Field Evaluation of Alternative Earthen Final Covers

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ABSTRACT

Five methods to assess percolation rate from alternative earthen final covers (AEFCs) are described in the context of the precision with which the percolation rate can be estimated: trend analysis, tracer methods, water balance method, Darcy’s Law calculations, and lysimetry. Trend evaluation of water content data is the least precise method because it cannot be used alone to assess the percolation rate. The precision of percolation rates estimated using tracer methods depends on the tracer concentration, percolation rate, and the sensitivity of the chemical extraction and analysis methods. Percolation rates determined using the water balance method have a precision of approximately 100 mm/yr in humid climates and 50 mm/yr in semiarid and drier climates, which is too large to demonstrate that an AEFC is meeting typical equivalency criterion (30 mm/yr or less). In most cases, the precision will be much poorer. Percolation rates computed using Darcy’s Law with measured profiles of water content and matric suction typically have a precision that is about two orders of magnitude (or more) greater than the computed percolation rate. The Darcy’s Law method can only be used for performance assessment if the estimated percolation rate is much smaller than the equivalency criterion and preferential flow is not present. Lysimetry provides the most precise estimates of percolation rate, but the precision depends on the method used to measure the collected water. The lysimeter used in the Alternative Cover Assessment Program (ACAP), which is described in this paper, can be used to estimate percolation rates with a precision between 0.00004 to 0.5 mm/yr, depending on the measurement method and the flow rates.
I. INTRODUCTION

Final covers are used frequently as a remediation strategy to reduce the quantity of water that infiltrates into contaminated soils and waste deposits. Reducing the volume of infiltrating water reduces the rate of leachate generation and the risk of additional groundwater contamination. At most sites, regulations prescribe that the cover employ resistive principles, that is, layers having low saturated hydraulic conductivity (compacted clay barriers, geosynthetic clay liners, and/or geomembranes). These principles are used to provide the hydraulic impedance that limits flow into underlying contaminated materials or waste. However, many regulations also permit alternative cover designs provided that the alternative is hydraulically equivalent to the prescriptive cover. Hydraulic equivalency generally means that percolation from the base of the alternative cover is less than or equal to percolation from the prescriptive cover. In many cases, alternative covers can be much less costly than their prescriptive counterparts, and yet can be equally effective (Ankeny et al., 1997).

A common alternative cover design is the "alternative earthen final cover" (AEFC) that exploits the water storage capacity of finer-textured soils and the water removal capability of vegetation (Licht, 1993; Wing and Gee, 1994; Benson and Khire, 1995; Stormont and Morris, 1998; Nyhan et al., 1997; Ward and Gee, 1997). AEFCs are also referred to as "evapotranspiration or ET" covers, although this nomenclature is not used here because evapotranspiration occurs from nearly all final covers, regardless of design. Evapotranspiration has a particularly important role for AEFCs because water stored in the cover must ultimately be removed by evaporation or transpiration if an AEFC is to be effective. In most applications, the role of plants is critical, because root water uptake is the key means of removing water stored in the AEFC. Thus, in the context of remediation via containment, AEFCs are classified as a phytoremediation technology.

A demonstration of equivalency is generally required for an alternative cover to be approved by regulatory authorities. The demonstration may compare the percolation rate for the alternative cover to a predefined equivalency criterion for the prescriptive cover (e.g., SAIC, 1999; Benson, 2000). Alternatively, a comparison may be made between percolation rates for the alternative and prescriptive covers under identical meteorological conditions. Demonstrating that percolation from an AEFC is less than percolation from a prescriptive cover is challenging because existing computational methods for predicting the hydraulic performance of AEFCs either are not available or have not been verified in the field. This is particularly true for cases where the acceptable rate of percolation is very low (i.e., on the order of 10 mm/yr or less). Consequently, field demonstrations of equivalency are often required to verify that an AEFC meets its percolation objective. In some cases, the field demonstration may consist of side-by-side test sections simulating the alternative and prescriptive cover designs. This article describes five methods that are employed for field equivalency demonstrations and the precision with which the percolation rate can be determined with each method. These approaches are similar to those used to estimate recharge, as reviewed by Gee and Hillel (1988).
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II. WATER BALANCE METHOD

The water balance method consists of measuring or estimating all other variables in the water balance, and then using a mass balance approach to calculate the percolation rate \( P_r \), that is

\[
P_r = P - ET - R - \Delta S
\]

where \( P \) is precipitation, \( R \) is runoff, ET is evapotranspiration, and \( \Delta S \) is the change in soil water storage during a fixed period of time. The precision with which each of the quantities on the right side of Eq. 1 can be measured directly controls the precision with which the percolation rate can be determined.

