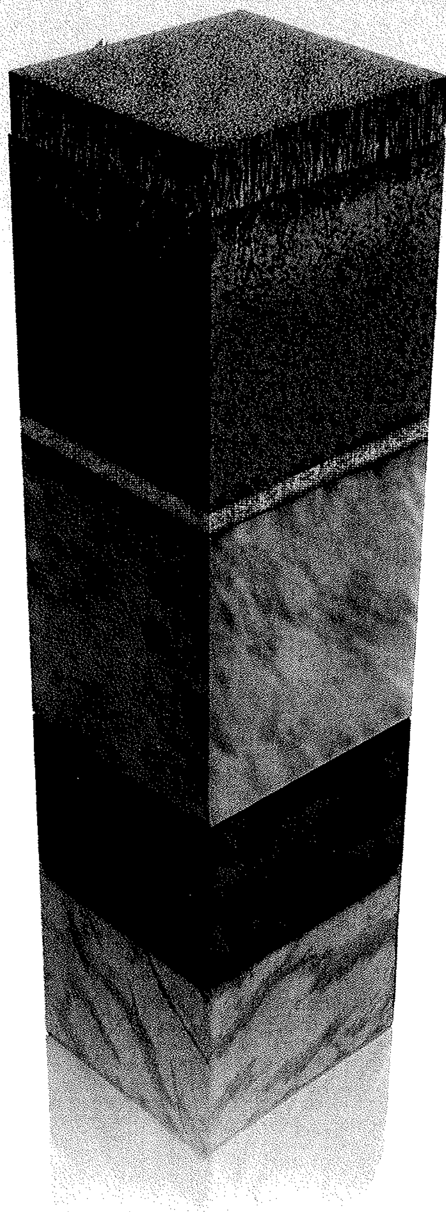
# Water Balance Covers for Waste Containment

## *Principles and Practice*



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CHAPTER 7

# Lessons Learned from the Field

The material presented in this book so far has focused on how to evaluate whether a WB cover is suitable and how to design the cover for site-specific conditions. Based on this process, an expectation is formed regarding field performance. This expectation should be checked against field observations reported by others and, in some cases, by conducting a field demonstration project. This chapter describes lessons learned from field experiences associated with the U.S. Environmental Protection Agency's Alternative Cover Assessment Program (ACAP), provides recommendations on how to address equivalency, and suggests methods that can be used to evaluate the efficacy of a WB cover design in the field.

## ACAP Field Performance Data

Field data from ACAP provide an ideal means to evaluate the expected performance of a WB cover design. Profiles of the ACAP covers are summarized in Fig. 7-1. At the start of the program (1999–2002) each of the covers shown in Fig. 7-1 was designed to have a very low percolation rate (typically <3 mm/year) using methods available in practice at the time. The covers vary considerably in thickness, with some covers nearly 3 m thick and others approximately 1 m thick. This wide range in thicknesses reflects the site-specific aspect of WB cover design.

The locations of the field sites are shown in Fig. 7-2 and the characteristics are summarized in Table 7-1. The sites have climates ranging from very hot and arid (Apple Valley, California) to warm and humid (Albany, Georgia) to cool and humid (Cedar Rapids, Iowa). This diversity in climates is evident in the average annual precipitation, which ranges more than one order of magnitude (119 to 1,263 mm/year), and the range in P/PET (0.06 to 1.10). As defined in Chapter 4, Introduction to Ecology and Revegetation of Water Balance Covers, P = precipitation and PET = potential evapotranspiration; PET is therefore a measure of the energy available in the atmosphere to remove water from the soil profile via evaporation and transpiration. Thus, at the field sites evaluated in ACAP, some sites have much more energy available for water removal relative to the amount of water to be managed (e.g., Apple Valley, California, with P/PET = 0.06),

