8}	1.7×10^{-6}
	Interim	0.450	0.394	0.436	0.080	0.133	7.2×10^{-9}	1.7×10^{-6}
Polson	Surface	0.415	0.297	0.237	0.016	0.005	5.3×10^{-7}	2.7×10^{-6}
	Clay barrier	0.420	0.307	0.409	0.167	0.079	4.2×10^{-9}	1.3×10^{-7}
	Interim	0.397	0.250	0.250	0.050	0.050	6.1×10^{-5}	6.1×10^{-5}

J. Geotech. Geoenviron. Eng. 2013.139:1-12.

Table 4. Predicted Water Balance Data for ACAP Composite Cover Test Sections Made Using HELP with Input Parameters for As-Built and In-Service Conditions

Year	Precipitation (mm)	Surface runoff (mm)		Lateral flow (mm)		Percolation (mm)	
		As-built	In-service	As-built	In-service	As-built	In-service
Site: Altamont							
2000–2001	226	146	1.5	0.0	54	5.5	0.0
2001–2002	287	212	10	0.0	100	5.5	0.0
2002–2003	425	329	75	0.0	66	3.9	0.0
2003–2004	325	221	23	0.0	75	3.0	0.0
2004–2005	499	358	20	0.0	85	2.4	0.0
Site: Apple Valley							
2001–2002	0	0.0	0.0	0.0	0.0	0.0	4.6
2002–2003	177	10	1.3	41	58	0.0	0.0
2003–2004	116	0.0	0.0	0.0	9.9	0.0	0.0
2004–2005	272	22	3.1	37	76	0.0	0.0
2005–2006	131	0.0	0.0	0.0	3.5	0.1	0.0
Site: Boardman							
2000–2001	75	0.0	0.0	0.4	1.5	0.0	0.1
2001–2002	164	3.2	0.0	0.0	40	0.0	0.3
2002–2003	185	5.4	0.0	0.0	58	0.0	0.3
2003–2004	211	20	15	0.0	58	0.0	0.2
2004–2005	189	15	2.7	0.0	62	0.0	0.2
Site: Cedar Rapids							
2000–2001	664	393	126	0.1	131	0.1	8.2
2001–2002	603	418	98	0.0	95	0.2	2.3
2002–2003	843	517	74	0.0	173	0.2	1.7
2003–2004	1028	664	134	0.0	296	0.1	1.9
Site: Marina							
1999–2000	2	0.0	0.0	0.1	41	0.0	2.4
2000–2001	493	396	4.2	8.5	259	0.0	0.0
2001–2002	401	317	7.9	8.8	223	2.4	0.0
2002–2003	467	375	22	7.9	250	0.0	0.0
2003–2004	409	320	18	7.3	221	0.0	0.0
Site: Omaha							
2000–2001	612	429	65	22	131	1.0	15
2001–2002	552	373	20	42	34	2.2	4.2
2002–2003	721	513	49	46	147	1.8	2.3
2003–2004	725	519	80	57	110	1.6	1.6
2004–2005	313	232	41	18	39	0.4	0.3
Site: Polson							
1999–2000	215	0.5	0.5	6.7	33	0.5	0.5
2000–2001	358	0.0	0.0	55	51	0.0	0.0
2001–2002	308	0.0	0.0	38	70	0.0	0.0
2002–2003	326	1.8	1.5	79	64	0.0	0.0
2003–2004	273	0.0	0.0	39	62	0.0	0.0
2004–2005	117	0.0	0.0	35.1	20	0.0	0.0

Summary and Conclusions

Field data describing the water balance from seven large-scale test sections simulating landfill covers with composite hydraulic barriers have been presented for climates ranging from cool and humid to warm and arid. When constructed using methods that minimize the potential for damage to the geomembrane, the average annual percolation was limited to ≤ 2.8 mm/year (≤ 0.4% of precipitation). Much higher percolation rates can be realized when the cover is constructed with methods that promote puncture of the geomembrane.

