

# **LANDFILL COVERS: WATER BALANCE, UNSATURATED SOILS, AND A PATHWAY FROM THEORY TO PRACTICE**

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## **ABSTRACT**

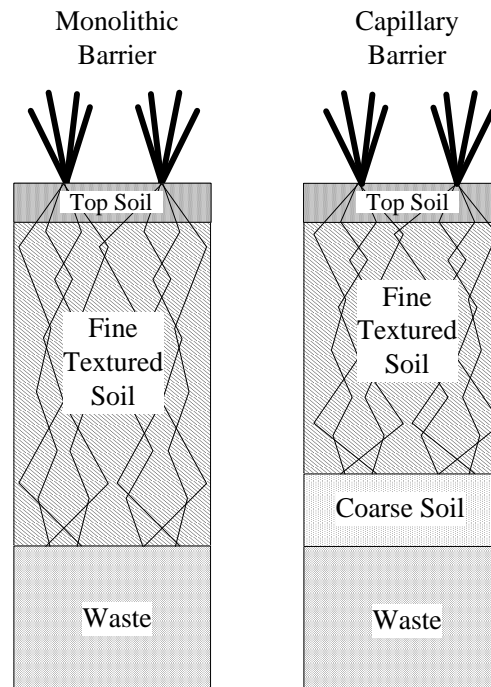
This paper describes key steps in the design process for water balance covers using a case history at a municipal solid waste landfill in Missoula, Montana, USA as an example. The intent is to illustrate how state-of-the-art concepts can be applied in the state-of-the-practice. The process begins by understanding the design objective (including regulatory requirements) and investigating lines of evidence indicating that a water balance cover is likely to function satisfactorily at the design location. Data from two other instrumented water balance covers in the region are used to evaluate efficacy along with historical meteorological data and information contained in a prior unsuccessful submittal for a water balance cover at the Missoula landfill. Site characterization is conducted to define properties of the soil resources and vegetation at the site for preliminary cover sizing and numerical modeling of the water balance. A numerical model is used with various design meteorological conditions as input to evaluate whether the cover will meet the design goal under realistic conditions. The final design consists of a monolithic cover comprised of a 1.22-m storage layer overlain by a 0.15-m topsoil layer. A field test with a fully instrumented lysimeter was constructed and monitored to confirm that the cover performs as anticipated in the design.

## **INTRODUCTION**

Final covers for waste containment that rely on principles of variably saturated flow to control percolation into underlying waste have become accepted as a viable methodology for long-term isolation of waste, particularly in semi-arid and arid regions where precipitation is favorably balanced by the energy available for evaporation (Khire et al. 2000, Zornberg et al. 2003, Albright et al. 2004, Malusis and Benson 2006). These covers are referred to using various names, including water balance covers, store-and-release covers, evapotranspirative (or “ET”) covers, and

alternative covers. The nomenclature “water balance cover” is used by the authors because this term represents the basic principle on which these covers function – the ability to balance storage of water corresponding to an acceptable level of percolation with the ability of plants and the atmosphere to remove stored water and replenish the water storage capacity of the cover profile. The authors specifically do not use the “ET cover” nomenclature because evapotranspiration is the predominant component of the water balance in nearly all cover systems, and thus is not particularly descriptive. The balance between water balance quantities is the feature that makes water balance covers unique.

Monolithic barriers and capillary barriers are the most common forms of water balance covers (Benson 2001, Ogorzalek et al. 2007, Bohnhoff et al. 2009) (Fig. 1). Monolithic barriers consist of a thick layer of fine-textured soil that is engineered and placed with appropriate compaction specifications so that the cover stores infiltrating water with little drainage while unsaturated. Capillary barriers generally consist of a two-layer system comprised of an overlying fine-textured storage layer similar to a monolithic cover that is underlain by a clean coarse-grained layer that provides a contrast in unsaturated hydraulic properties. The “capillary break” formed at the interface of the two layers enhances the storage capacity of the fine-textured layer (Stormont and Morris 1998, Khire et al. 2000), and can also promote lateral diversion of water in the fine-textured layer (Stormont 1995). For both types of covers, thickness of the storage layer is selected to have adequate capacity to store infiltrating water during the wet season while ensuring the cover meets the design percolation rate (Benson 2001). A surface layer of topsoil normally is placed over the storage layer of either type of cover to provide a hospitable environment for the plant community. Storage capacity of the topsoil layer generally is ignored during design.



**FIG. 1. Schematic of monolithic and capillary barriers.**

Water balance covers are designed to be compliant with natural hydrologic conditions and to rely on hydrologic processes comparable to those in the surrounding landscape. Natural hydrologic controls are employed in lieu of engineered hydraulic barriers because, in most cases, final covers must function for decades to centuries, and in some case millennia. A system engineered to be compliant with nature is more likely to function over these long periods compared to a system that employs engineered hydraulic barriers not commonly found in nature. However, because natural hydrologic controls are employed, water balance covers may not be appropriate for all climates (e.g., controlling percolation to minute quantities in a humid region with high precipitation may not be practical). Understanding this limitation is important, and the engineer must resist the temptation to force-fit water balance covers into applications where they are not appropriate.

Sustainability is an intrinsic principle in water balance covers. These covers employ natural hydrologic processes congruent with the surrounding landscape, which reduces long-term maintenance requirements. On-site materials (soils and plants) are employed, which minimizes transportation requirements, and straightforward construction methods are employed that can be implemented by local personnel. As a result, energy consumption and emissions are reduced, natural resource consumption is limited, and local economies are supported. In the current regulatory climate, a tacit assumption is made that the waste being contained is stabilized and has minimal or no value as a resource. This assumption may not be realistic and requires examination in the context of sustainability.

Over the last two decades, the senior author (Benson) has been intimately involved in research focused on exploring the mechanisms controlling performance of water balance covers, developing measurement methods to characterize the engineering properties needed for design (e.g., ASTM D 6093 and D 6836, Suwansawat and Benson 1998, Khire et al. 1995, Meerdink et al. 1995, Albrecht et al. 2003, Wang and Benson 2004, Benson et al. 2007a, 2007b, 2011a, Schlicht et al. 2010), developing methods and models for sizing covers and predicting performance (e.g., Khire et al. 1997, 1999, 2000; Benson and Chen 2003; Shackelford and Benson 2006; Albright et al. 2010; Ogorzalek et al. 2007; Benson 2007, 2010; Bohnhoff et al. 2009; Smesrud et al. 2012), and defining methods to confirm field performance (e.g., Benson et al. 1994, 1999, 2001, 2011b; Kim and Benson 2002; Benson and Wang 2006, Waugh et al. 2008, 2009). Connecting theory and practice as well as coupling bench-scale to field-scale have been threads throughout this research program. This research effort has been sponsored by a broad set of stakeholders concerned with long-term waste containment, including the National Science Foundation, the US Environmental Protection Agency's (USEPA) Alternative Cover Assessment Program (ACAP), the US Department of Energy's (DOE) Environmental Management (EM) and Legacy Management (LM) programs, and the US Nuclear Regulatory Commission. Dr. William Albright (Desert Research Institute) and Dr. William "Jody" Waugh (Stoller Corporation and DOE-LM) have been collaborators in this effort since 1999.

In 2008, USEPA commissioned a guidance document summarizing the knowledge gained from these two decades of research, development, and practice. This document evolved into the book *Water Balance Covers for Waste Containment:*

*Principles and Practice*, by Albright, Benson, and Waugh, which was published by ASCE Press in 2010 (Albright et al. 2010). The objective of the guidance document and book was to facilitate the transition from state-of-the-art to state-of-the-practice. Practitioners and environmental regulatory agencies in the US and abroad have adopted the principles and strategies described in this book.

A case history is described in this paper where state-of-the-art principles described in the book were employed in the state-of-the-practice to evaluate, design, and demonstrate the viability of a water balance cover for an operating municipal solid waste (MSW) landfill in Missoula, Montana. While this case study applies to MSW containment in a semi-arid climate, the principles are universal and can be (and have been) adapted to design covers for other types of waste and in other climates. The discussion contained herein is brief to meet publication constraints; more detailed discussion of each of the issues is covered in the book. Moreover, the extensive citations common in academic scholarship have been forgone. The book serves as the primary reference, and within the book numerous citations are included.

## **PROCESS**

The procedure for designing and evaluating a water balance cover consists of five steps, which can be summarized as follows (Albright et al. 2010):

1. **Preliminary assessment** – determine the performance goal and seek lines of evidence that a water balance cover may be successful at the proposed location. Understand the expectations of the overseeing regulatory authority and constraints required by the owner.
2. **Site characterization** – characterize the soils and vegetation available for the water balance cover.
3. **Storage assessment** – estimate the required thickness of the water balance cover by determining the amount of water that must be stored and the capacity of the cover to store the water.
4. **Water balance modeling** – predict the performance of the cover identified in the storage assessment for realistic meteorological data using a numerical model that simulates variably saturated flow and root water uptake in a multilayer system with a climatic flux boundary at the surface; refine the cover thickness if necessary.
5. **Performance demonstration** – conduct a performance demonstration to validate that the design meets the performance goal by instrumenting the actual cover or constructing a full-scale test section.

Each of these steps was conducted when evaluating, designing, and demonstrating the water balance cover for the site in Missoula.

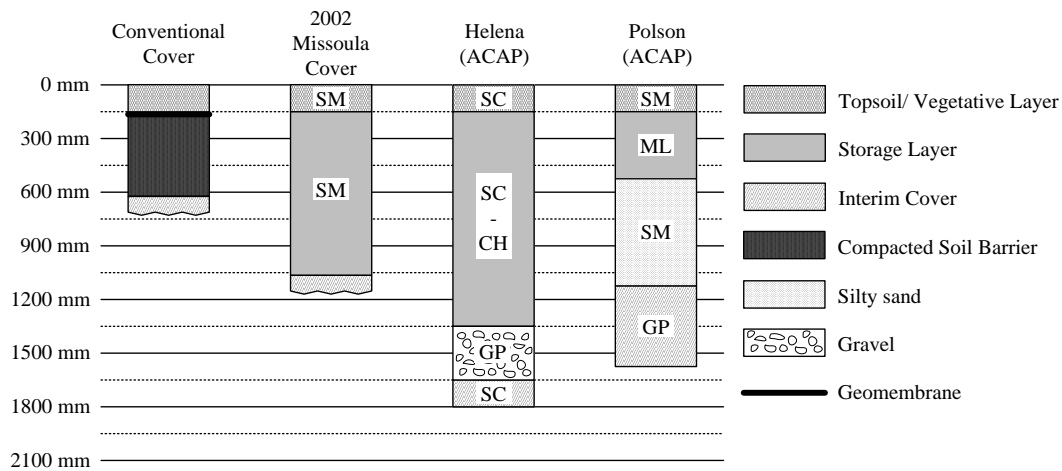
## PRELIMINARY ASSESSMENT

The preliminary assessment addresses two fundamental questions:

- What is the design goal for the project?
- What evidence exists that the design goal can be achieved with the climate, soils, and vegetation at the site?

