Field Water Balance of Landfill Final Covers

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ABSTRACT

Landfill covers are critical to waste containment, yet field performance of specific cover designs has not been well documented and seldom been compared in side-by-side testing. A study was conducted to assess the ability of landfill final covers to control percolation into underlying waste. Conventional covers employing resistive barriers as well as alternative covers relying on water-storage principles were monitored in large (10 × 20 m), instrumented drainage lysimeters over a range of climates at 11 field sites in the United States. Surface runoff was a small fraction of the water balance (0–10%, 4% on average) and was nearly insensitive to the cover slope, cover design, or climate. Lateral drainage from internal drainage layers was also a small fraction of the water balance (0–5.0%, 2.0% on average). Average percolation rates for the conventional covers with composite barriers (geomembrane over fine soil) typically were less than 12 mm/yr (1.4% of precipitation) at humid locations and 1.5 mm/yr (0.4% of precipitation) at arid, semiarid, and subhumid locations. Average percolation rates for conventional covers with soil barriers in humid climates were between 52 and 195 mm/yr (6–17% of precipitation), probably due to preferential flow through defects in the soil barrier. Average percolation rates for alternative covers ranged between 33 and 160 mm/yr (6 and 18% of precipitation) in humid climates and generally less than 2.2 mm/yr (0.4% of precipitation) in arid, semiarid, and subhumid climates. One-half (five) of the alternative covers in arid, semiarid, and subhumid climates transmitted less than 0.1 mm of percolation, but two transmitted much more percolation (26.8 and 52 mm) than anticipated during design. The data collected support conclusions from other studies that detailed, site-specific design procedures are very important for successful performance of alternative landfill covers.

Closure of solid and hazardous waste landfills in the United States is largely regulated through the Resource Conservation Recovery Act (RCRA) or comparable state regulations that supercede those in RCRA. The final covers recommended in RCRA employ a resistive barrier layer as the primary impediment to percolation into the underlying waste, and are often referred to as "conventional" final covers in the solid (hazardous and nonhazardous) waste industries. Depending on the type of base liner underlying the waste at the landfill, the barrier layer in a conventional cover may consist of a fine-grained soil having low saturated hydraulic conductivity or a "composite barrier" consisting of a geomembrane (plastic sheet, 1–2 mm thick) underlain by fine-grained soil (USEPA, 1992). The layer of fine-grained soil (typically 450 mm thick) is compacted to achieve sufficiently low saturated hydraulic conductivity ($<10^{-5}$ or $<10^{-7}$ cm/s, depending on the properties of the base liner in the landfill). Alternatively, a geosynthetic clay liner (thin, factory-manufactured material consisting of 3.5 to 6.0 kg/m^2 of bentonite clay sandwiched between two geotextiles) may be substituted for the compacted fine-grained soil. In most cases, conventional covers are required to meet material specifications (e.g., a maximum saturated hydraulic conductivity for the barrier layer), but are not subjected to a performance criterion such as a maximum percolation rate.

The RCRA also includes a provision that permits alternative final covers that are "equivalent" to the recommended conventional cover in terms of percolation rate (i.e., the percolation rate from the alternative cover must be less than or equal to that from the conventional cover) [U.S. Code of Federal Regulations, Section 258.60(b)(1); United States Government, 2002]. Because of the relatively high cost of conventional covers and questions regarding the long-term durability of compacted fine-grained barrier layers, the provision for alternative designs has received considerable attention. Most of the alternative designs rely on water storage principles (i.e., controlling percolation by water storage during periods of high precipitation and evapotranspiration during periods of low precipitation) and are often referred to as "evapotranspirative covers." A capillary break (i.e., a layer of fine-grained soil over a layer of coarse soil) is sometimes added to increase the water storage capacity of the cover. Covers employing these principles are often referred to as "alternative" covers in the solid waste industry (Albright et al., 2003). The "alternative cover" nomenclature is used herein.

Despite the widespread use of both conventional and alternative cover designs throughout the United States, a limited number of systematic field studies evaluating the hydrologic behavior of final covers have been conducted (Hakonson et al., 1994, 1997; Khire et al., 1997, 1999; Melchior, 1997; Ward and Gee, 1997; Chadwick et al., 1999; Gee et al., 2002; Dwyer, 2001; Nyhan et al., 1997) and most have addressed one or a few cover designs at a single location. The USEPA initiated the Alternative Cover Assessment Project (ACAP) in 1998 to provide a more general understanding of the hydrologic behavior of conventional and alternative landfill final covers (Albright et al., 2003).

The most important element of ACAP was a distributed network of field sites for monitoring final covers

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Abbreviations: ACAP, Alternative Cover Assessment Project; SWCC, soil water characteristic curve; TDR, time domain reflectometry.

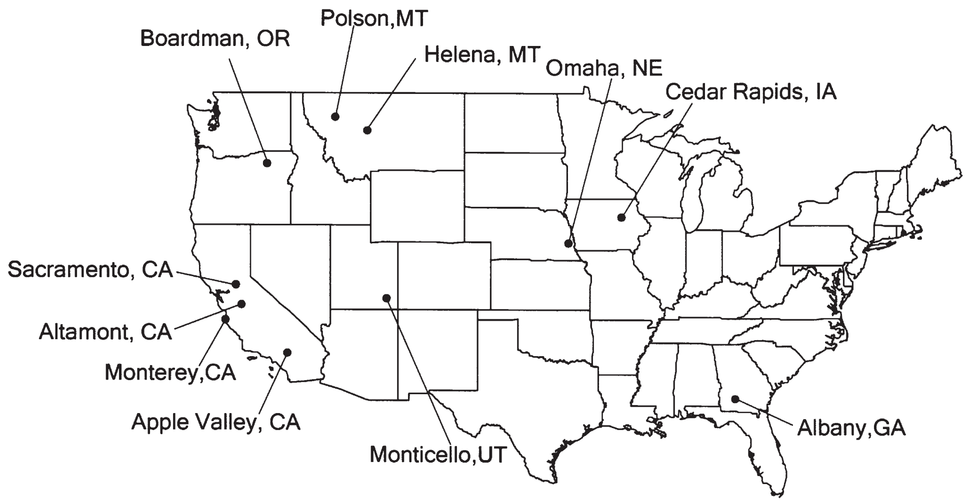

Fig. 1. Locations of Alternative Cover Assessment Project (ACAP) field sites.

in climates ranging from arid to humid and from hot to cold. Both conventional and alternative covers were monitored, and at several sites, side-by-side comparisons were made. The primary focus was on the water balance, with emphasis on the percolation rate from the base of the cover. Other factors, such as physical stability, wind and water erosion, gas control, and biointrusion, all of which may influence the long-term performance of landfill covers, were not studied directly. This paper describes the field sites and the cover designs that were evaluated, presents a summary of the water balance data collected through June 2003, and provides an interpretation of the water balance data in the context of cover type and climate.

MATERIALS AND METHODS

Site Descriptions

Locations of the field sites are shown in Fig. 1 and a summary of cover types and climate characteristics is given in Tables 1 and 2. There were 11 sites located in seven states so as to represent a broad range of climatological conditions as well as types of soil and vegetation. Based on the definitions described in United Nations Educational, Scientific and Cultural Organization (1979), which use the ratio of precipitation (P) to potential evapotranspiration (PET) to define climatic zones, one site has an arid climate ($0.03 < P/PET \leq 0.2$), six sites have a semiarid climate ($0.2 < P/PET \leq 0.5$), one site has a subhumid climate ($0.5 < P/PET \leq 0.75$), and three have a humid climate ($P/PET > 0.75$). The average annual precipitation ranges from 119 (Apple Valley, CA) to 1263 mm (Albany, GA). Snowfall is appreciable at five sites (Helena and Polson, MT; Omaha, NE; Cedar Rapids, IA; Monticello, UT). The maximum average monthly high temperature ranges from 22°C (Marina, CA) to 37°C (Apple Valley, CA), and the minimum average monthly low temperature ranges from −11°C (Helena, MT, and Omaha, NE) to 8°C (Albany, GA).

The cover profiles evaluated are shown in Fig. 2 and 3. Ten conventional covers and 14 alternative covers were evaluated, with side-by-side comparisons at eight sites. Three of the conventional covers had compacted soil barriers and seven had composite barriers. Two of the conventional covers with composite barriers used a geosynthetic clay liner (GCL) as the fine-grained soil barrier. Eight of the alternative covers were monolithic covers (i.e., a thick layer of finer-textured soil overlain by topsoil) and six were capillary barriers. All of the capil-

Table 1. Cover types and climate characteristics of Alternative Cover Assessment Project (ACAP) sites for arid, semiarid, and subhumid locations.

Site	Cover type	Average annual recipitation	Average precipitation/potential evapotranspiration	Climate type†	Average temperature (high and low with month)	Precipitation type
		mm/yr			°C	
Altamont, CA	monolithic barrier and conventional with composite barrier	358	0.31	semiarid	32 (August), 2 (January)	rain, snow rare
Apple Valley, CA	monolithic barrier, conventional with soil barrier, conventional with composite barrier	119	0.06	arid	37 (July), −1 (January)	rain, snow rare
Boardman, OR	two monolithic barriers (1220 and 1840 mm thick) and conventional with composite barrier (geosynthetic clay liner, GCL)	225	0.23	semiarid	32 (July), −2 (January)	rain and infrequent snow
Helena, MT	capillary barrier	289	0.44	semiarid	28 (July), −11 (January)	rain and snow
Marina, CA	capillary barrier and conventional with composite barrier	466	0.46	semiarid (coastal)	22 (September), 6 (January)	rain
Monticello, UT	capillary barrier	385	0.34	semiarid	29 (July), −9 (January)	rain and snow
Polson, MT	capillary barrier and conventional with composite barrier	380	0.58	subhumid	28 (July), −7 (January)	rain and snow
Sacramento, CA	two monolithic barriers (1080 and 2450 mm thick)	434	0.33	semiarid	34 (July), 3 (January)	rain, snow rare

† Based on climate definitions described in United Nations Educational, Scientific and Cultural Organization (1979).

Table 2. Cover types and climate characteristics of Alternative Cover Assessment Project (ACAP) sites for humid locations.