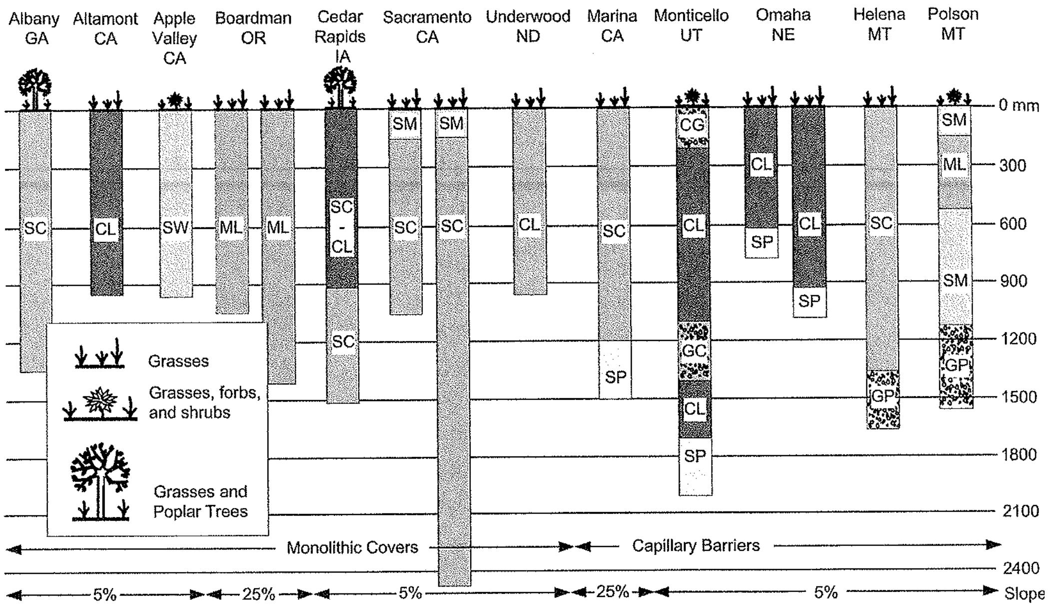


**Figure 7-1.** WB cover profiles evaluated in ACAP. *Source:* Adapted from Apiwantragoon (2007). United Soil Classification System symbols (e.g., SC, CL) are shown.

whereas others have more water to manage than the energy available to remove water (e.g., Albany, Georgia, with P/PET = 1.10). Accordingly, a wide range of field performance should be anticipated.

Performance of the ACAP WB covers is summarized in Table 7-1. Six of 15 tested covers had average annual percolation of less than 1 mm/year; another two

