Field Hydrology of Water Balance Covers for Waste Containment

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Abstract: A study was conducted at 12 sites across the United States to evaluate field-scale hydrology of landfill final covers using water balance methods to control percolation. The sites were located in climates ranging from arid to humid, with annual precipitation varying from 119 to 1,263 mm. Fifteen test sections were constructed with large (10×20 m) drainage lysimeters for continuous and direct monitoring of the water balance over a period of 3–6 years. Monolithic and capillary barrier designs were used for water storage, and plant communities consisting of grasses, grasses and shrubs, or grasses and trees were used to promote evapotranspiration. Data from these test sections are analyzed along with data from 10 other sites in the literature to draw general inferences regarding the hydrology of water balance covers. Percolation ranges from 0 to 225 mm/year (0–34% of precipitation) on an average annual basis and is shown to be affected by annual precipitation, preferential flow, and storage capacity of the cover. Evapotranspiration is the largest component of the water balance (>60% of precipitation) and varies with water availability from precipitation, energy demand as characterized by potential evapotranspiration, and type of plant community. Surface runoff is the smallest fraction (<16% of precipitation) and depends on the saturated hydraulic conductivity of the surface soils, intensity of precipitation, and the occurrence of snowmelt and frozen ground. **DOI: 10.1061/(ASCE)GT.1943-5606.0001195.** © *2014 American Society of Civil Engineers.*

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Introduction

Water balance covers are earthen final covers used for sustainable waste containment that rely on the capacity of fine-textured soils to store infiltration during wetter periods and evapotranspiration (ET) to remove the stored water during drier periods (Benson and Khire 1995; Albright et al. 2004, 2010; Bohnhoff et al. 2009). Water balance covers promote sustainability because they are constructed with natural materials generally available on site or nearby, function harmoniously with local hydrological processes, and can be constructed by local labor sources without specialized equipment (Benson and Bareither 2012).

Fine-textured soils are used for water balance covers because they can store appreciable amounts of water with minimal drainage. The nomenclature *fine textured* refers to soils that are similar in hydrological behavior to silts and clays but may or may not be classified as fine-grained soils (e.g., silty sands and clayey sands are coarse grained but may behave as fine-grained soils from a hydrological perspective). Most soils characterized as fine textured have at least 20% fines. However, unlike fine-grained soils, no specific engineering definition exists for fine-textured soil. Percolation is transmitted from the base of the cover when water storage capacity of the fine-textured soil is exceeded or if preferential flow occurs (Benson 2000). Percolation can be controlled to an acceptable quantity by selecting a soil profile that provides sufficient storage capacity to retain infiltration and a vegetation community with sufficient transpiration capacity to remove the stored water.

Monolithic or capillary barrier designs are commonly used in water balance covers. Monolithic barriers consist of a layer of engineered fine-textured soil functioning as a water storage layer (Benson and Khire 1995). Monolithic water balance covers generally are constructed from a single type of fine-textured soil, but two or more fine-textured soils are used in some cases depending on the availability of borrow soil. Capillary barrier covers consist of layers of contrasting soil texture, ranging from a simple two-layer design with a fine-over-coarse configuration (Khire et al. 1995, 1997, 1999) to multiple-layer designs consisting of finer-textured and coarser-textured soils (Morris and Stormont 1997; Nyhan et al. 1997). The contrast in texture at the interface results in an abrupt transition in hydraulic properties that enhances the storage capacity of the finer layer and can divert water laterally (Stormont and Morris 1998; Khire et al. 2000). For both cover types, the uppermost 100–300 mm is a surface layer generally consisting of fine-textured topsoil to support vegetation establishment and growth.

The U.S. EPA's Alternative Cover Assessment Program (ACAP) was conducted to develop the technology needed to design and implement water balance covers with confidence (Albright et al. 2004, 2010). The ACAP included construction and monitoring of 15 large-scale field test sections simulating landfill final covers at 12 locations across the United States. Hydrologic monitoring of the test sections was conducted for 3–6 years. In this paper, data from the ACAP test sections, combined with data from other water balance cover studies in the literature, are used to draw inferences regarding the hydrology of water balance covers. The emphasis is on the primary components of the near-surface water balance: precipitation, surface runoff, ET, and

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percolation from the base of the cover. Implications for design are provided based on the lessons learned.

ACAP Test Sections

The test sections described in this study were located at 12 sites in eight states (shown as solid circles in Fig. 1) that represent a broad range of geography, climates, soils, and vegetation communities across the continental United States (Albright et al. 2004). Elevation and climate characteristics for each site are summarized in Table 1. The climatic designation for each site is based on the ratio of precipitation (P) to potential ET (PET) following definitions in UNESCO (1979). One site is arid, seven are semiarid, two are subhumid, and two are humid. This diversity in climates is evident in the range of average annual precipitation (119−1,263 mm/year) and the range in P/PET (0.06–1.10). Snowfall is common at eight sites. Freezing temperatures occur at all sites, but do not persist long enough to freeze the soil below the immediate surface at the sites in California, Oregon, and Georgia (Albright et al. 2004).

Cover Designs

Profiles of the ACAP water balance covers are shown in Fig. 2; nine were monolithic covers and six were capillary barriers. All of the capillary barriers used a simple two-layer fine-overcoarse design. Thickness of the storage layers ranged from 0.45 to 2.3 m (Table 2). A mixture of annual and perennial grasses was used at each site, shrubs were included at Apple Valley, California, Monticello, Utah, and Polson, Montana, and trees were used at Albany, Georgia and Cedar Rapids, Iowa (Table S1) (Bolen et al. 2001).

Materials and Methods

The ACAP test sections were constructed between July 1999 and December 2000 (except at Apple Valley, California, April 2002, and Underwood, North Dakota, June 2004). The test sections were built on slopes of 5 or 25% (Table 2) depending on the predominant condition at each site. Soils available onsite or from a nearby borrow area were used to simulate practice expected for construction of full-scale cover at each facility.

Each test section included a large (10 × 20 m) pan-type lysimeter (Fig. 3) for direct measurement of the water balance. Methods used to install the lysimeters are described in detail in Benson et al. (1999, 2001), and site-specific details are in Bolen et al. (2001). The lysimeters were constructed with textured 1.5-mm linear low-density polyethylene geomembrane. A geocomposite drainage layer (GDL) was placed between the lysimeter geomembrane and the cover soils to protect the geomembrane during soil placement and to rapidly transmit percolation to a volumetric measurement system. All welds were tested with air pressure and/or a vacuum box and a leak test that included filling the lysimeter sump area with water. A sump test pipe was also included to permit periodic leak testing of the sump (Benson et al. 1999). Extensive effort was undertaken to preclude sidewall flow, including mechanical compaction of soil in each lift adjacent to the sidewall and placement of a bentonite fillet around the perimeter of the sidewall after placing each lift. These efforts rendered sidewall flow highly unlikely (Benson et al. 1999, 2001).

The GDL at the base of the lysimeter can create a capillary break that affects flow. Recent field studies by Khire and Mijares (2010) and Mijares and Khire (2012), however, have shown that the impact of GDLs on the water balance is negligible, particularly when the overlying cover soils have a saturated hydraulic conductivity no more than 1×10^{-6} m/s (i.e., most in-service soils for water balance covers) (Benson et al. 2007, 2011). Nevertheless, strategies to minimize the potential impacts of a capillary break were incorporated into the ACAP lysimeter design. The GDL was overlain by interim cover soil mimicking the interim cover used at full scale, and a geosynthetic root barrier was installed over the interim cover soil to prevent root intrusion. This arrangement at the base of the lysimeter mimics the condition in the field, where finer textured interim cover soil is placed over coarser waste, creating

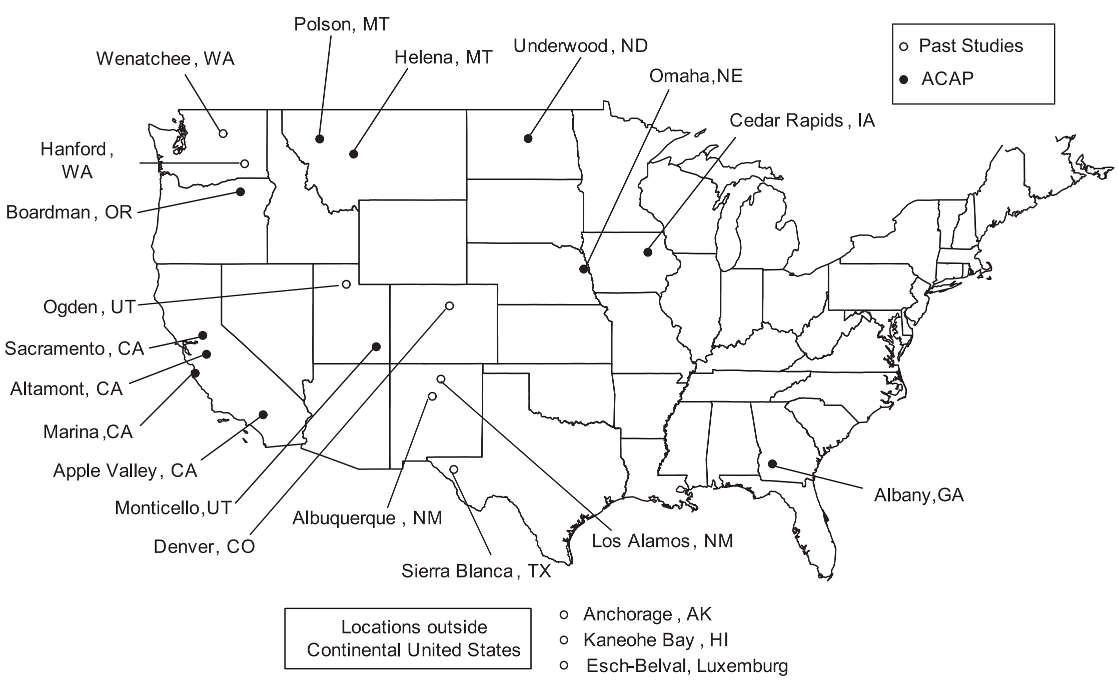

Fig. 1. Field sites in U.S. EPA's ACAP (solid circles) and past studies (open circles)

Table 1. Elevation and Climatic Characteristics of ACAP Covers

Site location	Elevation (m-msl)	Precipitation (mm/year)[a]	Snowfall (mm/year)	P/PET	Climate[b]	Monthly air temperature (low, high) (°C)	Relative humidity (low, high) (%)
Albany, Georgia	62	1,263	2	1.10	Humid	8, 33	51, 85
Altamont, California	227	358	2	0.31	Semiarid	2, 32	24, 95
Apple Valley, California	898	119	38	0.06	Arid	−1, 37	18, 77
Boardman, Oregon	95	225	185	0.23	Semiarid	−2, 32	30, 96
Cedar Rapids, Iowa	263	915	723	1.03	Humid	−8, 23	61, 80
Helena, Montana	1,204	312	1,288	0.44	Semiarid	−11, 28	30, 85
Marina, California	15	466	0	0.46	Coastal semiarid	6, 22	70, 92
Monticello, Utah	2,153	385	1,498	0.34	Semiarid	−9, 29	19, 96
Omaha, Nebraska	320	760	711	0.64	Subhumid	−6, 25	45, 90
Polson, Montana	892	380	648	0.58	Subhumid	−7, 28	30, 95
Sacramento, California	31	434	0	0.33	Semiarid	3, 34	25, 92
Underwood, North Dakota	622	442	813	0.47	Semiarid	−19, 28	52, 86

Note: Precipitation, snowfall, and PET are average annual quantities. Temperature and relative humidity are average monthly quantities; m-msl = meters above mean sea level.
[a]Historical long-term average.
[b]Based on definitions in UNESCO (1979).

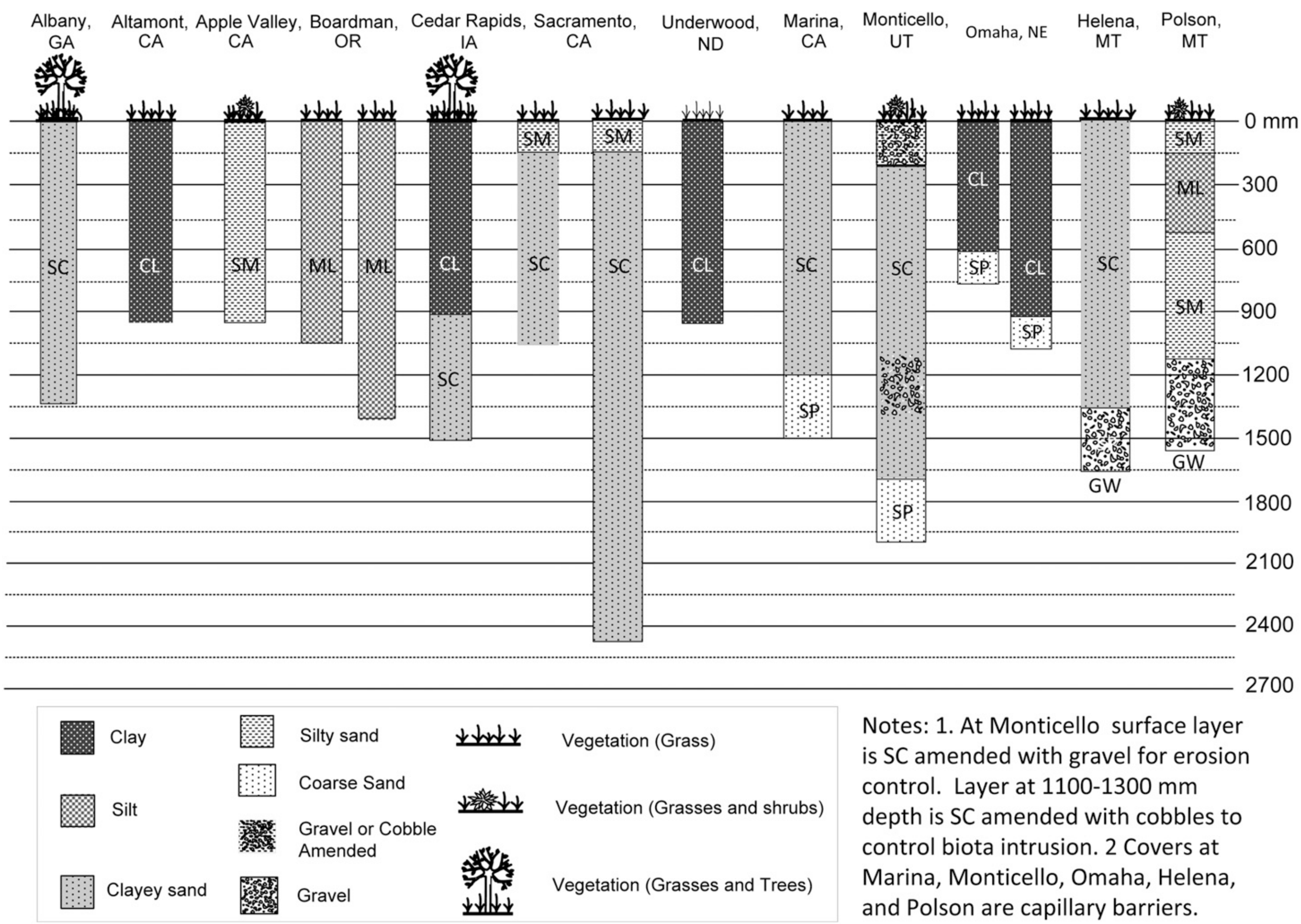

Fig. 2. Profiles of ACAP water balance covers: soil classifications and group designations are from the Unified Soil Classification System

a capillary break. The root barrier also prevents roots from penetrating into the interim cover soil (and below). As such, the interim cover soil remains near field capacity after the first penetration of water through the cover, minimizing any future capillary barrier effect. These conditions also minimize any complexity introduced by the properties of the interim cover soil and are one reason why numerical models with realistic parameterization have been effective in predicting the hydrology of ACAP covers without