Precision and accuracy of precipitation measurements depend on the location at which the measurements are made, the method used to make the measurements, the form of precipitation (frozen vs. unfrozen), and the amount of spatial variability existing in the precipitation (Smith, 1992). Measurements made directly on a cover or test section improve precision and accuracy, but still may be in appreciable error. For example, heated tipping buckets used in semiarid regions with snowfall can underestimate precipitation from individual snow events by 30 to 80% due to evaporation of heated snow (Hanson et al., 1983). Inadequate wind shielding of rain gauges can also bias the precipitation measurement by 50% or more (Larson and Peck, 1974). With appropriate shielding, errors as large as 30% can still exist at high wind velocities (> 8 m/s). Even under ideal conditions, precipitation measurements have a precision less than ±10% (Gee and Hillel, 1988).

Soil water storage can be measured more accurately than precipitation, but the best measurement devices (those employing nuclear or dielectric techniques) can only provide water contents within ±2% (Topp et al., 1980; Gee and Ward, 1999). Calibration bias can also result in errors in water content on the order of 5% (Benson and Bosscher, 1999), especially for fine-textured soils often used for earthen covers. Thus, for a cover 1 m thick, measured soil water storage can be determined with a precision of 20 mm at best (i.e., 0.02 × 1000 mm = 20 mm).

Evapotranspiration cannot be measured directly at the canopy scale and, as discussed below, methods of estimating evapotranspiration vary in precision and accuracy. Potential evapotranspiration (PET) can be estimated with reasonable accuracy, but at most sites actual ET (AET) will be less than PET during at least some portion of the year. At sites where water stress exists, AET may be much less than PET during much of the year. Inasmuch as aggressive uptake of water by vegetation is key to the success of AEFCs, water stress is likely to exist at most sites and thus AET will be less than PET.

Actual ET can be estimated from latent heat flux measurements using micrometeorological methods (e.g., eddy correlation or Bowen ratio techniques, Rosenberg et al., 1983). Of the meteorological methods, eddy correlation appears to be the most reliable method for estimating AET, but errors of approximately 10% are typical (Twine et al., 2000). As the data needed to estimate AET with micrometeorological methods are usually scarce or nonexistent, other methods to compute AET are usually used and include empirical formulas (e.g., using crop coefficients) or consti-
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tutive relationships using numerical methods that simulate transpiration by root water uptake and evaporation by applying a diffusive flux boundary condition at the ground surface. Constitutive methods to compute actual evaporation and transpiration have been described by Nimah and Hanks (1973a), Feddes et al. (1978), Fayer et al. (1992), Tratch et al. (1995) and others. All of these methods depend on some method of partitioning evapotranspiration into evaporation and transpiration. The partitioning is often based on a best estimate (e.g., Nimah and Hanks, 1973b) or is computed using an empirical relationship based on vegetative parameters such as leaf area index (e.g., Ritchie and Burnett, 1971; Chadwick et al., 1999). The constitutive methods also must be combined with a numerical model describing water status in the root zone.

Under the best of circumstances, estimates of ET made using the constitutive approach have a precision of 15 mm/yr in humid climates and 5 mm/yr in semiarid to arid climates (Nimah and Hanks, 1973b; Feddes et al., 1974; Fayer et al., 1992; Khire et al., 1999). Errors associated with empirical methods can be larger. For example, Khire et al. (1997) determined ET for two AEFCs using detailed monitoring facilities employing large-scale lysimeters. A cross section of their lysimeters is shown in Figure 1 (Benson et al., 1994). One facility was constructed in a humid climate and the other in a semiarid climate. Instruments were installed to measure precipitation, runoff, soil water storage, and percolation from the base of the cover. Evapotranspiration was computed as the residual of the mass balance (Eq. 1) using measurements of precipitation, runoff, soil water storage, and percolation. Meteorological data obtained directly adjacent to the lysimeters, measured soil properties, and measured characteristics of the vegetation were used for estimating ET. Analysis of these data shows that errors in the empirical estimates of ET were approximately 20 mm/yr for both sites. Given that less detailed information is typically available for most sites, even larger errors are likely. Gee and Hillel (1988) indicate that errors on the order of 20% of the estimated ET are common.