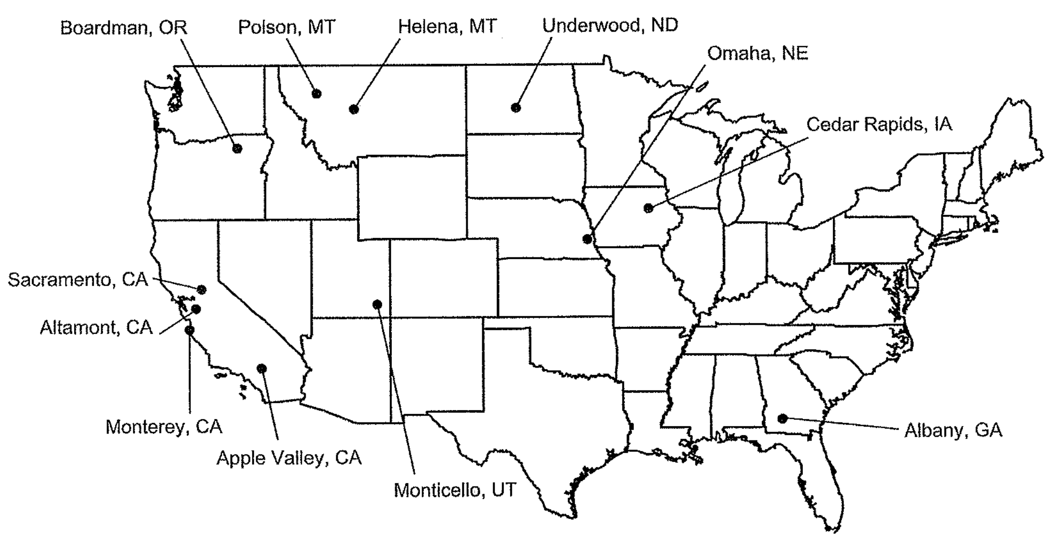


**Figure 7-2.** Locations of the ACAP field sites.

**Table 7-1.** Summary of Climatic Conditions and Percolation Rates for ACAP WB Covers

| *Site Location* | *Long-Term Average Annual Precipitation (mm/yr)* | *Average Annual P/PET* | *Climate* | *Cover Type* | *Average Annual Precipitation During Monitoring (mm/yr)*[a] | *Average Annual Percolation* | |
|---|---|---|---|---|---|---|---|
| | | | | | | *mm/yr*[a] | *% of Precipitation*[a] |
| Albany, GA | 1,263 | 1.10 | Humid | Monolithic Cover | 1,202 (723–1,412) | 109.2 (7.4–192.7) | 9.1 (0.8–18.7) |
| Altamont, CA | 358 | 0.31 | Semi-arid | Monolithic Cover | 378 (226–499) | 44.8 (0.0–139.3) | 11.8 (0.0–27.9) |
| Apple Valley, CA | 119 | 0.06 | Arid | Monolithic Cover | 172 (116–272) | 0.5 (0.0–1.8) | 0.3 (0.0–0.7) |
| Boardman, OR | 225 | 0.23 | Arid | Monolithic Cover | | | |
| | | | | 1.25 m thick | 181 (147–195) | 0.0 (0.0–0.0) | 0.0 (0.0–0.0) |
| | | | | 1.56 m thick | 181 (147–195) | 0.0 (0.0–0.0) | 0.0 (0.0–0.0) |
| Cedar Rapids, IA | 915 | 1.03 | Humid | Monolithic Cover | 923 (722–928) | 207.3 (60.9–259.3) | 22.5 (8.2–35.9) |
| Helena, MT | 312 | 0.44 | Semi-arid | Capillary Barrier | 273 (196–319) | 0.0 (0.0–0.1) | 0.0 (0.0–0.0) |
| Marina, CA | 466 | 0.46 | Semi-arid | Capillary Barrier | 463 (401–493) | 63.3 (44.6–82.4) | 13.7 (9.1–20.2) |
| Monticello, UT | 385 | 0.34 | Semi-arid | Capillary Barrier | 410 (209–520) | 0.7 (0.0–3.8) | 0.2 (0.0–0.7) |
| Omaha, NE | 760 | 0.64 | Sub-humid | Capillary Barrier | | | |
| | | | | 0.76 m thick | 733 (585–794) | 56.1 (49.7–98.5) | 7.7 (8.5–13.5) |
| | | | | 1.07 m thick | 733 (585–794) | 27.0 (16.5–57.9) | 3.7 (2.9–9.2) |
| Polson, MT | 380 | 0.58 | Sub-humid | Capillary Barrier | 349 (298–379) | 0.2 (0.0–0.4) | 0.0 (0.0–0.1) |
| Sacramento, CA | 434 | 0.33 | Semi-arid | Monolithic Cover | | | |
| | | | | 1.08 m thick | 422 (271–546) | 54.8 (0.0–108.4) | 13.0 (0.0–30.0) |
| | | | | 2.45 m thick | 422 (271–546) | 2.7 (0.0–8.5) | 0.6 (0.0–1.9) |
| Underwood, ND | 442 | 0.47 | Semi-arid | Monolithic Cover | 420 (391–449) | 7.2 (2.9–4.6) | 0.9 (0.7–1.0) |

[a]The ranges of annual precipitation and annual percolation rates shown in parentheses.
P, precipitation; PET, potential evapotranspiration.
*Source:* Adapted from Apiwantragoon (2007).

had less than 10 mm/year; the highest had nearly 110 mm/year. The following sections discuss several factors important to WB cover performance.

### *Need for Site-Specific Design*

Several of the sites in ACAP provide examples of how performance can vary geographically and based on site-specific design issues. The ACAP sites in Montana (Polson and Helena) are examples of successful WB cover designs in cool and seasonable semi-arid to sub-humid climates. The field data from these sites illustrate important differences despite the modest distance (240 km) between the sites. Polson is a sub-humid climate with 380 mm/year of precipitation, on average, and P/PET of 0.58. Helena has a drier climate than Polson, with nearly 70 mm less precipitation each year (average annual precipitation of 312 mm/year) and an annual P/PET of 0.44. Helena also receives most of its precipitation in the late spring and summer and has drier conditions in the winter. Both locations have a favorable balance of energy available for water removal relative to the amount of water to be managed. However, both sites receive snow and have cold winter temperatures, which are challenging for WB cover design. Evapotranspiration (ET) of water stored in the soil is greatly reduced when snow is present, and snowmelt events can result in rapid infiltration into the cover profile that can overwhelm the storage capacity.

A water balance graph with cumulative water balance quantities is shown in Fig. 7-3 for the capillary barrier in Polson. Polson has a seasonal precipitation

