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Use of Moisture Profiles and Lysimetry to Assess Evapotranspirative Cover Performance

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ABSTRACT: The performance of evapotranspirative landfill covers, often used in municipal and hazardous waste disposal applications, is quantified in this study using basal percolation and soil moisture content data obtained over six years through a comprehensive field monitoring program. Specifically, this paper presents applications of soil moisture profiles and numerical modeling to verify percolation measured by a lysimeter. Inconsistencies between the recorded lysimeter percolation and the results of the moisture profile and numerical modeling analyses suggest both a potential capillary break between the lysimeter and the cover soil as well as preferential flow through isolated flow channels. Nonetheless, the utility of moisture profiles and numerical modeling is stressed. Numerical modeling using boundary conditions from meteorological data and initial conditions from moisture profiles was found to provide a realistic base-case scenario for performance assessment. Moisture profiles provide continuous feedback of cover performance without interfering with flow conditions.

Keywords: Evapotranspirative covers, TDR moisture profile, lysimeters

1 INTRODUCTION

One of the key engineered components in landfills is the cover system. The design of final cover systems for new municipal and hazardous waste containment systems in the United States is prescribed by the Resource Recovery and Conservation Act (RCRA) Subtitles D and C, respectively. Federal- and state-mandated cover systems for municipal and hazardous waste landfills have endorsed the use of "resistive barriers". Resistive type cover systems involve a liner (e.g. a compacted clay layer) constructed with a low saturated hydraulic conductivity (typically 10^{-7} cm/s or less) to reduce percolation, or basal flux. Figure 1(a) illustrates the water balance components in this comparatively simple system, in which percolation control is achieved by maximizing overland flow. Although satisfactory performance has been reported for prescriptive systems in humid climates, problems induced by desiccation cracking of clay liners has led to inadequate performance in arid climates (e.g. the Western USA). Also, resistive covers required at some containment facilities have resulted in significant material and construction costs.

In order to enhance cover performance and lower construction costs, RCRA regulations allow alternative cover systems if comparative analyses and/or field demonstrations can satisfactorily demonstrate equivalence with prescriptive systems. One such alternative cover system, the evapotranspirative cover, is expected to have adequate long-term performance while mimicking natural systems by using a soil layer placed in natural conditions and a vegetative cover consisting of a diverse native plant community. Figure 1(b) illustrates schematically the water balance components in an evapotranspirative cover system. Evapotranspiration and moisture storage, two components that do not play a major role in resistive barriers, are significant elements in the performance of this system. The novelty of this approach is the mechanism by which percolation control is achieved: an evapotranspirative cover acts not as a barrier, but as a sponge or a reservoir that stores moisture during precipitation events, and then releases it back to the atmosphere as evapotranspiration. Evapotranspirative covers are vegetated with native plants that survive on the natural precipitation. The superior performance in arid climates of evapotranspirative covers relative to conventional resistive covers can be attributed to the lower unsaturated hydraulic conductivity of the selected cover soils. Additional advantages of evapotranspirative covers over typical clay barrier systems include their invulnerability to desiccation and cracking during and after installation, their relatively simple constructability, and their low maintenance. Also, as evapotranspirative covers can function correctly with a reasonably broad range of soils, they are typically constructed using soils from nearby areas. The adequacy of alternative cover systems for arid locations has been acknowledged by field experimental assessments ([1] & [2]), and procedures for quantitative evaluation of the variables governing the performance of this system have been compiled in a systematic manner for final cover design [7].