Both of these questions need to be addressed during the preliminary assessment. The first question seems obvious, but is often overlooked until the project is far along. The second question is particularly important. If strong evidence is not available indicating a water balance cover will be successful, the engineer must carefully consider whether the design process should continue.

Discussions with the Montana Department of Environmental Quality (MDEQ, the regulatory agency with jurisdiction over the site), and review of MDEQ's *Draft Alternative Final Cover Guidance* (v. 9-11), indicated that the water balance cover for the Missoula landfill must be hydraulically equivalent to the conventional cover required in Montana for MSW landfill cells containing a composite liner. The conventional cover consists of a composite barrier with a compacted soil barrier having a saturated hydraulic conductivity no more than  $10^{-5}$  cm/s overlain by a geomembrane and a vegetated surface layer (Fig. 2).



**FIG. 2. Cover profiles at Missoula (conventional cover and 2002 Missoula Cover) and water balance cover profiles in Polson and Helena, MT. Soil classification based on Unified Soil Classification System.**

MDEQ does not stipulate statewide equivalent percolation rates for conventional covers. Owners are required to propose an equivalent percolation rate for consideration and possible concurrence by MDEQ. For this project, the design percolation rate recommended by ACAP for conventional composite covers (3 mm/yr average percolation rate, Benson 2001) was proposed, and accepted by MDEQ as the design goal. The rate is reported in units of length/time, which corresponds to units

of volume/time per area. The equivalency criterion for this project is similar to, but slightly less than the recommendation in Apiwantragoon (2007) for covers with composite barriers (4 mm/yr). North Dakota also stipulates 4 mm/yr for an equivalent percolation rate.

### **Supporting Evidence**

Evidence was sought to determine if a design percolation rate of 3 mm/yr was realistic for the Missoula landfill. Field data from other projects in similar climates and with similar soils and vegetation generally comprise the best evidence. In this case, water balance covers had been evaluated at MSW landfills in Polson and Helena, Montana as part of ACAP (Albright et al. 2004, Apiwantragoon 2007). These sites are 115 km north (Polson) and 185 km east (Helena) of Missoula. Index and hydraulic properties of the cover soils were available for both sites (Benson et al. 2011a) as well as data from an ACAP-style lysimeter (Apiwantragoon 2007) used to characterize the water balance and verify the percolation rate. At both landfills, the water balance cover evaluated with the ACAP lysimeter was deployed as final cover.

Profiles of the water balance covers evaluated in Polson and Helena by ACAP are shown in Fig. 2. Both included a capillary break. At Polson, however, the contrast between the layers was modest because the underlying sand contained fines. At Helena, the storage layer was thick and had relatively high air entry pressure. Consequently, the water balance covers at Polson and Helena functioned like monolithic covers, even though they included a break in soil texture (Apiwantragoon 2007). For this analysis, the covers at Polson and Helena were assumed to function as monolithic covers.

The covers at Polson and Helena functioned remarkably well, with average percolation rates of 0.5 mm/yr (Polson) and 0.0 mm/yr (Helena) during the ACAP monitoring period (2000-04) (Apiwantragoon 2007). Thus, these covers provided a good benchmark for assessing the viability of a water balance cover in Missoula. That is, if the climate in Missoula is sufficiently similar to the climates in Polson and Helena, then a water balance cover for Missoula should function comparable to the covers in Polson and Helena, provided the cover in Missoula has similar available water storage capacity relative to the required storage capacity.

Additional information was available from an application made by the landfill owner in 2002 (Miller 2002) to deploy a water balance cover with a 0.91-m-thick storage layer (Fig. 2). This application was based primarily on findings from a numerical modeling exercise using on-site soil hydraulic properties. The modeling indicated that percolation would be nil for typical meteorological conditions. The application was not approved because the site characterization was limited, wetter than normal conditions were not assessed, and no provision was made to demonstrate performance at full scale. This proposed cover is referred to henceforth as the “2002 Missoula Cover,” although a cover was never constructed based on this design.

The data from Polson and Helena were evaluated in the context of the conditions in Missoula to determine if these sites could be used as analogs, and to determine if the design goal for Missoula was realistic given the meteorological conditions at the site, the soil resources available, and the local vegetation. Soil hydraulic properties reported in Miller (2002) were used for this preliminary assessment.

## Climate Assessment

Meteorological data for Missoula were obtained from the National Weather Service. Climate type, average annual precipitation, and average high and low temperatures for Missoula, Polson, and Helena are summarized in Table 1. The data correspond to the period 1952-2010, for which a complete record of precipitation and temperature was available for all three sites.

Missoula and Helena have semiarid climates based on the definitions in UNESCO (1999), whereas Polson is subhumid. Polson has the highest average annual precipitation (380 mm) and the highest ratio of annual precipitation (P) to annual potential evapotranspiration (PET). The ratio P/PET is a measure of the amount of water to be managed (a fraction of P) relative to the energy available to manage water via evapotranspiration. Lower P/PET corresponds to greater aridity and higher confidence in managing precipitation with minimal percolation; i.e., the likelihood of achieving a percolation goal increases as annual P/PET decreases. Annual precipitation at all three locations was close to average during 2000-04, when data were collected from the ACAP-style lysimeters at Polson and Helena (Table 1). Thus, the water balance data from Polson and Helena during this period represent typical conditions.

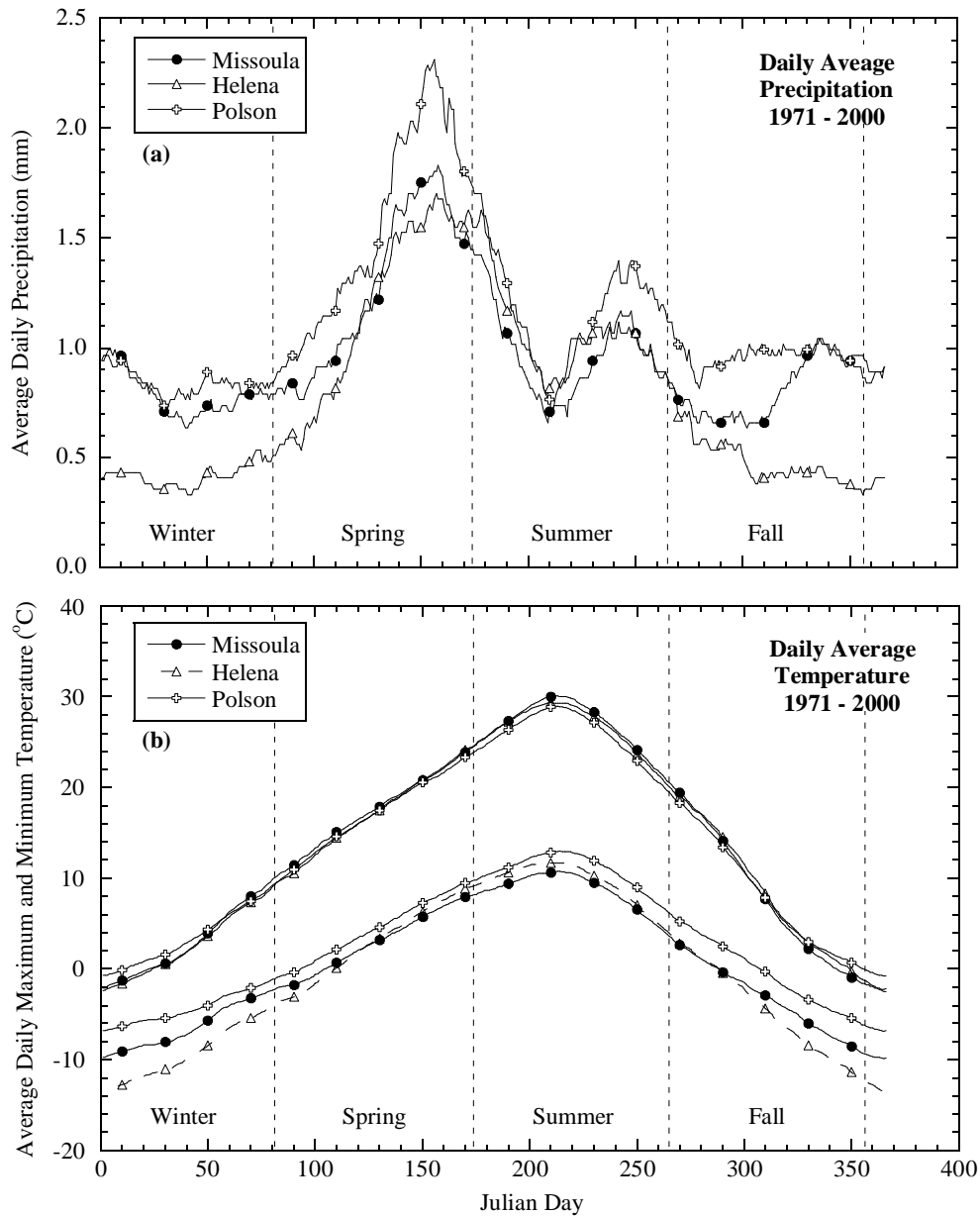
**Table 1. Climatic data for Missoula, Helena, and Polson, Montana.**

Site	Climate	Avg. Annual Precip. (mm)	Avg. Annual P/PET	Avg. Annual Precip. During ACAP (mm)	Avg. Air Temperature (°C)	
					High with Month	Low with Month
Missoula	Semi-arid	337	0.40	333	30 (July)	-10 (Jan.)
Helena	Semi-arid	289	0.44	270	29 (July)	-13 (Jan.)
Polson	Sub-humid	380	0.58	362	29 (July)	-7 (Jan.)

Daily average precipitation is shown in Fig. 3a for Missoula, Polson, and Helena. The annual precipitation pattern is similar for all three sites, with the wettest period occurring at the end of spring and beginning of summer, followed by a much drier period in mid summer and a wetter period in late summer and early fall. Fall and winter are the driest seasons. Daily precipitation at Missoula is more similar to precipitation in Polson than Helena. However, Missoula is drier than Polson, particularly in the spring. Missoula is wetter than Helena in the winter and spring, and comparable in the summer (Fig. 3a).

Daily average minimum and maximum air temperatures at all three sites (Fig. 3b) show similar seasonality. Missoula has slightly higher maximum daily air temperatures than Polson and Helena, except in late fall and winter. The daily average minimum air temperature tends to be cooler in Missoula than Polson and

Helena during late spring, summer, and early fall (Fig. 3b), which is indicative of a clearer sky and lower humidity during the summer. Polson exhibits the least seasonal variation in temperature of the three sites, and a slightly smaller difference between daily maximum and minimum temperature, due to buffering provided by Flathead Lake (adjacent to Polson).