Site	Cover type	Average annual precipitation	Average precipitation/potential evapotranspiration	Average temperature (high and low with month)	Precipitation type
		mm/yr		°C	
Albany, GA	monolithic barrier and conventional with soil barrier	1263	1.10	33 (July), 8 (December)	rain
Cedar Rapids, IA	monolithic barrier, conventional with soil barrier, conventional with composite barrier	915	1.03	23 (July), −8 (January)	rain and snow
Omaha, NE	two capillary barriers (760 and 1060 mm thick), conventional with composite barrier	760	0.75	23 (July), −11 (January)	rain and snow

lary barriers employed a simple two-layer fine-over-coarse design where the primary purpose of the capillary break was to enhance the storage capacity of the overlying finer-textured layer. Capillary barrier designs employing textural contrasts to facilitate lateral diversion were not evaluated. The test sections were sloped at 5 or 25%, depending on the predominant condition at each site (Table 3). Construction of all but one of the ACAP test sections was completed by fall 2000 (Apple Valley, CA, was a late addition to the program, and was constructed in March 2002). A detailed description of the construction of each test section can be found in Bolen et al. (2001) and Roesler et al. (2002).

All covers were constructed with local, often on-site soils. An extensive sampling program was conducted during construction of the covers to thoroughly characterize all soils used. A description of sampling and analytical results is given in the next section.

The vegetation used at each site is summarized in Table 4. All of the sites were vegetated with a mixture of annual and perennial grass mixtures. Three of the sites (Apple Valley, CA; Monticello, UT; Polson, MT) also included shrubs and two sites (Albany, GA; Cedar Rapids, IA) had hybrid poplar trees with an understory of grasses.

Lysimeters

A key feature of all ACAP test sections was a large (10 × 20 m) instrumented pan-type lysimeter (Fig. 4) used for direct measurement of surface runoff (R), soil water storage (S), lateral drainage (L, conventional covers only), and percolation (P_c) from a full-depth cover profile. The base and sidewalls of each lysimeter were comprised of polyethylene geomembrane. The geomembrane in the base of the lysimeter was overlain with a geocomposite drainage layer to protect the geomembrane and to transmit water from the base of the cover profile to a collection and measurement system. Tests were conducted on the lysimeters during construction to ensure that each lysimeter was free of leaks (Bolen et al., 2001). Diversion berms

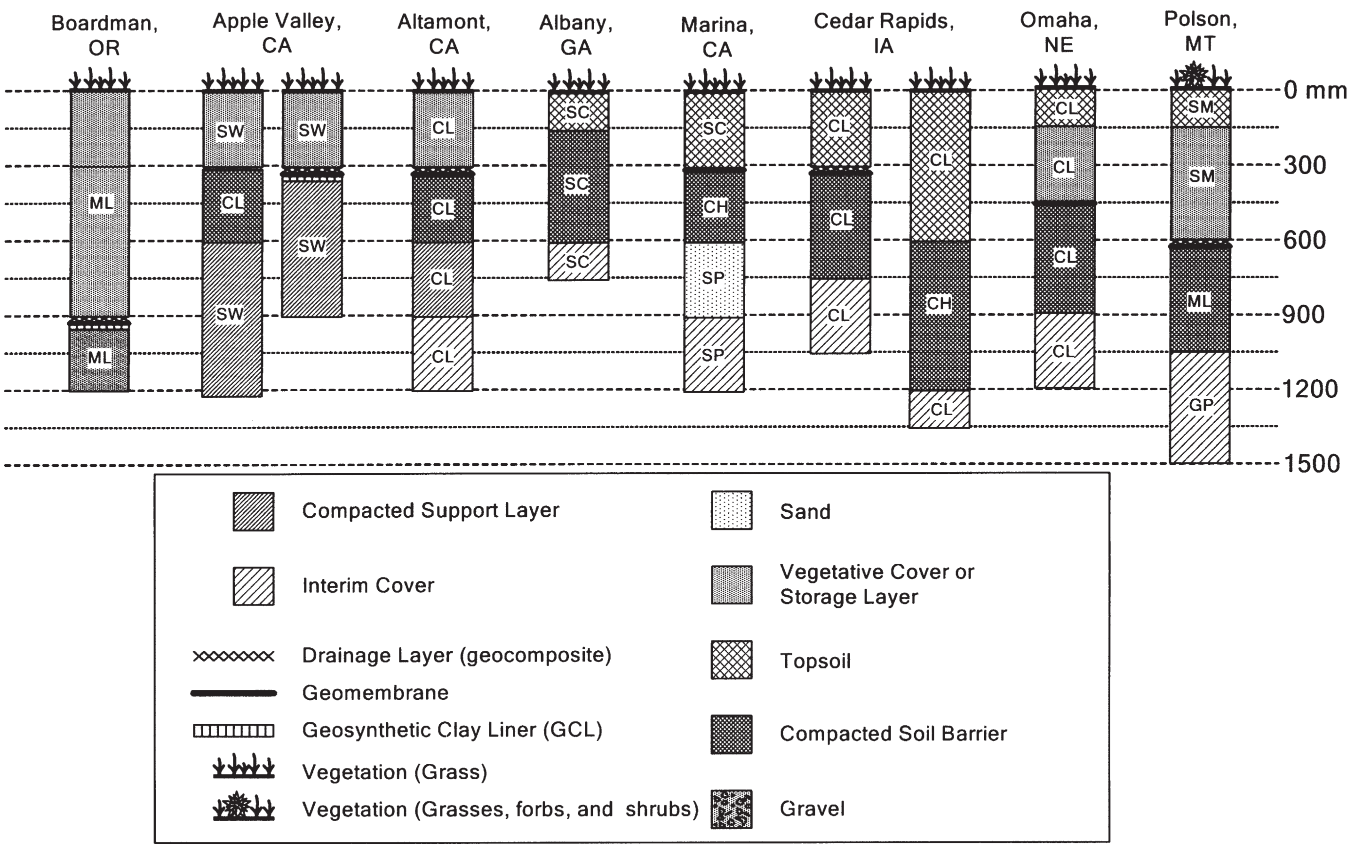

Fig. 2. Profiles for conventional covers evaluated by the Alternative Cover Assessment Project (ACAP). Two-letter designations are designations in the Unified Soil Classification System per ASTM D 2487: CL, low-plasticity clay; CH, high-plasticity clay; GC, clayey gravel; GP, poorly graded gravel; ML, low-plasticity silt; SC, clayey sand; SM, silty sand; SP, poorly graded sand; and SW, well-graded sand.

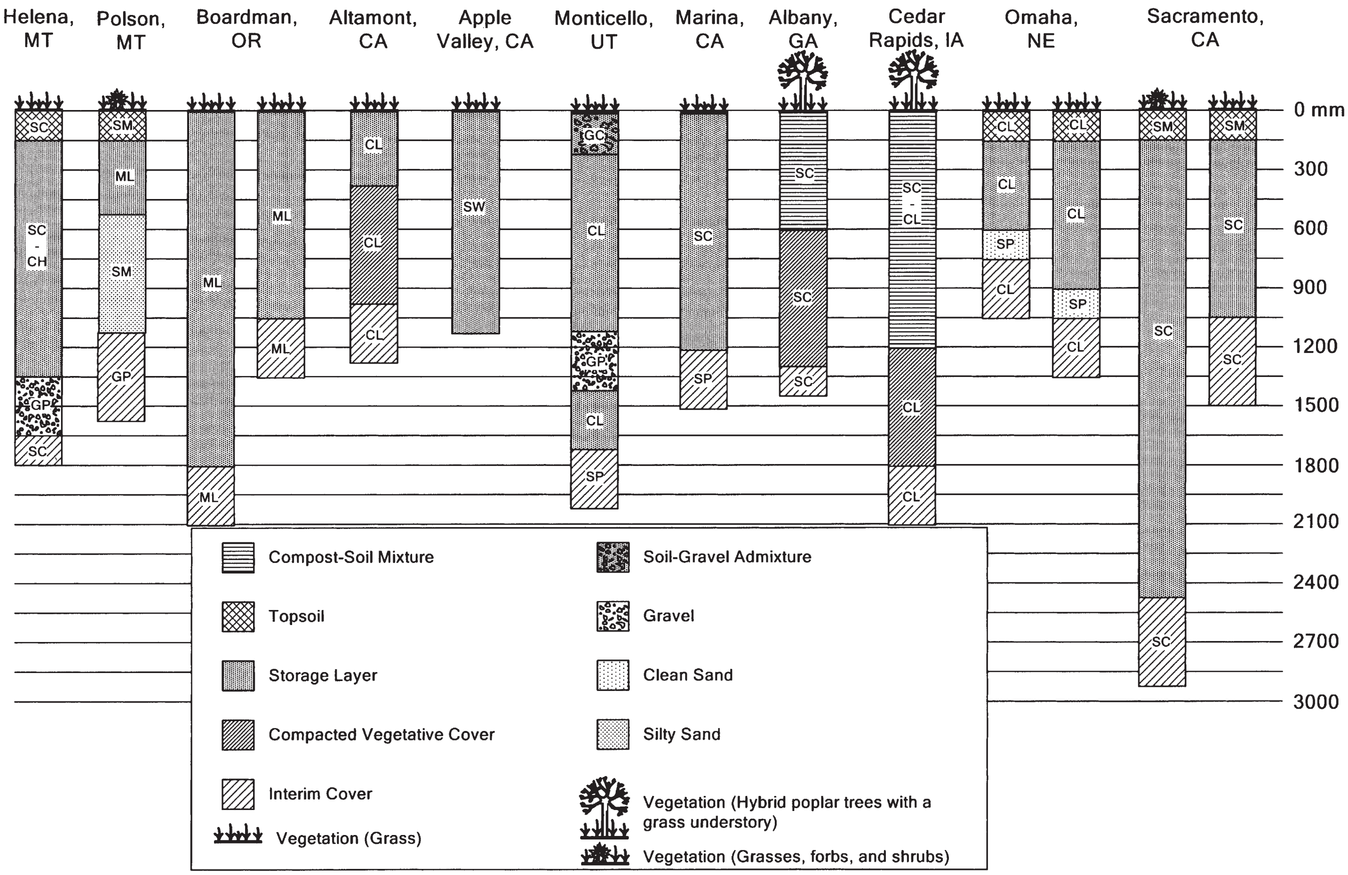

Fig. 3. Profiles for alternative covers evaluated by the Alternative Cover Assessment Project (ACAP). Two-letter designations are designations in the Unified Soil Classification System per ASTM D 2487: CL, low-plasticity clay; CH, high-plasticity clay; GC, clayey gravel; GP, poorly graded gravel; ML, low-plasticity silt; SC, clayey sand; SM, silty sand; SP, poorly graded sand; and SW, well-graded sand.

on the surface were used to prevent run-on and collect runoff for measurement as well as to delineate the edges of the lysimeter. Lateral drainage caused by flow along the low-conductivity layers in conventional covers was collected at the lower end of the lysimeters and transmitted to the measurement system via ports through the sidewalls. Methods used to install the lysimeters are described in Benson et al. (1999).