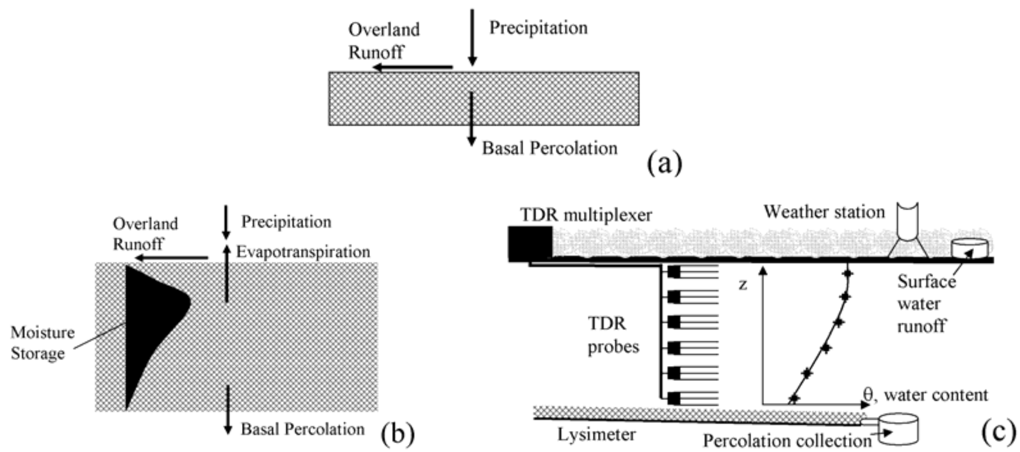

Figure 1: Water balance components: (a) in a resistive barrier; (b) in an evapotranspirative cover system; (c) Schematic of an instrumented evapotranspirative covers.

Designing a truly impermeable barrier (i.e. one leading to zero percolation) should not be within any engineer's expectations. Instead, the overall objective should be to design a system that minimizes percolation of rainwater into the waste to prevent leachate generation that may lead to environmental contamination of soil and groundwater. Quantification of this minimized, though finite, percolation of liquid into the waste poses significant challenges. In the past decade, there has been a significant effort to expand the knowledge base by constructing full scale field test plots [8]. However, there are shortcomings in the current monitoring schemes. The only available method for directly monitoring percolation is a lysimeter, which is typically constructed beneath the soil cover using a geocomposite for water collection (consisting of a geonet for in-plane drainage sandwiched between two filtration geotextiles) underlain by an impermeable geomembrane, as shown in Figure 1(c). While lysimeter measurements may define if the cover performs adequately (or not), they do not provide insight into reasons for poor or adequate performance. In addition, under unsaturated conditions expected in the field, lysimeters can cause unrealistic behavior in the overlying soil [5]. Consequently, as the overall performance of an evapotranspirative cover system relies on its ability to store moisture until it may be removed by evapotranspiration, other variables (e.g. moisture content or suction profiles) can be monitored to assess why the evapotranspirative cover performs adequately (or not). In addition, numerical modeling is often used to complement monitoring data by calculating the expected percolation under measured boundary and initial conditions.

The main objective of this paper is show how moisture content profiles can be used in tandem with lysimetry to evaluate the performance of evapotranspirative covers. First, moisture content profiles and numerical modeling are used to verify percolation amounts measured by lysimeters beneath instrumented evapotranspirative covers. Second, various techniques are presented for using moisture profiles to evaluate the performance of an evapotranspirative cover with or without a lysimeter present. This research will prove relevant to future design, analysis, and monitoring of evapotranspirative covers.

2 EVAPOTRANSPIRATIVE TEST COVERS, SOIL DATA, AND EQUIPMENT

Four evapotranspirative test covers were constructed in Denver, Colorado, USA in the Summer of 1998 [5]. These covers are referred to as covers A, B, C and D. The climate in Denver is semiarid, with an average annual precipitation of 396 mm and an average pan evaporation of 1394 mm (as quantified for the 1948 to 1998 period). The wettest months of the year (April to October) are also the months with the highest pan evaporation; optimal conditions for an evapotranspirative cover. The covers were each constructed using site-specific silt soils atop large pan lysimeters (9.1 m by 15.2 m), placed on a 3 percent grade to allow drainage in the geocomposite. The covers are separated by 2.4 m buffers, and the covers and buffers were vegetated with local grasses and shrubs. Details of the soil thicknesses (i.e. to the lysimeter) and relevant geotechnical soil properties for covers A, B, C, and D are presented in Table 1. Cover A is constructed of a low plasticity sandy silt, with only 43% fines content, while covers B, C, and D were constructed using higher plasticity silt with nearly 60% fines content. Covers A and D were constructed with the same depth to compare the performance of both soils, while covers B and C were constructed to investigate the influence of the cover depth.