Table 2. Test Section Geometry and As-Built Hydraulic Properties of Cover Soils for ACAP Test Sections

				As-built soil hydraulic properties[a]				
Test site	Slope (%)	Soil layers (top to bottom)	Layer thickness (mm)	θ_r	θ_s	α (m^{-1})	n	K_s (m/s)
Albany, Georgia	5	Surface	150	0.00	0.37 (0.33–0.42)	0.05 (0.02–0.33)	1.37 (1.24–1.46)	3.8×10^{-9} (6.8×10^{-11}–3.3×10^{-7})
		Storage 1	450	0.00	0.37 (0.33–0.42)	0.05 (0.02–0.33)	1.37 (1.24–1.46)	3.8×10^{-9} (6.8×10^{-9}–3.3×10^{-5})
		Storage 2	700	0.00	0.32 (0.28–0.33)	0.04 (0.02–0.06)	1.38 (1.32–1.47)	3.0×10^{-9} (3.5×10^{-10}–1.3×10^{-8})
Altamont, California	5	Surface	460	0.00	0.37 (0.36–0.38)	0.05 (0.02–0.18)	1.33 (1.12–1.34)	5.2×10^{-9} (9.2×10^{-10}–5.8×10^{-11})
		Storage	600	0.00	0.35 (0.32–0.37)	0.03 (0.01–0.10)	1.54 (1.16–1.48)	4.5×10^{-9} (5.5×10^{-10}–2.8×10^{-7})
Apple Valley, California	5	Surface	600	0.00	0.26	0.28	1.4	8.3×10^{-7}
		Storage	450	0.00	0.26	0.28	1.4	5.0×10^{-7}
Boardman, Oregon	25	Surface	150	0.01 (0.00–0.03)	0.39 (0.35–0.42)	0.16 (0.07–0.32)	1.51 (1.34–1.68)	1.2×10^{-7} (1.8×10^{-8}–7.2×10^{-7})
		Storage	1,070	0.01 (0.00–0.03)	0.39 (0.35–0.42)	0.16 (0.07–0.32)	1.51 (1.34–1.68)	1.2×10^{-7} (1.8×10^{-8}–7.2×10^{-7})
	25	Surface	150	0.01 (0.00–0.03)	0.39 (0.35–0.42)	0.16 (0.07–0.32)	1.51 (1.34–1.68)	1.2×10^{-7} (1.8×10^{-8}–7.2×10^{-7})
		Storage	1,690	0.01 (0.00–0.03)	0.39 (0.35–0.42)	0.16 (0.07–0.32)	1.51 (1.34–1.68)	1.2×10^{-7} (1.8×10^{-8}–7.2×10^{-7})
Cedar Rapids, Iowa	5	Surface	150	0.01 (0.00–0.03)	0.34 (0.32–0.35)	0.02 (0.01–0.05)	1.63 (1.31–2.21)	2.1×10^{-8} (8.6×10^{-10}–3.0×10^{-7})
		Storage 1	770	0.01 (0.00–0.03)	0.34 (0.32–0.35)	0.02 (0.01–0.05)	1.63 (1.31–2.21)	4.4×10^{-9} (3.7×10^{-10}–7.9×10^{-8})
		Storage 2	600	0.00 (0.00–0.02)	0.30 (0.27–0.35)	0.02 (0.01–0.04)	1.45 (1.32–1.72)	1.4×10^{-9} (2.4×10^{-9}–9.6×10^{-10})
Helena, Montana	5	Surface	150	0.01 (0.00–0.01)	0.28 (0.27–0.28)	5.0 (4.3–5.8)	1.40 (1.38–1.41)	1.9×10^{-7} (1.5×10^{-7}–2.5×10^{-7})
		Finer Soil	1,200	0.01 (0.00–0.04)	0.34 (0.27–0.39)	1.17 (0.06–1.87)	1.20 (1.18–1.24)	1.5×10^{-9} (3.2×10^{-10}–7.2×10^{-9})
		Coarser Soil	300	0.05	0.41	24.6	3.00	0.0071
Marina, California	25	Surface	150	0.00	0.32 (0.28–0.39)	0.03 (0.01–0.29)	1.61 (1.21–1.53)	8.6×10^{-9} (1.9×10^{-11}–2.8×10^{-8})
		Finer Soil	1,070	0.00	0.32 (0.28–0.39)	0.03 (0.01–0.29)	1.61 (1.21–1.53)	8.6×10^{-10} (1.9×10^{-10}–2.8×10^{-8})
		Coarser Soil	300	0.05	0.46 (0.43–0.50)	5.0 (4.4–5.4)	2.60 (2.14–3.46)	3.2×10^{-5} (1.1×10^{-5}–5.4×10^{-5})
Monticello, Utah	5	Surface	200	0.00	0.33	0.07	1.23	6.2×10^{-7}
		Storage 1	920	0.00	0.31 (0.29–0.34)	0.03 (0.01–0.11)	1.41 (1.25–1.57)	1.4×10^{-7} (3.7×10^{-9}–9.9×10^{-7})
		Storage 2	300	0.00	0.27	0.028	1.42	3.0×10^{-7}
		Finer Soil	300	0.00	0.31 (0.29–0.34)	0.03 (0.01–0.11)	1.41 (1.25–1.57)	1.4×10^{-7} (3.7×10^{-9}–9.9×10^{-7})

J. Geotech. Geoenviron. Eng.

Table 2. (*Continued.*)

Test site	Slope (%)	Soil layers (top to bottom)	Layer thickness (mm)	As-built soil hydraulic properties[a] θ_r	θ_s	α (m^{-1})	n	K_s (m/s)
		Coarser soil	300	0.00	0.43	3.76	5.00	9.0×10^{-4}
Omaha, Nebraska	25	Surface	150	0.00	0.39 (0.35–0.42)	0.02 (0.00–0.04)	1.50 (1.18–2.04)	1.6×10^{-9} (1.8×10^{-10}–5.7×10^{-8})
		Finer soil	460	0.00	0.38 (0.34–0.44)	0.03 (0.01–0.17)	1.71 (1.25–3.20)	2.6×10^{-8} (3.8×10^{-10}–2.8×10^{-7})
		Coarser soil	150	0.00	0.32	3.40	3.81	2.02×10^{-4} (1.8×10^{-4}–2.2×10^{-4})
	25	Surface	150	0.00	0.39 (0.35–0.43)	0.01 (0.00–0.04)	1.94 (1.18–3.88)	1.6×10^{-7} (1.8×10^{-10}–5.7×10^{-8})
		Finer soil	760	0.00	0.38 (0.34–0.44)	0.03 (0.01–0.17)	1.71 (1.25–3.20)	2.6×10^{-8} (3.8×10^{-10}–2.8×10^{-7})
		Coarser soil	150	0.00	0.32	3.40	3.81	2.0×10^{-4} (1.8×10^{-4}–2.2×10^{-4})
Polson, Montana	5	Surface	150	0.00	0.37 (0.34–0.38)	6.76 (6.12–6.84)	1.42 (1.40–1.43)	3.4×10^{-7} (1.1×10^{-7}–5.6×10^{-7})
		Finer soil	460	0.00	0.30 (0.24–0.34)	1.95 (1.26–2.63)	1.28 (1.22–1.35)	4.0×10^{-9} (1.2×10^{-9}–9.2×10^{-9})
		Coarser soil	600	0.00	0.36 (0.33–0.38)	7.11 (6.71–7.94)	1.45 (1.41–1.50)	7.9×10^{-7} (4.2×10^{-7}–3.9×10^{-8})
Sacramento, California	5	Surface	150	0.01	0.30 (0.29–0.31)	0.56 (0.32–2.78)	1.40	1.5×10^{-8} (5.6×10^{-9}–3.9×10^{-8})
		Storage	920	0.02	0.31 (0.31–0.32)	0.07 (0.06–0.08)	1.26 (1.16–1.23)	1.8×10^{-8} (2.3×10^{-10}–7.4×10^{-6})
	5	Surface	150	0.01	0.29 (0.28–0.31)	0.56 (0.32–2.78	1.40	4.2×10^{-9} (1.1×10^{-9}–1.5×10^{-8})
		Storage 1	1,840	0.02	0.29 (0.28–0.30)	0.31 (0.07–2.27)	1.38 (1.20–1.57)	3.0×10^{-9} (1.8×10^{-9}–8.5×10^{-8})
		Storage 2	460	0.00	0.31 (0.31–0.32)	0.07 (0.06–0.08)	1.26 (1.16–1.23)	4.0×10^{-9} (4.0×10^{-9}–4.1×10^{-9})
Underwood, North Dakota	20	Surface	150	—	—	—	—	—
		Storage	760	0.00	0.40–0.42	0.05–0.17	1.22–1.34	5.7×10^{-9}

Note: In-service hydraulic properties are in Benson et al. (2011). K_s = saturated hydraulic conductivity; α and n = fitting parameters in van Genuchten's SWCC function; θ_r = residual water content; θ_s = saturated water content.

[a]For all as-built soil hydraulic properties values in parentheses show minimums and maximums, and the initial value is the mean.

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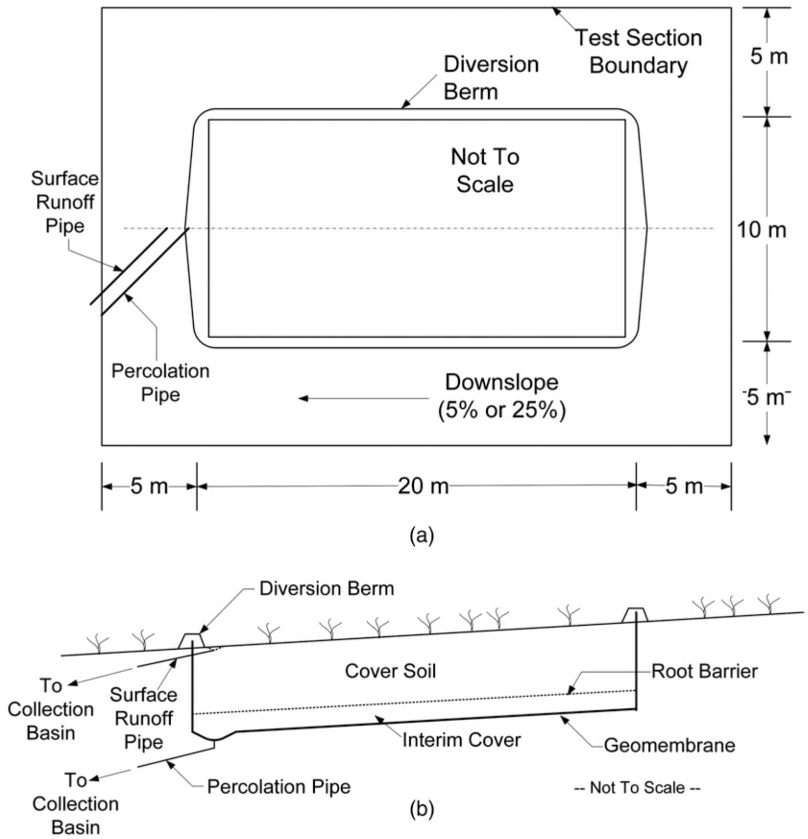

Fig. 3. Schematic of ACAP test section and lysimeter: (a) plan view; (b) cross section

incorporating a capillary break into the profile being modeled (Ogorzalek et al. 2008; Bohnhoff et al. 2009; Mijares and Khire 2012). Despite these extensive efforts to minimize the impact of the lower boundary and research by others demonstrating that the capillary barrier effect generally is not significant, there may be applications where the boundary used in the ACAP studies does not mimic the field condition. In such cases, the data presented herein should be interpreted in the context of differing boundary conditions.