Surface runoff from AEFCs can be measured with a precision of 2 to 3% of precipitation if the catchment being monitored is well defined and the outflow monitoring points are limited (Winter, 1981). Good definition of the catchment requires delineation of the catchment area using diversion structures (e.g., diversion berms) that prevent run on from adjacent areas and direct run off for measurement. Drainage from the catchment must not be impeded by the measurement system. If impediments exist, infiltration into the cover will be unrealistically large and runoff will be underestimated.

Estimates of surface runoff can be made using semiempirical methods (e.g., Soil Conservation Service, 1985) or using a constitutive approach based on infiltration capacity and surface roughness. Comparisons of measured and estimated runoff were made by Khire et al. (1997) using field data from the humid and semiarid installations mentioned previously. Runoff was estimated using the semiempirical SCS curve number method and an infiltration capacity technique that ignores surface roughness and slope effects. They found that the SCS method grossly underestimated runoff (~210 mm/yr error) for the humid installation and modestly underestimated runoff (~10 mm/yr error) for the semiarid site. The infiltration capacity method was superior at the humid facility (error < 2 mm/yr), but performed poorly at the semiarid facility.
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FIGURE 1. Schematic of lysimeter used in final cover studies by Khire et al. (1997) at sites located in Georgia and Washington, USA

The infiltration capacity method predicted that no runoff would occur at the semiarid facility, whereas the field data indicated that runoff was approximately 25 mm/yr. Many of the errors at both sites were attributed to poor estimates during snowmelt events. Better estimates might have been obtained using algorithms developed especially for the thermal and hydrological conditions during snow melt, such as those described in Flerchinger and Saxton (1989).

This assessment provides a basis for estimating the precision with which percolation rates can be determined using the water balance method. For example, consider an AEFC 1 m thick at a humid location with 1200 mm/yr of precipitation and a similar AEFC at a semiarid site with 200 mm/yr of precipitation. Assume that runoff and storage are measured with the best precision attainable with current technologies (both 2%), ET is estimated with a typical empirical method with a precision of 60 mm/yr at the humid site and 30 mm/yr at the semiarid site, and precipitation is measured with a quality-shielded rain gauge with an error of 10%. For these assumptions, the water balance method can be used to estimate percolation with a precision of 230 mm/yr at the humid site and 75 mm/yr at the semiarid site. When the error in precipitation is ignored, the precision is approximately 100 mm/yr for the humid site and 50 mm/yr at the semiarid site.

These estimates of precision need to be viewed in the context of percolation criteria stipulated for AEFCs. The equivalent percolation rate for a prescriptive cover generally is site specific, but some guidance on typical equivalent percolation rates is provided through the U.S. Environmental Protection Agency’s Alternative Cover Assessment Program (ACAP). In lieu of a site-specific equivalency criterion, ACAP suggests that an AEFC is equivalent to a soil cover (e.g., a resistive cover design employing compacted clay) if the percolation rate is less than 10 mm/yr in semiarid and drier climates or 30 mm/yr in humid climates. For composite prescriptive covers (i.e., resistive cover designs employing a compacted clay layer overlain by a geomembrane), the equivalency criterion is 3 mm/yr regardless of climate (SAIC, 1999; Benson, 2000). More stringent criteria have been used at other sites (Wing and Gee, 1994; Boehm et al., 1998, Chadwick et al., 1999). Most importantly, all of these equivalency criteria are much smaller than the precision with which percolation can be measured with the water balance method. Thus, performance assessments made using the water balance method have insufficient precision to demonstrate that an AEFC is achieving the desired percolation rate.
III. SOIL MOISTURE AND POTENTIAL MONITORING

Monitoring water contents and pore water potentials using nests of probes is often suggested as a method to assess the performance of an AEFC. Inferences regarding performance are made either by evaluating trends in the data or by calculating fluxes using the monitoring data and estimates of hydraulic conductivity.

A. Inferences Based on Trend Analysis

The absence of a trend or variation in water content at depth is often incorrectly assumed to mean that flow is not occurring at depth and that percolation is not being transmitted from the base of a cover. This inference is incorrect because flow of liquid water occurs due to a gradient in total hydraulic head (comprised of pressure and gravitational heads) rather than a gradient in water content. In addition, water may also flow in the form of vapor as a result of gradients in vapor pressure and temperature (Scanlon and Milly, 1994). For example, Coons et al. (2000) calculated that vapor-driven fluxes can be as large as 3 mm/yr at some sites.