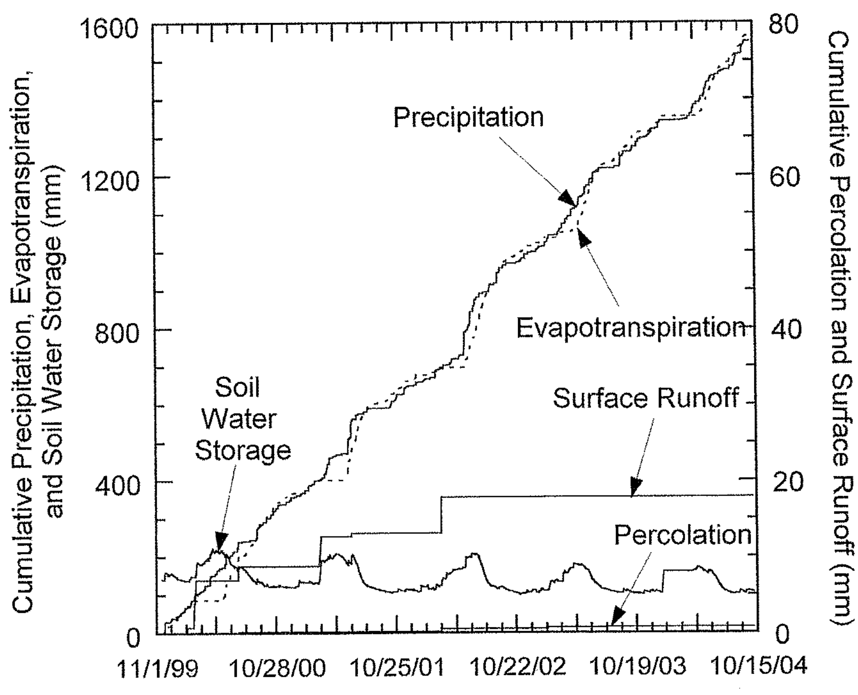


**Figure 7-3.** Water balance graph for capillary barrier evaluated by ACAP in Polson, Montana.

record, with greater precipitation in winter and spring than in summer and fall. The soil water storage record varies in a consistent annual cycle, with water accumulation during the wetter periods and water removal during drier periods. This seasonality is reflected in the ET record, which closely follows the precipitation record but with a seasonal lag. Nearly all of the water in the WB cover at Polson was stored and then released via ET (i.e., the precipitation and ET curves are coincident). A dense, deep-rooted shrub community was established quickly on the test section. This plant community persisted throughout the monitoring period and was very effective in transpiring stored water. Surface runoff was a very small fraction of the water balance (2.6 mm/year, or 0.7% of precipitation on average), and occurred in episodes in response to snowmelt. Most importantly, less than 1 mm of percolation was transmitted during the entire 5-year monitoring period.

Good performance was also observed at the ACAP site in Helena, where a capillary barrier cover was evaluated. The plant community on the test section in Helena was much less dense than at Polson and consisted primarily of grasses, which reflects the drier climate.

The water balance graph for Helena (Fig. 7-4) has some characteristics similar to the water balance graph for Polson (Fig. 7-3). The strong seasonality in