All of the test sections were constructed with methods and procedures typical of engineering practice for construction of landfill covers. Full-scale construction equipment was used to place the soils and to compact the soil barrier layers. For the test sections with a composite barrier, a single hole, 9 mm in diameter, was cut in the geomembrane near the center of the test section. This hole was intended to represent a typical construction defect and was sized based on recommendations in Giroud and Bonaparte (1989). Installing a single hole resulted in an areal defect frequency 10 times larger than is typical in practice (approximately 5 holes/ha; Giroud and Bonaparte, 1989). However, installing less than one hole was not possible.

An extensive sampling program was conducted during construction to characterize the in-place cover soils. Four disturbed samples (20-L buckets) and four undisturbed samples were collected from each lift of soil immediately after placement. Two of the undisturbed samples were collected through the entire lift in thin-wall sampling tubes (76-mm diameter) and two were collected as hand-carved blocks (200-mm diameter and length). The disturbed samples were analyzed for particle size distribution (ASTM D 422), Atterberg limits (ASTM D 4318), organic matter content (ASTM D 2974), and compaction behavior (ASTM D 698). The undisturbed samples were tested to determine the saturated hydraulic conductivity (ASTM D 5084 or D 5856) and the soil water characteristic curve (SWCC) (ASTM D 6836). Results of all of the tests are contained in Gurdal et al. (2003). The ASTM methods are from the American Society for Testing and Materials (West Conshohocken, PA).

Saturated hydraulic conductivities of the soil barrier layers in the conventional covers are summarized in Table 5 along with the soil water storage capacities (S_c) for the alternative covers. For both properties, the median, upper bound, and lower bound are reported in Table 5. The soil water storage capacities were computed using the SWCCs from the samples collected during construction. For the monolithic alternative covers, the storage capacity was computed as the product of field capacity (water content at 33 kPa soil water matric potential) and thickness. This calculation of storage represents the total water stored in the soil profile rather than available water storage capacity (the difference between field capacity and wilting point), a parameter commonly used during cover design. Soil water storage capacity of the capillary barriers was computed using the method in Khire et al. (2000), which accounts for the additional storage in an overlying finer layer provided by the textural contrast at the capillary break. Storage capacities were computed for each SWCC.

Each cover profile was constructed within the lysimeter and in a buffer area at least 3 m wide around the perimeter of each lysimeter to reduce boundary effects and to provide an area for annual sampling of soil and vegetation. Before construction of the final cover profile, an additional layer of soil simulating the existing interim cover on the waste was placed between the geocomposite drainage layer and the final cover profile to replicate the field condition above the waste as closely as practical. The thickness of the interim cover layer depended on site-specific conditions including regulatory requirements and soil type planned for use as interim cover at the sites. The thickness of the interim cover layer varied between 150 and 600 mm with a 300-mm-thick layer being most common. A root barrier (a nonwoven geotextile studded with nodules containing trifluralin, a root inhibitor) was placed between the interim and final cover soils to prevent root intrusion into the interim cover soils, the geocomposite drainage layer, and the percolation collection system. Inclusion of this soil layer and root barrier between the lysimeter geomembrane and the bottom of the final cover soils addresses most of the concerns associated with use of drainage lysimeters. Foremost among these concerns are that (i) placement of the lysimeter geomembrane and overlying geocomposite drainage layer increases the water storage capacity in the soils above the lysimeter by creation of a capillary break at the soil–geocomposite interface and (ii) roots transpire the additional water held in storage by the capillary break (an issue for the eight test sections with monolithic cover profiles). However, inclusion of the root barrier probably resulted in less water being transpired than might occur in an actual cover, where roots can grow through the interim cover and possibly into the waste. The authors believe that the root barrier prevents plants from having access to water retained in the collection and measurement system that would otherwise become deep drainage in an actual landfill.

Depending on the properties of the interim cover soils, most of the increased storage caused by the capillary break is contained in a relatively thin layer (150–600 mm) of soil immediately above the geocomposite drainage layer. Exclusion of roots from this layer by placement of the interim soil layer and the root barrier minimizes transpiration of the artificially stored water and defines the root zone. In the ACAP lysimeters, the occurrence of percolation required some additional water to pass through the final cover into the underlying interim soils to bring the interim soils to field capacity and initiate percolation. Most of the ACAP lysimeters did record some percolation and the authors believe that, while percolation may have been delayed, the measured percolation rate was representative once percolation was initiated.

A capillary break is also realized in most field scenarios at the interface between the interim cover soil and the solid waste. The SWCC for solid waste typically resembles that of a very coarse soil (Benson and Wang, 1998). Thus, the authors believe that the capillary break created by the geocomposite drainage layer is representative of actual field conditions at many waste disposal sites.

Data Collection

Percolation, lateral flow, and surface runoff were routed by pipes to basins equipped with instruments (pressure transducer, tipping bucket, and float switch) each capable of measuring flows with a precision better than 1 mm/yr. A discussion of the flow measurement system and its precision can be found in Benson et al. (2001).

Soil water content was measured in three nests located at the quarter points along the centerline of each test section (Fig. 4). Each nest contained four to six low-frequency (40 MHz) time domain reflectometry (TDR) probes (Model 615; Campbell Scientific, Logan, UT) (Campbell and Anderson, 1998) in a vertical stack. The central nest also contained co-located thermal dissipation sensors (Model 229; Campbell Scientific) (Phene et al., 1992) for monitoring soil water matric potential. Soil water storage was determined by integration of the point measurements of water content. The TDR probes were calibrated at six moisture contents with the soils in which they

Table 3. Summary of water balance data for conventional covers.

Site	Duration	Slope	Total precipitation (1 July–30 June) 2000–2001	2001–2002	2002–2003	Surface runoff	Lateral flow	Evapotranspiration	Total	Percolation (1 July–30 June) 2000–2001	2001–2002	2002–2003	Average
	d	%	mm							mm/yr			
						Composite cover							
Altamont	781	5	NF†	291.1	394.2	59.0 (6.5‡)	4.0 (0.4)	825.0 (91.3)	4.0 (0.4)	NF	0.0 (0.0)	4.0 (1.0)	1.5 (0.4)
Apple Valley	251	5	NA§	NF	148.0	6.8 (4.6)	0.0 (0.0)	134.14 (90.6)	0.0 (0.0)	NA	NF	0.0 (0.0)	0.0 (0.0)
Boardman	747	25	NF	134.4	125.5	0.0 (0.0)	0.2 (0.1)	366.4 (109.2)	0.0 (0.0)	NF	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Marina	947	25	288.0	335.0	343.7	98.7 (10.2)	47.4 (4.9)	789.6 (81.6)	71.0 (7.3)	9.0 (3.1)	25.3 (7.6)	36.2 (10.5)	23.1 (7.3)
Polson	1137	5	350.0	292.1	290.6	17.7 (1.6)	40.5 (3.6)	1052.5 (94.3)	1.5 (0.1)	1.2 (0.3)	0.0 (0.0)	0.0 (0.0)	0.4 (0.1)
Cedar Rapids	621	5	NF	NF	791.2	54.1 (2.8)	96.2 (5.0)	1725.5 (90.5)	26.9 (1.4)	NF	NF	21.0 (2.7)	12.2 (1.4)
Omaha	815	25	NF	561.4	474.5	86.8 (5.8)	43.3 (2.9)	1266.0 (85.0)	16.5 (1.1)	8.5 (1.4)	1.0 (0.2)	9.2 (1.9)	6.0 (1.1)
						Soil barrier							
Apple Valley	251	5	NA	NF	148.0	3.4 (2.3)	0.0 (0.0)	120.3 (81.2)	0.0 (0.0)	NA	NF	0.0 (0.0)	0.0 (0.0)
Albany	985	5	909.0 (909.0¶)	798.3 (996.2¶)	1447.8 (1560.0¶)	359.4 (9.9)	NA	2682.90 (73.7)	623.7 (17.1)	291.9 (32.1)	237.6 (23.8)	51.6 (3.4)	195.2 (17.1)
Cedar Rapids	621	5	NF	NF	791.2	79.6 (4.2)	29.5 (1.5)	1595.9 (83.7)	113.6 (6.0)	NF	NF	93.8 (12.0)	51.6 (6.0)

† Data not available for a full year.
‡ Percentages of precipitation are given in parentheses.
§ Not applicable.
¶ Total precipitation for Albany includes irrigation.

Table 4. Design vegetation at Alternative Cover Assessment Project (ACAP) sites.

Site	Vegetation
Omaha, NE	brome, switchgrasses
Albany, GA	Bermuda grass, annual rye, hybrid poplar (trees on alternative cover only)
Altamont, CA	soft chess, slender oat, foxtail chess, Italian ryegrass, red-stemmed filaree, black mustard, yellow star-thistle, prickly lettuce, bull thistle, prickly sow-thistle, blue dicks, California poppy, purple owl's-clover, miniature lupine
Apple Valley, CA	creosote bush, bladder wort, Russian thistle
Cedar Rapids, IA	Indian grass, little bluestem, big bluestem, side oat, switch grass (conventional covers), tall fescue, hybrid poplars (alternative)
Boardman, OR	Siberian, bluebunch, and thickspike wheatgrasses, alfalfa, yellow blossom sweetclover
Helena, MT	bluebunch, slender, and western wheatgrasses, sandburg bluegrass, sheep fescue, blue gramma, green needlegrass, needle-and-thread
Sacramento, CA	California brome, purple needlegrass, zorro fescue, arroyo lupin
Marina, CA	blue wild rye, California brome, creeping wild rye, pacific hairgrass
Polson, MT	thickspike, bluebunch, slender, and crested wheatgrasses, mountain brome, Idaho fescue, prairie junegrass, needle-and-thread, meadow brome, Canada and Kentucky bluegrasses, yarrow, fringed sagewort, alfalfa, rubber rabbitbrush, prickly rose, arrowleaf, balsamroot, dolted gayfeather, lewis flax, silky lupine, cicer milkvetch
Monticello, UT	western and crested wheatgrasses, gray rabbitbrush, sagebrush, pinyon, juniper

were placed (Kim and Benson, 2002). The thermal dissipation sensors were calibrated at four potentials in Warden silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids). The focus of this paper is on the water balance of the cover designs and analysis of data from the thermal dissipation sensors is not included.

Meteorological parameters (precipitation, air temperature, relative humidity, solar radiation, wind speed, and wind direction) were also measured with a weather station mounted in the buffer area. All data were collected and recorded by a datalogger every 15 min and were normally stored on 1-h intervals. At times of intense activity (e.g., an intense rain event with high surface runoff), data were stored at time intervals as short as every 15 s.

Evapotranspiration (ET) was estimated as the difference between precipitation (P) and the sum of the other components of the water balance ($R + L + P_c + \Delta S$). Potential evapotranspiration (PET) was computed using the Penman–Monteith method with on-site meteorological data (Roesler et al., 2002).