Table 1. Cover thicknesses and soil geotechnical properties

Cover	Cover thickness (cm)	Soil type	Granulametric data	Atterberg limits	
			Average % passing #200 Sieve (% fines)	Average PL	Average LL
A	106.68	1	43.4	9	24.4
B	121.92	2	60.2	12.8	27.6
C	152.4	2	59.2	11.7	26.7
D	106.68	2	61.5	12	26.8

To aid in unsaturated flow analyses, the pressure plate, hanging column and dew point potentiometer methods [4] were used to define relationships between the suction (ψ), volumetric moisture content (θ), and saturated hydraulic conductivity ($K_{saturated}$) for the two cover soil types, at a relative compaction of approximately 70% of the maximum dry density (1.96 g/cm^3). Figure 2(a) shows the ψ–θ laboratory data along with the soil water characteristic curve fitted by the van Genuchten model [6], and the corresponding theoretical ψ-K(ψ) curve calculated from the van Genuchten-Mualem model [6] for soil type 1 (cover A). Figure 2(b) shows similar information for soil type 2 (covers B, C, and D). Figures 2(a) and 2(b) also include the $K_{saturated}$ values, as well as the van Genuchten model parameters: α, n, $\theta_{saturated}$, and $\theta_{residual}$.

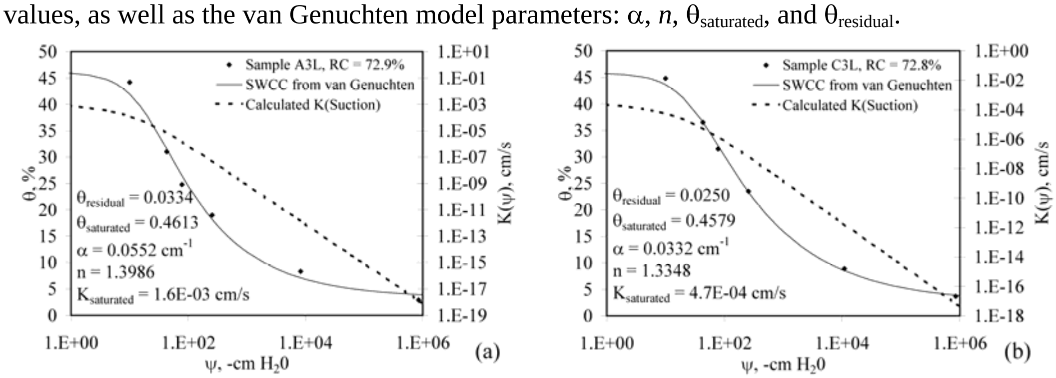

Figure 2: Soil characteristic curves for (a) Cover soil type 1; (b) Cover soil type 2

Percolation, precipitation, soil moisture storage, and runoff were monitored for the four test covers using the instrumentation layout shown in Figure 1(c). These variables (along with evapotranspiration) are collectively referred to as water balance variables, because considering the conservation of mass of water, the precipitation is equal to the sum of the evapotranspiration, the surface runoff, the percolation and the change in the soil moisture storage [1]. Percolation was collected from the lysimeter and measured using a tipping-bucket rain gauge. Rain and snow were measured using an all season gauge. The vertical volumetric moisture content profile was measured using arrays of TDR probes spaced evenly with the depth in the covers. Runoff was collected by polyethylene geomembrane swales around the cover perimeters.