The percolation generally corresponded to high soil-water storage in the surface layer and lateral flow in the drainage layer over the geomembrane. Little percolation (< 1 mm) was observed when the annual precipitation was less than 400 mm; for higher annual precipitation rates, the percolation rate increased approximately linearly with higher annual precipitation. The lateral flow increased with the annual precipitation and maximum daily precipitation, and

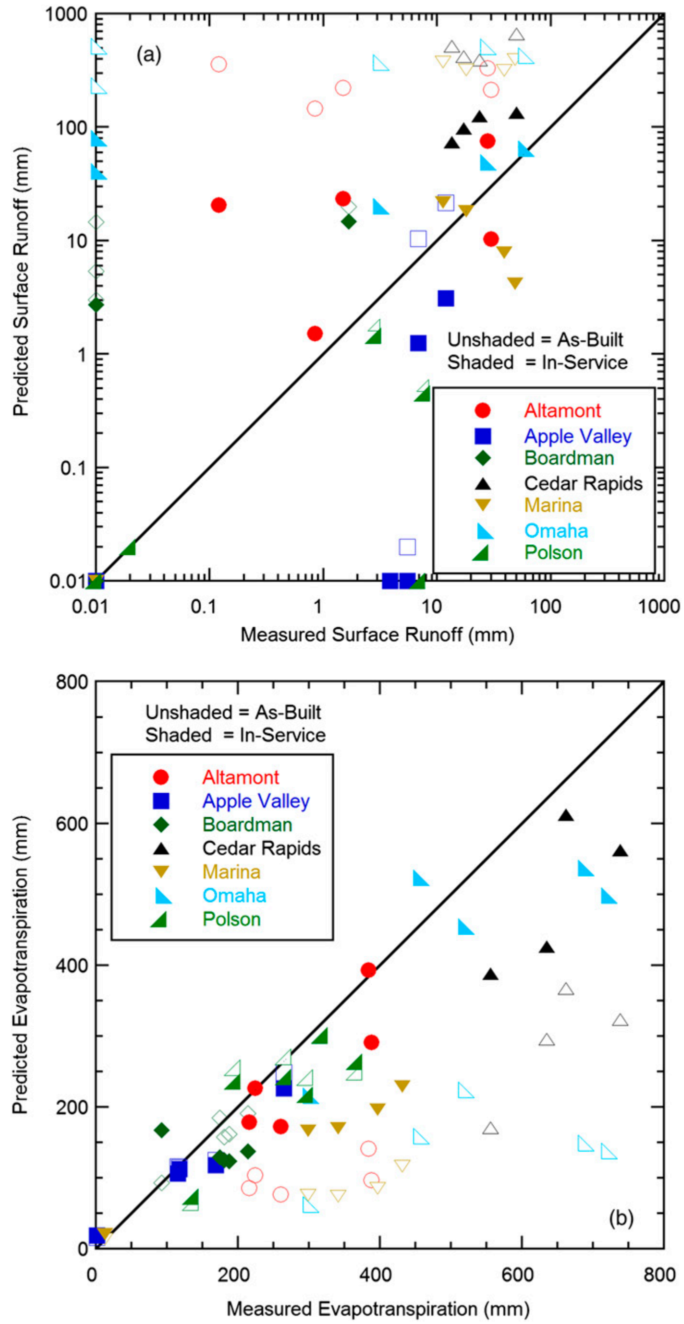

Fig. 10. (Color) Water-balance quantities predicted with HELP versus field-measured water balance quantities for as-built conditions and in-service hydraulic properties of the ACAP test sections: (a) surface runoff; (b) evapotranspiration