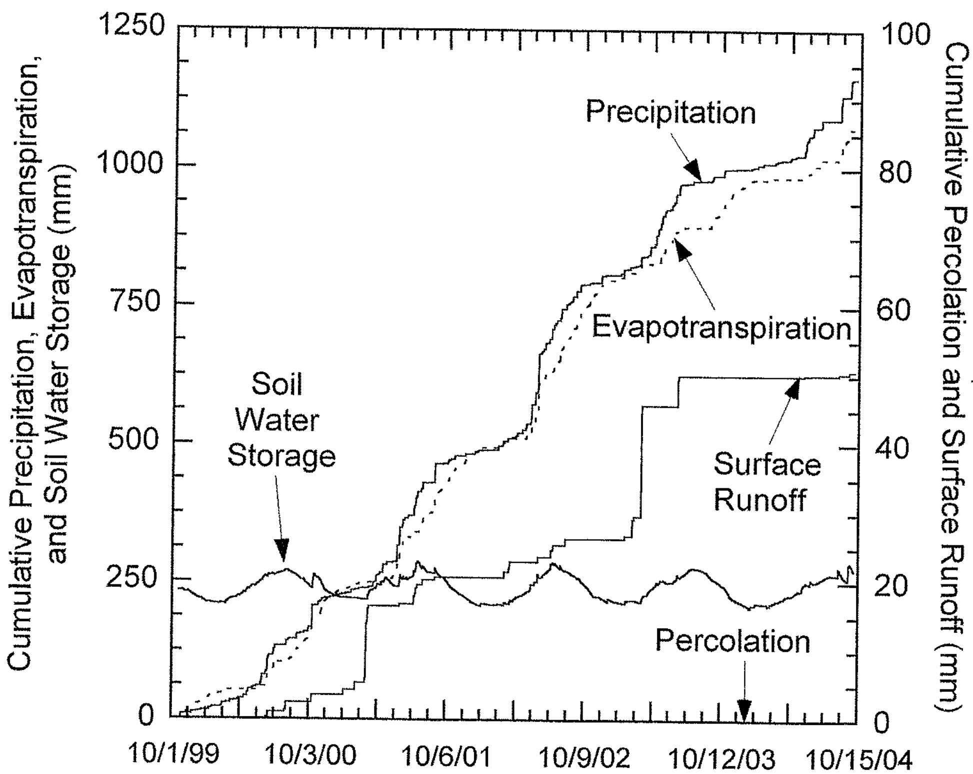


**Figure 7-4.** Water balance graph for capillary barrier evaluated by ACAP in Helena, Montana.

precipitation is reflected in the soil water storage curve, which shows water accumulation during the wetter months in late spring and early summer followed by water removal in late summer and fall. The ET curve also follows the precipitation curve closely, with a modest shift to reflect the lag between accumulation and removal of water. As observed at Polson, surface runoff is a small fraction of the water balance (12.5 mm/year, or 4.6% of precipitation, on average). Most importantly, percolation was limited to 0.0 mm/year, on average, over the 5-year monitoring period. Thus, despite the differences in soil and climate between Helena and Polson, very effective covers were designed for both sites.

Significant differences in the water balance of the covers at Polson and Helena are evident in Figs. 7-3 and 7-4. Despite higher precipitation, water storage in the cover at Polson was consistently lower (water storage ranged approximately between 100 and 225 mm) than at Helena (water storage ranged approximately between 190 and 270 mm). Since the storage layers in the covers were of comparable total thickness (1,210 mm at Polson, 1,350 mm at Helena), differences in water storage can be attributed to soil hydraulic properties, climate, and vegetation. The individual characteristics and interactions between these factors form the basis of WB cover design, which must include site-specific design and analysis.

### *Importance of Vegetation*

Vegetation plays a critical role in WB covers in all but the most arid environments by removing water from depth via root water uptake. Thus, in most environments, the vegetation must function as expected for a WB cover to function properly. Data from the ACAP test site in Sacramento, California, illustrate how vegetation can influence performance of a WB cover.

Two ACAP test sections simulating monolithic covers were monitored in Sacramento. One cover was 1.08 m thick and the other was 2.45 m thick (Fig. 7-1). They are referred to as the thin and thick test sections. Sacramento has a warm, semi-arid climate with 434 mm/year of precipitation and an annual average P/PET = 0.33. The test sections were constructed with a broadly graded alluvium (primarily silty and clayey sand) and were planted with a mixture of perennial grasses selected for their deep rooting depth, long growing season, and high wilting point suction. Average percolation rates for the two test sections are summarized in Table 7-1. Both test sections were designed to transmit less than 3 mm/year of percolation. A water balance graph for the thin test section is shown in Fig. 7-5.

The thin test section behaved as expected during the first year. Soil water storage increased during the wetter and cooler winter months, and then diminished in the spring and summer as water was removed by ET. A modest amount of runoff occurred and percolation was essentially nil. In the second year, soil water storage accumulated during the winter months as expected, little percolation was transmitted, and the soil water storage began to diminish during the spring months. However, the stored water was only partially removed during the second year, leaving the cover partially filled with water prior to the next wet winter season. As a result, the available storage in the third year was greatly reduced. As

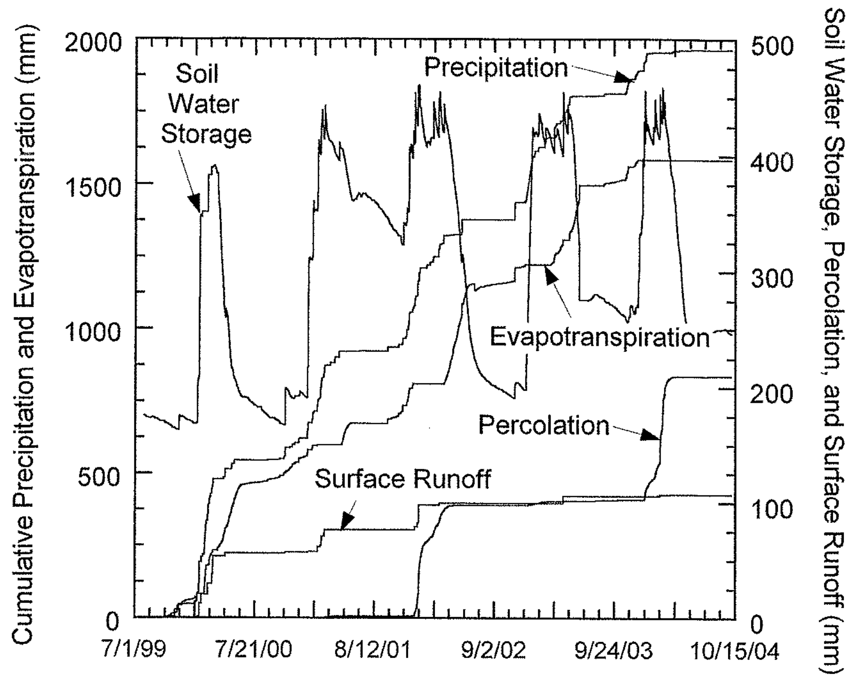


**Figure 7-5.** Water balance graph for capillary barrier evaluated by ACAP in Sacramento, California.

water accumulated in the winter of the third year, the storage capacity was reached during the winter season, and more than 100 mm of percolation was transmitted!