Calibration and Data Quality Control

Annual site visits were made for calibration, quality control checks, and characterization (Albright and Benson, 2003, 2004). The flow measurement systems (dosing basins, tipping bucket gauges, pressure transducers) were calibrated annually. Results of these analyses indicate that the detection limit for drainage (percolation) was ±0.1 mm. The meteorological instruments receive annual maintenance and calibration checks. Undisturbed samples from the top 300 to 600 mm of soil were collected annually in thin-wall sampling tubes for laboratory tests to evaluate the accuracy of the TDR probes. Comparisons between oven-dry water contents and those obtained with the TDR probes generally have been in close agreement (±2%).

Comparisons were also made between the on-site meteorological data and data from nearby weather stations operated by the U.S. National Oceanic and Atmospheric Administration (NOAA). Annual precipitation collected on-site and at nearby NOAA stations is shown in Fig. 5. The annual precipitation measured on-site ranges from +76 to −247 mm of the annual precipitation recorded by NOAA (Fig. 5a), with most sites falling 0 to 100 mm below the NOAA precipitation (the median on-site annual precipitation is 39 mm lower than the annual precipitation measured by NOAA). Some of the differences between the NOAA and on-site precipitation data probably were due to spatial variability in precipitation. However, the absence of shielding for the on-site rain gauges was most likely responsible for the downward bias in the on-site precipitation data.

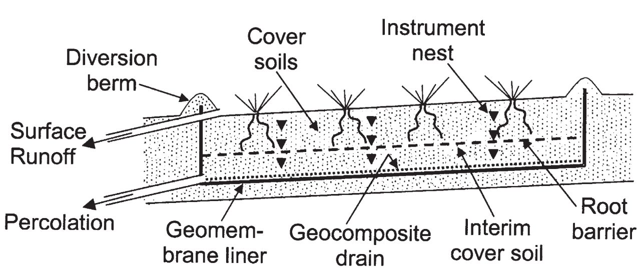

Fig. 4. Schematic of lysimeter used for monitoring the water balance of the Alternative Cover Assessment Project (ACAP) test sections.

Comparison of the long-term annual average precipitation and actual annual precipitation recorded by NOAA near each of the sites (see data in Tables 1, 2, 3, and 6) shows that the annual precipitation varied between +150 and −394 mm of the long-term annual average on a program-wide basis, with a median bias of −42 mm (Fig. 5b). In general, precipitation at the arid, semiarid, and subhumid sites during the monitoring period was "typical" in terms of percent deviation from the average mean precipitation (median percent bias = −5.6%, maximum percent deviation = +41.3%, minimum percent deviation = −39.4%), whereas precipitation at the humid sites was lower than normal (median percent bias = −14.3%, maximum deviation = +1.2%, minimum deviation = −36.2%).

Performance Criteria

A site-specific criterion was established at most sites to assess whether the alternative cover being considered was "equivalent" to the conventional cover required by regulation. In many cases, equivalency was established if the percolation rate transmitted from an alternative cover was less than that from the conventional cover, or both were below a minimum threshold (e.g., 3 mm/yr). When a site-specific criterion was not established, the following program-wide default criteria were applied based on percolation rate: conventional covers with composite barriers, <3 mm/yr; conventional covers with soil barriers in humid climates, <30 mm/yr; conventional covers with soil barriers in arid, semiarid, and subhumid climates, <10 mm/yr (Bolen et al., 2001). These relatively low percolation rates are consistent with the current objective of minimizing the ingress of water into solid waste so as to minimize the production of leachate that can contaminate ground water (Koerner and Daniel, 1997).

RESULTS

Water balance quantities for the test sections are summarized in Table 3 (conventional covers) and Table 6 (alternative covers). All data reported in Tables 3 and 6

Table 5. Soil water storage capacities of the alternative covers and saturated hydraulic conductivities of the soil barrier layers in conventional covers.

	Storage capacities of alternative covers			Saturated hydraulic conductivities of soil barriers in conventional covers†		
Site	Low	Geometric mean	High	Low	Geometric mean	High
		mm			cm/s	
Altamont	332	373	396	1.2×10^{-7}	1.7×10^{-7}‡	2.3×10^{-7}
Apple Valley	121	184	376	2.7×10^{-9}	1.7×10^{-8}§	1.5×10^{-7}
				2.1×10^{-9}	3.2×10^{-9}‡¶	4.1×10^{-9}
Boardman	327	430	494	2.1×10^{-9}	3.2×10^{-9}‡¶	4.1×10^{-9}
	493	649	745			
Helena	305	392	469	NA#	NA	NA
Marina	283	385	498	1.2×10^{-8}	1.9×10^{-8}‡	6.3×10^{-8}
Monticello	480	513	558	NA	NA	NA
Polson	197	250	301	1.5×10^{-7}	4.2×10^{-7}‡	8.7×10^{-7}
Sacramento	290	312	327	NA	NA	NA
	395	610	718			
Albany	347	432	480	1.4×10^{-8}	4.0×10^{-8}§	1.1×10^{-7}
Cedar Rapids	452	486	531	5.1×10^{-9}	1.6×10^{-8}§	5.1×10^{-8}
				5.1×10^{-9}	1.6×10^{-8}‡	5.1×10^{-8}
Omaha	204	235	267	4.5×10^{-7}	1.5×10^{-6}‡	9.4×10^{-6}
	302	350	399			

† At the end of construction.
‡ Soil barrier layer in cover with composite barrier layer.
§ Cover with soil barrier.
¶ Geosynthetic clay liner.
# Not applicable.

are through June 2003 unless otherwise noted. Individual years from 1 July through 30 June represent a water year. Continuous data records for each site can be found in Albright and Benson (2004).

Surface Runoff

Surface runoff generally was a small fraction of the water balance and ranged from 0.0 to 10.2% of precipitation and averaged 3.8% (Tables 3 and 6). Comparisons were made to determine if the fraction of the water balance comprising runoff was affected by key variables generally considered to influence runoff from landfill covers (i.e., slope, cover type, or climate). These comparisons are shown in Fig. 6 in terms of box plots. The center line in each box represents the median, the outer edges of each box represent the interquartile range (25th–75th percentiles), and the outermost lines ("whiskers") represent the 5th and 95th percentiles. We conducted *t* tests at the 5% significance level to determine if the means of the groups being compared are statistically different (see *t* statistics in Fig. 6). In each case, there is no statistically significant difference (i.e., $p > 0.05$) between the means of the data sets being compared. That is, the mean surface runoff, as a fraction of precipitation, is statistically independent of the slope of the cover, the type of cover, or the climate.

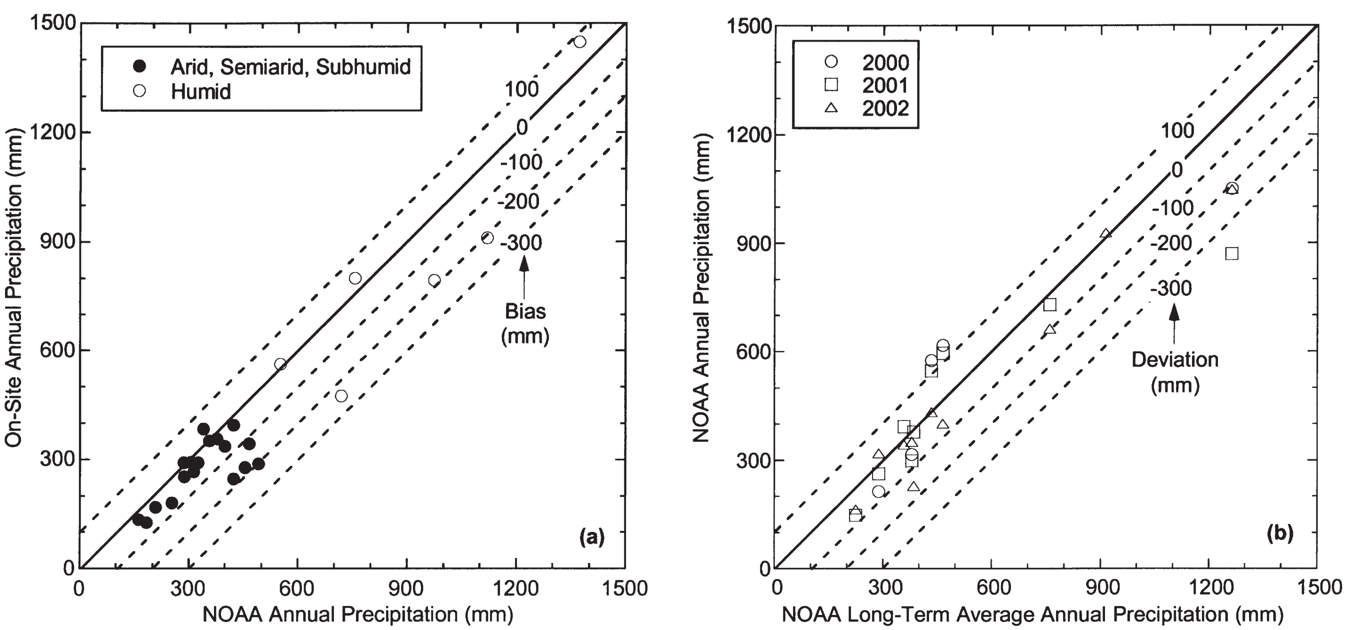

Fig. 5. (a) Comparison of precipitation measured on-site and by nearby National Oceanic and Atmospheric Administration (NOAA) stations and (b) comparison of annual precipitation and long-term average annual precipitation reported by nearby NOAA stations.

Table 6. Summary of water balance data for alternative covers.