Surface berms were used to collect surface water runoff for measurement and to exclude surface water run-on. Percolation and runoff were conveyed through pipes to basins equipped with a dosing siphon for automated measurement (Benson et al. 2001). The volume of water collected in each basin was measured using a pressure transducer and a float switch. Flow in the percolation basin was also metered with a tipping bucket gauge. The flow monitoring systems resolve percolation to less than 0.1 mm/year and runoff to less than 0.4 mm/year (Benson et al. 2001). Runoff and percolation were stored and recorded on 1-h intervals, except during intense events, when the data were recorded at time intervals as short as 15 s.

Soil water content was measured with water content reflectometers (WCRs) (Model CS 615, Campbell Scientific, Logan, Utah), soil suction was measured using thermal dissipation sensors (Model 229, Campbell Scientific), and soil temperature was measured with Type-T thermocouples. The WCRs were installed in three nests at the quarter-points along the centerline of each lysimeter, with each nest containing three to eight probes stacked vertically. Thermal dissipation sensors were installed at the central nest and were colocated with the WCRs. The sensors were calibrated for site-specific soils using the temperature-compensation method in Kim and Benson (2002) and Albright et al. (2004). Soil water storage was computed by integrating soil water content measured with the WCRs over the representative volumes of the cover profiles.

Meteorological conditions were measured with an onsite weather station. Precipitation was measured with a tipping bucket equipped with a snowfall adapter using propylene glycol and was assumed to be frozen when the air temperature was less than 0°C. Other meteorological data recorded by the weather station included wind speed and direction, air temperature, relative humidity, and solar radiation. The PET was computed using the meteorological data with the Food and Agriculture Organization (FAO)-Penman-Monteith method described in Chapter 2 of Allen et al. (1998).

Actual ET was estimated on a daily basis as the residual of the water balance

$$\mathrm{ET} = P - R - P_r - \Delta S \qquad (1)$$

where P = precipitation; R = runoff; P_r = percolation; and ΔS = change in soil water storage. This form of the water balance equation assumes that lateral flow is negligible and includes canopy interception with ET. The ET estimated in this manner includes actual ET and errors inherent in the other water balance measurements. However, as will be shown subsequently, ET computed with Eq. (1) is consistent with ET from covers reported by others, as well as other ET-P-PET relationships from the literature.

Annual and average annual water balance quantities for the ACAP test sections are summarized in Table 3. Runoff, ET, and percolation are shown as total quantities and as a percentage of annual precipitation. The water balance quantities are reported in water years, which begin on July 1 and end on June 30 each year.

Table 3. Annual and Average Annual Precipitation, Surface Runoff, ET, and Percolation (mm/yr) for ACAP Water Balance Covers

Site	Cover thickness (m)	Component	Year in monitoring period 1	2	3	4	5	6	Average
Albany, Georgia	1.25	Precipitation	1,291	999	1,380	**646**[a]	N/A	N/A	1,263
		Runoff	6.1 (0.5%)	0.0 (0.0%)	2.5 (0.2%)	**0.4 (0.1%)**[a]	N/A	N/A	5.1 (0.4%)
		Percolation	135 (13%)	3.1 (0.3%)	218 (15%)	**12 (1.9%)**[a]	N/A	N/A	109 (9.1%)
		ET	1,025 (96%)	1,062 (102%)	1,243 (85%)	**578 (93%)**[a]	N/A	N/A	1,109 (92%)
Altamont, California	1.06	Precipitation	**226**[b]	287	425	325	499	N/A	358
		Runoff	**3.0 (1.3%)**[b]	54 (19%)	28 (6.5%)	1.6 (0.5%)	1.2 (0.2%)	N/A	19 (4.9%)
		Percolation	**0.0 (0.0%)**[b]	1.5 (0.5%)	2.6 (0.6%)	65 (20%)	139 (28%)	N/A	45 (12%)
		ET	**203 (90%)**[b]	298 (104%)	304 (71%)	181 (56%)	256 (51%)	N/A	268 (71%)
Apple Valley, California	1.05	Precipitation	177	116	272	131	N/A	N/A	119
		Runoff	0.0 (0.0%)	6.5 (5.6%)	12.7 (4.7%)	1.5 (1.2%)	N/A	N/A	5.1 (3.0%)
		Percolation	0.4 (0.2%)	0.0 (0.0%)	1.8 (0.7%)	0.0 (0.0%)	N/A	N/A	0.5 (0.3%)
		ET	123 (69%)	151 (130%)	233 (86%)	151 (116%)	N/A	N/A	163 (95%)
Boardman, Oregon		Precipitation	**75**[c]	164	185	211	190	N/A	225
	1.22	Thin cover							
		Runoff	**0.0 (0.0%)**[c]	0.0 (0.0%)	0.0 (0.0%)	0.4 (0.2%)	0.0 (0.0%)	N/A	0.1 (0.1%)
		Percolation	**0.0 (0.0%)**[c]	0.0 (0.0%)	0.0 (0.0%)	0.0 (0.0%)	0.0 (0.0%)	N/A	0.0 (0.0%)
		ET	**39 (52%)**[c]	234 (143%)	164 (89%)	238 (113%)	204 (108%)	N/A	193 (107%)
	1.84	Thick cover							
		Runoff	**0.0 (0.0%)**[c]	0.0 (0.0%)	0.0 (0.0%)	1.0 (0.5%)	0.0 (0.0%)	N/A	0.2 (0.1%)
		Percolation	**0.0 (0.0%)**[c]	0.0 (0.0%)	0.0 (0.0%)	0.0 (0.0%)	0.0 (0.0%)	N/A	0.0 (0.0%)
		ET	**67 (90%)**[c]	224 (136%)	195 (105%)	293 (139%)	193 (102%)	N/A	195 (107%)
Cedar Rapids, Iowa	1.52	Precipitation	**582**[d]	**790**[e]	975	898	**264**[f]	N/A	915
		Runoff	**20 (3.5%)**[d]	**29 (6.0%)**[e]	10 (1.1%)	99 (11%)	**0.5 (0.2%)**[f]	N/A	46 (5.0%)
		Percolation	**130 (22%)**[d]	**65 (13%)**[e]	157 (16%)	366 (41%)	**1.3 (0.5%)**[f]	N/A	225 (23%)
		ET	**448 (77%)**[d]	**385 (80%)**[e]	764 (78%)	484 (54%)	**334 (127%)**[f]	N/A	696 (75%)
Helena, Montana	1.45	Precipitation	**116**[g]	255	315	287	223	352	312
		Runoff	**1.7 (1.4%)**[g]	21 (8.3%)	14 (4.3%)	28 (9.6%)	0.8 (0.4%)	6.1 (1.7%)	13 (4.6%)
		Percolation	**0.0 (0.0%)**[g]	0.0 (0.0%)	0.0 (0.0%)	0.0 (0.0%)	0.0 (0.0%)	0.1 (0.0%)	0.0 (0.0%)
		ET	**85 (73%)**[g]	240 (94%)	289 (92%)	266 (93%)	231 (103%)	262 (75%)	242 (89%)
Marina, California	1.52	Precipitation	493	401	467	407	N/A	N/A	466
		Runoff	0.0 (0.0%)	0.0 (0.0%)	0.0 (0.0%)	0.0 (0.0%)	N/A	N/A	0.0 (0.0%)
		Percolation	45 (9.1%)	64 (16%)	51 (11%)	82 (20%)	N/A	N/A	63 (14%)
		ET	511 (104%)	356 (89%)	420 (90%)	319 (78%)	N/A	N/A	434 (94%)
Monticello, Utah	2.02	Precipitation	**394**[h]	213	338	351	663	287	385
		Runoff	**4.7 (1.2%)**[h]	5.6 (2.6%)	0.0 (0.0%)	1.5 (0.4%)	35 (5.3%)	4.4 (1.5%)	8.3 (2.0%)
		Percolation	**0.0 (0.0%)**[h]	0.0 (0.0%)	0.0 (0.0%)	0.0 (0.0%)	3.4 (0.5%)	0.6 (0.2%)	0.7 (0.2%)
		ET	**424 (108%)**[h]	218 (107%)	334 (99%)	346 (99%)	445 (67%)	322 (112%)	373 (91%)
Omaha, Nebraska		Precipitation	**612**[i]	552	721	725	**313**[j]	N/A	760
	0.76	Thin cover							
		Runoff	**60 (9.7%)**[i]	7.7 (1.4%)	21 (3.0%)	1.3 (0.2%)	**2.4 (0.8%)**[j]	N/A	23 (3.2%)

J. Geotech. Geoenviron. Eng.

Table 3. (*Continued.*)

Site	Cover thickness (m)	Component	Year in monitoring period 1	2	3	4	5	6	Average
		Percolation	**101 (17%)**[i]	3.4 (0.6%)	51 (7.1%)	69 (9.4%)	**0.3 (0.1%)**[j]	N/A	56 (7.7%)
		ET	**461 (75%)**[i]	531 (96%)	664 (92%)	668 (92%)	**297 (95%)**[j]	N/A	657 (90%)
	1.06	Thick cover							
		Runoff	**45 (7.4%)**[i]	3.3 (0.6%)	7.8 (1.1%)	4.7 (0.7%)	**1.2 (0.4%)**[j]	N/A	16 (2.1%)
		Percolation	**58 (9.5%)**[i]	4.2 (0.8%)	29 (4.0%)	16 (2.2%)	**0.7 (0.2%)**[j]	N/A	27 (3.7%)
		ET	**497 (81%)**[i]	577 (104%)	632 (88%)	709 (98%)	**322 (103%)**[j]	N/A	686 (94%)
Polson, Montana	1.21	Precipitation	**216**[k]	358	308	326	316	**178**[l]	380
		Runoff	**6.6 (3.1%)**[k]	4.1 (1.1%)	5.1 (1.7%)	2.1 (0.7%)	1.1 (0.3%)	**0.0 (0.0%)**[l]	2.6 (0.7%)
		Percolation	**0.0 (0.0%)**[k]	0.02 (0.0%)	0.4 (0.1%)	0.2 (0.1%)	0.0 (0.0%)	**0.0 (0.0%)**[l]	0.2 (0.0%)
		ET	**176 (82%)**[k]	348 (97%)	282 (92%)	403 (124%)	319 (101%)	**186 (105%)**[l]	352 (101%)
Sacramento, California		Precipitation	**546**[m]	379	456	426	361	347	434
	1.07	Thin cover							
		Runoff	**56 (10%)**[m]	20 (5.3%)	23 (5.1%)	6.1 (2.3%)	1.4 (0.4%)	9.2 (2.7%)	21 (4.9%)
		Percolation	**0.0 (0.0%)**[m]	1.4 (0.4%)	96 (21%)	3.9 (1.4%)	108 (30%)	97 (28%)	55 (13%)
		ET	**476 (87%)**[m]	184 (49%)	392 (86%)	210 (78%)	289 (80%)	194 (56%)	327 (77%)
	2.45	Thick cover							
		Runoff	**55 (10%)**[m]	11 (3.0%)	0.4 (0.1%)	0.0 (0.0%)	0.0 (0.0%)	0.5 (0.1%)	12 (2.9%)
		Percolation	**0.0 (0.0%)**[m]	0.0 (0.0%)	8.5 (1.9%)	0.0 (0.0%)	0.6 (0.2%)	5.9 (1.7%)	2.7 (0.6%)
		ET	**464 (85%)**[m]	210 (55%)	475 (104%)	228 (84%)	294 (81%)	426 (123%)	375 (89%)
Underwood, North Dakota	0.91	Precipitation	585	300	**186**[n]	N/A	N/A	N/A	442
		Runoff	40 (6.8%)	9.8 (3.3%)	**3.5 (1.9%)**[n]	N/A	N/A	N/A	23 (4.8%)
		Percolation	9.4 (1.6%)	1.9 (0.6%)	**2.9 (1.5%)**[n]	N/A	N/A	N/A	6.0 (1.3%)
		ET	547 (94%)	334 (111%)	**203 (110%)**[n]	N/A	N/A	N/A	469 (101%)

Note: Percentage of NOAA precipitation shown in parentheses. Data with partial years are in bold.
[a]07/01/03–01/07/04.
[b]11/10/00–06/30/01.
[c]12/09/00–06/30/01.
[d]10/03/00–06/30/01.
[e]07/01/01–10/18/01 and 05/04/02–06/30/02.
[f]07/01/04–10/04/04.
[g]10/19/99–06/30/00.
[h]08/12/00–06/30/01.
[i]10/05/00–06/30/01.
[j]07/01/04–10/03/04.
[k]11/19/99–06/30/00.
[l]07/01/04–11/13/04.
[m]7/29/99–06/30/00.
[n]07/01/06–10/25/06.

J. Geotech. Geoenviron. Eng.

Soil Properties

Soil samples were collected in sampling tubes and as large blocks from each lift during construction of the test sections using methods in ASTM D1587 (ASTM 2012) and ASTM D7015 (ASTM 2013). Disturbed samples of cohesionless soils were collected in 20-L buckets.

As-built hydraulic properties for the cover soils are summarized in Table 2. Gurdal et al. (2003) and Benson and Gurdal (2013) provide a detailed description of the sampling and testing methods, as well as a summary of all measured soil properties (including index properties). Saturated hydraulic conductivity (K_s) was measured using flexible wall permeameters following the procedures described in ASTM D5084 (ASTM 2010). The effective confining pressure was 15 kPa and the hydraulic gradient was 10 to simulate field conditions while also achieving good contact between the specimen and membrane and reasonable testing times. Soil-water characteristic curves (SWCCs) were measured using hanging columns (coarse soils) and pressure plate extractors (fine soils) along with a chilled mirror hygrometer following the methods described in ASTM D6836 (ASTM 2002). Data from the SWCC tests were fitted with the van Genuchten equation

$$\theta = \theta_r + (\theta_s - \theta_r)\left[\frac{1}{1+(\alpha\psi)^n}\right]^{1-(1/n)} \tag{2}$$

where θ = volumetric water content; θ_s = saturated volumetric water content; θ_r = residual volumetric water content; ψ = soil suction; and α and n = fitting parameters. Only drying SWCCs were measured because of the complexity associated with measuring wetting curves and scanning curves for fine-textured soils. Methods to account for hysteresis between the wetting and drying SWCCs are described in Apiwantragoon (2007) and Albright et al. (2010). Kool and Parker (1987) provide methods to estimate the scanning curves from the drying and wetting curves.