3 MONITORING RESULTS

This section presents monitored water balance variables for cover A. The results for the other three covers are similar, with expected differences in moisture storage and percolation due to the different soil types and cover thicknesses. Monitoring commenced on July 10, 1998, designated as day 1, and continued until July 31, 2003. The vertical dashed lines in this and all further figures denote January 1st of each monitoring year. The cumulative water balance for cover A is shown in Figure 3, with the cumulative precipitation for each year shown in mm. Above average amounts of precipitation occurred in 1999 and 2001. The moisture storage was calculated by integrating the θ values obtained from each TDR probe over the depth of the cover. Over the lifetime of the cover, the soil moisture storage increases in response to the years with higher precipitation, while moisture storage recovers to a lower level in years with lower precipitation. The trend in the runoff mimics that of the precipitation, and is greatest in the spring during heavy storms; little runoff was collected from melting snow. The evapotranspiration calculated from the other water balance variables exceeds the precipitation, especially after day 400, when the vegetation was fully established. The percolation amounts collected by the lysimeters are negligible: less than 1 mm was collected from the covers during the study.

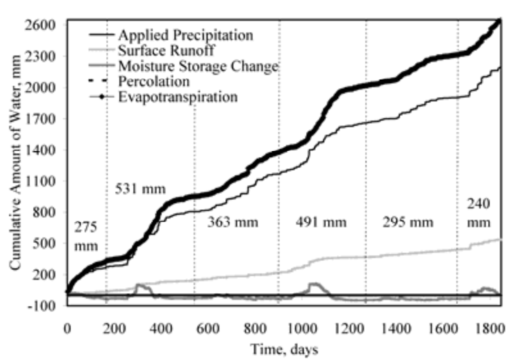

Figure 3: Cumulative water balance for cover A with cumulative precipitation amounts

4 VERIFICATION OF PERCOLATION AMOUNTS FROM LYSIMETERS

4.1 *Assessment of Percolation using Numerical Modeling*

As with any field instrumentation project, the reliability of the different sources of data must be verified. Accordingly, the main motivation of this section is to infer if the amounts of percolation recorded by the lysimeter are consistent with the observations from numerical modeling and moisture profile monitoring. The unsaturated flow model UNSAT-H [3] was used to quantify the expected performance from a freely draining soil layer in the field in response to the meteorological conditions shown in Figures 3(a) and 3(b). UNSAT-H is a one-dimensional finite-difference code that simulates liquid water flow using Richards' equation and water vapor diffusion using Fick's law. UNSAT-H requires extensive input data for analysis of evapotranspirative covers, including soil, meteorological, and vegetation data. The hydraulic data shown in Figures 2(a) and 2(b) were used to define the material parameters. A flux upper boundary condition was selected equal to the moisture infiltration, which is the runoff subtracted from the precipitation. A unit hydraulic gradient (i.e. the change in total head equal to the change in elevation head) lower boundary condition was selected. This is a valid assumption when liquid flow is driven by gravity alone, representative of deeper regions of the soil profile that are not affected by matric suction gradients induced by evapotranspiration or temperature changes. Simulation of the four covers was from January 1st 1999 to December 31st, 2002, with the θ values from January 1st, 1999 to initialize the model. Further modeling details can be found in Zornberg and McCartney (2004).

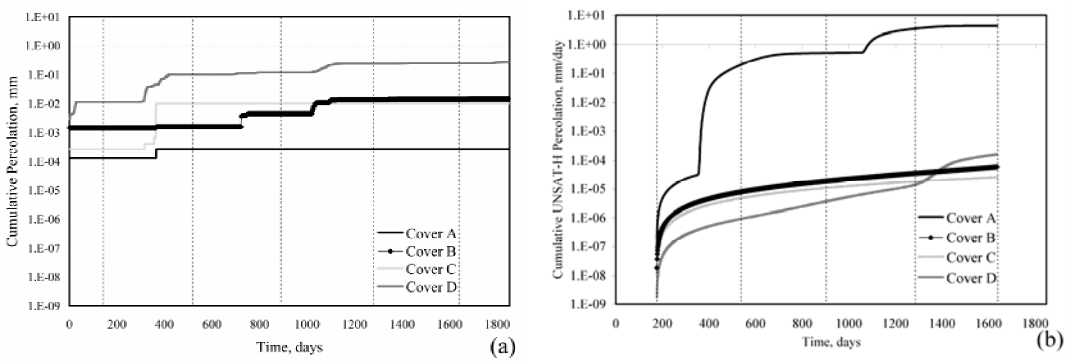

Figure 4: Percolation for test covers: (a) Recorded by lysimeter; (b) Calculated using UNSAT-H