The following example illustrates percolation rates due to flow of liquid water that may exist even when water contents appear to be constant at depth. Consider a monolithic cover comprised of a 1.5-m-thick layer of silty clay loam that is vegetated with local grasses. Data collected from probes in the cover indicate that the water content has remained unchanged over time at depths greater than 0.6 m, and that water contents are essentially the same at all monitoring points beneath 0.6 m. This condition corresponds to gravity driven flow (i.e., unit hydraulic gradient) in the soil at depths > 0.6 m, and thus the percolation rate equals the hydraulic conductivity of the soil at the existing water content. The relationship between hydraulic conductivity and water content for a typical silty clay loam used in a monolithic cover is shown in Figure 2 (Winkler, 1999) along with percolation rates corresponding to gravity.

B. Calculating Percolation Rate from Water Contents and Suctions

The percolation rate can be calculated from the water content data using Darcy's Law (Allison et al., 1983; Stephens and Knowlton, 1986; Boehm et al., 1998) if the unsaturated hydraulic properties of the cover soils are known (soil water characteristic curve [SWCC] and hydraulic conductivity). This approach, which is referred to herein as the "Darcy's Law" method, is to calculate the percolation rate \( P_r \) as:

\[
P_r = K_y i
\]  

(2)

where \( K_y \) is the hydraulic conductivity at suction \( \psi \) and \( i \) is the hydraulic gradient. The hydraulic gradient is computed with suctions \( \psi \) corresponding to the measured water contents and the elevations at which the water contents are measured. An example is shown in Figure 3, which is from an AEFC test facility in Arizona, USA. A monolithic cover 1.2 m thick was evaluated at this site. The profile of water
contents (Figure 3a) is converted to a profile in total head, \( h = z - \psi \) (Figure 3b), using
suctions determined from the SWCC (Figure 3c). The hydraulic gradient \( i \) is the
slope of the total head profile \( (i = \Delta h/\Delta Z) \). The hydraulic conductivity is estimated
from the average suction at the depths where the gradient is calculated and the
unsaturated hydraulic conductivity curve (Figure 3d). For this example, \( i = 6.2 \), \( K_v = 5 \times 10^{-9} \) cm/s, and \( P_r \) is 1.2 mm/yr. This value for \( P_r \) pertains only to the time when
the water content data were collected. Similar calculations are made on a daily or
weekly basis to define the temporal characteristics of \( P_r \).

The “Darcy’s Law” method has several limitations that can lead to errors in the
calculated percolation rate. Perhaps the largest potential source of error is due to
preferential flow through macroscopic features (Khire et al., 1997) or lateral flow due
due to fine variations in texture or anisotropy in hydraulic properties (McCord and
Stephens, 1987). With regard to flow through macroscopic features, most probes
used to measure water content or matric suction (e.g., time domain reflectometry
probes or heat dissipation units) yield data characteristic of conditions within the soil
matrix and not along cracks, fissures, or macropores that conduct preferential flow.
Even if probes can detect preferential flow, placing probes along preferential flow
paths is nearly impossible because locations of these paths are not known \textit{a priori}.

FIGURE 2. Relationship between hydraulic conductivity and volumetric water content with
corresponding percolation rates for a monolithic cover comprised of silty clay
loam. Unit downward hydraulic gradient assumed to exist at depth. Parameters
describing the hydraulic conductivity were obtained from Winkler (1999).
FIGURE 3. Graphs depicting data used in estimating percolation using the Darcy’s Law method: (a) profile of water content; (b) profile of total head computed using measured water contents, SWCC, and elevations of water content probes; (c) soil water characteristic curve for cover soil; and (d) unsaturated hydraulic conductivity function for cover soil.
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(and may never be known). Khire et al. (1997) provide an example of preferential flow in a 0.8-m-thick AEFC instrumented with water content probes and a lysimeter (subsurface collection pan; see Figure 1) for collecting percolation. Data collected during the winter of 1995 are shown in Figure 4. Pulses of percolation transmitted through preferential flow paths were regularly collected in the lysimeter shortly after precipitation events (Figure 4a) 2 months before the deepest probes indicated that water was reaching the base of the cover (Figure 4b).

Errors in $K_v$ also have a significant effect on the estimated percolation rate. Typically, $K_v$ is estimated from the saturated hydraulic conductivity ($K_{sat}$) and the shape of the SWCC using equations based on capillary tube models (e.g., the van Genuchten-Mualem model [van Genuchten 1980]). Capillary tube models provide reasonable estimates of unsaturated hydraulic conductivity for coarse-grained soils, but often underestimate the unsaturated hydraulic conductivity of finer-textured soils such as those used for AEFCs (Fredlund et al., 1994; Meerdink et al., 1995; Chiu and Shackelford, 1998). Measurements of the unsaturated hydraulic conductivity can be made to reduce this error, but they are tedious, time consuming, and expensive. These measurements can also be subject to errors as large as those present in capillary tube models (Stephens, 1996; Benson and Gribb, 1997).