Geometric means are reported in Table 2 for K_s and α because these parameters are log-normally distributed. Arithmetic means are reported for θ_s, θ_r, and n because they are normally distributed (Benson and Gurdal 2013). Minimums and maximums are shown in Table 2 in parentheses.

Vegetation Properties

Field samples of vegetation were collected from the test sections periodically for measurement of leaf area index (LAI) and root length density. Measurements of leaf area index were made in the laboratory using a LI-COR LI-3100 (LI-COR, Lincoln, Nebraska) area meter on clippings of replicated samples collected at the peak of the growing season and in the field using a LI-COR LAI-2000 (LI-COR) plant canopy analyzer. Root length density was measured using the method described in Liang et al. (1989) on undisturbed samples collected using the Weaver-Darland box method (Böhm 1979). Maximum LAI and parameters of the root length density function assigned to each cover are reported in Table S1.

Data from Past Studies on Water Balance Covers

Data collected from the ACAP test sections were pooled with data from other field studies of water balance covers that used large-scale drainage lysimeters (Nyhan et al. 1990, 1997; Warren et al. 1996; Nyhan 2005; Anderson et al. 1993; Gee et al. 1993; Hakonson et al. 1994; Karr et al. 1999; Khire et al. 1999; Chadwick et al. 1999; Scanlon et al. 2012, 2005; Wagner and Schnatmeyer 2002; Dwyer 2003; Ward et al. 2005; Schnabel et al. 2012). Locations of these sites are shown as open circles in Fig. 1. Data from sites without drainage lysimeters were not included, as lysimetry is regarded as the most practical and reliable means currently available to monitor the hydrology of covers (Gee and Hillel 1988; Benson et al. 2001, 2011; Malusis and Benson 2006). In addition, the data are limited to covers exposed to natural or realistic climatic conditions (i.e., covers that were intentionally inundated were excluded). Covers with resistive hydraulic elements (e.g., compacted clay or geomembrane barrier layers; plastic or metal sheets at the surface) were not included. A summary of each past study (except Schnabel et al. 2012) can be found in Apiwantragoon (2007).

Characteristics of field sites and water balance covers in the past studies are summarized in Table 4. Profiles of the covers are shown in Fig. 4. Annual average water balance quantities (when available) and monitoring periods are summarized in Table 5.

Surface Runoff

Annual runoff for the entire data set (ACAP and past studies) is shown as a function of annual precipitation in Fig. 5(a) and as a percentage of annual precipitation in Fig. 5(b). The runoff data from the ACAP sites are comparable to the runoff data reported in past studies. For all sites, annual runoff ranges from 0.0 to 106 mm/year [Fig. 5(a)] and is a small fraction of precipitation (<18.6% and generally <10%) [Fig. 5(b)].

There is no general trend between annual runoff and annual precipitation either as a total quantity [Fig. 5(a)] or as a percentage of annual precipitation [Fig. 5(b)]. However, the two largest annual runoff quantities (99 and 106 mm/year) occurred at locations having annual precipitation exceeding 900 mm/year (Cedar Rapids, Iowa and Kaneohe Bay, Hawaii). Also, the driest sites (P_a < 200 mm/year) (Tables 3 and 5) typically had annual runoff less than 10 mm/year. Larger runoff quantities typically occurred during the first year of studies (average = 3.7%, range = 0.0–10.2% of precipitation), which reflects changes in the surface of the cover over time (e.g., increases in vegetation or pedogenic effects on hydraulic properties) that impede flow and/or promote infiltration (Albright et al. 2004).

Surface runoff is shown in Fig. 6(a) as a function of mean precipitation intensity (I_p) relative to K_s of the surface layer (as an indicator of infiltration capacity) and as a function of K_s alone in Fig. 6(b). Mean precipitation intensity was estimated as the annual geometric mean of nonzero hourly precipitation. With the exception of three outlier points (Cedar Rapids, Iowa, Helena, Montana, and Omaha, Nebraska each with snow and frozen ground), runoff increases as I_p/K_s increases and decreases significantly as the saturated hydraulic conductivity of the surface layer increases. This trend is consistent with higher runoff quantities observed in the first year of monitoring compared with subsequent years, as mentioned previously. During the first year, K_s of the surface layer typically is lower relative to subsequent years when the surface layer has been affected by pedogenic processes such as freeze-thaw and wet-dry cycling and biota intrusion (Benson et al. 2007, 2011).

The three outlier data points in Fig. 6(a) are for years that included large snowmelt events at the ACAP sites in Cedar Rapids, Helena, and Omaha when frozen ground existed. Under these conditions, the infiltration capacity is exceeded because the hydraulic conductivity of the surface layer is reduced because of the presence of ice in the pores (Male and Gray 1981). An example is shown in Fig. 7 for the Helena, Montana, site. The shaded vertical bands in Fig. 7 correspond to periods of snow accumulation. Runoff caused by snowmelt occurred three times during the winter of 2003 (January 27, February 15–19, and March 11–13), with the largest runoff event in early

Table 4. Site and Cover Characteristics of Past Field Studies of Water Balance Covers

Location (source)	Precipitation (mm/year)	P/PET	Climate	Snow (%)	Low and high temperature (°C)	Cover types	Lysimeter size (m × m)	Soil properties?	Vegetated?
Los Alamos, New Mexico (Nyhan et al. 1990)	469	0.33	Semiarid	32	−7, 27	MC, CB	3.7 × 10.7	No	Yes
Los Alamos, New Mexico (Nyhan et al. 1997; Nyhan 2005)						CB	1.0 × 10.0	Yes	No
Hanford, Washington (Gee et al. 1993)	160	0.12	Arid	38	−3, 32	CB, four designs	2.0-m diameter	Yes	Yes and no
Hanford, Washington (Ward et al. 2005)						CB	14.0 × 23.0	Yes	Yes
Ogden, Utah (Hakonson et al. 1994; Warren et al. 1996)	520	0.50	Semiarid	40	−7, 33	MC, CB	5.0 × 10.0	Partial	Yes
Denver, Colorado (Chadwick et al. 1999)	396	0.28	Semiarid	45	−6, 30	MC	9.1 × 15.2	Yes	Yes
Kaneohe Bay, Hawaii (Karr et al. 1999)	970	0.95	Humid	—	—	MC	3.0 × 8.2	No	Yes
Wenatchee, Washington (Khire et al. 1999)	230	0.33	Semiarid	50	−25, 40	CB	12.2 × 18.3	Yes	Yes
Esch-Belval, Luxemburg (Wagner and Schnatmeyer 2002)	876	1.46	Humid	N/A	N/A	CB	Not reported	No	Yes
Albuquerque, New Mexico (Dwyer 2003)	220	0.14	Arid	19	−5, 32	MC, CB	13.0 × 50.0	Yes	Yes
Sierra Blanca, Texas (Scanlon et al. 2002, 2005)	311	0.13	Arid	20	−4, 34	CB	12.0 × 12.0	Yes	Yes
Anchorage, Alaska (Schnabel et al. 2012)	409	0.61, 0.85	Subhumid	9	−10, 14	MC	19.8 × 10.7	Partial	Yes

Note: All water balance quantities are annual averages. Snowfall reported as percentage of precipitation. Geocomposite drainage layer beneath cover soils in Chadwick et al. (1999) may have introduced capillary barrier effects. CB = capillary barrier; MC = monolithic cover.

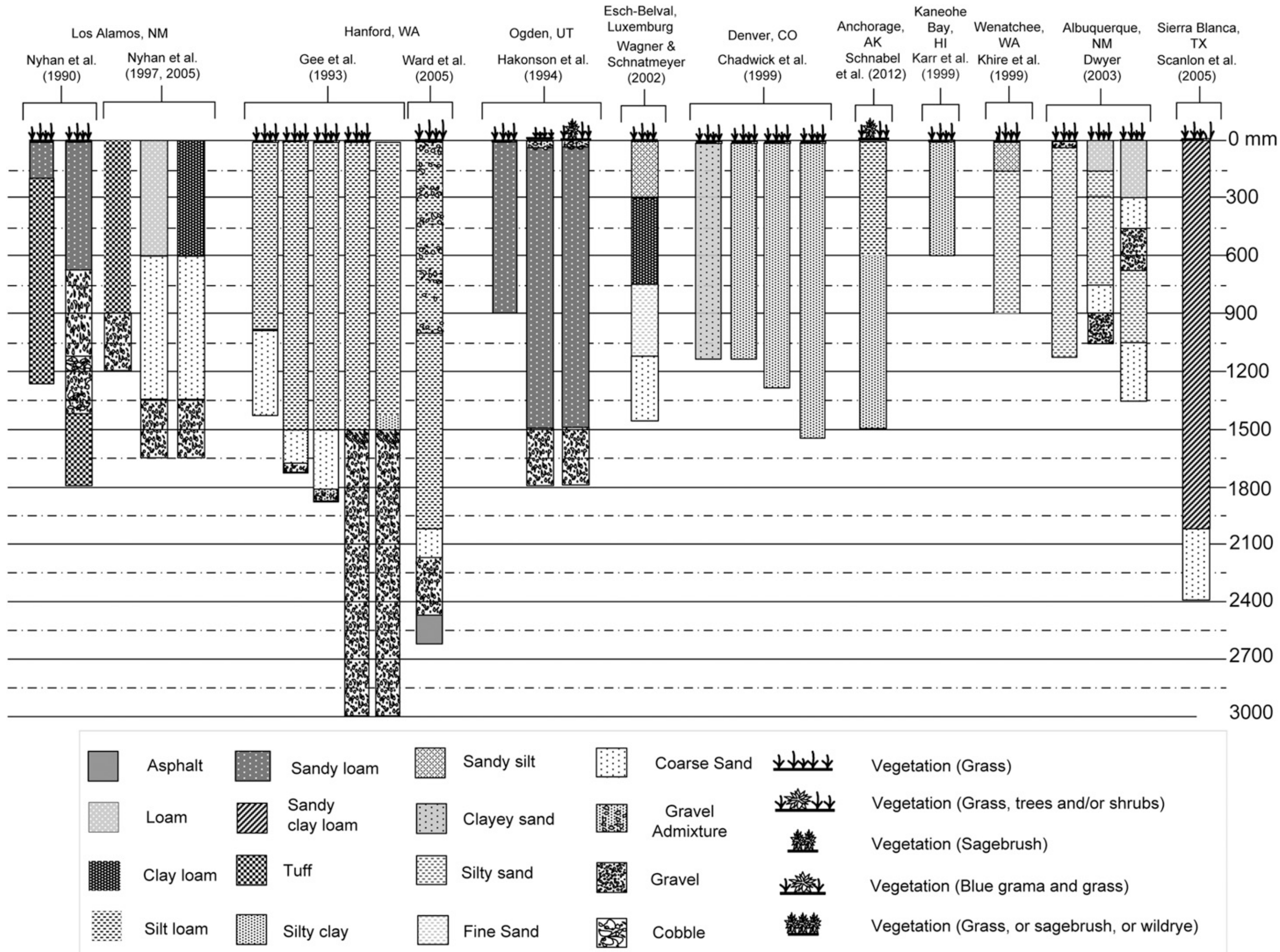

Fig. 4. Profiles of water balance covers from past studies: soil classification or texture based on descriptions provided in past studies and may not fit definitions in the Unified Soil Classification System

March coinciding with a sudden increase in air temperatures greater than 0°C when soil temperatures were warming but approximately 0°C.

Runoff caused by snowmelt on frozen ground constitutes a significant fraction of total annual runoff at sites with snow and frozen ground, as illustrated in Table 6. The data are grouped by periods with frozen precipitation and liquid precipitation (assumed to occur when air temperature is below or above 0°C). On average, runoff during periods of snow and frozen ground is 8.3% of precipitation (2.7% during other periods) and is 13–57% of total runoff. Ward and Gee (1997) also reported that snowmelt constituted a significant fraction of total runoff from the Hanford, Washington, prototype barrier (46% of total runoff during 1997), and Khire et al. (1999) reported a significant amount of runoff from their capillary barrier in Wenatchee, Washington, during snowmelt events on frozen ground.

Effect of slope on runoff was evaluated by grouping annual runoff as a percentage of precipitation from the covers with shallow slopes (<5%), medium slopes (5–15%), and steep slopes (>15%) (Fig. 8). No trend of runoff with slope is evident, which was confirmed by ANOVA conducted at the 0.05 significance level (Fig. 8) ($p > 0.05$). The absence of trend may be caused by nonsystematic evaluation of slope effects, the limited data available for covers with steep slopes, and/or the small watershed represented in lysimeter studies. Nyhan et al. (1997) and Nyhan (2005) are the only studies to evaluate the effect of slope on the hydrology of water balance covers systematically. They showed that runoff increased by as much as a factor of 4 as the slope increased from 5 to 25%.

The plant canopy can affect runoff by intercepting precipitation (Gregory 1984), reducing surface sealing (Link et al. 1994), and delaying the onset of soil saturation and runoff via transpiration (Gray and Leiser 1982). However, no systematic trend between runoff and LAI was found (Fig. S1), although runoff was a larger percentage of annual precipitation at sites with lower LAI (<1). This suggests that runoff is affected less by plant canopy (as measured by LAI) relative to other factors (intensity of precipitation, soil hydraulic properties, snowmelt, and frozen ground).