Site	Duration	Slope	Total precipitation (1 July–30 June) 1999–2000	2000–2001	2001–2002	2002–2003	Surface runoff	Evapotranspiration	Total	Percolation (1 July–30 June) 1999–2000	2000–2001	2001–2002	2002–2003	Average
	d	%	mm							mm/yr				
							Monolithic barrier							
Altamont	781	5	NA†	NF‡	291.1	394.2	84.1 (9.3§)	770.1 (85.3)	4.0 (0.4)	NA	NF	1.5 (0.5)	2.5 (0.6)	1.5 (0.4)
Apple Valley	251	5	NA	NA	NF	148.0	0.0 (0.0)	79.5 (0.5)	0.0 (0.0)	NA	NA	NF	0.0 (0.0)	0.0 (0.0)
Boardman (1220 mm)	747	25	NA	NF	134.4	125.5	0.0 (0.0)	348.6 (103.9)	0.0 (0.0)	NA	NF	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Boardman (1840 mm)							0.0 (0.0)	398.5 (118.8)	0.0 (0.0)	NA	NF	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Sacramento (1080 mm)	1228	5	517.9	356.6	277.1	245.1	105.5 (7.6)	1064.2 (77.1)	101.5 (7.4)	0.0 (0.0)	1.4 (0.4)	96.2 (34.7)	3.9 (1.7)	26.8 (7.4)
Sacramento (2450 mm)							66.9 (4.8)	1089.4 (78.9)	8.5 (0.6)	0.0 (0.0)	0.0 (0.0)	8.5 (3.1)	0.0 (0.0)	2.2 (0.6)
Albany	985	5	NF	909.0 (1078.5¶)	798.3 (1038.6¶)	1447.8 (1455.9¶)	18.5 (0.5)	3445.6 (92.0)	394.0 (10.5)	NF	134.1 (12.4)	3.1 (0.3)	218.3 (15.0)	123.3 (10.5)
Cedar Rapids	621	5	NA	NF	NF	791.2	59.9 (3.1)	1463.7 (76.8)	351.6 (18.4)	NA	NF	NF	157.1 (20.0)	159.6 (18.4)
							Capillary barrier							
Helena	1169	5	NF	180.9	265.2	252.0	50.1 (6.6)	680.2 (89.5)	0.0 (0.0)	NF	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Marina	947	25	NF	288.0	335.0	343.7	0.0 (0.0)	902.5 (93.3)	159.9 (22.9)	NF	44.7 (15.5)	64.2 (19.2)	51.1 (14.9)	52.0 (16.5)
Monticello	872	5	NA	343.7	167.6	382.8	10.2 (1.2)	938.3 (104.7)	0.0 (0.0)	NA	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Omaha (1060 mm)	815	25	NA	NF	561.4	474.5	88.7 (6.0)	1258.9 (84.6)	155.3 (10.4)	NA	137.0 (22.5)	3.4 (0.6)	50.9 (10.7)	56.9 (10.4)
Omaha (1360 mm)							56.5 (3.8)	1311.9 (88.1)	90.7 (6.1)	NA	78.6 (12.9)	4.2 (0.7)	28.7 (6.0)	33.3 (6.1)
Polson	1137	5	NF	350.0	292.1	290.6	17.8 (1.6)	1133.2 (1.0)	0.2 (0.0)	NF	0.2 (0.1)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)

† Not applicable.
‡ Data not available for a full year.
§ Percentages of precipitation are given in parentheses.
¶ Total precipitation for Albany includes irrigation.

The absence of a slope effect may reflect the relatively small scale of the test sections relative to the scale associated with a typical landfill cover (200 m^2 vs. multiple ha). Nevertheless, given the dramatically different slopes being compared (5 vs. 25%), absence of a slope effect suggests that the slope of landfill covers may be less important to runoff than is believed in solid waste engineering practice. The absence of a climate effect may reflect the relatively short monitoring period (approximately 3 yr) at most sites. However, the box plots shown in Fig. 6c suggest that surface runoff is a slightly greater fraction of precipitation at humid sites.

The similarity of the runoff fractions for conventional and alternative covers also suggests that resistive barrier layers do not promote runoff. Surface runoff from landfill covers was controlled more by conditions at the soil–atmosphere interface, particularly the hydraulic conductivity of the surficial soil and the density of the vegetation, than by the presence of a resistive barrier layer at depth. For example, the covers being monitored in Albany, GA (conventional clay barrier cover with grasses and alternative monolithic barrier with grasses and trees) were constructed with similar soils. The surfaces of the two test sections differed in vegetation coverage and density (e.g., peak leaf area index [LAI] = 2.2 for grasses on alternative and 0.2 for conventional) because amendments were added to the surface layer of the alternative cover to facilitate vegetative growth (Bolen et al., 2001). The alternative cover also had a rougher surface because trenches were excavated for the poplar tree cuttings. Both the rough surface and denser vegetation on the alternative cover provided greater resistance to surface flow, resulting in less surface runoff for the alternative cover (0.5% of precipitation) than the conventional cover (10% of precipitation) (Tables 3 and 6). A gradual trend of lower annual surface runoff was also observed at the sites in Marina, CA; Omaha, NE; Polson, MT; and Cedar Rapids, IA (Albright and Benson, 2003), which may reflect increasing maturity of the plant communities at these sites, and the importance of surface features in controlling runoff.

Lateral Drainage

Lateral drainage was measured for the nine conventional covers where a drainage layer was placed directly on top of the resistive barrier layer. As with surface runoff, lateral drainage typically was a small fraction of the water balance (0–5%, average = 2% of precipitation) (Table 3). More lateral drainage occurred (on an absolute basis) at sites with greater precipitation. Comparison of the average fractions indicates that lateral drainage was a larger fraction of the water balance at the humid sites relative to the arid, semiarid, and subhumid sites (3 vs. 1.5%). A statistical analysis was not conducted to evaluate the significance of this difference due to the small number of samples.

The small fraction of the water balance comprised by lateral drainage indicates that the hydrology of a conventional cover is controlled largely by processes above the barrier layer. This finding is consistent with

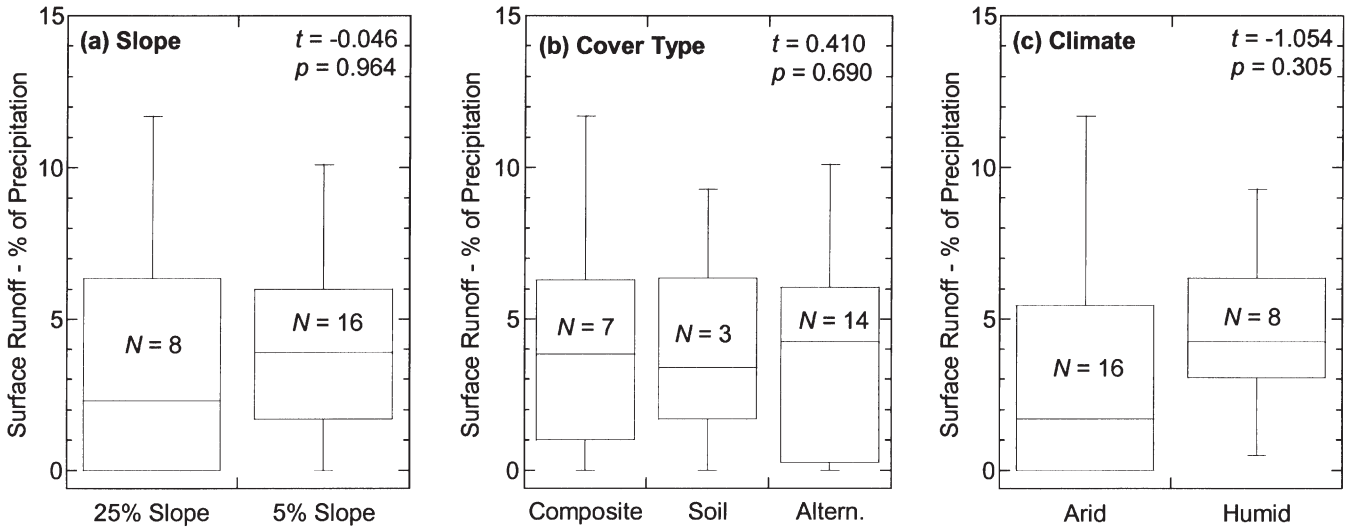

Fig. 6. Comparison of surface runoff quantities: (a) covers with 5 and 25% slope; (b) conventional and alternative covers; and (c) humid vs. arid, semiarid, and subhumid climates. The values of *t* (*t* statistic) and *p* (probability) are from *t* tests conducted to determine if the means of the groups are statistically different at the 0.05 significance level.

the supposition that surface runoff is controlled by conditions at the immediate surface rather than by the type of barrier used in the cover. Nevertheless, the amount of water diverted as lateral flow in the drainage layer was significant in the field experiments. Without the barrier and drainage layers, much of the water diverted by the drainage layer would become percolation.

Percolation

Conventional Covers with Composite Barriers

Composite covers were tested at Altamont, Apple Valley, and Marina, CA; Boardman, OR; Polson, MT; Omaha, NE; and Cedar Rapids, IA. Two of the test sections contained a composite barrier consisting of geomembrane and geosynthetic clay liner (Apple Valley, Boardman). The others employed a fine-grained soil layer beneath the geomembrane.

The average percolation rate (over the study period) from each composite cover was less than 1.4% of precipitation at all sites except the cover at Marina, where percolation was 7% of precipitation. For the composite covers at sites in arid, semiarid, and subhumid locations, the average individual percolation rates were no more than 1.5 mm/yr (except at Marina, 23.1 mm/yr) and in most years no percolation was transmitted (Table 3). In contrast, percolation was transmitted each year at the humid sites and the percolation rates were higher (6–12 mm/yr). These percolation rates are comparable with rates reported for composite covers by Dwyer (2001) in semiarid Albuquerque, NM, USA (0.04 mm/yr) and Melchior (1997) in humid Hamburg, Germany (3.1 mm/yr). Koerner (2003) indicates that Dwyer placed too many defects in the geomembrane of his cover with a composite barrier, and suggests that lower percolation rates occur under more realistic field conditions. Nevertheless, the percolation rates reported by Dwyer (2001) are on the same order as those measured in this study and by Melchior (1997) for conventional covers with composite barriers.

Percolation from the composite covers was closely linked to precipitation events at all sites, especially events resulting in surface runoff and lateral drainage. An example of the coincidence of percolation and lateral drainage is shown in Fig. 7 for the composite cover at Cedar Rapids in June and July 2002. Sustained periods of lateral drainage lag slightly behind periods of heavy precipitation due to the gradual drainage of water from the relatively thin (300 mm) cover soils overlying the drainage layer. A sustained period of percolation lags slightly behind the onset of lateral drainage and continues after lateral drainage has ceased. A similar percolation response was observed for the composite cover in humid Omaha and the composite covers in semiarid and subhumid Altamont, Marina, and Polson. For example, periods of very heavy rainfall in May 2001 and 2003 resulted in lateral drainage and nearly all of the percolation that was transmitted from the composite cover in Omaha, NE (Albright and Benson, 2004).