**FIG. 3. Daily average precipitation (a) and daily average maximum and minimum temperature (b) between 1971 and 2000 for Missoula, Helena, and Polson.**



Annual daily average solar radiation, relative humidity, and wind speed (all affecting ET) for the period 1991-2005 for Missoula, Polson, and Helena (period for which complete data are available for all three sites) are shown in Fig. 4 using box plots. The centerline of the box is the median, the outer boundaries represent the interquartile range (i.e., 25<sup>th</sup> and 75<sup>th</sup> percentile), and the upper and lower whiskers represent the 10<sup>th</sup> and 90<sup>th</sup> percentiles of the data. Outliers are shown as individual data points above or below the whiskers (e.g., Fig. 4c). Solar radiation at each site is comparable since the three locations are at similar latitude. Polson is the most humid site, due to the proximity of Flathead Lake. Helena is the least humid and windiest site (Fig. 4b and c). Missoula falls between Polson and Helena for all three meteorological parameters.

### Soil Resource Assessment

Index properties of the soil proposed by Miller (2002) for the 2002 Missoula Cover are summarized in Table 2 along with the properties of the storage layers in Polson and Helena. The Missoula soil is a broadly graded silty sand with gravel (SM). The storage layer at Polson has an upper layer of lean clay (CL-ML) over a lower layer of silty sand (SM). At Helena, the storage layer is silty clay (SC). The soils at Polson and Helena contain less gravel ( $\leq 6\%$ ) than the Missoula soil reported by Miller (2002) (33% gravel, Table 2).

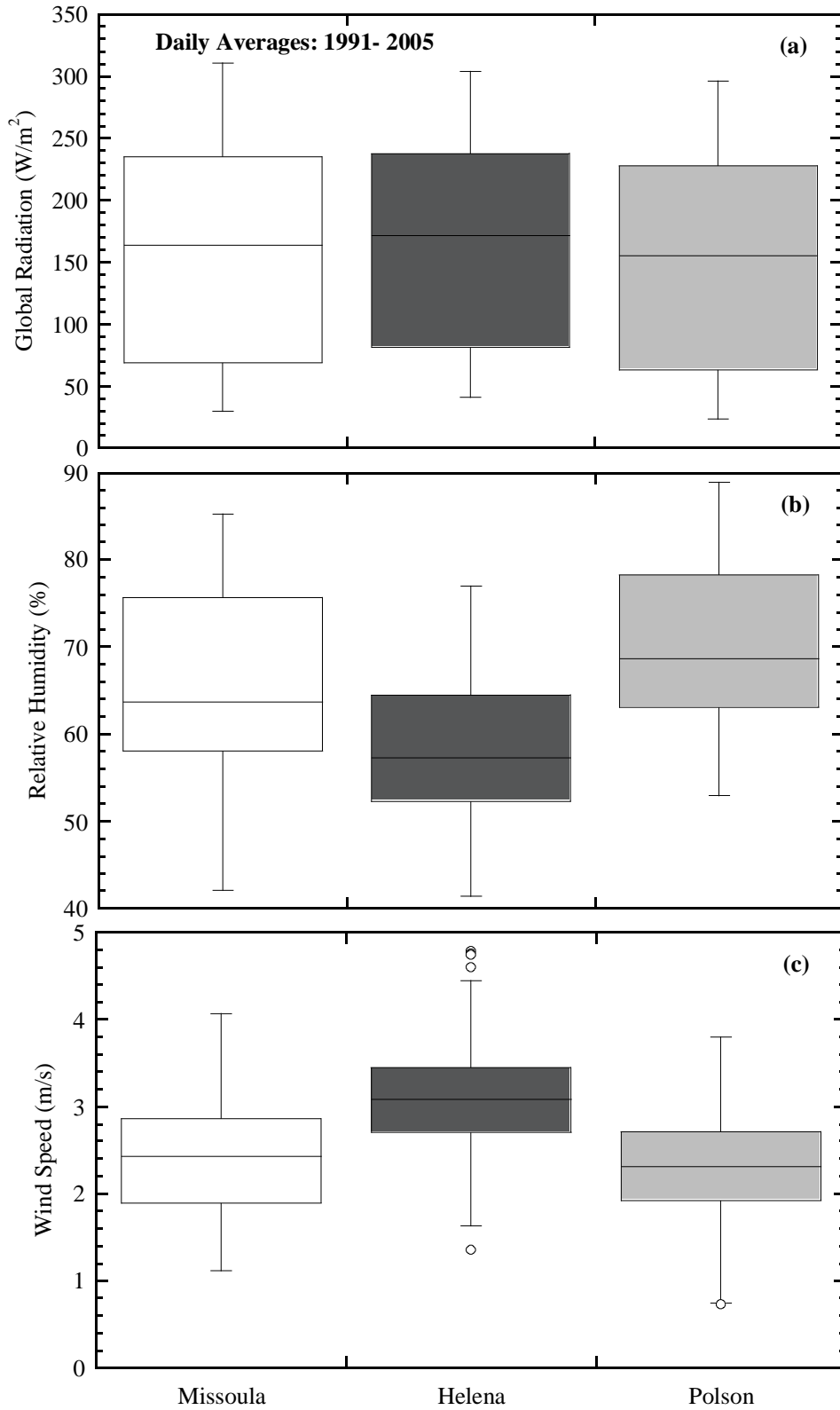
**Table 2. Composition and classification of storage layer soils at Missoula (Miller 2002) and Polson and Helena (Albright et al. 2004).**

Site	Unified Soil Classification	Particle Size Distribution (%)				Atterberg Limits	
		Gravel	Sand	Fines	2 $\mu$ m Clay	Liquid Limit	Plasticity Index
Missoula	SM	33	34	33	NR	NR	NR
Helena	SC	2	54	44	30	67	47
Polson	SM	6	54	42	5	NP	NP
	CL-ML	0.8	6.1	93.2	18	28	7

Notes: NR = not reported; NP = non-plastic as defined in ASTM D 2487; particle sizes based on definitions in the Unified Soil Classification System (ASTM D 2487): gravel > 4.8 mm, 4.8 mm > sand > 0.75 mm, fines < 0.75 mm

The silty clay at Helena has a similar distribution of predominant particle sizes as the silty clay at Polson (Table 2), but the Helena soil has moderately plastic fines and a larger clay fraction (30% vs. 5%). Although Atterberg limits were not reported for the Missoula soil by Miller (2002), the high percentage of sand and gravel and the relatively high saturated hydraulic conductivity (see subsequent discussion), suggests that the Missoula soil probably is non-plastic.

Saturated and unsaturated hydraulic properties reported by Miller (2002) for the Missoula soil are in Table 3 along with properties for covers in Polson and Helena. The hydraulic properties at Polson and Helena were measured during construction as well as 9 yr after the covers had been in service (cited as the “in-service” condition



**FIG. 4.** Box plots of daily average global radiation (a), relative humidity (b), and wind speed (c) from 1991 to 2005 for Missoula, Helena, and Polson.

henceforth). The saturated hydraulic conductivities ( $K_s$ ) of the Missoula soil and the as-built silty sand at Polson ( $4.2 \times 10^{-5}$  to  $4.9 \times 10^{-5}$  cm/s) are comparable. The silty clay at Polson and clayey sand at Helena were less permeable when constructed ( $K_s = 1.5 \times 10^{-7}$  to  $4.0 \times 10^{-7}$  cm/s). However, samples collected after 9 yr of service indicated that pedogenesis had altered the soils ( $K_s = 2 \times 10^{-6}$  to  $8 \times 10^{-6}$  cm/s), making them nearly as permeable as the Missoula soil. (Benson et al. 2007, 2011a).

Soil water characteristic curves (SWCC) for the soils at Polson, Helena, and Missoula (as described in Miller 2002) are shown in Fig. 5. van Genuchten's (1980) equation was used to describe the SWCC:

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left\{ \frac{1}{1 + (\alpha\psi)^n} \right\}^m \quad (1)$$

where  $\alpha$  and  $n$  are fitting parameters,  $\theta_s$  is the saturated volumetric water content,  $\theta_r$  is the residual water content, and  $m = 1 - 1/n$ . The fitted parameters are summarized in Table 3 for as-built conditions in Polson and Helena, and laboratory-compacted conditions for the Missoula soil as reported by Miller (2002). The SWCCs in Fig. 5 correspond to the as-built and in-service conditions for Polson and Helena, and the laboratory-compacted Missoula soil reported by Miller (2002).