During the summer of the third year, nearly all of the stored water was removed via ET. As a result, the cover performed well during the next winter, transmitting little percolation. However, partial depletion of stored water occurred again the following spring, and more than 100 mm of percolation was transmitted again during the following winter. Partial depletion of soil water storage occurred again in the following spring.

Similar conditions occurred in the thick test section at Sacramento. However, the additional soil water storage afforded by the thicker profile provided enough capacity to maintain percolation rates at a low level (Table 7-1).

When the test sections in Sacramento were decommissioned, a study was conducted to determine how the properties of the test sections had changed and why only a portion of the stored water was removed in many of the spring–summer periods (Benson et al. 2006; Smesrud et al. 2010). The investigation uncovered two important factors contributing to inadequate removal of stored water: (1) the cover was compacted more densely than specified during design, and (2) the designed vegetation community had been replaced by annual grasses characteristic of the grasses surrounding the landfill. Overcompaction occurred due to an error in compaction quality control procedures. This resulted in a soil profile that roots found difficult to penetrate. If the soil had been looser, the perennial grasses may have had a better chance to become permanently established on the test sections. Perennial grasses have a longer growing season that extends into the summer and a higher wilting point suction compared to annual grasses. As a result, the perennials can remove water for a longer period of time and to a drier state.

The experience at Sacramento showed that construction conditions must be controlled carefully to ensure a hospitable condition for plants to become established. This is particularly true when the plant species employed are different from the species that dominate the surrounding area. The experience also illustrated that successfully using plant species that differ from those plants that are predominant in the surroundings can be challenging. Additional effort may be required to establish and maintain the intended vegetation under such conditions.

### *Providing Sufficient Storage Capacity*

The experience at the ACAP site in Marina, California, provides an excellent example of the importance of providing adequate storage capacity. A capillary barrier consisting of 1.2 m of sandy clay over 300 mm of clean sand was evaluated at this site. Annual precipitation at Marina is 466 mm/year and the average annual P/PET is 0.46. The average annual percolation rate for the cover at Marina was 63 mm/year (Table 7-1). The water balance graph for Marina was presented in Chapter 2 (Fig. 2-5B). Percolation is transmitted each year when the soil water storage exceeds the storage capacity (300 mm). Increasing the thickness of the cover by 300 mm (combined with appropriate consideration of the vegetation characteristics) would provide sufficient storage and essentially eliminate percolation.

### *Performance in More Humid Climates*

The ACAP test sections in Omaha, Nebraska, provide perspective on how WB covers function in more humid climates. Two capillary barriers constructed with silty clay over clean sand were evaluated in Omaha. The covers had 600 mm or 950 mm of silty clay (thin or thick cover, respectively); the sand layer in both covers was 150 mm thick. Average annual precipitation in Omaha is 760 mm/year, and the average annual P/PET is 0.64. Summers in Omaha are hot and humid, winters are cool with snow and frozen ground, and spring rains can be heavy and persistent. Rain on accumulated snow is common during the spring in Omaha.

The water balance graph for the thin cover is shown in Fig. 7-6. This graph has two features that are distinctly different from the water balance graphs for the sites in Montana and California. First, Omaha does not exhibit the same well defined periodicity in soil water storage that is characteristic of the semi-arid and sub-humid climates in Montana and California. There is an annual cycle in storage but the amplitude varies each year, the seasonality is not as well defined, and spikes occur periodically within the record. Second, the precipitation curve is consistently higher than the ET curve, indicating that some of the water is not being managed by release to the atmosphere.