Evapotranspiration

The relationship between annual ET (ET_a) and annual precipitation (P_a) (including irrigation if applicable) is shown in Fig. 9(a). The dashed lines correspond to the ET_a-P_a relationships reported by Zhang et al. (2001). Trend lines representing the data from water balance covers in ACAP and past studies (solid lines) are also shown

Table 5. Water Balance Data from Past Studies

Location (source)	Year	Applied water (mm/year)	Cover type and thickness	Runoff (mm/year)	ET (mm/year)	Lateral flow (mm/year)	Percolation (mm/year)
Los Alamos, New Mexico (Nyhan et al. 1990)	1984–1987	579	CB (1.25 m)	0.0 (0.0%)	565 (98%)	0.0 (0.0)	0.0 (0.0%)
			CB (1.80 m)	0.0 (0.0%)	549 (95%)	6.4 (1.1%)	8.8 (1.5%)
Los Alamos, New Mexico (Nyhan et al. 1997; Nyhan 2005)	1991–1995	366	CB (1.20 m)	2.9–12 (0.8–3.2%)	292–317 (80–89%)	21–43 (5.7–12%)	0.0–2.4 (0.0–0.7%)
			CB (1.75 m)	6.1–13 (1.7–3.2%)	318–325 (87–89%)	13–25 (3.6–6.7%)	0.0–1.5 (0.0–0.4%)
			CB (1.75 m)	6.1–17 (1.4–3.8%)	391–423 (88–95%)	13–26 (2.8–5.9%)	0.9–7.5 (0.2–1.7%)
Hanford, Washington (Gee et al. 1993)	1988–1993	169	CB (V) (1.40 m)	N/A	188 (118%)	N/A	0.7 (0.5%)
			CB (U) (1.70 m)	N/A	168 (105%)	N/A	0.5 (0.4%)
			CB (V) (1.85 m)	N/A	194 (120%)	N/A	0.3 (0.2%)
	1988–1990	322	CB (U) (3.00 m)	N/A	333 (104%)	N/A	0.9 (0.3%)
			CB (V) (3.00 m)	N/A	388 (123%)	N/A	0.6 (0.2%)
	1991–1993	457	CB (U) (3.00 m)	N/A	413 (89.9%)	N/A	10.7 (2.6%)
			CB (V) (3.00 m)	N/A	455 (100%)	N/A	0.0 (0.0%)
Hanford, Washington (Ward et al. 2005)	1994–2004	201	CB (2.60 m)	0.0 (0.0%)	213 (105%)	N/A	0.0 (0.0%)
	1995	626	CB (2.60 m)	1.8 (0.3%)	745 (119%)	N/A	0.0 (0.0%)
	1996–1998	458	CB (2.60 m)	12 (2.3%)	433 (95%)	N/A	0.0 (0.0%)
	1999–2004	172	CB (2.60 m)	0.0 (0.0%)	179 (106%)	N/A	0.0 (0.0%)
Ogden, Utah (Hakonson et al. 1994; Warren et al. 1996)	1990–1993	441	CB (0.90 m)	3.7 (0.9%)	379 (82%)	53 (12%)	72 (16%)
			CB (1.80 m)	5.9 (1.5%)	389 (84%)	32 (6.9%)	75 (16%)
			MC (1.80 m)	16 (3.4%)	318 (69%)	N/A	157 (34%)
Wenatchee, Washington (Khire et al. 1999)	1992–1995	204	CB (0.90 m)	27 (16%)	153 (84%)	N/A	1.6 (0.6%)
Denver, Colorado (Chadwick et al. 1999)	1998–1999	724	MC (1.10–1.55 m)	52 (7.2%)	N/A	N/A	<0.1
	1999–2000	284	MC (1.10–1.55 m)	11 (3.9%)	N/A	N/A	
	2000–2001	546	MC (1.10–1.55 m)	8.3 (1.5%)	N/A	N/A	
	2001–2002	236	MC (1.10–1.55 m)	2.3 (1.0%)	N/A	N/A	
Kaneohe Bay, Hawaii (Karr et al. 1999)	1995–1998	721	MC (0.6 m)	78 (8.6%)	780 (86%)	N/A	50 (5.5%)
Esch-Belval, Luxemburg (Wagner & Schnatmeyer 2002)	1996	713	CB (1.45 m)	15 (1.4%)	417 (59%)	N/A	82 (12%)
	1997	1,037	CB (1.45 m)	40 (5.6%)	637 (61%)	N/A	152 (15%)
Albuquerque, New Mexico (Dwyer 2003)	1997–2002	247	CB (1.15 and 1.35 m)	3.4 (1.2%)	246 (97%)	N/A	0.2 (0.1%)
			CB (1.15 and 1.35 m)	3.7 (1.3%)	257 (104%)	N/A	0.0 (0.0%)
			MC (1.1 m)	2.9 (1.0%)	252 (100%)	N/A	0.1 (0.0%)
Sierra Blanca, Texas (Scanlon et al. 2002, 2005)	1998	428	CB (2.4 m)	60 (14%)	307 (72%)	N/A	0.0 (0.0%)
	1999–2000	189	CB (2.4 m)	7.0 (4.3%)	225 (116%)	N/A	0.0 (0.0%)
	1998	423	MC (2.4 m)	56 (13%)	308 (73%)	N/A	0.0 (0.0%)
	1999–2001	192	MC (2.4 m)	8.9 (5.1%)	212 (108%)	N/A	0.0 (0.0%)
Anchorage, Alaska (Schnabel et al. 2012)	2005–2006	387	MC (1.5 m)	26 (6.7%)	317 (82%)	N/A	43 (11%)
	2006–2007	461	MC (1.5 m)	17 (3.7%)	349 (76%)	N/A	95 (21%)
	2007–2008	462	MC (1.5 m)	21 (4.5%)	393 (85%)	N/A	49 (11%)
	2008–2009	326	MC (1.5 m)	12 (3.7%)	301 (92%)	N/A	14 (4.3%)

Note: Applied water includes precipitation and irrigation. CB = capillary barrier; MC = monolithic cover; U = unvegetated; V = vegetated.

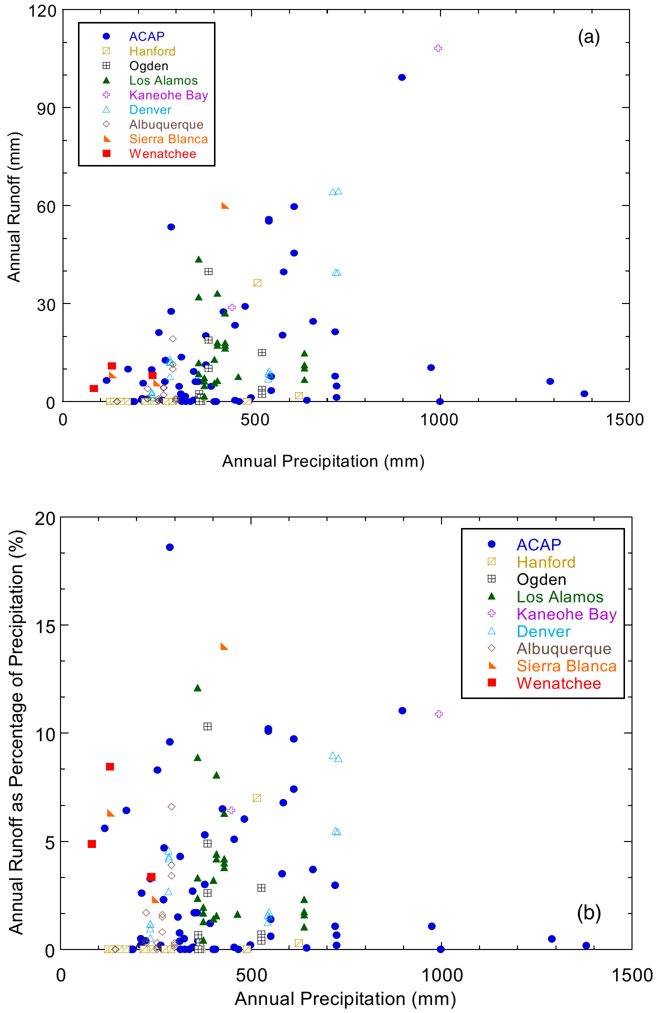

Fig. 5. (Color) (a) Annual runoff as a function of annual precipitation; (b) annual runoff as a percentage of precipitation as a function of annual precipitation from water balance covers in ACAP and past studies

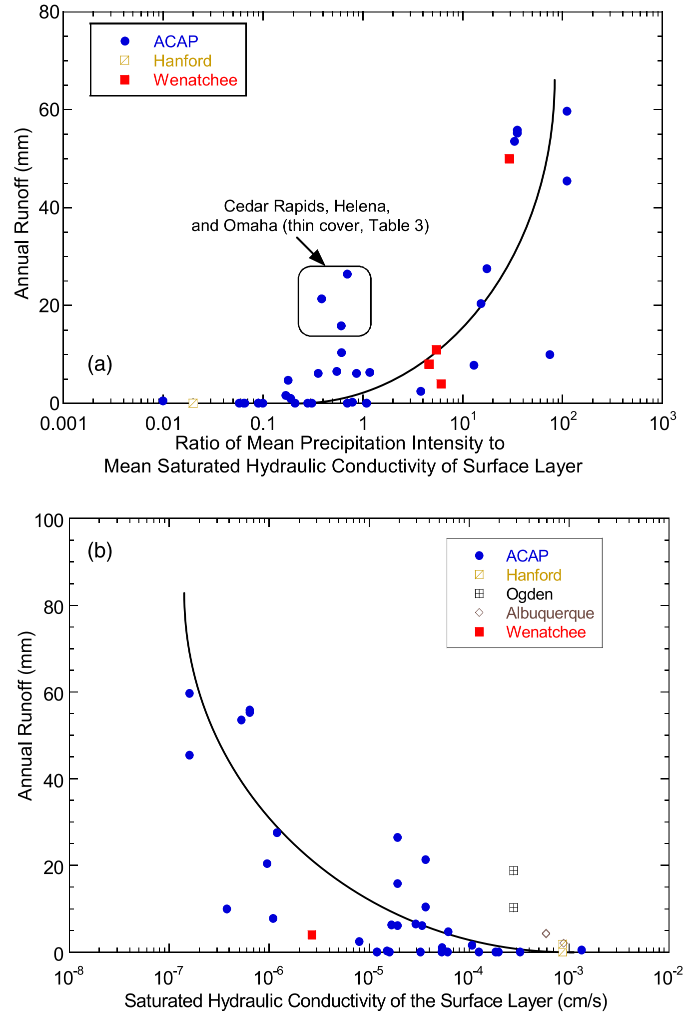

Fig. 6. (Color) Annual runoff as a function of (a) the ratio of mean precipitation intensity to mean saturated hydraulic conductivity of the surface layer (I/K_s); (b) the K_s of surface layer for water balance covers in ACAP and past studies; data from past studies included when hourly precipitation data available and no irrigation applied

in Fig. 9(a). Zhang et al. (2001) derived their ET_a-P_a relationships from a collection of field studies conducted on catchments worldwide with grasses or trees. Their ET_a-P_a relationships are consistent with relationships reported by others (Pike 1964; Budyko 1974). The trend lines for water balance covers in Fig. 9(a) were obtained by averaging ET_a and P_a in 100-mm increments of P_a for covers vegetated with grasses alone or grasses and trees and fitting a smooth interpolation function to the averages using least-squares methods. The ET_a defined by the trend lines for water balance covers is similar to, but slightly higher than, ET_a defined by the relationships in Zhang et al. (2001).

ET_a increases with increasing P_a, which reflects increasing availability of water [Fig. 9(a)]. Except at low P_a where no data for covers with grasses and trees are available, the trend line for covers with grasses and trees has higher ET_a than for covers with grasses alone. Moreover, the difference between ET_a for covers with grasses and trees and for covers with grasses alone increases as P_a increases (particularly for $P_a > 750$ mm). This deviation is also evident in the relationships reported by Zhang et al. (2001). Regardless of type of vegetation, the fraction of precipitation removed by ET (slope of the ET_a-P_a relationship) diminishes with increasing P_a, indicating the control on ET_a transitions from water availability (P_a) to the energy availability for ET.

The combined effects of availability of water (P_a) and energy for evaporation [in terms of annual PET (PET_a)] are shown in Fig. 9(b). ET_a approaches ~5% of PET_a as $PET_a/P_a \gg 1$ because of the limited availability of water. Similarly, ET_a approaches PET_a as the amount of water available for evaporation becomes comparable to the amount of energy available for evaporation (i.e., as $PET_a/P_a \rightarrow 1^+$), reflecting the control imposed by energy availability. A power function representing the trend in the data was obtained using least-squares regression ($R^2 = 0.90$)

$$\frac{ET_a}{PET_a} = 0.84\left(\frac{P_a}{PET_a}\right)^{0.913} \quad (3)$$

Relationships between ET_a, P_a, and PET_a reported by Pike (1964) and Budyko (1974) are also shown in Fig. 9(b) along with the functions reported by Zhang et al. (2001). The functions are similar; the deviations can be attributed to different types of vegetation and differences in the data sets used for calibration. This suggests that ET_a can be estimated using P_a and PET_a obtained from meteorological records. Estimates of ET_a obtained using Eq. (3) are not sufficiently accurate for predictive purposes, but are useful for

checking design assumptions, field data, and model predictions for reasonableness.

The effect of the type of vegetation on ET is shown in Fig. 10 using box plots of ET_a as a percentage of precipitation (ET_{ap}) for covers vegetated with grasses alone, grasses and/or shrubs, and grasses and trees. The median ET_{ap} for covers with grasses and shrubs is larger than the median ET_{ap} for covers with grasses alone, which was confirmed with a t-test at the 0.05 significance level ($p = 0.0031 \ll 0.05$). The t-tests also showed that differences between the mean ET_{ap} for covers with grasses and covers with grasses and trees are not statistically different ($p = 0.362 > 0.05$). However, all of the covers with grasses and shrubs were located in arid and semiarid sites ($P_a < 400$ mm/year), whereas the covers with grasses alone were located in both semiarid and subhumid sites ($P_a = 225$–760 mm/year), and the covers with trees were located in humid climates ($P_a = 915$–$1{,}265$ mm/year). Thus, the covers with grasses and shrubs may have had larger ET_{ap} because they were located in drier climates, where nearly all of the precipitation becomes ET regardless of type of vegetation (Fig. 9).