**Table 3. Hydraulic properties of storage layers at Polson and Helena and for 2002 Missoula Cover.**

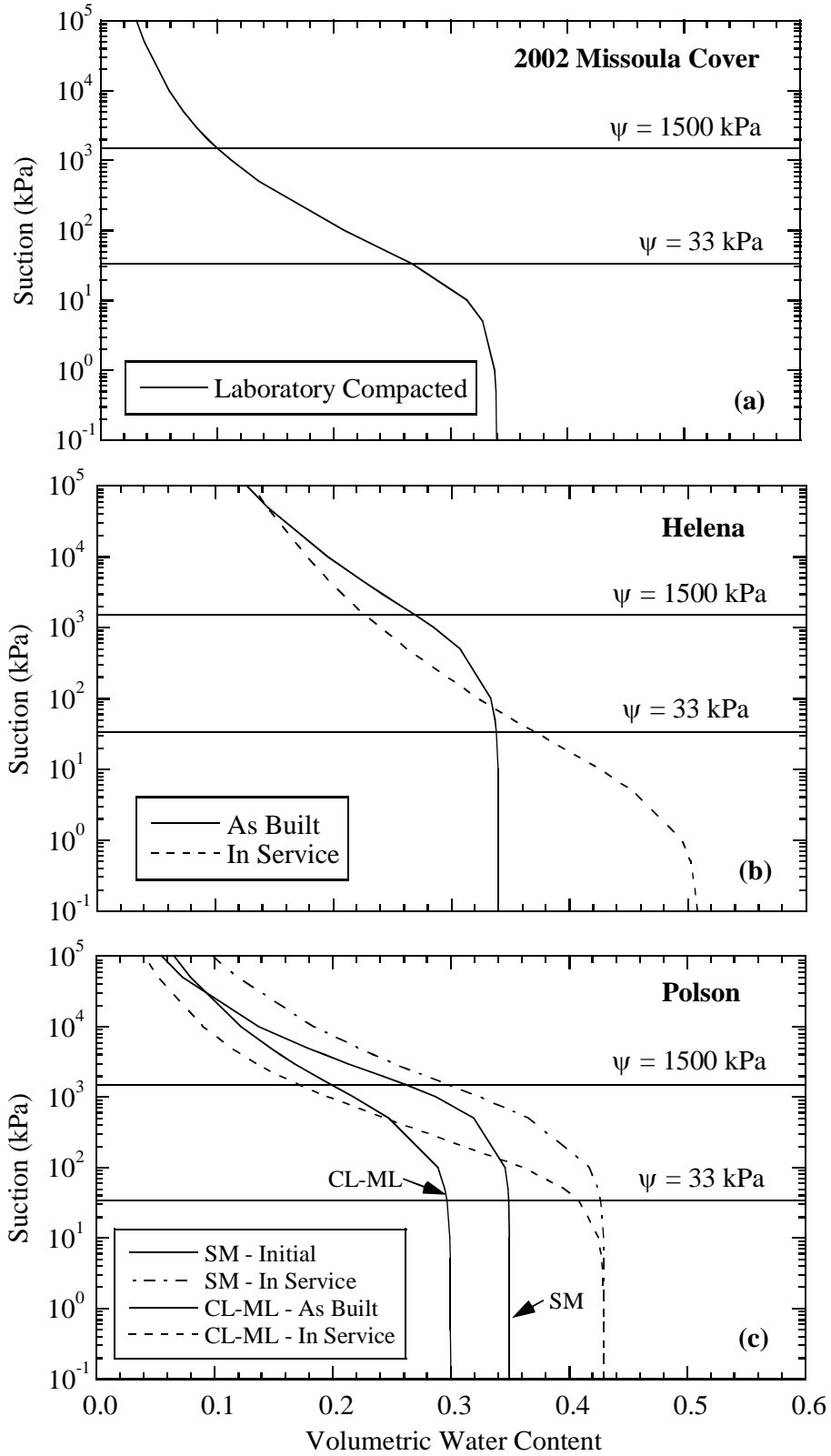
Site	Soil	Hydraulic Properties				
		$K_s$ (cm/s)	$\alpha$ (kPa <sup>-1</sup> )	$n$	$\theta_s$	$\theta_r$
2002 Missoula Cover	SM	$4.9 \times 10^{-5}$	0.052	1.28	0.34	0.00
Helena	SC	$1.5 \times 10^{-7}$	0.0018	1.19	0.34	0.00
Polson	SM	$4.2 \times 10^{-5}$	0.0010	1.40	0.35	0.00
	CL-ML	$4.0 \times 10^{-7}$	0.0027	1.27	0.30	0.00

The as-built soils for Polson and Helena and the Missoula soil have similar  $\theta_s$  and  $\theta_r$  (Table 3), but the  $\alpha$  parameter reported by Miller (2002) for the Missoula soil is more than one order of magnitude larger than the as-built  $\alpha$  for the soils at Polson and Helena (0.0010-0.0027 1/kPa). However, the in-service  $\alpha$  for both Polson and Helena (0.01-0.05 1/kPa, Benson et al. 2011a) after 9 yr of service is similar to  $\alpha$  for the Missoula soil reported by Miller (2002). All of the soils have similar  $n$  (1.19 to 1.40) in the as-built and in-service conditions (Benson et al. 2011a).

### Storage Assessment

**Available Soil Water Storage Capacity.** Available soil water storage capacity ( $S_A$ ) was computed for the covers in Polson and Helena along with the profile proposed previously for the 2002 Missoula Cover (Miller 2002) using:

$$S_A = L (\theta_{FC} - \theta_{WP}) \quad (2)$$



**FIG. 5. Soil water characteristic curves (SWCCs) for Missoula (a), Helena (b), and Polson (c).**

where  $L$  is the thickness of the storage layer,  $\theta_{FC}$  is the field capacity, and  $\theta_{WP}$  is the wilting point (Albright et al. 2010). Available soil water storage capacity is reported in units of length (volume per unit area = length). Field capacity ( $\theta_{FC}$ ) is the water content at which drainage becomes negligible under gravity and is estimated from the SWCC as the volumetric water content ( $\theta$ ) at  $\psi = 33$  kPa. The wilting point ( $\theta_{WP}$ ), the water content at which transpiration ceases, was estimated as  $\theta$  at  $\psi = 1500$  kPa. In semi-arid regions such as western Montana, wilting points can be as high as 5-7 MPa (Apiwantragoon 2007). Thus, defining  $\theta_{WP}$  based on 1500 kPa underestimates available storage (a conservative estimate).

The following  $S_A$  were computed: Polson – 90/166 mm, Helena – 82/164 mm, and 2002 Missoula – 134 mm (the latter  $S_A$  for Polson and Helena correspond to in-service conditions). The increase in  $S_A$  at Polson and Helena is due to pedogenic changes in the SWCC, which are known to increase  $\theta_s$  and  $\alpha$  (Benson et al. 2007a, 2011a). For these soils, the increase in available storage due to the increase in  $\theta_s$  was more significant than the reduction in available storage due to the increase in  $\alpha$ . When the in-service condition is considered for Polson and Helena, the 2002 Missoula Cover has approximately 30 mm less storage than the covers in Polson and Helena, and therefore could transmit more percolation.

**Required Soil Water Storage.** Required soil water storage ( $S_R$ ) was computed for the 2002 Missoula Cover and the covers in Polson and Helena using Eq. 3 and the procedures outlined in Albright et al. (2010):

$$S_r = \sum_{m=1}^6 \Delta S_{FW,m} + \sum_{m=7}^{12} \Delta S_{SS,m} \quad (3)$$

where  $\Delta S_{FW,m}$  is monthly accumulation of soil water storage in fall and winter ( $m = 1-6$  corresponding to October through March):

$$\Delta S_{FW,m} = P_m - \beta_{FW} PET_m - \Lambda_{FW} \quad (4)$$

and  $\Delta S_{SS,m}$  is monthly accumulation of soil water storage in spring and summer ( $m = 7-12$ , April through September).

$$\Delta S_{SS,m} = P_m - \beta_{SS} PET_m - \Lambda_{SS} \quad (5)$$

In Eqs. 4 and 5,  $P_m$  is monthly precipitation and  $PET_m$  is monthly PET for the  $m^{\text{th}}$  month,  $\beta_{ij}$  is the ratio of ET to PET for fall-winter (FW) or spring-summer (SS) conditions, and  $\Lambda_{ij}$  is the water balance residual (runoff, percolation, and internal lateral flow, if any) for fall-winter (FW) or spring-summer (SS) conditions. For sites with snow and frozen ground,  $\beta_{FW} = 0.37$ ,  $\beta_{SS} = 1.00$ ,  $\Lambda_{FW} = 0$ , and  $\Lambda_{SS} = 168$  (Albright et al. 2010). PET was computed using methods presented in Allen et al. (1998). For months when  $P/PET$  was less than 0.51 (fall and winter months) or 0.32 (spring and summer months), the monthly accumulation was set at zero, as recommended in Albright et al. (2010). In addition, if  $\Delta S_{FW,m}$  or  $\Delta S_{SS,m}$  computed with Eqs. 4-5 was less than zero for any  $m$ , the monthly accumulation was set to zero for that month as recommended in Albright et al. (2010).

Required storage for each site during 2000-04 (period when Polson and Helena were monitored) is summarized in Table 4. The required storage for Missoula during this period (35-156 mm, annual average = 92 mm) is comparable to the required storage in Polson (49-134 mm, annual average = 89 mm), and appreciably more than the required storage in Helena (14-42 mm, annual average = 12 mm).

**Table 4. Required and available storage for ACAP monitoring period (2000-04) for 2002 Missoula Cover and covers in Polson and Helena.**

Site	Available Storage $S_A$ (mm)	Year	Precip. (mm)	PET (mm)	Required Storage $S_R$ (mm)	$S_R/S_A$
2002 Missoula Cover	134	2000	314	861	156	1.17
		2001	337	846	95	0.71
		2002	258	783	35	0.26
		2003	370	875	106	0.80
		2004	386	826	66	0.49
Helena	164	2000	213	1038	42	0.26
		2001	273	1105	6	0.04
		2002	319	1004	0	0.00
		2003	238	1093	0	0.00
		2004	308	990	14	0.08
Polson	166	2000	382	822	134	0.81
		2001	341	856	81	0.49
		2002	356	812	49	0.29
		2003	343	898	80	0.48
		2004	386	777	103	0.62

Historical meteorological data for Missoula were used to compute required storage for a typical year (year with annual precipitation closest to long-term average, 1984 – 338 mm) and the more challenging design scenarios recommend in Albright et al. (2010): the wettest year on record (1998, 556 mm) and the 95<sup>th</sup> percentile precipitation year (1975 – 469 mm). Required storage for these cases is summarized in Table 5.

The required storage for Missoula computed from the historical data varies by a factor of four between the typical year (1984 –  $S_R = 51$  mm) and the 95<sup>th</sup> percentile precipitation year (1975,  $S_R = 204$  mm). Moreover, the required storage is higher for the 95<sup>th</sup> percentile precipitation year ( $S_R = 204$  mm), even though the wettest year on record (1998,  $S_R = 133$  mm) received more precipitation. This unexpected difference in  $S_R$  reflects differences in the temporal distribution of precipitation. In 1998, large precipitation events were received during summer when ET was high, whereas the

large precipitation events in 1975 occurred in late fall and winter, when ET was low and water was accumulating in the cover. A wetter winter also occurred in 1975. Thus, the wettest year is not necessarily the worst-case scenario for Missoula.

**Table 5. Required storage and required-available storage ratio for 2002 Missoula Cover for wet-year scenarios cited in Albright et al. (2010).**

Quantity	Meteorological Year		
	Wettest	95 <sup>th</sup> Percentile	Typical
Year	1998	1975	1984
Precipitation (mm)	556	469	338
PET (mm)	851	762	953
Required Storage, $S_R$ (mm)	133	204	51
$S_R/S_A$ ( $S_A = 134$ mm)	0.99	1.53	0.38

**Relative Storage.** Each cover was evaluated using the relative storage ratio  $S_R/S_A$ , which describes the required storage relative to the available storage in the cover profile for a given meteorological year. When  $S_R/S_A$  is  $\ll 1$ , negligible percolation is anticipated because the cover has adequate capacity to store infiltrating precipitation. Percolation is anticipated when  $S_R/S_A$  is  $\approx 1$  or  $> 1$  because the water to be stored is comparable to or larger relative to the storage capacity available in the cover. For  $S_R/S_A > 1$ , the annual percolation rate can roughly be estimated as  $S_R - S_A$ .

A summary of  $S_R/S_A$  is in Table 4 for Polson, Helena, and the 2002 Missoula Cover for the 2000-04. For the covers in Polson and Helena,  $S_R/S_A$  is  $< 1$  for each year, which is consistent with the very low percolation rates measured for these covers ( $< 1$  mm/yr). For the 2002 Missoula Cover,  $S_R/S_A$  is  $< 1$  for all years except 2000. However, the average  $S_R/S_A$  for the 2002 Missoula Cover (0.69) during 2000-04 is larger than for the covers in Polson (0.54) and Helena (0.08).