Hysteresis in the SWCC is another source of error (i.e., the suction corresponding to a given water content depends on whether the soil is wetting, drying, or is in transition between wetting and drying). Most calculations made using the Darcy’s Law method employ a single SWCC (typically a drying curve) and ignore hysteresis. This error can be avoided by monitoring suctions (using devices such as tensiometers, psychrometers, or heat dissipation units) at the same depths at which the water content probes are placed. However, suctions measured with these devices are also subject to error.

A more fundamental approach to estimate the percolation rate from water content data is to fit Richards’ equation (the governing equation for flow of liquid water in unsaturated soil) to the data using a numerical model. Percolation rate is determined using the water contents and suctions at the base of the cover that are predicted using Richards’ equation. The SWCC and unsaturated hydraulic conductivity are needed in this approach as well, as are detailed data describing boundary conditions (e.g., meteorological conditions and evapotranspiration). The data needed in this approach render it impractical in most cases and no more accurate than the “Darcy’s Law” method.

If preferential flow is ignored, the precision of the “Darcy’s Law” method can be assessed by evaluating the precision with which $\psi$ and $K_v$ can be estimated. Errors in $\psi$ due to hysteresis can be as large as an order of magnitude as are errors in $K_v$. Thus, estimates of percolation rate made using the “Darcy’s Law” method have a precision of one to two orders of magnitude. In addition, spatial variability in the SWCC and $K_v$ may increase the precision by an order of magnitude. This relatively poor precision may be acceptable if the calculated percolation rate is very low (e.g., 0.0001 mm/yr), but is unacceptable if the calculated percolation rate is close to the equivalent percolation rate.
FIGURE 4. Data from Lysimeter in Washington, USA reported in final cover study by Khire et al. (1997): (a) precipitation and percolation during January-March 1995 showing close correspondence between precipitation and percolation data, (b) water contents measured in cover during January-March 1995, suggesting that water did not reach the base of the cover until late February.
IV. TRACERS

Tracers have been suggested as a means of demonstrating that percolation from an AEFC does not occur below a particular depth (e.g., Coons et al., 2000). Soil at the near surface of an AEFC is spiked with a conservative solute not normally found in pore water (e.g., bromide or deuterium oxide). Test pits are excavated in the AEFC at various times during the monitoring period and soil samples are collected from various depths for chemical analysis of the pore water. Percolation is assumed to occur only to the depth at which the tracer is detected.

The precision of this method depends on the concentration of the solute when the soil is spiked, the amount of uptake of the solute through plant roots, the detection limit for the chemical analysis, the amount of water flowing through the cover during the monitoring period, the presence of preferential flow paths, and the quality of the mass balance achieved. Given the number of factors that can affect the precision of this technique and the limited experience with it, a quantitative assessment of precision currently is not possible.

V. LYSIMETRY

In the context of evaluating cover performance, lysimetry is the use of buried containers with open tops that collect and measure soil water. In contrast to the indirect methods mentioned so far, lysimetry provides a direct measurement of percolation rate from an AEFC. There are two types of lysimeters: weighing and volumetric. A weighing lysimeter employs a scale to measure the total weight of soil within the monitoring area and a drainage pipe at the base to collect percolation from the base of the cover profile (Figure 5). Changes in soil water storage are inferred from the changes in weight recorded by the scale (i.e., the only significant changes in mass are assumed to be due to changes in soil water storage). A volumetric lysimeter consists of a pan for collecting water percolating from the base of the profile being monitored (e.g., Figure 1). Changes in soil water storage in a volumetric lysimeter are determined by integrating profiles of water content measured using nests of probes placed in the cover. Weighing lysimeters are normally limited to smaller test sections (1 to 2 m²) because of the limited capacity of scales. Volumetric lysimeters are employed when a less costly monitoring system is desired or a large section of an AEFC is being monitored.

A. Advantages and Disadvantages of Lysimeters

Direct measurement of the percolation rate is the key advantage of lysimetry. Percolation rates can be measured with a precision of 0.5 mm/yr or better using lysimeters (Gee and Hillel, 1988; Benson et al., 1994; Ward and Gee, 1997). Precise changes in soil water storage can also be measured when weighing lysimeters are employed.