The relatively rapid transmission of percolation from the composite covers following precipitation events was not expected given that only a single small hole was included in the geomembrane. This behavior may indicate that the soil barriers in the composite covers are essentially field-saturated (i.e., any water that enters the soil barrier displaces water as percolation). The soil barriers were compacted at relatively high water contents (the degree of saturation at placement was on the order of 90%; Bolen et al., 2001) so as to achieve low saturated hydraulic conductivity. Data from the TDR probes also indicate that the water content of the soil barriers changed little following installation. Alternatively, preferential flow through the soil barriers may have occurred, although no evidence was collected to suggest that weathering or other processes that would result in preferential flow paths damaged the soil barri-

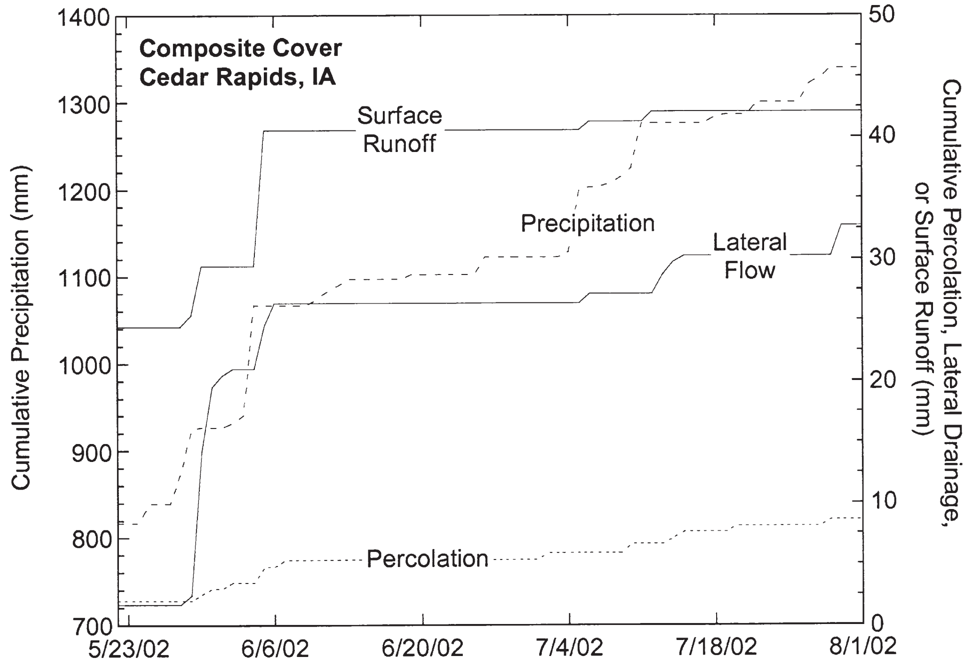

Fig. 7. Precipitation, surface runoff, lateral drainage, and percolation for the composite cover at Cedar Rapids, IA, USA, between 22 May 2002 and 1 Aug. 2002.

ers. Studies where composite barriers in landfill covers have been exhumed have shown that geomembranes are very effective in protecting soil barriers from weathering provided the geomembrane is surcharged, or weighted, with overlying soils (Corser and Cranston, 1991; Melchior, 1997; Benson, 2001).

The high percolation rate from the cover in Marina was not expected and may have been due to punctures in the geomembrane. A cushion (geotextile or sand) was not placed on the geomembrane before placing the overlying cover soils and these soils contained cobbles and other debris. The geomembrane has not been inspected for defects since construction and the presence of defects cannot be confirmed. Nevertheless, the coincidence of higher than anticipated percolation rate and atypical construction practice suggests that quality control during construction of final covers can influence hydrologic performance.

Conventional Covers with Soil Barriers

Conventional covers where the barrier layer is compacted fine-grained soil were monitored at two humid sites (Cedar Rapids, IA, and Albany, GA) and one arid site (Apple Valley, CA). The covers at the humid sites transmitted percolation at an average rate of 195 mm/yr (Albany, 17% of precipitation) and 52 mm/yr (Cedar Rapids, 6% of precipitation), both of which were much higher than anticipated (<30 mm/yr) for covers having a soil barrier with saturated hydraulic conductivity $\leq 10^{-7}$ cm/s. No percolation was transmitted from the conventional cover with a soil barrier at Apple Valley, CA. However, the cover at Apple Valley was only in place for approximately one year.

Preferential flow is believed to be responsible for the high percolation rates at Albany, GA, and Cedar Rapids, IA. Percolation from the conventional cover at Albany increased immediately after a 6-wk drought in fall 2000. During this period the soil profile, including the soil barrier, dried appreciably for the first time since construction (Fig. 8a) and desiccation cracks formed in the soil barrier layer (Albright and Benson, 2003). Before the drought, the percolation rate was relatively constant (reflecting the damping of flows expected by a layer with low saturated hydraulic conductivity) and showed little temporal response to precipitation events. In contrast, when precipitation resumed after the drought in mid-November 2000, percolation was transmitted within hours of precipitation events. The percolation rate also exhibited a stair-step pattern that suggests preferential flow. The percolation rate after the drought increased to 326 mm/yr on average and never returned to the pre-drought rate (77 mm/yr).

A similar change in behavior was observed at Cedar Rapids, but the exact time of the change is obscured by a gap in the data that occurred between October 2001 and March 2002 due to a datalogger failure. The more recent data show a close temporal relation between precipitation and percolation events similar to the site at Albany. For example, three periods of heavy precipitation are shown in Fig. 8b (labeled A, B, and C). Each was quickly followed by a high rate of percolation with little change in soil water storage. These observations may be the result of either preferential flow or pulses of water moving through cover soils at relatively high water content (about 90% of field capacity).

It is unknown whether preferential flow paths in the soil barriers will close over the long term. However, other studies suggest that these flow paths are likely to persist. Melchior (1997) reports that preferential flow regularly occurred through desiccation cracks in the clay

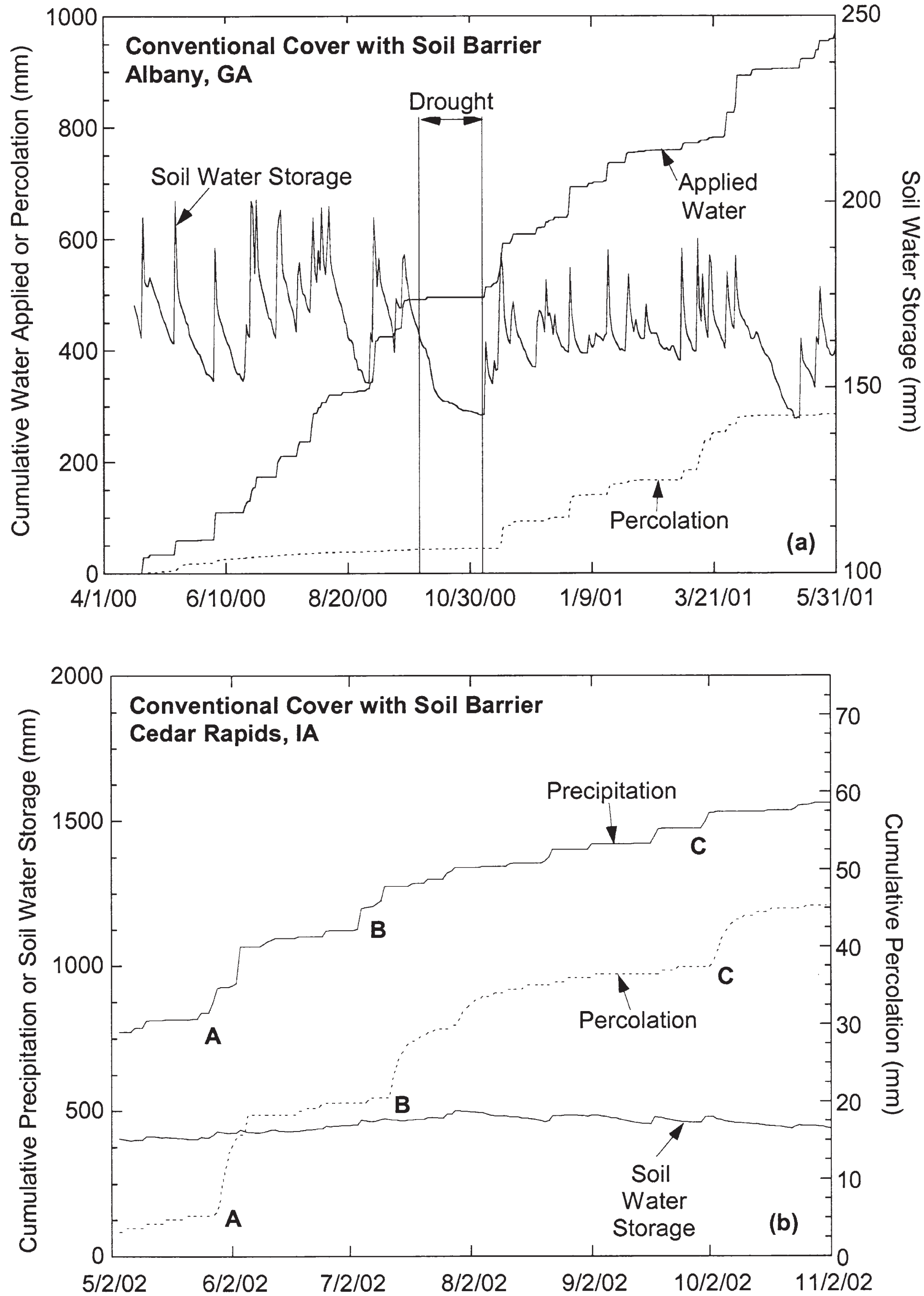

Fig. 8. Water balance data for conventional covers with soil barriers: (a) Albany, GA, and (b) Cedar Rapids, IA. At Albany, applied water is the sum of precipitation and irrigation to establish vegetation. Percolation data ceased at Albany in late 2002 due to a clog in the collection system. No repair was made. Large precipitation events at Cedar Rapids are labeled A, B, and C.

barrier of a conventional final cover for 4 yr after the cracks formed during a dry summer. Hydraulic conductivity tests on desiccated clays conducted by Albrecht and Benson (2001, 2002) over a period of approximately 1 yr have also shown that preferential flow paths in clays persist even with continuous access to water. Albrecht and Benson (2001, 2002) describe observations of soil barriers in landfill covers in Minnesota and Wisconsin, USA, where extensive cracking of the barrier occurred. Roots were present in many of the cracks and moisture was present on the crack surfaces, suggesting that preferential flow through the cracks had occurred for an extended period. No evidence was found of infilling or other mechanisms that would impede or eliminate preferential flow through the barrier over time.