Ratios of  $S_R/S_A$  for the 2002 Missoula Cover computed using historical meteorological data are summarized in Table 5;  $S_R/S_A = 0.38$  for a typical year, 0.99 for the wettest year on record, and 1.53 for the 95<sup>th</sup> percentile precipitation year.

### Overall Assessment

Comparison of the meteorological data from Missoula, Polson, and Helena indicates that a water balance cover in Missoula should function comparably as the water balance cover in Polson, and maybe as well the water balance cover in Helena (both Polson and Helena had very low percolation rates during 2000-04), provided the cover in Missoula has adequate storage capacity and the vegetation at all three sites has similar ability to remove water from the profile. This is supported by the relative magnitudes of the average annual P/PET, which is lower in Missoula than in Polson and Helena. A wheatgrass blend similar to the vegetation at Polson and Helena is present in the grasslands surrounding the Missoula landfill (Table 6). Thus,

the vegetation at Missoula should have similar ability to remove stored water as the vegetation at Polson and Helena.

**Table 6. Vegetation at Missoula, Polson, and Helena as reported in Miller (2002), Roesler et al. (2002), and Albright et al. (2004).**

Site	Vegetation
Missoula	Critana thickspike, sodar streambank, and pryor slender wheatgrass, sheep fescue, yellow sweetclover.
Helena	Bluebunch, slender, and western wheatgrass, sandburg bluegrass, sheep fescue, blue gamma, green needlegrass, needle-and-thread.
Polson	Thickspike, bluebunch, slender, and crested wheatgrass, 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.

The 2002 Missoula Cover profile should be adequate under typical conditions, which is consistent with the predictions made by Miller (2002). However, a thicker cover profile is needed to provide sufficient storage capacity for wetter conditions. For example,  $S_R/S_A$  exceeds 1 for the Missoula cover when the meteorological data from 2000 are used to compute  $S_R$  (Table 4). For this same year,  $S_R/S_A = 0.81$  for Polson and 0.26 for Helena. The year 2000 was wetter than the other years during the 2000-04 monitoring period in Polson and Helena, but was not exceptionally wet. Thus, in wetter years, the 2002 Missoula cover has a higher likelihood of transmitting percolation than the covers at Polson or Helena. MDEQ agreed with this assessment, and concurred that a thicker cover was necessary.

### Path Forward

Based on the preliminary assessment, MDEQ was satisfied that a properly sized water balance cover could function satisfactorily at Missoula. However, discussions with MDEQ indicated that approval for a water balance cover would require more comprehensive analysis and design, including (i) more comprehensive evaluation of soil resources, (ii) site-specific assessment of vegetation properties, (iii) additional modeling to evaluate wetter conditions, and (iv) a full-scale demonstration to validate that the cover functions as designed. These requirements from MDEQ are consistent with their *Draft Alternative Final Cover Guidance* (v. 9-11) and the approach recommended in Albright et al. (2010). The following steps were conducted to address these concerns:

- a soil resource evaluation was conducted and the saturated and unsaturated hydraulic properties were measured for potential cover soils,
- vegetation at the site was sampled and the leaf area index (LAI) and root density function were measured,



- data describing the phenology of the wheatgrass blend in the region were obtained from the literature,
- preliminary design was conducted to estimate the required thickness of the storage layer under wetter conditions (wettest year on record and 95<sup>th</sup> percentile precipitation year) using soil hydraulic properties from the soil resource evaluation,
- percolation from the cover identified in preliminary design was predicted using a numerical model employing site-specific meteorological data, soil properties, and vegetation properties as input; meteorological data for typical and much wetter conditions were employed,
- a test section was constructed so that the water balance (particularly the percolation rate) could be measured at field scale to confirm the sufficiency of the design.

## **SOIL RESOURCES**

A soil resource evaluation was conducted to determine the suitability of the on-site soils. Ten soil samples were collected from test pits excavated at four sites (Sites 1-4) where soil was available for the cover. Sites 1-3 were soil stockpiles excavated from previous cell construction. Native ground was sampled at Site 4, and at Site 1 in an area adjacent to the soil stockpile at Site 1. Topsoil was sampled at Sites 3 and 4.

The site has an abundance of soil and availability of soil is not an issue. Thus, the characterization focused on identifying soils that were suitable for the cover and not the volume of each soil that was available.

Test pits were excavated with a backhoe at each sampling site. Each test pit was inspected visually to assess homogeneity of the borrow source. Disturbed samples were collected with hand tools and placed in 20-L buckets. All buckets were sealed with plastic lids containing rubber gaskets.

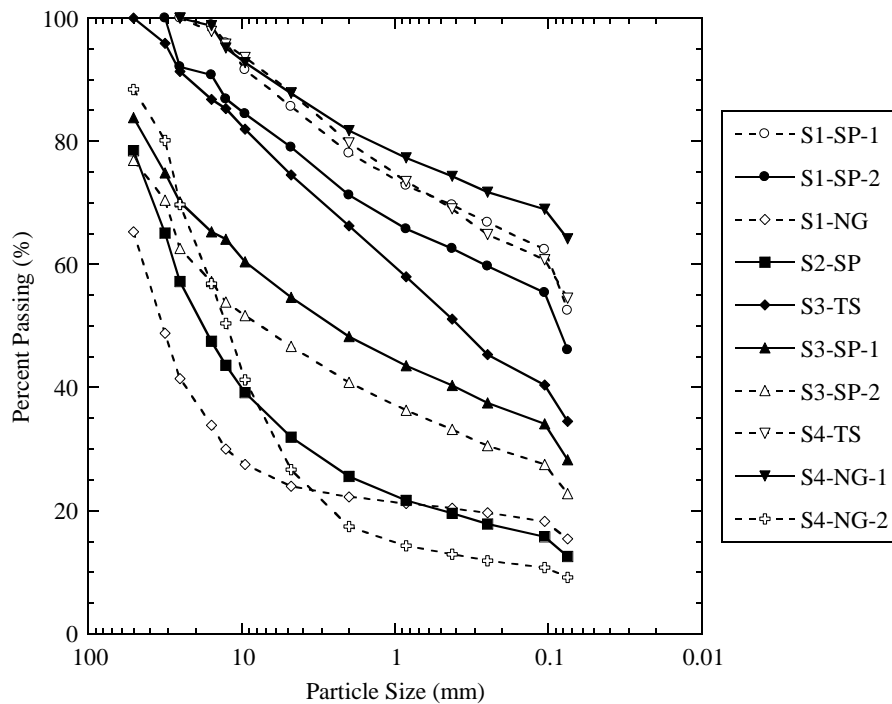
### **Particle Size Distribution**

Particle size analyses were conducted on each sample following ASTM D 422. The particle size distributions are shown in Fig. 6. Atterberg limits were not measured. The average particle size fractions for the stockpile soils (gravel = 39%, sand = 27%, and fines = 32%) are comparable to those for the Missoula soil cited in Miller (2002).

Five soils were selected for additional testing (solid symbols and solid lines in Fig. 6). These soils included three stockpile soils, one at each of Sites 1-3 (S1-XX to S3-XX; XX is an identifier), the topsoil at Site 3 (S3-TS), and the finer-textured native ground from Site 4 (S4-NG-1). Topsoil at Site 3 was selected to define topsoil properties for use in water balance modeling. The topsoil at Site 3 was coarser than the topsoil at Site 4, and was expected to provide a conservative representation of topsoil available for the cover. The three stockpile soils constitute a broad range in particle size distribution (Fig. 6), and were selected to define a range of anticipated hydraulic properties. The fine-grained native ground soil (S4-NG-1 in Fig. 6) was selected for comparison with the stockpile soils.

## Compaction Properties

Compaction tests were conducted on the five soils using ASTM D 698 (standard Proctor). All soils were scalped on a 9.5-mm sieve, and a coarse-fraction correction was applied to account for particles larger than 9.5 mm using the procedure in ASTM D 4718. Compaction curves for the three stockpile soils were comparable, with maximum dry unit weight ( $\gamma_{dmax}$ ) ranging between 18.3 and 20.1 kN/m<sup>3</sup> and optimum water content ( $w_{opt}$ ) ranging between 8.2 and 11.4% (Benson and Bareither 2011). The compaction curve reported by Miller (2002) for the 2002 Missoula Cover also falls in this range ( $\gamma_{dmax} = 19.9$  kN/m<sup>3</sup>,  $w_{opt} = 9.6\%$ ).



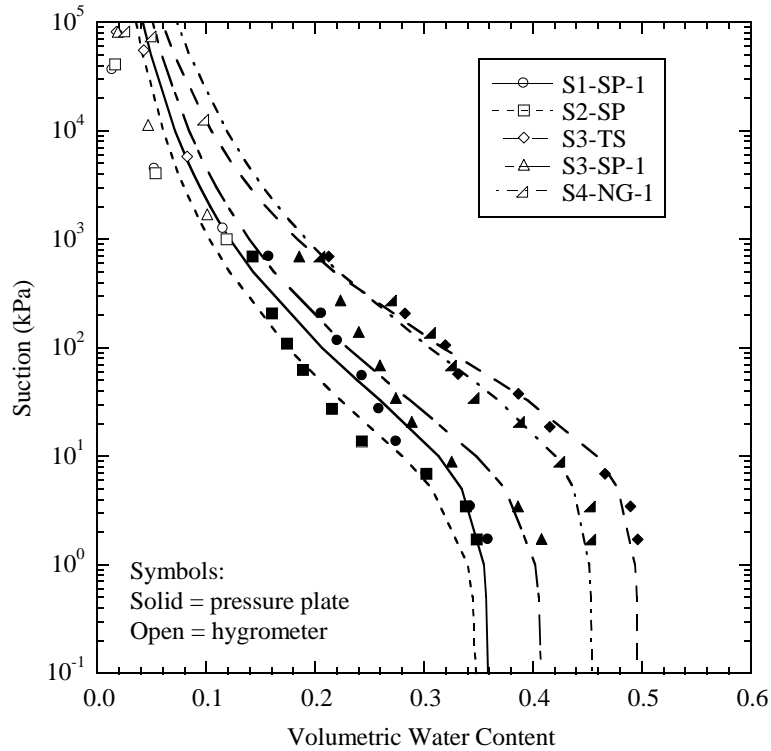
**FIG. 6. Particle size distribution curves for 10 soils sampled at Missoula landfill. Solid symbols correspond to soils selected for hydraulic property characterization; SP = stockpile, TS = topsoil, and NG = native ground.**

## Hydraulic Properties

Saturated hydraulic conductivity was determined on each of the five soils following the procedure in ASTM D 5084. Specimens were compacted to 85% of  $\gamma_{dmax}$  at  $w_{opt}$  per ASTM D 698 in 150-mm-diameter molds. Relatively low compaction is used to ensure that the cover soils provide a hospitable environment for root growth (Albright et al. 2010). The effective stress was set at 15 kPa and the hydraulic gradient at 10 to represent conditions existing in a cover.