The most significant disadvantage of lysimetry is the artificial no-flow boundary induced by the barrier at the base of the lysimeter. This boundary, which does not exist in the actual field setting, prevents upward and downward flow of vapor and liquid across the base of the lysimeter. In effect, the lysimeter acts as a rectifier. All
water that migrates downward to the base of the profile is collected and routed out of the system. Consequently, the collected water can never move upward as a result of natural upward gradients induced by evapotranspiration and temperature gradients, as might occur under natural conditions. Coons et al., (2000) indicate that percolation rates measured using lysimeters can be as much as 3 mm/yr too large due to the artificial trapping of water vapor by the lower boundary.

Most lysimeters also include an earthen or geosynthetic drainage layer directly on top of the lower boundary for directing percolation to a measuring point. The larger pores associated with drainage layers induce a capillary break at the base of the cover profile that might not exist under natural conditions (Khire et al., 1999). As a result, an artificial increase in the storage capacity of the cover profile may be incurred relative to natural conditions, as well as an artificial reduction in percolation rate. This issue is only problematic if the drainage layer has very different pores than the material over which the AEFC is being installed or the cover being monitored is very thin (< 1 m). For typical solid wastes, the air and water entry suctions are very low (~10 mm; Benson and Wang, 1998), and most AEFCs have a thickness ≥ 1 m. Thus, the capillary break effect generally does not significantly affect percolation estimates.
Lateral diversion can be a significant problem with lysimetry if the areal extent of the lysimeter is insufficient and the lysimeter does not have vertical sidewalls (Figure 6) (Bews et al., 1999). Diversion occurs under unsaturated conditions due to the tendency for water to be retained within finer textured cover soils rather than coarser textured drainage layers (i.e., due to a capillary break). Lysimeters that are too small or narrow collect too little water and underestimate the percolation rate. Chiu and Shackelford (1994, 2000) suggest that the breadth of a lysimeter should be at least five times the depth of the profile being monitored to prevent diversion from affecting the percolation rate.

The precision of percolation rates measured with lysimeters is also affected by leakage, which is minimized or eliminated through careful construction and post-construction testing. Artificial root water uptake (i.e., uptake of water stored in the drainage collection system that would drain below the root zone if the lysimeter was not present) can also affect measurements of percolation rate.

FIGURE 6. Effect of Lysimeter width on diversion of percolation. Thickness of cover profile being monitored is L and breadth of Lysimeter is B.
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B. Alternative Cover Assessment Program (ACAP) Lysimeter

Lysimeters are an essential element of the test facilities constructed as part of ACAP. The purpose of ACAP is to collect field scale data regarding the hydrologic behavior of prescriptive and alternative covers, with particular emphasis on percolation rates. Large-scale lysimeters for measuring percolation rates have been installed at ten ACAP field sites. The lysimeter used in ACAP was designed to provide precise estimates of percolation rate by minimizing the disadvantages associated with lysimetry and by providing redundancy in the measurements. Schematics of the lysimeter design are shown in Figure 7. A detailed description of the lysimeter is in Benson et al. (1999).

The lysimeter is 10 m by 20 m in areal extent and is located in the center area of a test section (Figure 7a). The areal extent of the lysimeter was selected to capture spatial variability in the properties of cover soils and vegetation by ensuring that the lysimeter is several times larger than correlation lengths (i.e., the average distance over which properties exhibit statistical correlation) associated with typical fill soils and vegetation properties (Benson, 1991; Pelgrum et al., 2000). A large lysimeter was also used to ensure that preferential flow processes (e.g., rapid flow in features such as cracks, fissures, root channels, and worm holes) are captured in the test and so that the construction process would mimic full-scale conditions.

Linear low-density polyethylene (LLDPE) geomembrane is used to line the lysimeter because it is highly puncture resistant and readily welded in the field. LLDPE is used to form the pan along the base of the lysimeter and the vertical sidewalls, the latter preventing lateral diversion (Figure 7b). The probability of leakage from the liner is minimized by using double-track seams, air pressure testing of seams, and by conducting a hydrostatic leak test prior to filling the lysimeter with soil (Benson et al., 1999). A geocomposite drainage layer containing nonwoven geotextiles heatbonded to each side of a geonet is placed directly on the geomembrane to function as a drainage layer and as a cushion during placement of soils. The sump is checked periodically using a test pipe (Figure 7a).

Placement of a 300-mm-thick layer of typical interim cover soil between the geocomposite drainage layer and the AEFC reduces capillary break effects. In this configuration, the drainage layer on top of the geomembrane simulates the coarse texture of waste and the interim layer simulates the soil that exists on top of the waste before the AEFC is constructed. In a field scenario, the interim cover soil might be an existing thin soil cover at an old landfill or dump or interim cover placed over the last layer of waste at a new landfill.