Alternative Covers: Humid Climates

Alternative covers at the humid sites transmitted the most percolation of all covers in terms of percolation rate and as a percentage of precipitation. Average percolation rates ranging between 33.3 mm/yr (thicker cap-

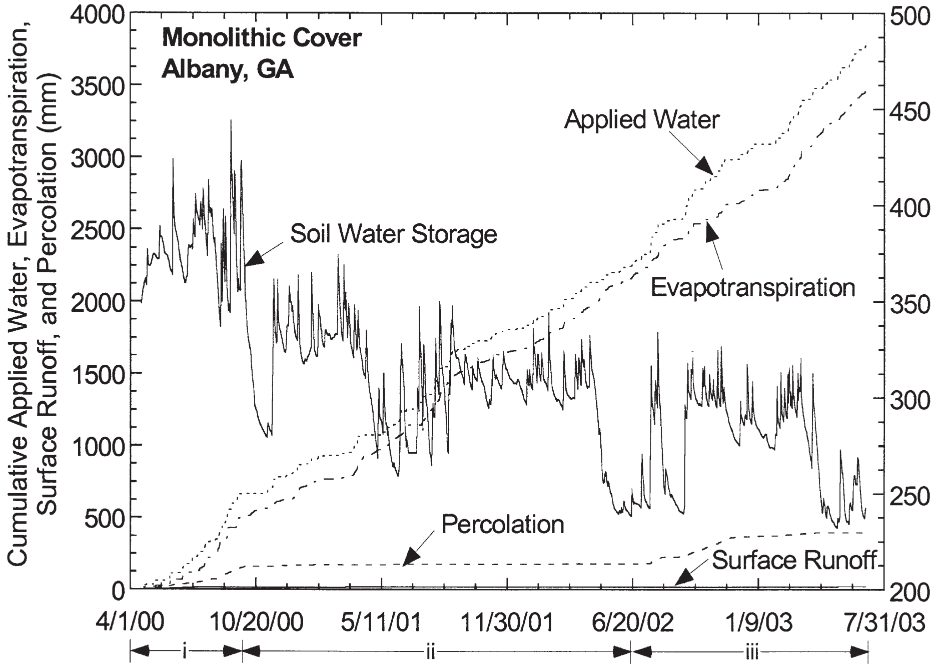

Fig. 9. Water balance data for monolithic alternative cover at Albany, GA, showing three distinct hydrologic periods indicated by the arrows at the bottom of the figure: (i) an initial 6-mo period characterized by high percolation rates and high soil water storage before the development of the poplar trees; (ii) a 21-mo period of little percolation characterized by rapid development of the poplar trees and drying of the soil profile in response to transpiration; and (iii) a final period, initiated by extensive drying of the soil profile in response to drought and transpiration, which was characterized by percolation rates equal to those recorded during the first 6 mo.

illary barrier in Omaha, NE) and 159.6 mm/yr (monolithic cover in Cedar Rapids, IA) were recorded. These percolation rates correspond to 6.1% (Omaha) and 18.4% (Cedar Rapids) of precipitation. Some of the alternative covers in humid climates behaved in accordance with water balance principles (i.e., percolation was transmitted when the storage capacity was exceeded). For example, nearly all of the percolation transmitted by the two capillary barriers at Omaha, NE (112 mm of a total of 155 mm for the thinner cover, 81 mm of 91 mm for the thicker cover) occurred when the soil water storage exceeded the calculated storage capacity during intense spring rainfalls in May 2001 and 2003. In contrast, percolation from the monolithic cover at Albany, GA, occurred regardless of the status of the soil water storage.

The data from Albany suggest that the behavior of alternative covers in humid climates is likely to change in response to maturation of the plant community and pedogenesis. These effects are evident in Fig. 9. Three distinct hydrologic periods are evident (labeled as i, ii, and iii in Fig. 9): (i) an initial 6-mo period characterized by high percolation rates and high soil water storage before the development of the poplar trees; (ii) a 21-mo period of little percolation characterized by rapid development of the poplar trees and drying of the soil profile in response to transpiration; and (iii) a final period, initiated by extensive drying of the soil profile in response to drought and transpiration, which was characterized by percolation rates equal to those recorded during the first 6 mo. During the third period, percolation followed soon after precipitation events, suggesting that desiccation cracks or root channels penetrated through the entire cover during the previous drying period.

Alternative Covers: Arid, Semiarid, and Subhumid Climates

Very low percolation rates (<1.5 mm/yr and 0.2% of precipitation, on average) were recorded for 7 of the 10 alternative covers located at the arid, semiarid, and subhumid sites. Less than 0.1 mm of percolation was transmitted from 5 of the 10 covers throughout the monitoring period. Greater percolation rates were transmitted from the two covers in semiarid Sacramento, CA (up to 27 mm/yr and 7% of precipitation, on average) and from the cover in coastal semiarid Marina, CA (52 mm/yr and 16% of precipitation, on average).

The small amounts of percolation transmitted at Altamont, CA, and Polson, MT (Table 6) occurred in one (Polson) or two (Altamont) events that coincided with heavy precipitation and surface runoff events as well as soil water storage well below the storage capacity. An example of an event of this type of event is shown in Fig. 10 using data from the Altamont site in December 2001. Heavy rainfall (51 mm over 7 d) resulted in percolation when the soil water storage was beginning to increase, but was well below the calculated storage capacity (373 mm). Percolation under these circumstances suggests that preferential flow or localized ponding occurred that was not detected by the TDR probes.

The large amounts of percolation transmitted from the alternative covers in Sacramento, CA, and Marina, CA, were not anticipated during design. There are several reasons that may explain why these alternative covers transmitted more percolation than the other alternative covers in similar climates. Quantity and distribution of precipitation may be one factor. Sacramento and Marina received more than 400 mm/yr of precipitation,

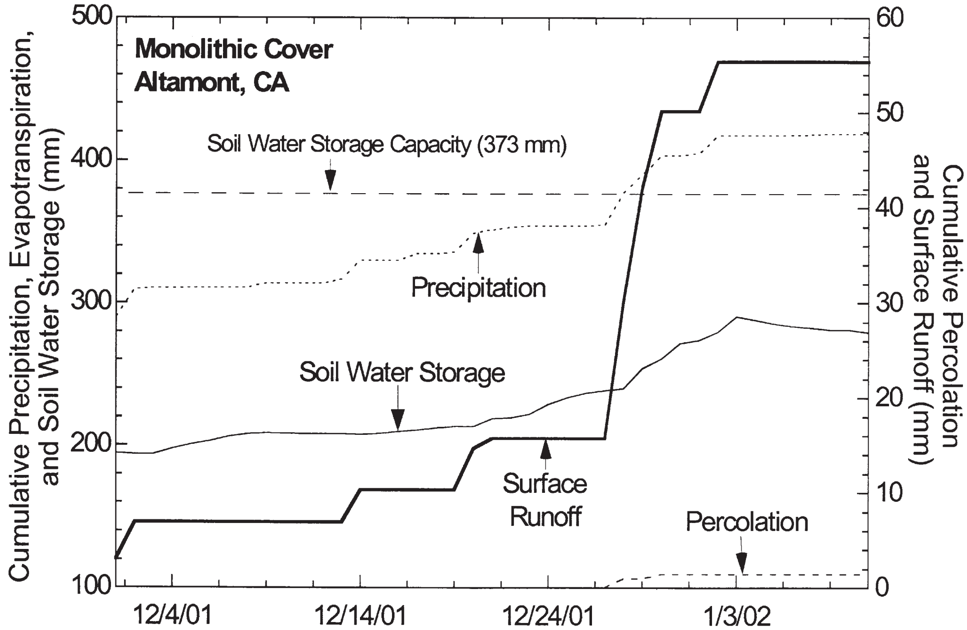

Fig. 10. Water balance data for monolithic alternative cover at Altamont, CA, during December 2001 and January 2002 showing percolation occurring when soil water storage begins to climb after heavy precipitation in December 2001.

whereas all other sites in similar climates received less than 400 mm/yr of precipitation. Moreover, both Sacramento and Marina received most of their precipitation in the winter months (October through March), when the evapotranspiration rate is lowest, whereas some of the other semiarid sites (e.g., Helena) received more precipitation in the summer than in the winter.

Deficiencies in the covers at Marina and Sacramento also probably contributed to the higher percolation rates. The deficiency at Sacramento appears to be tied to the transpiration capacity of the vegetation. Most of the percolation transmitted from the covers in Sacramento occurred in Water Year 2001–2002 (Table 6). This water year had the lowest annual precipitation during the study, but also followed a growing season during which the vegetation did not remove water from the covers effectively (Fig. 11a). Only 94 mm of water was removed from storage during the 2000 growing season compared with 224 mm in 2001, even though more (45 mm) water was available in 2001. As a result, there was insufficient storage available for the infiltration received during the winter of 2001–2002, which resulted in the soil water storage exceeding the storage capacity and transmission of percolation. In subsequent years, the vegetation was more effective in removing water and limited percolation to smaller quantities. Nevertheless, the vegetation at the Sacramento site appeared to be capable of removing about 250 mm of water from storage each year. The average annual precipitation in Sacramento is 434 mm (Table 1), 65% of which (282 mm) occurs in the winter months. Runoff comprised approximately 6% of precipitation (28 mm), resulting in 254 mm of infiltration to store during an average winter season. Thus, percolation from the covers in Sacramento should be expected after wet winters, even if the vegetation transpires water as expected.

At Marina, the soil water storage capacity of the cover appears to have been too low to store the infiltration that occurred during each wet season, resulting in soil water storage exceeding the storage capacity and transmission of percolation. Each year, the percolation rate from the alternative cover increased dramatically once the soil water storage reached approximately 300 mm (Fig. 11b). This effective soil water storage capacity (300 mm) was lower than the computed mean soil water storage capacity (385 mm, Table 5), which suggests that significant differences exist between the hydraulic properties of cover soils in situ and those measured in the laboratory. To evaluate this effect on a program-wide basis, a comparison was made between the annual percolation rate and the ratio of peak annual soil water storage (S_p) to the mean soil water storage capacity (S_c). This comparison is shown in Fig. 12. All of the sites where $S_p/S_c \leq 0.7$ (vertical line in Fig. 12) have annual percolation rates less than 1.5 mm/yr. The recent data from the monolithic cover in Albany, GA, are an exception, because percolation at this site was probably dominated by preferential flow for much of the experimental period. This threshold can be used as a conservative measure of the effective storage capacity of alternative cover soils (i.e., 70% of the storage capacity computed from the SWCC). However, at some sites this criterion will result in over design because many of the sites with $S_p/S_c > 0.7$ had percolation rates less than 1.5 mm/yr.