Soil water characteristic curves (SWCCs) were measured on specimens prepared to the same compaction conditions as specimens for the hydraulic conductivity tests.

Procedures described in ASTM D 6836 were followed. The wet end of each SWCC was measured using a pressure plate extractor and the dry end with a chilled mirror hygrometer. Eq. 1 was fit to the SWCC data using non-linear least-squares optimization (Fig. 7).



**FIG. 7. SWCCs for stockpile soils from Sites 1, 2, and 3, Site 3 topsoil, and Site 4 native ground.**

Saturated hydraulic conductivities and van Genuchten parameters for the SWCCs are summarized in Table 7. Saturated hydraulic conductivity of the stockpile soils varies in a narrow range from  $3.7 \times 10^{-6}$  cm/s to  $6.0 \times 10^{-5}$  cm/s. The SWCCs for the stockpile soils are also comparable (Fig. 8), with  $\alpha$  ranging from 0.0958 to 0.145 1/kPa,  $n$  ranging from 1.27 to 1.28, and  $\theta_s$  ranging from 0.35 to 0.41. Similar hydraulic properties were reported in Miller (2002) for the storage layer of the 2002 Missoula Cover (Table 3).

## VEGETATION

Vegetation samples were collected for measurement of site-specific properties for input to the numerical model. Four locations in the surrounding grassland were selected that had mature vegetation representative of the area surrounding the landfill. A test pit was excavated in each location for root samples and a sampling area was selected for collecting surface biomass. Root samples were collected at 150-mm intervals from the sidewall of each test pit using the modified Weaver-Darland

method described in Benson et al. (2007b) and placed in evacuated re-sealable plastic bags. Samples of surface biomass were collected from four 1-m<sup>2</sup> areas by removing all biomass with shears. Surface biomass samples were placed in evacuated plastic bags that were sealed in the field. All of the samples were stored in a refrigerator at 4 °C prior to analysis.

**Table 7. Saturated hydraulic conductivity and unsaturated hydraulic properties for soils sampled from Missoula Landfill.**

Sample	Sampling Site	K <sub>S</sub> (cm/s)	α (1/kPa)	n	θ <sub>s</sub>	θ <sub>r</sub>
S1-SP-2	1	6.0x10 <sup>-5</sup>	0.126	1.27	0.36	0.0
S2-SP	2	3.7x10 <sup>-6</sup>	0.0958	1.28	0.35	0.0
S3-TS	3	2.8x10 <sup>-6</sup>	0.0496	1.33	0.50	0.0
S3-SP-1	3	1.2x10 <sup>-5</sup>	0.145	1.28	0.41	0.0
S4-NG-1	4	1.6x10 <sup>-6</sup>	0.115	1.24	0.45	0.0
2002 Miss. Cover	-	4.9x10 <sup>-5</sup>	0.520	1.28	0.34	0.0

Notes: K<sub>S</sub> = saturated hydraulic conductivity; α and n = fitting parameters for van Genuchten equation (Eq. 1); θ<sub>s</sub> = saturated volumetric water content; θ<sub>r</sub> = residual volumetric water content; SP = stockpile; TS = topsoil; NG = native ground.

Leaf area of the clippings was measured using a LI-COR LI-3100C leaf area meter and leaf area index (LAI) was computed as the quotient of the total leaf area and the sampling area (1 m<sup>2</sup>). The following LAIs were obtained: 1.46, 1.61, 1.86, and 1.99.

Root densities were measured by soaking each root sample in tap water for 48 h, separating the roots from the soil particles, and air drying the root mass as described in Benson et al. (2007b). Normalized root density profiles for the four pits are shown in Fig. 8. The root profiles in each pit were remarkably similar, and a single root density function was fit to the combined data set from all four pits using least-squares regression.

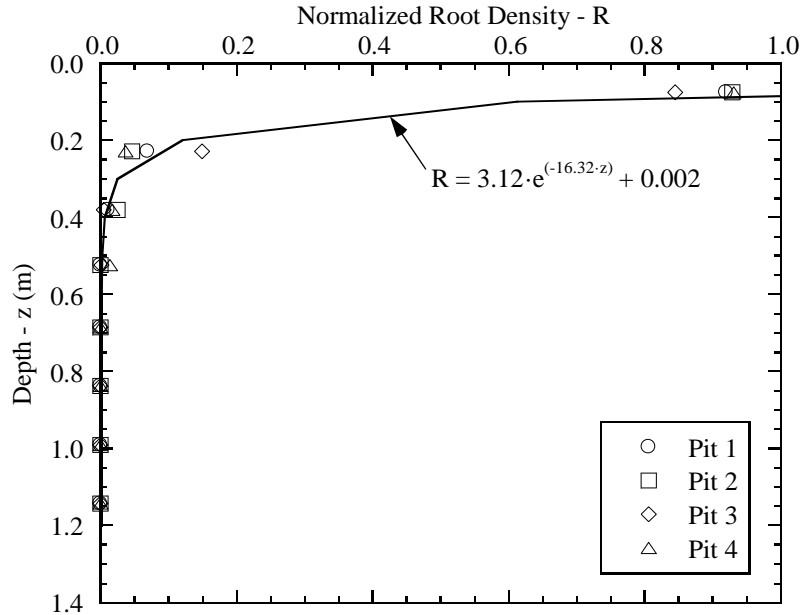
## STORAGE ANALYSIS

A storage analysis was conducted to determine the required thickness of the storage layer (L). This consisted of equating S<sub>R</sub> (Eqs. 3-5) and S<sub>A</sub> (Eq. 2) and solving for L:

$$L = S_R / (\theta_{FC} - \theta_{WP}) \quad (6)$$

SWCCs corresponding to the combinations of θ<sub>s</sub>, θ<sub>r</sub>, α, and n yielding the highest and lowest available storage capacity were used to define θ<sub>FC</sub> and θ<sub>WP</sub>. Computations were made using two required storage capacities (S<sub>R</sub>): (1) S<sub>R</sub> = 133 mm for the wettest year on record and (2) S<sub>R</sub> = 204 mm for the 95<sup>th</sup> percentile precipitation year. Accounting for pedogenesis increased S<sub>A</sub> for the Polson and Helena sites. Thus, pedogenesis was not included when computing the storage layer thickness with Eq. 4. In addition, pedogenesis is known to make cover soils more similar (Benson et al.

2007a, 2011a), and the hydraulic properties from the soil resource evaluation are similar to the in-service soils for Polson and Helena. Thus, adjusting the hydraulic properties of the Missoula soils obtained from the soil resource evaluation for pedogenesis probably would have been unrealistic.



**FIG. 8. Normalized root densities from the four test pits at Missoula landfill.**

The required storage layer thicknesses (Table 8) ranged from 740-950 mm for  $S_R = 133$  mm (average = 840 mm) and from 1190-1560 mm for  $S_R = 204$  mm (average = 1370 mm), with thicker layers required for the soil with lower storage capacity. Based on this analysis, a preliminary design was selected with a 1.22-m-thick storage layer overlain by a 0.15-m-thick topsoil layer. This cover was expected to provide acceptable storage capacity under most meteorological conditions for typical soils on site. A thicker cover could have been proposed to address worst case conditions, but the assumptions were conservative and increasing the thickness would have raised construction costs an unacceptable amount.

**Table 8. Storage layer thicknesses for required storage ( $S_R$ ) representing wettest year on record ( $S_R = 133$  mm) and 95<sup>th</sup> percentile precipitation year ( $S_R = 204$  mm).**

Storage Layer Capacity	Storage layer thickness (mm)	
	$S_R = 133$ mm	$S_R = 204$ mm
Lower Bound Storage Capacity <sup>1</sup>	950	1560
Upper Bound Storage Capacity <sup>2</sup>	740	1190

<sup>1</sup> $\alpha = 0.145$  1/kPa,  $n = 1.27$ ,  $\theta_s = 0.35$ ,  $\theta_r = 0.0$ ; <sup>2</sup> $\alpha = 0.096$  1/kPa,  $n = 1.28$ ,  $\theta_s = 0.41$ ,  $\theta_r = 0$ .

## **WATER BALANCE MODELING**

The variably saturated flow model WinUNSAT-H was used to predict the water balance for the proposed water balance cover. WinUNSAT-H (and its DOS counterpart UNSAT-H), is the most widely used numerical model for simulating the hydrology of water balance covers (Benson 2007). When properly parameterized, WinUNSAT-H provides a reliable prediction of the water balance of covers, and over predicts the percolation rate modestly in most cases (Khire et al. 1997, Ogorzalek et al. 2007, Bohnhoff et al. 2009). WinUNSAT-H simulates variably saturated flow, root water uptake, and climatic interactions (Benson 2007, 2010).

### **Soil Properties**

Hydraulic properties used in the design were selected so that the percolation would not be under-predicted, and likely would be over predicted. The topsoil layer was assigned the hydraulic properties associated with Soil S3-TS (Table 7), except the saturated hydraulic conductivity was increased one order of magnitude to account for pedogenesis and to ensure that runoff comprised no more than 10% of the annual water balance, as recommended in Albright et al. (2010). Saturated hydraulic conductivity of the storage layer was set at  $6 \times 10^{-5}$  cm/s, the highest of the saturated hydraulic conductivities (Soil S1-SP-2, Table 7) measured during the site characterization. The SWCC was defined using the combination of van Genuchten parameters measured during site characterization yielding the lowest storage capacity.

### **Vegetation**

The vegetation was assigned the minimum LAI (1.46) and the root density function (Fig. 8) obtained from the site characterization. Phenology and water stress parameters described previously (from Roesler et al. 2002) were input.

### **Meteorological Data**

Four meteorological data sets were used for the simulations: the typical year (1984), the wettest year on record, the 95<sup>th</sup> percentile precipitation year, and the 10-yr period with the highest precipitation (1977-1986). The 10-yr period with the highest precipitation is recommended for design in MDEQ's *Draft Alternative Final Cover Guidance*.

The simulations were conducted in two phases. The first phase consisted of a 5-yr simulation using meteorological data for the typical year for each year of the simulation (i.e., typical year repeated 5 times). This simulation had two purposes: (i) to create a realistic initial condition for the simulations conducted with the 10-yr record with the highest precipitation and (ii) to define a 'typical' percolation rate for the cover, as defined in Albright et al. (2010). The second phase followed immediately after the first phase, and consisted of one of the following: (i) the wettest year on record run 5 times sequentially, (ii) the 95<sup>th</sup> percentile precipitation year run 5

times sequentially, and (iii) the complete 10-yr record with the highest average precipitation. All three of these scenarios are suggested in Albright et al. (2010).