J. Geotech. Geoenviron. Eng. 2013.139:1-12.

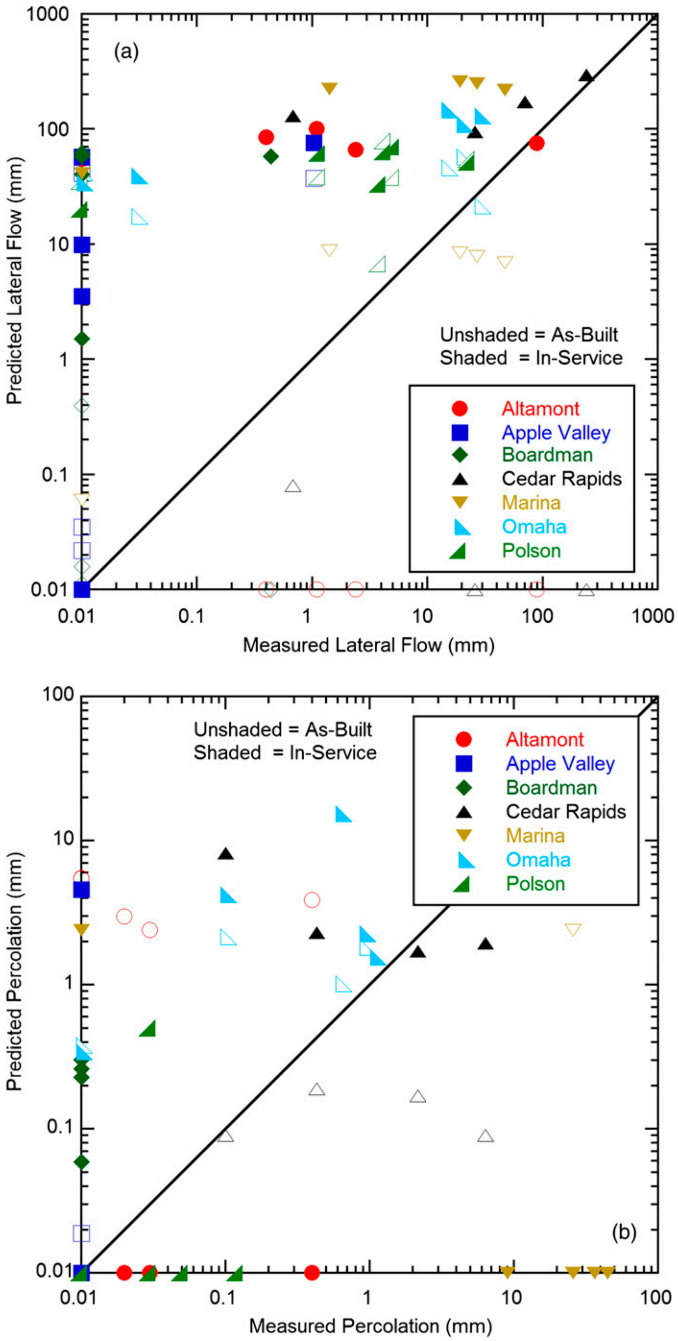

Fig. 11. (Color) Water-balance quantities predicted with HELP versus field-measured water balance quantities for as-built conditions and in-service hydraulic properties of the ACAP test sections: (a) lateral flow; (b) percolation

was as high as 230 mm (annual) and 14.2 mm (daily). Low annual percolation (< 1 mm) generally was associated with low annual lateral flow rates (< 50 mm). Equations to compute the upper bounds for the lateral flow rate and percolation rate have been presented.

The predictions made with the HELP model using the data measured in the field along with the as-built and in-service hydraulic properties of the soil layers were compared with the measured water-balance quantities. HELP overpredicted runoff and underpredicted evapotranspiration when the as-built hydraulic properties were used as input; much closer agreement was obtained when the in-service hydraulic properties were used. The lateral flow was consistently overpredicted using the as-built and in-service hydraulic properties because the algorithms in HELP ignore the capillary barrier effect at the interface between the surface layer and the lateral drainage layer. No correspondence was found between the predicted and measured percolation rates, although the predicted and measured percolation rates were of the same order of magnitude ($\approx 0.01 - 10$ mm/year). These findings suggest that predictions made with HELP should employ hydraulic properties reflecting the in-service conditions of the soil layers. In addition, a comparison of percolation predicted by HELP to the ACAP database suggests these modeled estimates may be viewed as an approximate quantity with a precision $\pm$ 10 mm/year.

Acknowledgments

Funding for this study was provided through the Environmental Protection Agency (EPA), Department of Energy (DOE), and Nuclear Regulatory Commission (NRC). Each of the site owners contributed to the cost of construction of the test sections. The EPA support was provided through the Superfund Innovative Technology Evaluation (SITE) Program. The DOE support was provided under Cooperative Agreement No. DE-FC01-06EW07053, entitled the Consortium For Risk Evaluation With Stakeholder Participation III, awarded to Vanderbilt University. The opinions, findings, conclusions, and recommendations expressed herein are solely those of the authors, and do not necessarily represent the views of the EPA, DOE, NRC, or Vanderbilt University.

References

Albright, W., et al. (2004). "Field water balance of landfill final covers." *J. Environ. Qual.*, 33(6), 2317–2332.

ASTM. (2007a). "Standard test method for particle size analysis of soils." *D422-63*, West Conshohocken, PA.

ASTM. (2007b). "Standard guide for installation of geosynthetic clay liners." *D6102-12*, West Conshohocken, PA.

ASTM. (2007c). "Standard test methods for laboratory compaction characteristics of soil using standard effort." *D698-12*, West Conshohocken, PA.