A thin geosynthetic layer impregnated with herbicide (a "geosynthetic root barrier") is placed between the interim cover soil and the bottom layer of the AEFC to prevent roots from penetrating into the drainage layer and its associated piping. The geosynthetic root barrier is not placed directly on the geocomposite drainage layer to avoid sliding that might occur during construction due to insufficient friction between the geocomposite drainage layer and the root barrier. In an actual field scenario, roots would likely penetrate into the interim cover soil.

Influence of the underlying geomembrane on vapor flow was unavoidable in the ACAP design. The effects of vapor flow, combined with the use of the root barrier
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![Diagram of lysimeter](attachment:lysimeter_diagram.png)

**FIGURE 7.** Schematic of lysimeter used in ACAP: (a) plan view and (b) cross-section. LLDPE = linear low-density polyethylene and PVC = polyvinyl chloride.
FIGURE 7. (continued)
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to prevent roots from growing into the interim cover soil, probably result in an overestimate of the percolation rate. Overestimating the percolation rate is not optimal for carefully defining field behavior, but does result in a conservative assessment of the performance of an AEFC.

C. Precision of Percolation Rate Measured with the ACAP Lysimeter

Percolation collected from the lysimeter is routed through polyvinyl chloride (PVC) pipe to a collection basin for measurement. The collection basin is equipped with three redundant measurement devices having different levels of precision (Figure 8). Water draining into the basin first passes through a tipping bucket-type precipitation gauge and then accumulates in the basin. The volume of water in the basin is recorded using a pressure transducer, which can be translated into a percolation rate. Once a preset water level is reached in the basin, it rapidly drains (approximately 95 L in 25 s) using a dosing siphon. Each “flush” of the siphon is recorded using a float switch.

The dosing siphon is an essential element of the percolation monitoring system. Dosing siphons operate on the same flushing principle used in gravity flow toilets and are commonly used in residential wastewater treatment systems to route water from septic tanks to drain fields. They have no moving parts and work equally well in clean and turbid water. Using the dosing siphon precludes leakage problems normally associated with mechanical drainage methods, such as solenoid-operated valves.

The three measurement methods provide an indication of the precision with which percolation can be measured using the ACAP lysimeter. Percolation measured with the tipping bucket has a maximum precision equal to its least count. The least count is 8 mL, which corresponds to 0.00004 mm of water for the 200-m² lysimeter. However, the error associated with each tip is approximately 2%. Thus, as the percolation rate increases, the precision of the percolation rate measured with the tipping bucket decreases. For percolation rates on the order of 30 mm/yr, the precision of percolation rates measured with the tipping bucket is 0.6 mm/yr. Percolation rates measured with the pressure transducer have a precision of 0.02 mm/yr and those measured with the dosing siphon (based on least count of about 100 L) have a precision of 0.5 mm/yr. Thus, at best the precision associated with percolation measured by the ACAP lysimeter is on the order of 0.00004 mm/yr (one tip of the tipping bucket) and at worst it is 0.5 mm/yr. The operative precision falls between these two limits, and from a practical perspective it is about 0.1 mm/yr.

D. Other ACAP Measurements

A variety of other instruments are included in the ACAP lysimeter to allow a detailed understanding of the water balance. An intention of ACAP is to combine measurements of percolation and other components of the water balance for evaluation of models used for design and analysis.

Surface runoff is collected with diversion berms and routed to a collection basin comparable to that used for measuring the percolation rate. Given that runoff volumes are much larger than percolation volumes, runoff measurements are made using only two devices: a transducer and a float switch to record flushes of the dosing
FIGURE 8. Collection basin employing three redundant methods to measure percolation: tipping bucket, pressure transducer, and float switch.
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siphon. A similar system is employed to measure lateral drainage in cover profiles that promote lateral drainage.

Profiles of water content are measured in nests located at three equi-spaced points along the centerline of the lysimeter. A dielectric technique is used to measure water content (Bilskie, 1997; Campbell and Anderson, 1998; Veldcamp and O'Brien, 2000). A profile of matric suction is also measured in the center of the lysimeter using thermal conductivity probes (Gee and Ward, 1999; Shuai and Fredlund, 2000) at the same depths at which water contents are measured. All water content and matric suction probes have a site-specific calibration.