The simulations with the wettest year and the 95<sup>th</sup> percentile precipitation year are relatively simple to conduct, and are expected to be very conservative (the likelihood over 5 sequential very wet years is very small). Many engineers believe this design strategy is unrealistic and too conservative. The record for the 10-yr wettest period is realistic, but is more difficult and time consuming to simulate.

### Water Balance Predictions

Annual water balances predicted by WinUNSAT-H are summarized in Table 9 for each year of the 10-yr period with highest precipitation along with the average water balance over the 10-yr period, the typical year, the wettest year on record, and the 95<sup>th</sup> percentile precipitation year. Predictions for the five-year repetitive simulations are for the final year. The maximum annual runoff was 6.6% (95<sup>th</sup> percentile precipitation year), indicating that nearly all precipitation reaching the surface became infiltration. Thus, the water balance predictions met the runoff criterion (< 10% of annual water balance) suggested in Albright et al. (2010), which applies to arid and humid climates.

**Table 9. Predicted water balance quantities for water balance cover with 1.22-m-thick storage layer and 0.15-m-thick topsoil layer.**

Year	Annual Water Balance Quantity					
	Cum-ulative Precip. (mm)	Cum-ulative Runoff (mm)	Cum-ulative ET (mm)	Cum-ulative Percolation (mm)	Avg. Soil Water Storage (mm)	Runoff (% Precip.)
1977	322	0.0	276	1.1	203	0.0
1978	299	0.0	330	7.1	242	0.0
1979	263	0.0	268	4.3	228	0.0
1980	483	16	446	5.7	246	3.3
1981	441	1.5	422	3.0	223	0.3
1982	390	7.8	367	15.9	270	2.0
1983	424	0.0	417	6.6	244	0.0
1984	339	0.1	387	4.2	224	0.0
1985	318	0.3	338	1.5	195	0.1
1986	425	0.0	406	1.5	206	0.0
Avg. (77-86)	370	2.5	366	5.1	228	0.7
Typ. (1984)	338	0.0	366	1.1	197	0.0
Wettest (1998)	556	19.0	522	21.3	285	3.4
95 <sup>th</sup> % (1975)	469	30.8	410	36.4	294	6.6

The annual percolation rate during the wettest 10-yr period ranged from 1.1 to 15.9 mm/yr, with an average of 5.1 mm/yr. The percolation rate was no more than 3.0 mm/yr for four years in the 10-yr period, and no more than 1.5 mm/yr for three years. For the typical year, the percolation rate was 1.1 mm/yr. Much higher percolation rates were obtained from the 5-yr repetitive simulations using the wettest year on record (21.3 mm/yr) and the 95<sup>th</sup> percentile precipitation year (36.4 mm/yr). The higher percolation rate predicted for the 95<sup>th</sup> percentile precipitation year is consistent with the findings from the storage assessment.

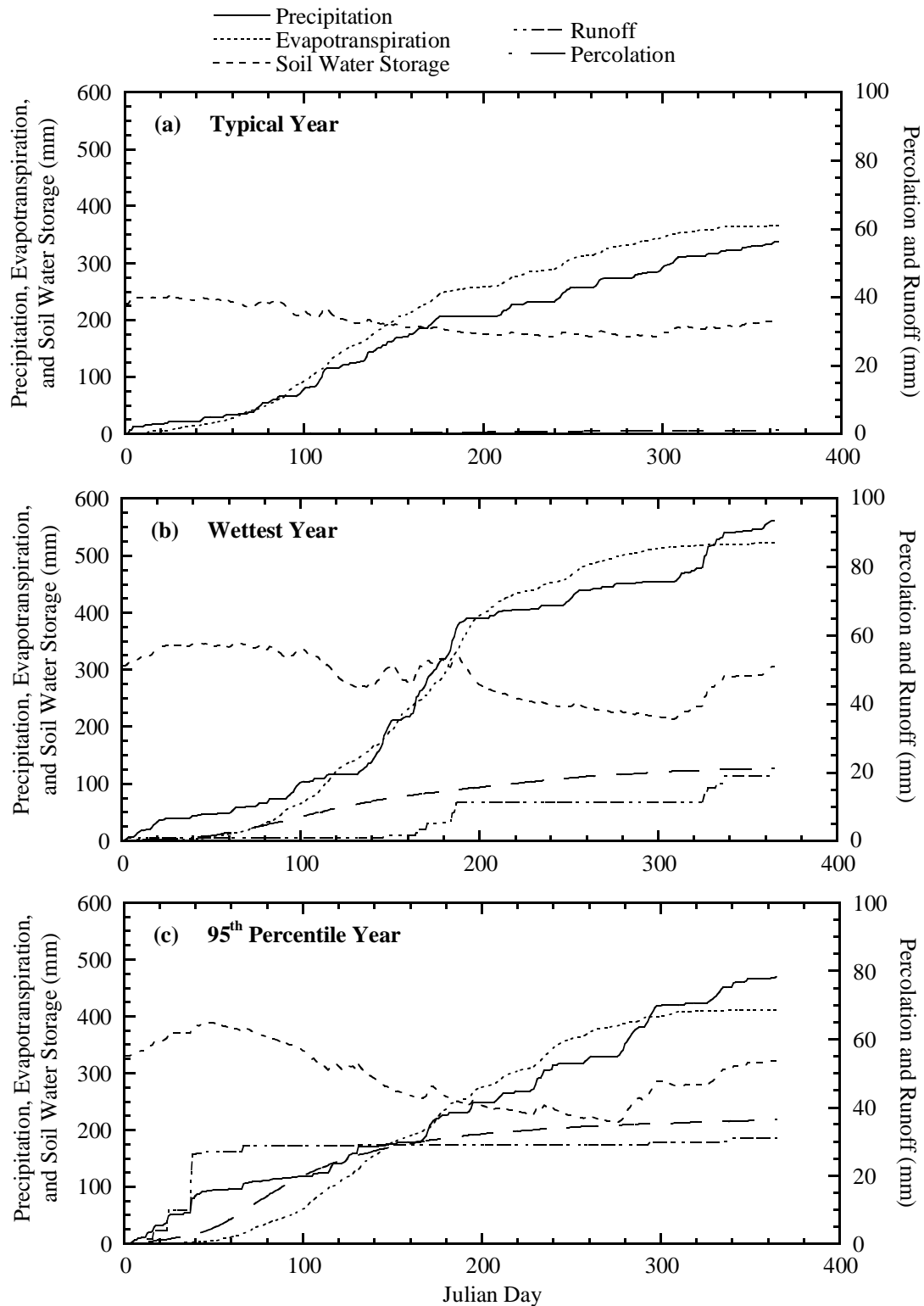
The water balance graphs for the typical, wettest, and 95<sup>th</sup> percentile precipitation years are shown in Fig. 9. These graphs illustrate that differences in the total amount of precipitation, as well as the time when precipitation is received, are responsible for the wide range of percolation rates transmitted for these meteorological conditions. During the typical year (Fig. 9a), most of the precipitation occurs in spring and summer ( $\approx$  Julian days 100-300), when ET is high. All of the precipitation during this period along with water stored in the cover is returned to the atmosphere, as evinced by a nearly monotonic drop in soil water storage during this period. Storage begins to climb again in mid-fall when ET begins to diminish ( $>$  Julian day 300), but the increase in storage is modest because the precipitation is small.

During the wettest year, the majority of the precipitation occurs in spring and early summer ( $\approx$  Julian days 90-190) (Fig. 9b). The precipitation between Julian days 130-190 is so heavy at times that soil water storage increases periodically during this period, even though ET is high. In mid-summer to early fall, however, the precipitation rate is low again and the soil water storage diminishes to 223 mm, although not to the very low storage (181 mm) in mid fall of the typical year. Heavy precipitation in late fall raises the soil water storage at the end of the year to 302 mm, 106 mm more than soil water storage at the end of the typical year. This additional storage, when combined with heavy precipitation during the first 25 d of the new year, results in peak storage of 341 mm that persists through spring. At this level of soil water storage, percolation is transmitted and continues through summer.

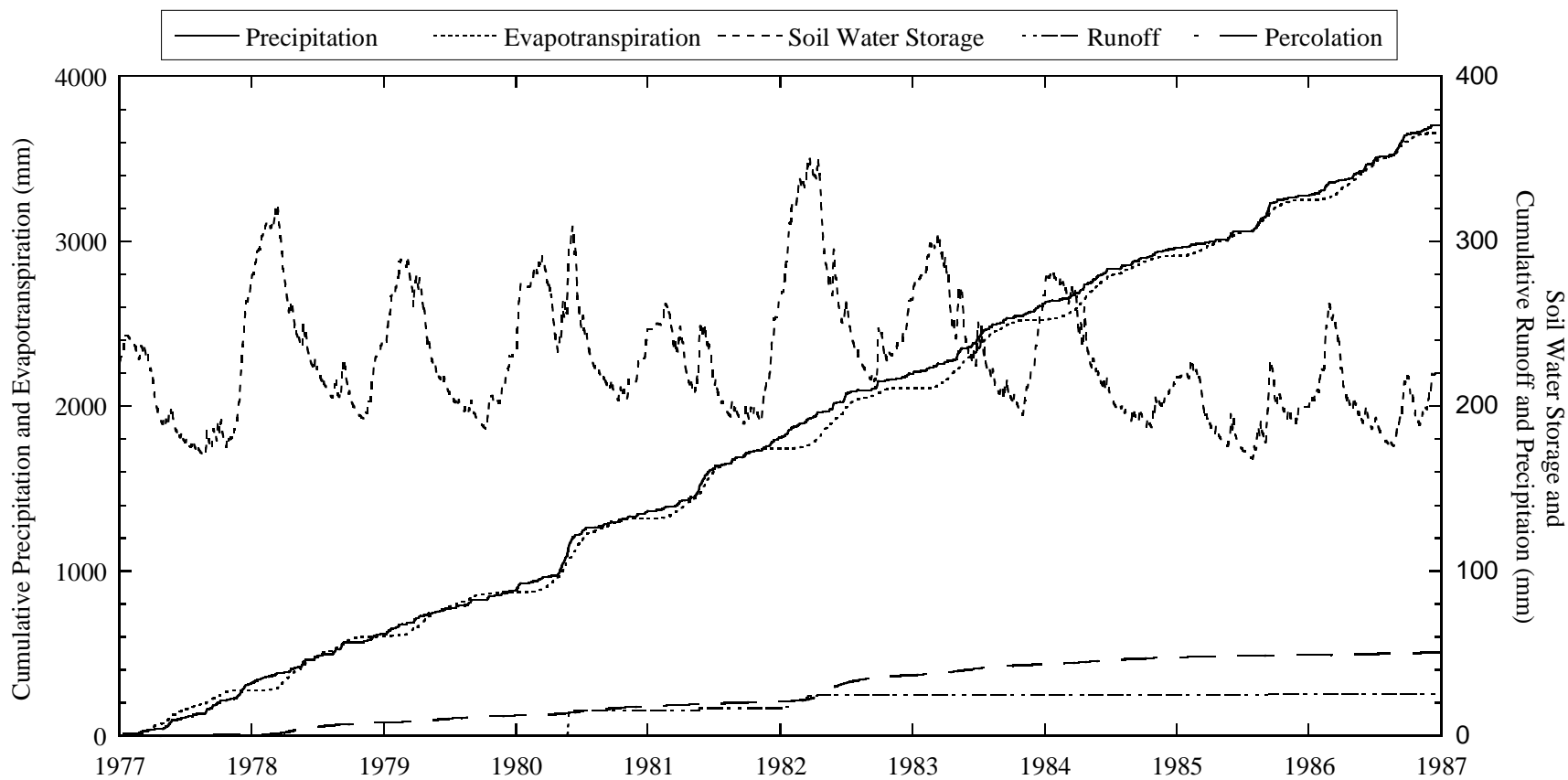
The 95<sup>th</sup> percentile precipitation year received less precipitation than the wettest year on record, but more precipitation (26 mm) was received during the fall than occurred in the fall of the wettest year (Fig. 9c). As a result, soil water storage was 325 mm at the end of the year, i.e., higher than at the end of the wettest year on record (302 mm). This high soil water storage, coupled with heavy precipitation during the first 40 d of the new year (100 mm, vs. 50 mm during the same period during the wettest year), resulted in a peak soil water storage of 380 mm at Julian day 49. Percolation began earlier in the year due to the high soil water storage at the end of the previous year, increased significantly as the soil water storage reached its peak, and continued through summer.