ASTM. (2007d). "Standard practice for geomembrane seam evaluation by vacuum chamber." *D5641-94*, West Conshohocken, PA.

ASTM. (2007e). "Standard practice for pressurized air channel evaluation of dual seamed geomembranes." *D5820-95*, West Conshohocken, PA.

ASTM. (2007f). "Standard test methods for liquid limit, plastic limit, and plasticity index of soils." *D4318-10*, West Conshohocken, PA.

ASTM. (2007g). "Standard test methods for measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter." *D5084-10*, West Conshohocken, PA.

ASTM. (2007h). "Standard practice for classification of soils for engineering purposes (Unified Soil Classification System)." *D2487-11*, West Conshohocken, PA.

Benson, C., et al. (2011). "Engineered covers for waste containment: changes in engineering properties and implications for long-term performance assessment." *NUREG/CR-7028*, Office of Research, U.S. Nuclear Regulatory Commission, Washington, DC.

Benson, C. H., Abichou, T., Albright, W. H., Gee, G. W., and Roesler, A. C. (2001). "Field evaluation of alternative earthen final covers." *Int. J. Phytoremediation*, 3(1), 105–127.

Benson, C. H., Abichou, T., Wang, X., Gee, G. W., and Albright, W. H. (1999). "Test section installation instructions, assessment program." *Geo Engineering Rep. No. 99-3*, Geo Engineering Program, Univ. of Wisconsin, Madison, WI.

Benson, C. H., Sawangsuriya, A., Trzebiatowski, B., and Albright, W. (2007). "Postconstruction changes in the hydraulic properties of water balance cover soils." *J. Geotech. Geoenviron. Eng.*, 133(4), 349–359.

Bolen, M. M., Roesler, A. C., Benson, C. H., and Albright, W. H. (2001). "Alternative cover assessment program: Phase II report." *Geo Engineering Rep. No. 01-10*, Univ. of Wisconsin, Madison, WI.

Daniel, D. E., and Benson, C. H. (1990). "Water content-density criteria for compacted soil liners." *J. Geotech. Engrg.*, 116(12), 1811–1830.

Dwyer, S. F. (2003). "Water balance measurements and computer simulations of landfill covers." Ph.D. dissertation, Univ. of New Mexico, Albuquerque, NM.

Giroud, J. P., and Bonaparte, R. (1989). "Leakage through liners constructed with geomembranes—Part II. Composite liners." *Geotext. Geomembr.*, 8(2), 71–111.

Gurdal, T., Benson, C., and Albright, W. (2003). "Hydrologic properties of final cover soils from the alternative cover assessment program." *Geo Engineering Rep. 03-02*, Univ. of Wisconsin, Madison, WI.

Khire, M. V., Benson, C. H., and Bosscher, P. J. (1997). "Water balance modeling of earthen landfill covers." *J. Geotech. Geoenviron. Eng.*, 123(8), 744–754.

Khire, M. V., Benson, C. H., and Bosscher, P. J. (2000). "Capillary barriers: Design variables and water balance." *J. Geotech. Geoenviron. Eng.*, 126(8), 695–708.

Kim, K., and Benson, C. (2002). "Water content calibrations for final cover soils." *Geo Engineering Rep. 02–12*, Univ. of Wisconsin, Madison, WI.

Melchior, S., Sokollek, V., Berger, K., and Steinert, B. (2008). "Results from 18 years of in situ performance testing of landfill cover systems in Germany." *Proc., Global Waste Management Symp.*, Penton Media, New York.

Meyer, P. D., and Gee, G. W. (1999). "Flux-based estimation of field capacity." *J. Geotech. Geoenviron. Eng.*, 125(7), 595–599.

Schroeder, P. R., Aziz, N. M., Lloyd, C. M., and Zappi, P. A. (1994). "The hydrologic evaluation of landfill performance (HELP) model, user's guide for version 3." *Rep. No. EPA/600/R-94/168a*, Office of Research and Development, U.S. Environmental Protection Agency, Washington, DC.

United Nations Educational, Scientific and Cultural Organization (UNESCO). (1979). "Map of the world distribution of arid regions. Accompanied by explanatory note." *MAB Technical Note No. 7*, UNESCO, Paris.

U.S. Environmental Protection Agency (USEPA). (1992). "USEPA subtitle D clarification, 40 CFR 257 and 258, EPA/OSW-FR-92-4146-6." *Fed. Regist.*, 57(124), 28626–28632.