Meteorological conditions (air temperature, solar radiation, relative humidity, wind speed and direction, and precipitation) are measured using a weather station located on the test section. A datalogger stores data from all of the meteorological sensors, probes within the lysimeter, and the sensors used to measure water volumes. Data stored in the datalogger are transmitted to the office periodically by cellular telecommunications. At the office, the data are subjected to quality control and assurance checks, are processed into physical quantities (e.g., soil water storage or percolation rate), and then are posted on a website (www.dri.edu/Projects/EPA).

E. Equivalency Demonstrations

Not all sites requiring an equivalency demonstration with a direct measure of percolation need to install an ACAP-style lysimeter. A simpler design can be used where only percolation from the base of the cover is measured. This system might consist of a lysimeter comprised of the geomembrane barrier, the drainage collection layer, a collection pipe, and a tank. Percolation could be monitored by measuring the water level in the tank using a pressure transducer, a float and pulse counter, or even a measuring tape. However, the method used to monitor the volume should be sufficiently precise so that the measured percolation rate can be compared with the percolation criterion used to define equivalency. A practical rule of thumb is to ensure that the precision in the percolation measurements is at least one order of magnitude smaller than the percolation criterion.

VI. SUMMARY

This article has described five methods used to assess percolation rate during a field demonstration of equivalency of an alternative earthen final cover (AEFC). These include (1) the water balance method, (2) trend analysis, (3) Darcy's Law calculations, (4) tracer methods, and (5) lysimetry. The precision with which percolation rate can be determined with these methods varies significantly.

Trend evaluation is the least precise method because soil water content data cannot be used alone to assess percolation rate (i.e., an inference regarding percolation rate cannot be made based on trends in water content data alone). The water balance method is the next least precise method. Percolation rates determined using the water balance method have a precision of approximately 100 mm/yr in humid climates and 50 mm/yr in semiarid and drier climates under the best circumstances,
which is too large to demonstrate that an AEFC is meeting typical equivalency
criteria (30 mm/yr or less).

Percolation rates computed using Darcy’s Law and measured profiles of water
content, matric suction, and reliable hydrological properties of the cover soil have a
precision of about two orders of magnitude relative to the estimated percolation rate.
Thus, the Darcy’s Law method can be used to determine if an AEFC is meeting a
percolation objective if the estimated percolation rate is at least two orders of
magnitude smaller than the equivalent percolation rate. Preferential flow usually is
not detected using the Darcy’s Law method, and thus this method can provide an
unconservative assessment of the percolation rate if preferential flow exists.

Tracer methods are used to determine the depth of percolation, but not the
percolation rate. The precision of tracer methods is affected by a number of factors
including the tracer concentration, percolation rate, and sensitivity to chemical
extraction and analysis methods, and cannot be reliably quantified at this time.

The most precise estimates of percolation rate are made using lysimeters, with the
precision being a function of the method used to measure the flow rates. The ACAP
lysimeter described in this article can be used to estimate percolation rates with a
precision between 0.00004 and 0.5 mm/yr depending on the method used to measure
the flow rates, and thus can be used to assess whether AEFCs are meeting their
percolation objective. Large lysimeters (> 100 m²) are preferred because the sensi-
tivity of the drainage measurement increases with size of the lysimeter. Large
lysimeters also provide a greater probability of properly accounting for preferential
flow and allow large construction equipment to be used to simulate full-scale
conditions. A disadvantage of lysimeters is the artificial boundary caused by the
barrier and drainage layer at the base of the cover. Errors introduced by this boundary
generally cause an overestimate in the percolation rate, which is conservative. This
bias can be as large as 3 mm/yr.

Not all lysimeters need to be as complex as those used for ACAP. Lysimeters that
have acceptable precision can be constructed using simpler monitoring systems
provided the system used to measure flow rates has sufficient precision and the
lysimeter is able to capture the effects of preferential flow within the cover system.
In many practical cases, the only elements that are required are the geomembrane
barrier, the drainage collection layer, piping, and a collection tank.

ACKNOWLEDGMENT

Financial support for the Alternative Cover Assessment Program (ACAP) is
provided by the United States Environmental Protection Agency through the Superfund
Innovative Technology Evaluation (SITE) program and the Remediation and Con-
tainment Branch of the National Risk Management Research Laboratory. Mr. Michael
Bolen of Science Applications International Corporation is the ACAP project man-
ager. Mr. Steve Rock is the ACAP program manager at USEPA. The efforts of Bolen
and Rock on behalf of ACAP are greatly appreciated by the authors. The authors also
appreciate the constructive criticism provided by the three anonymous reviewers as
well as thoughtful comments provided throughout the project by Dr. Mark Ankeny.
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