Comparison of the water balance graphs in Fig. 9 to the water balance graph in Fig. 10 for the 10-yr period with the most precipitation illustrates that high levels of soil water storage at the end of the previous year, combined with wetter than normal conditions in the winter and spring, consistently give rise to the highest percolation rates. The highest percolation rate predicted in the 10-yr simulation was in 1982 (15.9 mm/yr), which occurred in response to a sustained period of frequent and less intense precipitation beginning in late Fall 1981 and continuing into early Fall 1982. This





**FIG. 9. Predicted water balance quantities for fifth year of 5-yr analysis using hydraulic properties corresponding to lower bound storage.**



**FIG. 10. Water balance predictions for 10-yr period with highest average precipitation made with WinUNSAT-H using hydraulic properties corresponding to lower bound on storage properties.**

condition led to a very large increase in storage during the winter of 1982, even though four years during the 10-yr period (1980, 1981, 1983, and 1986) had higher annual precipitation than 1982.

The second highest annual percolation rate (7.1 mm/yr) occurred in 1978, even though this year was drier than average (299 mm precipitation vs. 337 mm, on average) and only one year during the 10-yr record had less annual precipitation (263 mm in 1979). Like 1982, percolation in 1978 occurred in response to a large increase in soil water storage in late Fall 1977 and Winter 1978 that was caused by a sustained period of frequent and less intense precipitation. Thus, the timing of precipitation and the sequencing from one year to the next has a critical impact on the accumulation of storage and the amount of percolation that occurs.

The timing and sequencing of precipitation is represented realistically using actual multi-year time series, whereas repetitive simulations with the wettest year on record or the 95<sup>th</sup> percentile year probably are unrealistic. As shown in Fig. 10, very wet years generally are not sequential, and the likelihood of five very wet years occurring sequentially is very small.

## **Implications**

None of the modeling predictions confirm that the design objective (3 mm/yr average percolation rate) will be accomplished. The percolation rate for the typical year (1.1 mm/yr) is lower than the design objective, but the average percolation rate over the 10-yr period with highest precipitation (5.1 mm/yr) exceeds the design objective. Percolation rates greatly in excess of the design objective were obtained from the 5-yr repetitive simulations, but these simulations are considered unrealistic.

The long-term percolation rate could be evaluated by simulating the entire 50-yr meteorological record or a very long record generated with a synthetic weather generator based on meteorological statistics for Missoula. However, either simulation would be very time consuming and computationally costly, and probably would not be practical for most projects. This type of simulation was considered impractical for the Missoula landfill.

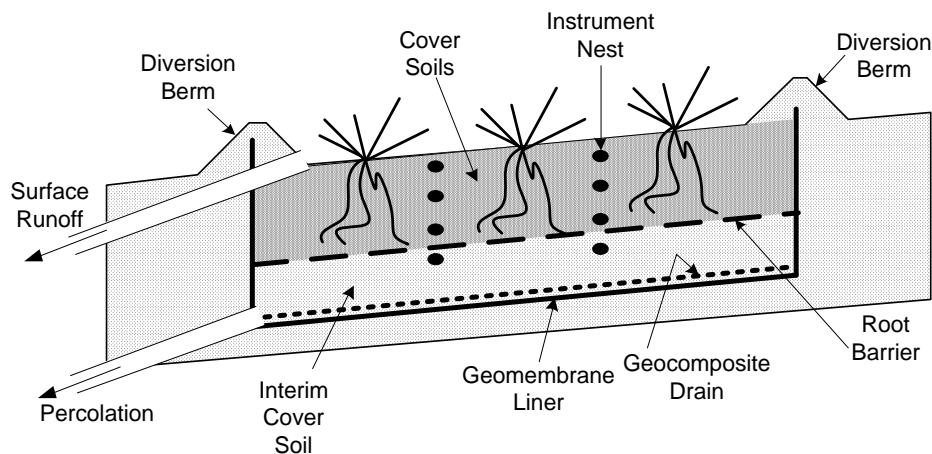
The average of the percolation rate from the typical year and from the 10-yr simulation is 3.1 mm/yr, which is slightly larger than the design objective. Given that the 10-yr record used in the simulation is the wettest decade on record, and that periods of drought will also occur along with typical conditions, the long-term average percolation rate is likely to be less than 3.1 mm/yr. Thus, the design objective likely will be met, and MDEQ concurred that this conclusion is reasonable.

Based on this assessment, and the favorable monitoring data from the covers in Polson and Helena, the final design consisted of a 1.22-mm-thick storage layer overlain by 0.15 m of topsoil.

## **TEST SECTION**

A field demonstration of the cover is being conducted using an ACAP-style test section constructed following the methods described in Benson et al. (1999). The test section slopes at 3% to simulate the actual top deck slope for the landfill, and faces

north to receive the greatest snow accumulation and lowest solar radiation (i.e., worst case orientation). The test section includes a 10 m x 20 m pan-type lysimeter (Fig. 11) for direct measurement of the water balance, including surface runoff, soil water storage, and percolation. The base and sidewalls of the lysimeter are comprised of linear low-density polyethylene geomembrane, and the base is overlain with a geocomposite drainage layer to protect the geomembrane and to transmit percolation to a zero-storage sump. Diversion berms are placed on the surface to prevent run-on and collect run-off.



**FIG. 11. Schematic of test section for evaluating performance of the water balance cover (not to scale).**

### **Instrumentation**

Percolation and surface runoff are routed by pipes to basins equipped with a pressure transducer, tipping bucket, and float switch (triple redundancy) capable of measuring flows with a precision better than 0.1 mm/yr (Benson et al. 2001). Soil water content is measured in three nests located at the quarter points along the centerline. Each nest contains 5 low-frequency (40 MHz) time domain reflectometry (TDR) probes in a vertical stack. Soil water storage is determined by integration of the point measurements of water content. Each probe includes a thermistor for monitoring soil temperature along with water content. Soil-specific calibration of the TDR probes was conducted using the method in Benson and Wang (2006).

Meteorological data (precipitation, air temperature, relative humidity, solar radiation, wind speed, and wind direction) are measured with a weather station mounted on the test section. Data are collected and recorded by a datalogger every 15 min and are stored on one-hour intervals. At times of intense activity (e.g., an intense rain event with high surface runoff), data are stored at time intervals as short as every 15 s. Data from the test section are stored on a server equipped with a screening level quality assurance (QA) algorithm. Detailed QA checks are conducted quarterly. At the time this paper was prepared, the duration of the monitoring period was too short to present the monitoring data in a useful manner.

## **Placement of Cover Profile**

Prior to constructing the cover profile, a layer of soil simulating the existing interim cover was placed on top of the geocomposite drainage layer. The interim cover layer was overlain with a root barrier (thin nonwoven geotextile studded with nodules containing trifluralin, a root inhibitor) to prevent root intrusion into the geocomposite drainage layer and the percolation collection system. Inclusion of the root barrier results in less water being transpired than might occur in an actual cover, where roots can grow through the interim cover and into the waste (Albright et al. 2004). However, 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 application.

The storage layer was constructed with soil from Site 3, which was placed over the root barrier using a bulldozer in three 0.41-m-thick lifts. The dry unit weight was required to be 80-90% of maximum dry unit weight per standard Proctor and the water content was required to be no wetter than optimum water content, as recommended in Albright et al. (2010). Thick lifts were used to minimize the potential for over compaction of the soil, as is common in practice during construction of water balance covers.

Topsoil stripped from Site 3 was placed on the surface and fertilized to stimulate growth. Seed was not added; the natural seed bank within the topsoil serves as the source of seed. This “live haul” approach creates a more realistic and sustainable plant community that is consistent with the surroundings.

## **SUMMARY AND CONCLUSIONS**

The key steps required to design and demonstrate a water balance cover have been illustrated in this paper using a case history where a cover was designed for a MSW landfill in Missoula, Montana. This design process evolved from two decades of research. The state-of-the-art developed through research is now being applied as state-of-the-practice.

The process begins by understanding the design objective (including regulatory requirements) and investigating lines of evidence indicating that a water balance cover is likely to function satisfactorily at the design location. For the Missoula case history, regional data from two instrumented water balance covers were used along with meteorological data to illustrate that a water balance cover could be successful in Missoula if sized properly. Site characterization was then conducted to define properties of the soil resources and vegetation at the site for preliminary cover sizing and numerical modeling of the water balance. A preliminary design was created using semi-empirical analytical methods and the design was evaluated by simulation with a numerical model using several design meteorological conditions as input.

The numerical modeling illustrated that predictions made with an actual multiyear time series (e.g., wettest 10-yr period in the meteorological record) are more realistic than predictions from 5-yr repetitive simulations using a worst case design year, which have been recommended historically and have become common in practice. The multiyear simulations preserve realistic sequencing of seasonal precipitation

patterns, which have a strong influence on soil water storage and percolation rate. The drawback is that multiyear simulations are more cumbersome and time consuming to conduct.

The final design for the Missoula landfill is a monolithic water balance cover comprised of a 1.22-m storage layer overlain by a 0.15-m topsoil layer. A field demonstration with a fully instrumented lysimeter was deployed in October 2011 to confirm that the cover performs as anticipated in the design.

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