DISCUSSION

Lysimeter Issues

Drainage was measured directly using pan or basin-type lysimeters for all ACAP tests. For reasons given by Gee and Hillel (1988), lysimeters are generally superior to other methods available including the use of water content and water potential sensing devices, micrometeorological methods, and water balance modeling, where

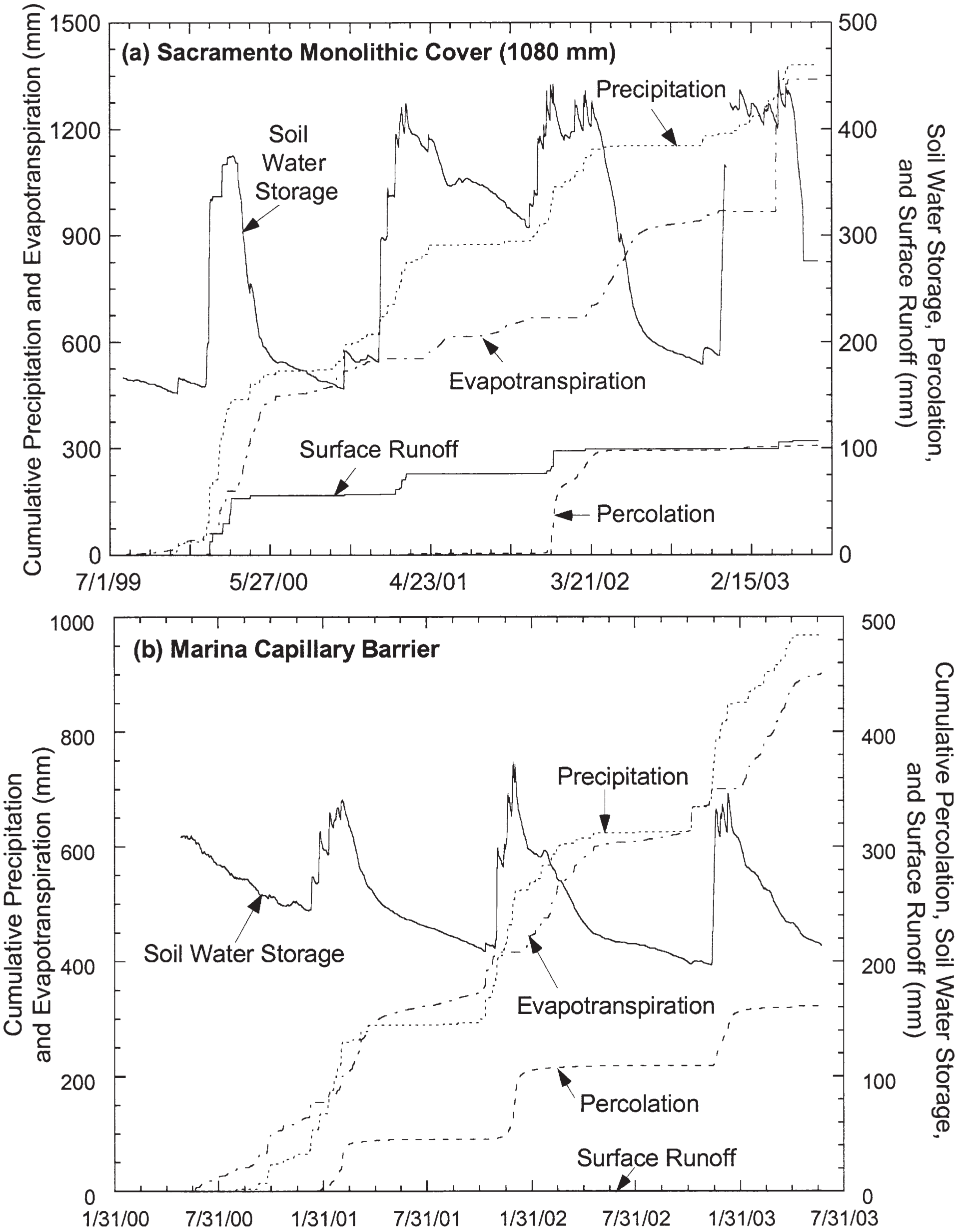

Fig. 11. Water balance data for (a) thinner monolithic cover at Sacramento, CA, and (b) capillary barrier at Marina, CA.

uncertainties of an order of magnitude in drainage are not uncommon. For pan (basin) lysimeters, a capillary barrier (fine capillary pores over coarse) occurs at the lower boundary (i.e., bottom of the lysimeter) and the soil above must approach saturation before drainage occurs. If deep enough, there is no effect of the lysimeter bottom on evapotranspiration, because the soil can act as an infinitely long column that drains well below the root zone. However, if shallow enough, this interface can give rise to elevated water contents within the reach of roots, potentially increasing evapotranspiration. The ACAP lysimeters were designed with a fixed root zone separated from the lysimeter bottom by an additional layer of soil to minimize the capillary barrier effect and to provide representative estimates of drainage from the alternative-cover systems tested. The particular features to control this effect on the alternative-cover lysimeters are described in the Materials and Methods section. It was reasoned that with a controlled root zone, the drainage produced in the lysimeters is a conservative estimate of actual drainage from a full-scale alternative cover.

Long-Term Issues and Extrapolation

The data presented here provide only a snapshot of cover performance for the monitored time period. There are several factors that could result in changes in the covers over time. Climatic variations during the relatively short monitoring period did not include conditions where precipitation was greatly above normal (resulting in unprecedented volumes of water to manage) or greatly below normal (causing unprecedented weathering of the cover soils). The episodic storm that may produce the most

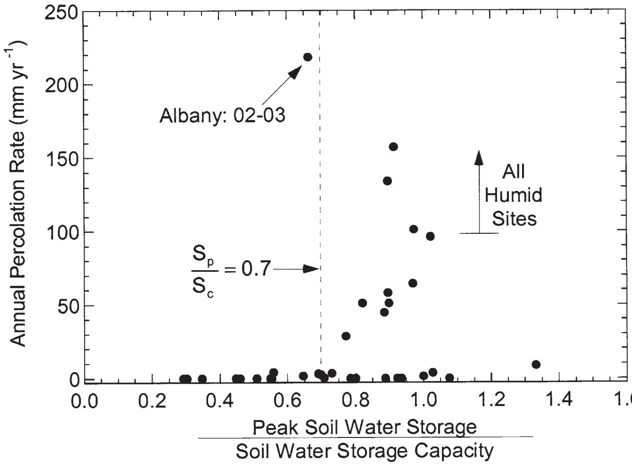

Fig. 12. Annual percolation rate as a function of ratio of annual peak soil water storage to soil water storage capacity.

net infiltration also was not realized at most sites. Gradual and catastrophic changes in vegetation can also affect cover performance by affecting evapotranspiration and erosion potential (Gee et al., 1992, 1998). The vegetation that is planted and growing in the first several years may not be the persistent climax species. Fire, drought, and disease can also alter the vegetation. Pedogenesis may also affect the hydraulic properties of the covers soils and can result in preferential flow, as has already been observed at some of the ACAP sites.

These issues indicate that caution must be used when making extrapolations based on the information presented in this paper, both temporally and spatially. Gee et al. (1998) describe examples where extrapolations resulted in failure and success. In one example, two capillary barriers and one monolithic cover were successfully tested in Los Alamos, NM. However, in a subsequent test in Ogden, UT, all three cover designs transmitted percolation at excessive rates because the covers had inadequate capacity to store infiltration during spring snow melts (Hakonson et al., 1994). Such snow melts are common in Ogden, but not in Los Alamos. More careful consideration of differences in climate, and their effect on hydrology of covers, may have avoided this failure. Another example is a successful field test in Ogden, UT, of a capillary barrier originally developed for the Hanford Site near Richland, WA (Gee et al., 1998). No percolation has been transmitted from this cover in Ogden since its construction in 1994, primarily because the capillary barrier developed at Hanford has a large storage capacity (>500 mm) (Ward and Gee, 1997). The large storage capacity is capable of storing infiltration from the annual snow melts in Ogden without transmitting percolation.

Added to these uncertainties in cover design are those inherent in the use of numerical simulation methods to predict the performance of landfill final covers. A recent study (Scanlon et al., 2002) compared simulated and field-measured fluxes and demonstrated the inability of current codes to predict performance with the accuracy required for regulatory permitting activities.

CONCLUSIONS

Water balance data from 24 test sections from the Alternative Cover Assessment Program (ACAP) are presented in this paper. These test sections, which simulated conventional and alternative landfill covers, were located at 11 locations throughout the United States. Each test section was instrumented for key components of the water balance (precipitation, runoff, lateral drainage, soil water storage, and percolation) as well as meteorological monitoring. Soils and vegetation were characterized at each site.

In most cases surface runoff and lateral drainage comprised a small fraction of the water balance (runoff: 0–10%, lateral drainage: 0–5%). The runoff fraction was relatively insensitive to type of cover (conventional vs. alternative), cover slope, and climate, although comparison of the data from the humid and arid, semiarid, and subhumid sites suggests that runoff was a slightly larger fraction of the water balance in humid climates.

Conventional covers with composite barriers (i.e., covers containing a soil barrier overlain by a geomembrane) generally were effective in limiting percolation. Average percolation rates for these covers were less than 12 mm/yr in humid climates (1.4% of precipitation) and 1.5 mm/yr (0.4% of precipitation) in arid, semiarid, and subhumid climates. The only exception was the composite cover at semiarid Marina, CA, which had an average percolation rate of 23 mm/yr (7% of precipitation). The high percolation rate at Marina was possibly the result of defects in the geomembrane incurred during construction.

Conventional covers with soil barriers only (i.e., no geomembrane) generally were not effective. Average percolation rates for these covers in humid climates ranged between 52 and 195 mm/yr (6.0–17% of precipitation). Preferential flow through cracks or other defects in the soil barrier was likely the primary contributor to percolation at these sites. A conclusion cannot be drawn at this time regarding the behavior of conventional covers with soil barriers in arid climates. Only one field site with a soil barrier was located in an arid, semiarid, and subhumid climate and the data record for this site is too short to draw an inference.

The alternative covers in humid climates also appeared ineffective in achieving low percolation rates. Average percolation rates between 123 and 160 mm/yr (10–18% of precipitation) were recorded for the monolithic covers with trees, whereas capillary barriers with grasses transmitted percolation at rates ranging between 33 and 57 mm/yr (6–10% of precipitation). In contrast, the alternative covers in the arid, semiarid, and subhumid sites were generally effective with performance comparable to that attained from conventional covers with composite barriers. Percolation rates for these alternative covers generally were less than 1.5 mm/yr (0.4% of precipitation).

The data from alternative covers indicate that these covers are not always successful in drier climates. At two sites in California (Sacramento and Marina), relatively high percolation rates were recorded. The high percolation rates as these sites, which had the highest annual precipitation of the arid, semiarid, and subhumid sites that were monitored, appear to be related to inadequate transpiration capacity and storage capacity. These unexpected conditions illustrate the need to carefully examine the attributes of vegetation and the storage capacity of cover soils at locations where greater precipitation needs to be managed. Analysis of the data from the ACAP sites suggests that the storage capacity effective in the field can be conservatively estimated as 70% of the storage capacity that is computed based on soil water characteristic curves measured in the laboratory.

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