The average annual percolation rate was 56 mm/year for the thin cover and 27 mm/year for the thick cover (Table 7-1). That is, the additional storage pro-

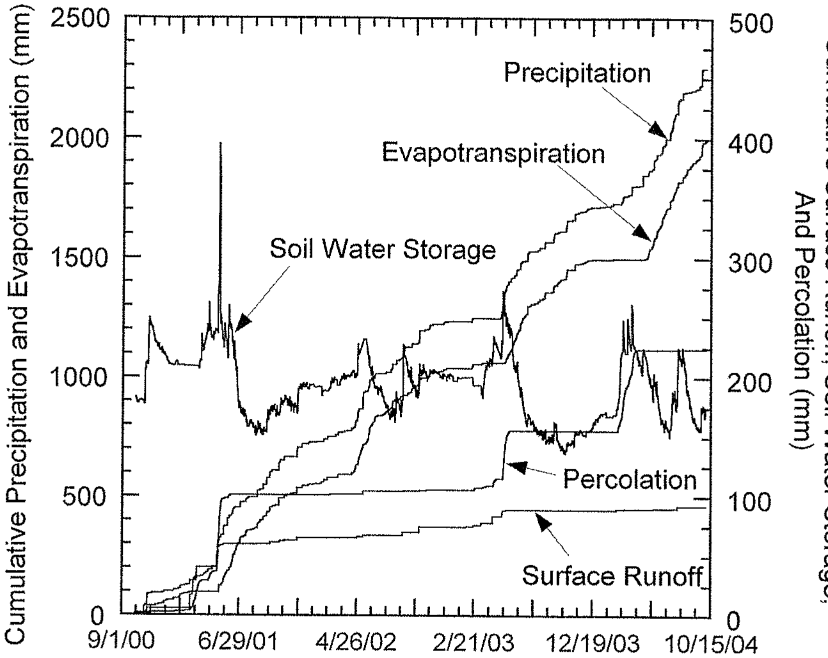


**Figure 7-6.** Water balance graph for capillary barrier evaluated by ACAP in Omaha, Nebraska.

vided by the thicker cover was effective in reducing average annual percolation by nearly half.

One of the key factors affecting percolation in Omaha and similar sites is spring rain on accumulated snow. This is a particularly challenging condition because ET is strongly limited by the presence of snow while rain and snowmelt are being directly applied to the cover. The presence of snow can also reduce runoff, thereby increasing infiltration. The influence of spring rain and snow on percolation is shown in Fig. 7-7. There is a strong trend of increasing annual percolation rate as the spring precipitation increases.

Achieving very low percolation rates (<3 mm/year) may not be practical in humid climates. Regional groundwater recharge rates are an indication of percolation rates that can be achieved with a WB cover. Although other factors affect the regional groundwater recharge rate, it is an indication of the amount of water that is typically transmitted through the vadose zone in a given region. Thus, the percolation rate for a WB cover should not be grossly different from the regional recharge rate.

## *Expectations in Other Areas*

Data from the ACAP test sections provide an assessment of performance at a particular geographic location. To generalize the findings from ACAP to a regional basis, Apiwantragoon (2007) used regression to relate the annual percolation rate to annual meteorological variables for a cover where the available and required

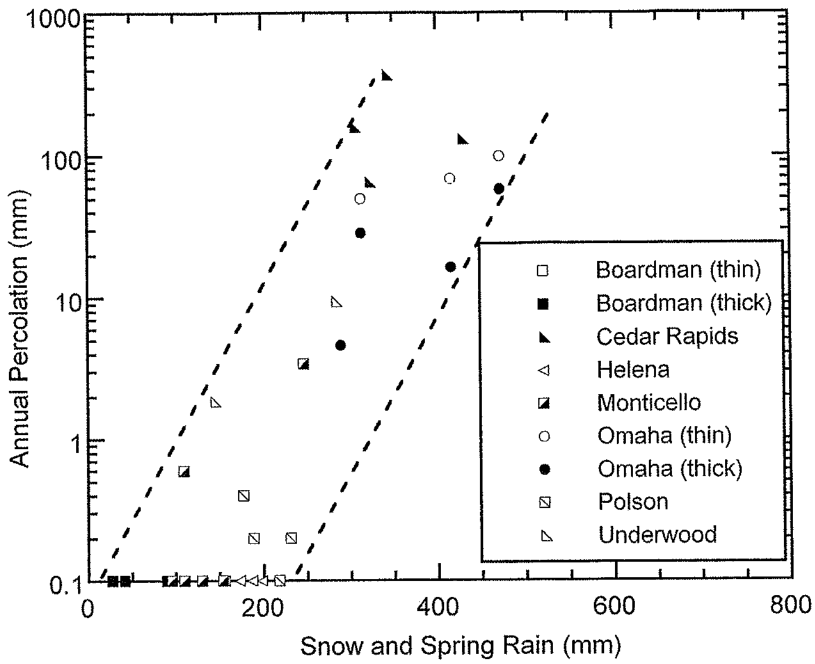


**Figure 7-7.** Effect of spring rain and snow on percolation rate at ACAP sites. *Source:* Adapted from Apiwantragoon (2007).

storage were equal. The model was based on annual precipitation, annual PET, total snow and spring rain, seasonality of precipitation (typically in spring and summer or fall and winter), and annual cumulative relative humidity. The latter variable is the integration of relative humidity over a period of 1 year, which is a generalized index of site humidity. A contour map of typical percolation rates was created using the regression model and NOAA meteorological data from cities throughout the United States as input. This contour map is shown in Fig. 7-8. The map is intended to illustrate how percolation rates vary geographically in the United States and should not be used as a design chart. For example, the contour map ignores the effects of high-altitude/mountain conditions, which can have an important effect on cover performance in some parts of the West.