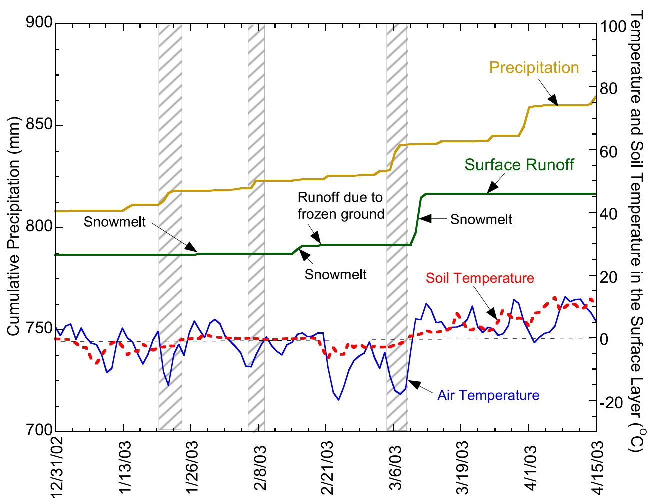

Fig. 7. (Color) Cumulative precipitation, cumulative surface runoff, and average daily air temperature and soil temperature in the surface layer during winter 2003 at Helena, Montana (shaded bands are periods of snow accumulation)

Others have evaluated how type of vegetation affects soil water conditions in water balance covers. Forman and Anderson (2005) reported that water contents in the root zone in a cover located in Idaho Falls, Idaho, were 5% lower in covers with native vegetation (grasses, forbs, and shrubs) relative to covers vegetated with crested wheatgrass. Similarly, data in Anderson et al. (1993) showed that soil water storage in covers at Idaho Falls vegetated with grasses (crested wheatgrass, great basin wildrye, streambank wheatgrass) was as much as 81 mm (36.7% of precipitation) higher (corresponding to higher water content) during the first growing season than a similar cover with Wyoming big sagebrush. However, the differences in soil water storage and water content diminished by the end of the third growing season. Scanlon et al. (2005) showed that invasion of salt cedar on a cover vegetated with grass increased soil suction (and therefore decreased soil water content) at a depth of 2 m by one order of magnitude. Although likely, none of these studies had sufficient information to demonstrate that ET was affected by a transition in vegetation.

Relationships between ET and LAI were explored using the ACAP data and the data from other studies, but no systematic trends were found (Fig. S2). Nevertheless, the presence of vegetation is important for water balance covers in most climates. Gee et al. (1993) evaluated two sets of identical water balance covers in Hanford using a capillary barrier: one without vegetation and the other with vegetation. The ET from the vegetated cover was as much as 58% greater than ET from the unvegetated cover. Also, no percolation was transmitted from the covers with vegetation, even when applied water (irrigation + precipitation) was as much as three times the average annual precipitation (480 mm/year). In contrast, more than 30 mm/year of percolation was transmitted from their unvegetated covers under the same condition. Similarly, Anderson et al. (1993) compared water content profiles in monolithic covers with and without vegetation at the site in Idaho Falls, Idaho. Water contents in the unvegetated covers were consistently higher than those in the vegetated covers, with the largest difference in water content (0.23) at the bottom of the covers.

Percolation

Average annual percolation for the ACAP sites ranged from 0 to 225 mm/year, and the annual percolation ranged from 0 to 366 mm/year (Table 3). The highest percolation rates were at Albany and Cedar Rapids, which had the highest annual average

Table 6. Cumulative Precipitation and Cumulative Runoff as Total Quantity and as a Percentage of Frozen and Liquid Precipitation at ACAP Sites Where Snow and Frozen Ground Occur

Site	Precipitation type	Precipitation (mm)	Runoff (mm)	Runoff (precipitation, %)	Runoff (total runoff, %)
Cedar Rapids, Iowa	Frozen	332	46	14	27
	Liquid	2,869	123	4.3	73
Helena, Montana	Frozen	183	22	12	33
	Liquid	1,159	44	3.8	67
Monticello, Utah	Frozen	491	9.8	2.0	28
	Liquid	1,421	26	1.8	72
Omaha, Nebraska	Frozen (thin)	328	45	14	48
	Liquid (thin)	2,596	48	1.8	52
	Frozen (thick)	328	36	11	57
	Liquid (thick)	2,596	27	1.0	43
Polson, Montana	Frozen	373	6.7	1.8	37
	Liquid	1,288	12	0.9	63
Underwood, North Dakota	Frozen	167	6.4	3.9	13
	Liquid	848	43	5.0	87

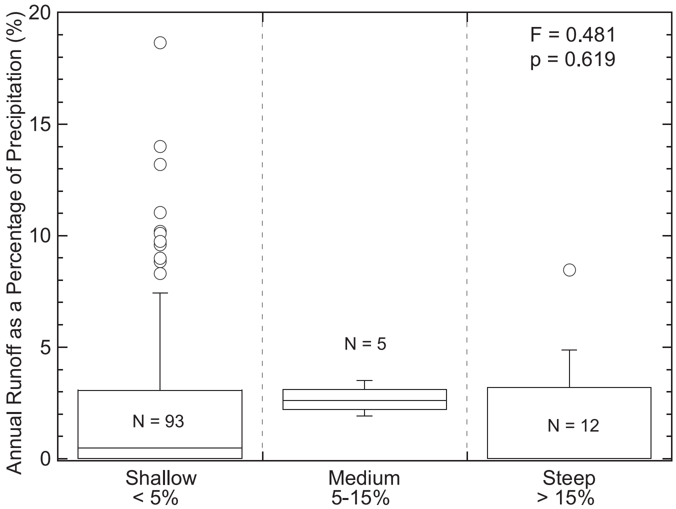

Fig. 8. Annual runoff as a percentage of precipitation as a function of cover slope for covers in ACAP and past studies (middle line in each box represents median, lower and upper edges represent 25th and 75th percentiles, and outermost lines represent 5th and 95th percentiles)

precipitation and $P_a/PET_a > 1.0$. Percolation rates from the other studies fall in the range measured in ACAP (Table 5).

Relationships between percolation and meteorological variables relating the amount of water to be managed and the energy available for evaporation (P/PET, P-PET, seasonal precipitation conditions, etc.) were explored. Annual precipitation was found to be as good a discriminator as any other variable and is a practical means to differentiate climates in the United States. In the continental United States, regions with low precipitation generally correspond to greater aridity (because of high evaporative demand relative to water available), whereas those with high precipitation are in humid regions with lower evaporative demand relative to precipitation. Thus, precipitation is a reasonable, albeit coarse, indicator of climate, as evinced by the strong coupling between P_a, PET, and ET_a shown in Fig. 9.

Annual percolation from the covers in ACAP and in past studies is shown in Fig. 11 in terms of annual precipitation. A semilog scale is used for percolation to avoid clustering of the data at low percolation rates. For sites where zero percolation was recorded, the percolation rate was set at 0.1 mm/year (the accuracy of percolation rates measured using ACAP lysimeters) (Benson et al. 2001). The data were binned into four groups corresponding to annual precipitation (0–250, 250–500, 500–750, and >750 mm/year) and were segregated into ACAP data (solid symbols on left side of bin) and data from past studies (open symbols on right side of bin). These bins were selected because they segregate the data into different types of behavior corresponding to different climates. The authors acknowledge, however, that this aggregated characterization of climate is simplistic and encourage others to develop more refined means to differentiate water balance cover hydrology with additional mechanistic hydrological variables.

In the driest climates ($P_a < 250$ mm/year), very low percolation rates were obtained in all cases regardless of cover thickness or soil properties. With only a modest amount of water to be managed, an abundance of energy available for evaporation relative to the amount of water available and vegetation that is opportunistic in extracting water, a broad range of fine-textured cover materials and cover designs can successfully limit percolation to very low percolation rates (<5 mm/year). Conversely, for annual precipitation in excess

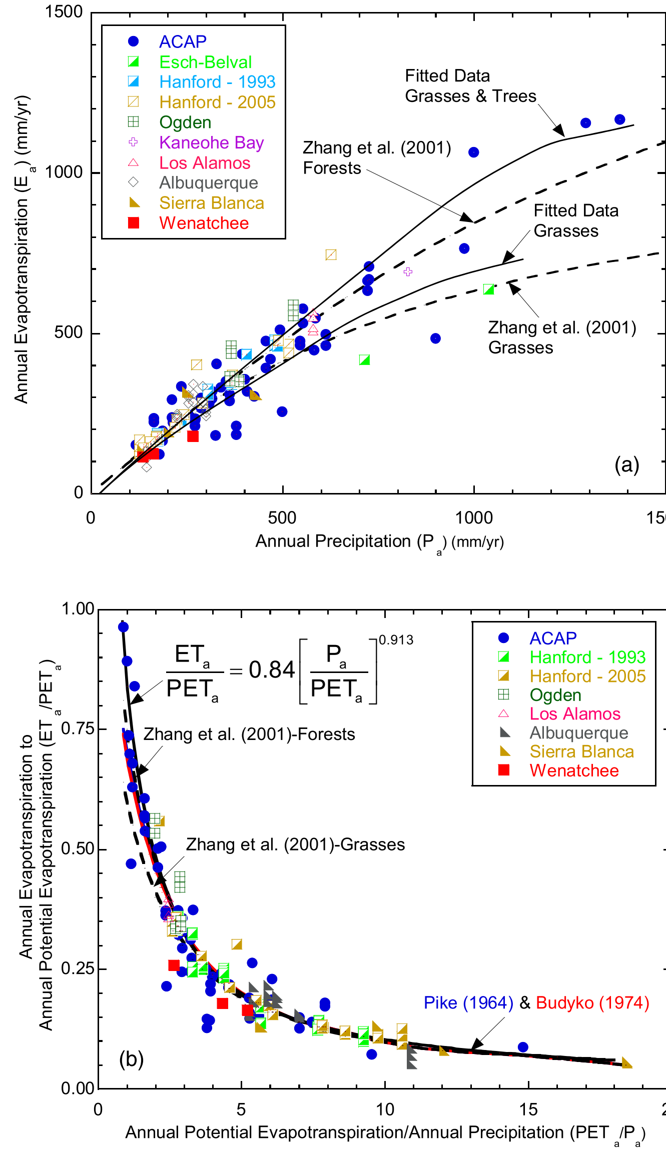

Fig. 9. (Color) (a) Annual ET (ET_a) as a function of annual precipitation (P_a) for ACAP water balance covers and other studies; (b) ratio of annual ET to annual PET (ET_a/PET_a) as a function of ratio of annual PET to annual precipitation (PET_a/P_a) from ACAP covers and other studies

of 750 mm/year, water balance covers can transmit considerably higher percolation rates (>50–100 mm/year) regardless of the cover design, soil properties, or vegetation. In these humid climates, the annual evaporative demand is comparable to the precipitation to be managed (in some very wet climates, such as Albany, $P_a > PET_a$), the vegetation generally has sufficient water for transpiration (i.e., water scavenging is not necessary), and the periods of greatest evaporative demand (summer) often are out of phase with periods having sustained precipitation and snowmelt (spring). These conditions correspond to excess water and drainage from the profile. Consequently, achieving percolation rates on the order of a few millimeters per year may not be realistic in locations with high annual precipitation (>750 mm/year), and a nonnegligible fraction of infiltration becomes percolation. Similar behavior occurs in natural systems in humid climates, where groundwater recharge rates greater than 100 mm/year are common (Delin and Risser 2007).

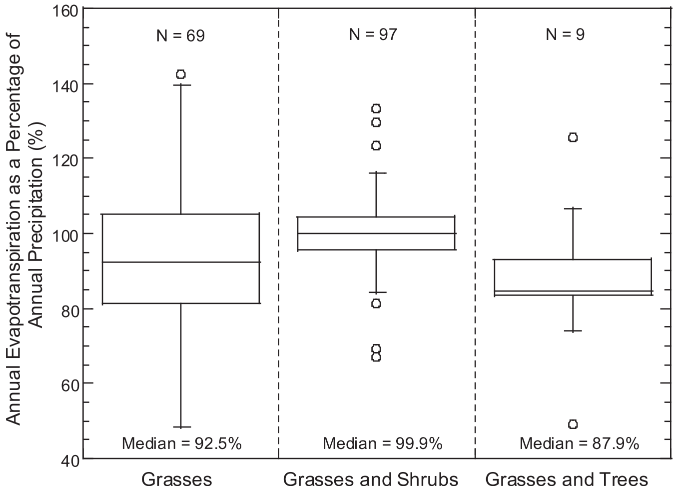

Fig. 10. Annual ET as a percentage of annual precipitation for ACAP covers and past studies vegetated with grasses alone, grasses and shrubs, or grasses and trees

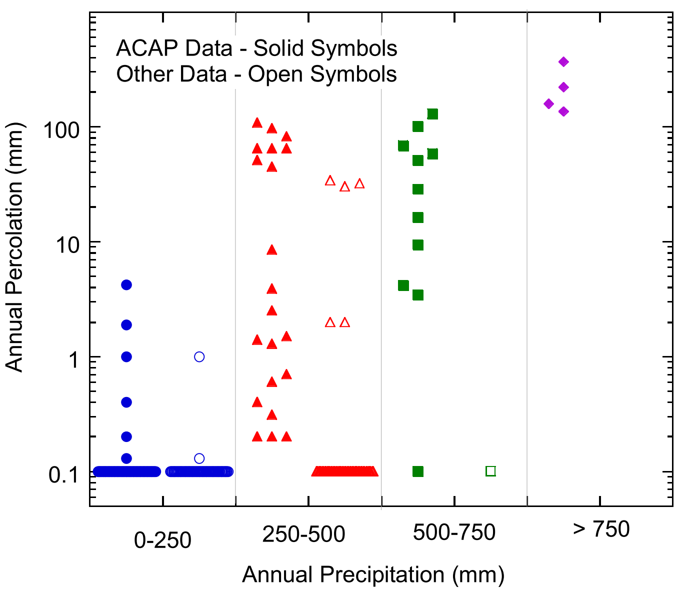

Fig. 11. (Color) Annual percolation for ACAP covers (closed symbols on left side of each bin) and past studies (open symbols on right side of each bin) for annual precipitation of 0–250, 250–500, 500–750, and >750 mm/year

A wide range of conditions can be realized for intermediate amounts of annual precipitation (250–750 mm/year), and the percolation rate that is achieved depends on how the cover is designed as well as unintended factors. The bin corresponding to annual precipitation ranging from 250 to 500 mm/year illustrates the broad range of percolation rates that can be realized for meteorological conditions in this range, from near zero (shown as 0.1 mm/year in Fig. 11) to approximately 100 mm/year. This wide range of percolation rates can be attributed to design issues (e.g., storage capacity, evaporative potential) as well as unintended conditions, such as preferential flow. With appropriate design, however, very low percolation rates can be achieved for annual precipitation <500 mm/year.

The bin corresponding to annual precipitation ranging from 500 to 750 mm/year also contains a broad range of percolation rates

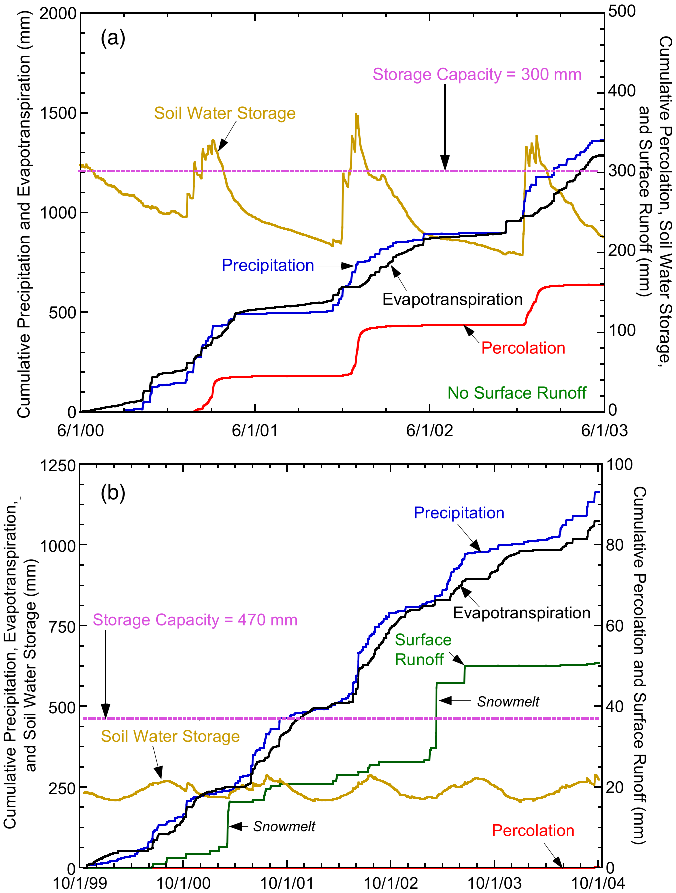

Fig. 12. (Color) Water balance components of ACAP covers at (a) Marina, California; (b) Helena, Montana; cumulative quantities shown except for soil water storage; storage capacities calculated from soil hydraulic properties in Table 2

(most in the range of 5–100 mm/year). Very low percolation rates are less common in this bin, and achieving very low percolation rates is challenging even with appropriate design. The following sections describe factors that contributed to different percolation rates for annual precipitation between 250 and 500 mm/year.

Adequacy of Storage Capacity

The very different percolation rates obtained at Helena, Montana ($P_a = 312$ mm/year), and Marina, California ($P_a = 466$ mm/year), can be attributed in part to differences in adequacy of soil water storage capacity. Methods to compute the required storage capacity and to select the cover thickness that ensures adequate storage capacity are described in Apiwantragoon (2007) and Albright et al. (2010). Soil water storage at Marina was depleted to approximately 200 mm each year in late autumn because of higher ET and lack of precipitation throughout the summer months. Winter precipitation and lower ET annually caused an accumulation of 80–140 mm of soil water storage, resulting in soil water storage exceeding the storage capacity (300 mm) [Fig. 12(a)] each year. Percolation commenced each year when soil water storage exceeded the storage capacity, continued for a few weeks, and ceased when actual storage dropped below storage capacity.

Soil water storage at Helena also follows a seasonal cycle with an increase in storage of approximately 50–100 mm each year and an annual peak of 260–280 mm [Fig. 12(b)]. However, in contrast to

Marina, soil water storage at Helena remains well below the storage capacity (470 mm) throughout the record. Because the storage capacity was never exceeded, essentially all of the precipitation that was stored was later removed by ET. Cumulative percolation over the 5-year record at Helena was 0.1 mm, which is more than 450 times lower than the annual percolation in any year at Marina (Table 3). Lower annual precipitation and runoff of snowmelt reduced the required soil water storage capacity at Helena. Nevertheless, the excess storage capacity provided at Helena is the reason why the percolation rate was very low.

The covers at Polson, Montana ($P_a = 380$ mm/year), Monticello, Utah ($P_a = 385$ mm/year), Sacramento, California ($P_a = 434$ mm/year, thick cover only), and Underwood, North Dakota ($P_a = 442$ mm/year), which also fall in the bins for P_a ranging between 250 and 750 mm/year, had low percolation rates (<6 mm/year) because these covers had adequate soil water storage capacity. If the cover at Marina had been thicker or a cover soil with greater storage capacity had been used, the percolation rate would have been lower. The thick cover at Sacramento, California, and the cover in Underwood, North Dakota, were at locations with annual precipitation similar to Marina, California, indicating that low percolation rates can be achieved for intermediate amounts of annual precipitation provided adequate soil water storage capacity is provided.

Plant Transpiration

The thin cover in Sacramento, California ($P_a = 434$ mm/year), exhibited highly variable annual percolation rates (0–108 mm/year), with significant percolation occurring in years when precipitation was slightly more (456 mm, 2001–2002) and significantly less (361 mm, 2003–2004) than the average annual precipitation of 434 mm (Fig. 13). The minimum water storage in autumn preceding winters within significant percolation was much higher than in other years (326 mm in 2001 and 258 mm in 2003 versus 160–190 mm in other years) (Fig. 13), suggesting that the vegetation was not effective in removing the stored water during the spring and summer of 2001 and 2003. The inadequate depletion in the spring and summer reduced the available water storage capacity the following winter, and insufficient capacity existed to store the winter infiltration. Consequently, the storage capacity was exceeded and significant percolation occurred in the winter of 2001–2002 and the winter of 2003–2004.

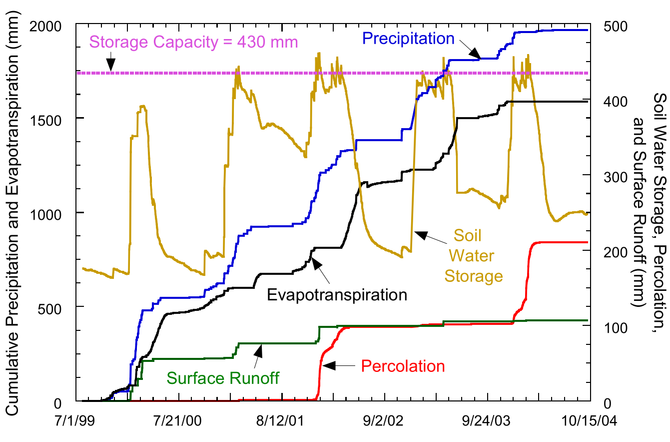

Fig. 13. (Color) Water balance components of thin ACAP cover at Sacramento, California; cumulative quantities shown except for soil water storage; storage capacities calculated from soil hydraulic properties in Table 2

Smesrud et al. (2012) decommissioned the test sections in Sacramento and determined that the original plant community comprised of perennial grasses transitioned to shallow-rooted annual grasses common in the surrounding landscape. These annual grasses had a lower wilting point potential, shorter growing season, and less capacity to remove stored water via transpiration. Consequently, the storage capacity was reduced, and the cover transmitted more percolation than intended. Water balance modeling conducted by Smesrud et al. (2012) demonstrated that sufficient soil water storage capacity would have been available each year and percolation would have been minimal if the original perennial grasses had been maintained. The lesson from this site was to select vegetation that exists in the surrounding landscape if possible and to understand the transpiration capacity of the local vegetation (e.g., wilting point, root depth and distribution, growing season). Establishing and maintaining vegetation species that differ from the surrounding plant communities can be difficult.

Preferential Flow

Some of the high percolation rates in the bins for annual percolation between 250 and 750 mm/year (Fig. 11) are caused by preferential flow. An example of preferential flow is illustrated in Fig. 14 using data collected during the winter and early spring of 2003 at Altamont, California ($P_a = 358$ mm/year). Soil water storage is shown in Fig. 14(a) as a function of time along with the storage capacity,

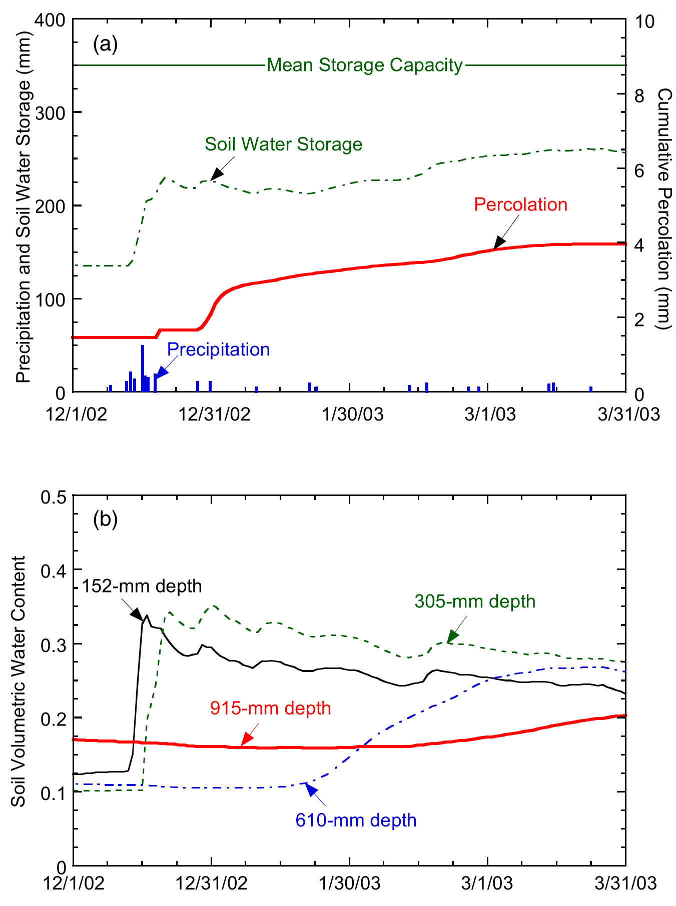

Fig. 14. (Color) Soil water storage, daily precipitation, and cumulative percolation as (a) daily precipitation, soil water storage, and cumulative percolation and (b) soil volumetric water content at various depths in the storage layer as a function of time from December 1, 2002, to March 31, 2003, at Altamont, California

daily precipitation, and cumulative percolation. Soil volumetric water contents are shown in Fig. 14(b) at depths of 152, 305, 610, and 915 mm below the ground surface.

Soil water storage increased as anticipated during periods of precipitation in the first half of December 2002 [Fig. 14(a)], which was caused by an increase in water content in the upper 460 mm of the cover as illustrated by water contents recorded at depths of 152 and 305 mm [Fig. 14(b)]. Little percolation was transmitted during the first half of December, and soil water storage remained below the storage capacity [Fig. 14(a)]. However, in the 10-day period between December 28, 2002 and January 7, 2003, 1.15 mm of percolation was transmitted even though water contents at the deepest depths (610 and 915 mm) remained unchanged. Because the water content at depth did not change, this water must have been transmitted nonuniformly through the cover. As noted previously, extensive efforts were made to prevent sidewall flow; thus, most of the flow probably occurred through preferential flow paths. For this site, 37% of the total annual percolation occurred when storage was below capacity, and no increase in water content was observed deep in the cover.

Preferential flow is more likely when covers are constructed with more plastic clayey soils that shrink and crack during drying. The cover at Altamont was constructed from a moderately plastic crushed claystone available on site. Use of less-plastic soil or soil with a larger fraction of coarse particles will reduce the propensity for cracking and preferential flow (Albrecht and Benson 2001; Benson et al. 2011). For example, the cover at Helena was constructed with clayey sand having very plastic fines. The large coarse fraction in the soil at Helena probably reduced the potential for shrinkage and cracking during drying, thereby precluding preferential flow. Albrecht and Benson (2001) and Benson et al. (2011) provide recommendations for soils that have lower propensity for preferential flow caused by shrinkage and cracking.

The significance of preferential flow in some instances indicates that direct measurement of percolation (e.g., using a lysimeter) is necessary if percolation is to be quantified reliably (Khire et al. 1997; Malusis and Benson 2006). Indirect estimates of percolation rate, such as those based on inferences from point measurements of state variables (e.g., water content or suction), may underestimate percolation considerably when preferential flow occurs. Moreover, predicting preferential flow when modeling the hydrology of water balance covers can be unreliable (Khire and Saravanathiiban 2013). Benson et al. (2011) provide recommendations on methods to measure percolation directly and monitor the performance of water balance covers.

Summary and Implications for Design

A review and assessment of hydrologic data collected from water balance covers monitored as part of the U.S. EPA's ACAP have been presented in this paper along with data from past studies. The following is a summary of the findings and the lessons learned for design in terms of the water balance quantities including runoff, evapotranspiration, and percolation.