Very low percolation rates are realized in the semi-arid and arid regions of the western United States (Fig. 7-8). Higher percolation rates are realized in the Midwest, the Atlantic seaboard, and the Pacific coast. Thus, achieving a very low percolation rate is more readily accomplished in many parts of the interior West compared to other regions in the United States. In some regions, such as the Atlantic seaboard, achieving very low percolation rates may be impractical.

## Performance Monitoring in the Field

Because performance predictions include inherent uncertainty and because the engineering properties of cover materials change over time, performance moni-

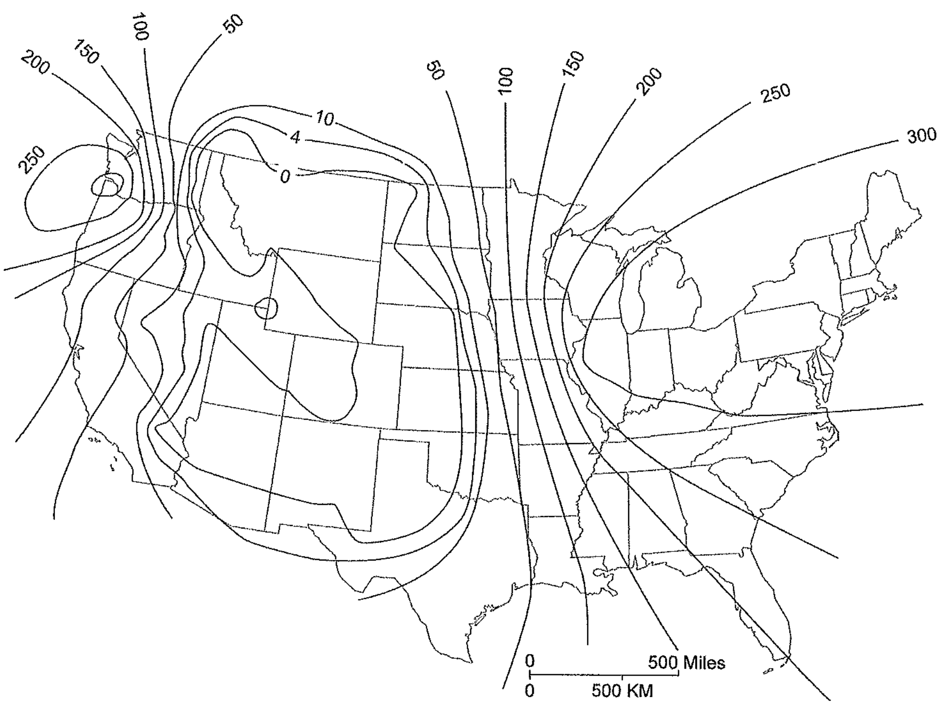


**Figure 7-8.** Contour map showing potential percolation rates anticipated for WB covers in the continental United States. *Source:* Adapted from Apiwantragoon (2007).

toring of covers is prudent to ensure that the cover is functioning as predicted in the performance assessment. For final covers, the primary performance variable is percolation from the base. Accordingly, performance monitoring of covers must consist of a method to continuously and nondestructively measure the *percolation rate*, that is, the rate at which water is transmitted from the base of the cover. In effect, this requires that an in situ device be installed that is large enough to represent field-scale conditions and simple enough to permit continuous, long-term monitoring with little to no maintenance. Cover monitoring may be conducted at two levels: (1) direct nondestructive performance monitoring, and (2) indirect (interpretive) monitoring. *Direct nondestructive monitoring* consists of directly and continuously monitoring the primary performance variable (percolation) using an in situ device. *Indirect monitoring* consists of measuring secondary variables related to the primary performance variable; often these data can be used to understand or interpret data obtained from primary performance monitoring.

Selection of the appropriate method for field evaluation of any engineered system begins with definition of the performance characteristic to be assessed and a method with sufficient accuracy to ensure that a reliable inference regarding performance can be achieved. A common rule of thumb is to employ an evaluation method that can quantify performance with a precision that is 10 times smaller than the performance criterion to be met. Thus, if the design percolation