Runoff

Factors having a major influence on runoff include intensity of precipitation, saturated hydraulic conductivity of soils in the surface layer, and snowmelt and frozen ground. Runoff increases with greater intensity of precipitation relative to the saturated hydraulic conductivity of the surface layer and decreases over time because of maturation of vegetation and increases in the saturated hydraulic conductivity of the surface layer caused by pedogenesis. Runoff (as a percentage of precipitation) is higher at sites where snow and frozen ground occur. The following are implications regarding runoff:

- Runoff generally is less than 10% of the annual water balance. Caution should be exercised when encountering predictions of annual runoff exceeding 10% of annual precipitation.
- Runoff is strongly affected by the saturated hydraulic conductivity of the surface layer. Designers should use care when selecting hydraulic properties of the surface layer during design (e.g., for input to computer models). Recommendations for hydraulic properties of the surface layer can be found in Benson et al. (2007, 2011).
- Runoff from snowmelt can be a significant fraction of total annual runoff in regions with snow and frozen ground. Accounting for snow accumulation, sublimation, snowmelt, and a frozen ground surface is important at sites with snow and frozen ground.
- Vegetation and slope did not exhibit systematic effects on runoff in the data evaluated in this study. Although these factors may affect runoff systematically, designers should be cautious when vegetation and slope are varied specifically to manipulate runoff and the water balance.

Evapotranspiration

Evapotranspiration is the largest component of the water balance. Factors affecting ET are water availability from precipitation, energy available for evaporation as described by PET, and type of vegetation. As annual PET/P decreases (i.e., water available from precipitation becomes larger relative to the energy available for evaporation), ET becomes increasingly comparable to PET, particularly for PET/P less than 5. The following are implications regarding ET:

- An estimate of annual ET can be made using Eq. (3) based on annual PET computed with the FAO-Penman-Monteith method and annual precipitation, both of which can be determined from meteorological data. Estimates made using Eq. (3) can be used to check predictions during design and to evaluate the evaporative demand that can be realized for a given climatic condition.
- ET is influenced by type of vegetation, but designers should be cautious of relying on enhanced ET from plant species that differ substantially from the surrounding plant community. Selecting vegetation consistent with surrounding plant communities is encouraged.
- Higher ET can be realized using trees in regions with higher annual precipitation (>500 mm/year). However, the additional ET obtained using trees cannot be defined reliably with the data currently available. Designers should be cautious of cover strategies that rely on trees to provide substantially higher ET than would be expected for other vegetation, particularly if trees are not part of the surrounding landscape.

Percolation

Percolation from water balance covers varies widely with annual precipitation. At semiarid and arid sites having low annual precipitation (<250 mm/year), percolation rates typically are less than 5 mm/year and are frequently less than 1 mm/year. In contrast, at humid sites with high annual precipitation (>750 mm/year), percolation rates can exceed 100 mm/year. With moderate annual precipitation (250–750 mm/year), percolation rates range from negligible (<1 mm/year) to in excess of 100 mm/year. The following are implications regarding percolation:

- Water balance covers in climates with annual precipitation <250 mm/year can be readily designed to achieve low

percolation rates (<5 mm/year). A 1-m-thick cover constructed with fine-textured soil can be adequate in many cases, although the thickness should be confirmed through appropriate analysis of required and available storage (Albright et al. 2010). A more robust process is necessary to design covers that will achieve low percolation rate when the annual precipitation exceeds 250 mm/year.
- Very low percolation rates are difficult to achieve when annual precipitation exceeds 500 mm/year and can be impractical when annual precipitation exceeds 750 mm/year. Requests for water balance covers with very low percolation rates in locations with annual precipitation in excess of 750 mm/year should be considered with skepticism.
- Adequate storage capacity is essential to achieve target percolation rates for all water balance covers but is particularly important when annual precipitation exceeds 250 mm/year. Many covers that transmitted more percolation than anticipated at sites with annual precipitation in excess of 250 mm/year had insufficient storage capacity. Methods to compute the required and available storage capacity are in Albright et al. (2010).
- Vegetation affects the recovery of storage capacity each year. Expectations for storage capacity must be consistent with the ability of the vegetation to remove the stored water to the anticipated minimum storage. Vegetation proposed for a cover should have the capability to remove stored water sufficiently, and to adequate depth, so that the minimum storage can be achieved reliably throughout the service life of the cover.
- Preferential flow caused by flow in macrofeatures in storage layers is difficult to predict, can prevent low percolation rates from being achieved, and will affect the annual percolation rate. Storage layers should be constructed using soil types and placement conditions resistant to shrinkage and formation of macrofeatures when practical. Recommendations for appropriate soils and placement conditions are in Albrecht and Benson (2001) and Benson et al. (2011).

The data presented in this study also illustrate the importance of using instrumented lysimeters for monitoring and interpreting the hydrologic performance of landfill covers. Direct measurement of hydrology using lysimetry combined with interpretive data provided by plant community assessment and soil and meteorological instruments provides the information needed to understand mechanisms important to cover performance.

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Supplemental Data

Table S1 and Figs. S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

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Supplemental Data

Table S1. Vegetation parameters for ACAP water balance covers measured 4-8 years following construction and during the peak growing season.

Test Site	Vegetation Type	Leaf Area Index	Parameters a, b, and c of Root Length Density Function*
Albany, GA	Grasses & Trees	0.73-2.17	a = 0.88, b = 5.3 m-1, c = 0.31 (2002)
Altamont, CA (1360 mm)	Grasses	1.22-2.31	a = 3.65, b = 7.6 m-1, c =0.03 (2002) a = 0.68, b = 4.9 m-1, c =0.00 (2003)
Apple Valley, CA (1212 mm)	Grasses & Shrubs	-	-
Boardman, OR (1220 mm)	Grasses	0.10-0.11	a = 0.30, b = 7.0 m-1, c = 0.01 (2000) a = 0.81, b = 6.9 m-1, c = 0.08 (2002
Boardman, OR (1840 mm)	Grasses	0.08-0.12	-
Cedar Rapids, IA	Grasses & Trees	0.99-1.16	-
Helena, MT (1800 mm)	Grasses	0.29-0.61	a = 0.38, b = 2.9 m-1, c = 0..00 (2001) a = 44.3, b = 43.4 m-1, c = 0.05 (2002)
Marina, CA (1520 mm)	Grasses	-	-
Monticello, UT (2020 mm)	Grasses & Shrubs	-	-
Omaha, NE (760 mm)	Grasses	1.26-1.84	-
Omaha, NE (1060 mm)	Grasses	1.25-1.43	a = 13.6, b = 26.8 m-1, c = 0.01 (2002
Polson, MT (1670 mm)	Grasses & Shrubs	0.18-1.28	a = 0.12, b = 1.9 m-1, c = 0.00 (2001) a = 3.16, b = 19.2 m-1, c = 0.04 (2002)
Sacramento, CA (1530 mm)	Grasses	1.97-2.85	a = 0.61, b = 10.7 m-1, c = 0.01 (2001)
Sacramento, CA (2910 mm)		1.71-1.75	-
Underwood, ND	Grasses	-	-

*Root length density (RLD) field data were fit to the equation: RLD = $ae^{-bz} + c$

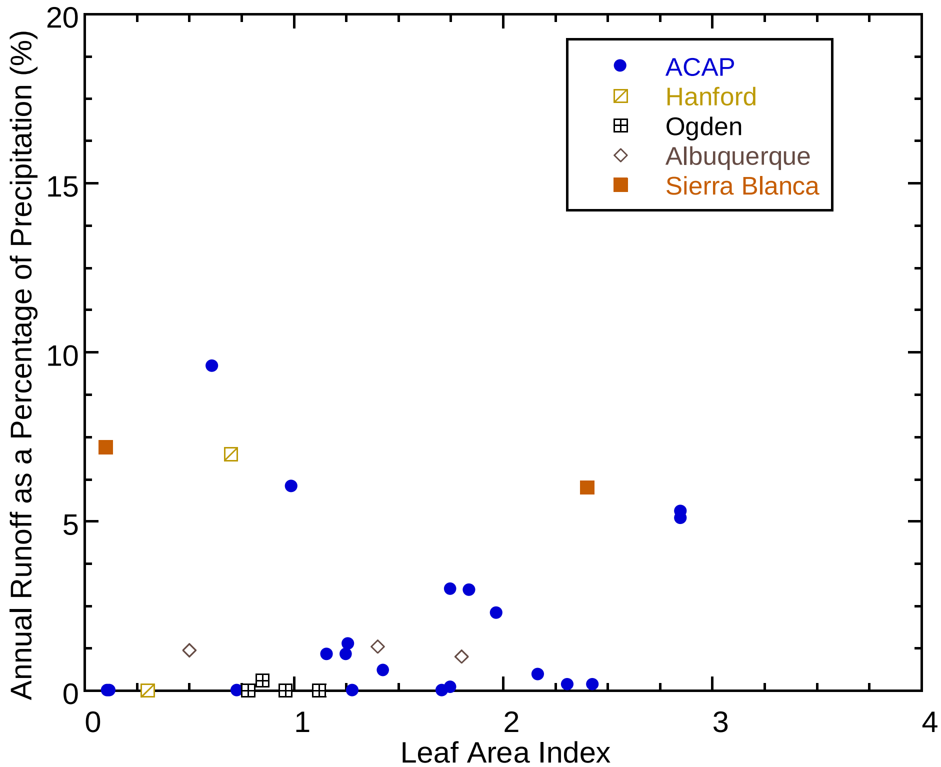
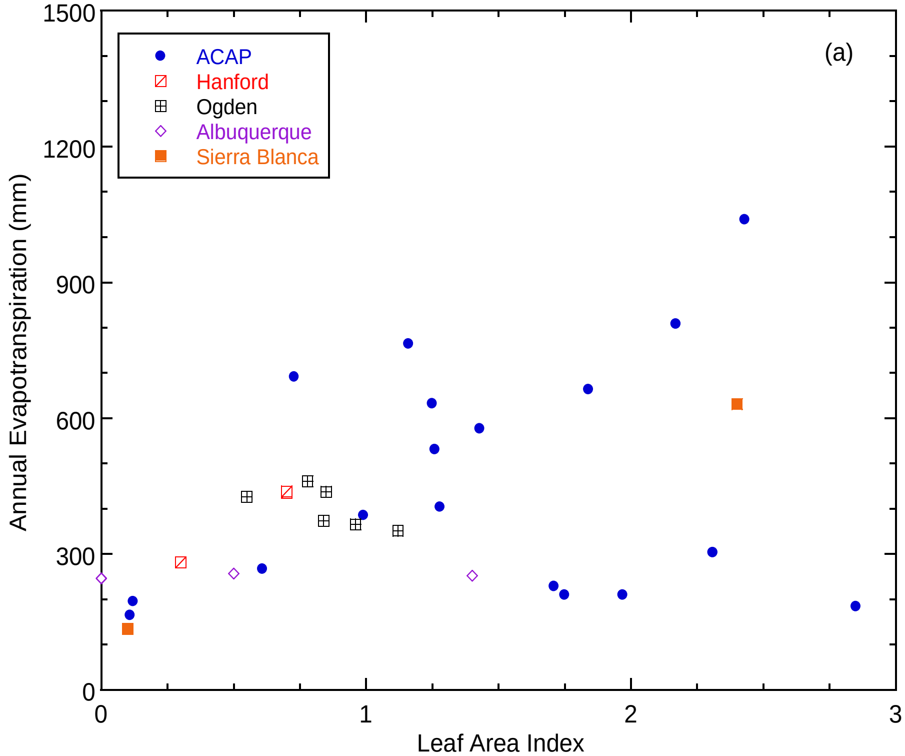


Figure S1. Annual runoff in terms of a percentage of precipitation as a function of leaf area index measured annually in this study and other studies.



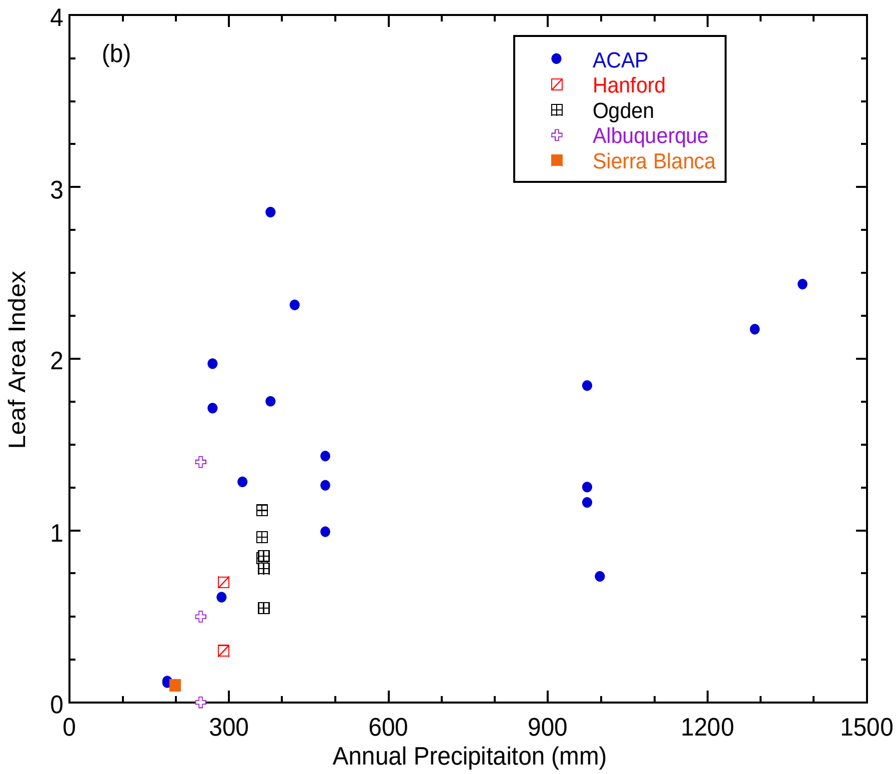


Figure S2. (a) Annual evapotranspiration as a function of leaf area index, and (b) leaf area index as a function of annual precipitation from this study and other studies.