Figure 4(a) shows the cumulative percolation recorded by the lysimeter, while Figure 4(b) shows the cumulative percolation calculated by UNSAT-H. Significant discrepancies are observed in the data. The percolation amounts recorded by the lysimeter indicate that cover D had a relatively large amount of percolation collected continuously throughout the study, while the other three covers had lesser amounts of percolation collected in discrete amounts. The percolation amounts calculated by UNSAT-H show a continuous increase in percolation over time. The performance of cover A indicated by the numerical model shows very high cumulative percolation, nearly 4 mm over the duration of the study, which is significantly different in magnitude from that recorded by the lysimeter (less than 0.0001 mm). Covers B, C and D showed better performance than cover A indicated by the numerical model, with cumulative percolation amounts less than 10^{-4} mm in order of their cover thicknesses. However, the percolation recorded by the lysimeter in the three covers is much greater than the calculated amounts. The inconsistencies in the results are most likely due to a combination of numerical error and an incorrect boundary condition needed to model a soil layer underlain by a lysimeter. Although a freely-draining lysimeter is desired so as to prevent disruption of flow (i.e. a unit gradient), the lysimeters observed in this study obviously do not allow free drainage of liquid. Section 4.2 will present an investigation of the formation of a capillary break in cover A, while Section 4.3 will show an investigation of preferential flow through macropores in Covers B, C and D.

4.2 *Investigation of a Lysimeter Capillary Break*

The UNSAT-H analysis predicted percolation values for cover A significantly greater than those recorded by a lysimeter. Stormont et al. (1999) reports that lysimeters consisting of a geonet sandwiched between two nonwoven geotextiles, such as that used in the field monitoring program, provide rapid drainage when saturated, but tend to create a capillary break between the geonet and the upper nonwoven geotextile when unsaturated, leading to slowed drainage or even diversion of downward percolation. A capillary break is created when a large-pored material has a much lower θ value than an overlying small-pored material at the same value of ψ because of differences in the θ−ψ relationships for the two materials. The small-pored material must become nearly saturated to reach a value of ψ at which water is able to flow into the large-pored material. In this case, the geonet is the material with large pores and the nonwoven geotextile is the material with smaller pores. In a capillary break, infiltrating moisture will pond above the lysimeter or divert laterally to zones of higher ψ. This is undesirable as a freely draining evapotranspirative cover should not be expected to reach saturation at the base, as percolation is certain to occur in this situation. For this reason a capillary break within the lysimeter leads to an unrealistic situation in the soil layer it is meant to monitor. However, when a capillary break occurs, the moisture content profile can be used to interpret the behavior of the cover.

The variation in θ with depth over the course of about 150 days in the spring of 1999 is shown in Figure 9(a). From an initial θ value of 10%, an infiltrating moisture front increases the θ value at the surface to 17% on day 258, with the moisture front reaching the base in approximately 35 days. After the moisture front reaches the base, ponding of moisture occurs, with a θ value of 35%, almost 20% more than the infiltrating moisture front. In a similar fashion, Figure 5(b) shows the retreat of the moisture front. The soil dries out evenly to its initial θ value after day 300, due to moisture uptake by evapotranspiration or lateral flow to the buffers. This same pattern in θ occurs at two other times, around day 1000 and day 1800 corresponding to high precipitation in early 2001 and 2003. During these ponding events, cover A showed negligible lysimeter percolation. Covers B and D show evidence of ponding, though percolation was observed to coincide with some (but not all) of the ponding events. Stormont et al. (1999) noted that the nonwoven geotextile in the lysimeter can still function as a drain despite the presence of the capillary break, but water is transmitted laterally through the geotextile rate less than its saturated transmissivity, so it is reasonable that the lysimeter collect some percolation. Cover C showed no ponding and negligible percolation after 1999 due to its greater depth. Additional observational evidence of lateral flow due to a capillary break is the superior plant health in the buffers (adjacent to the covers) compared to the plant health over the lysimeters.

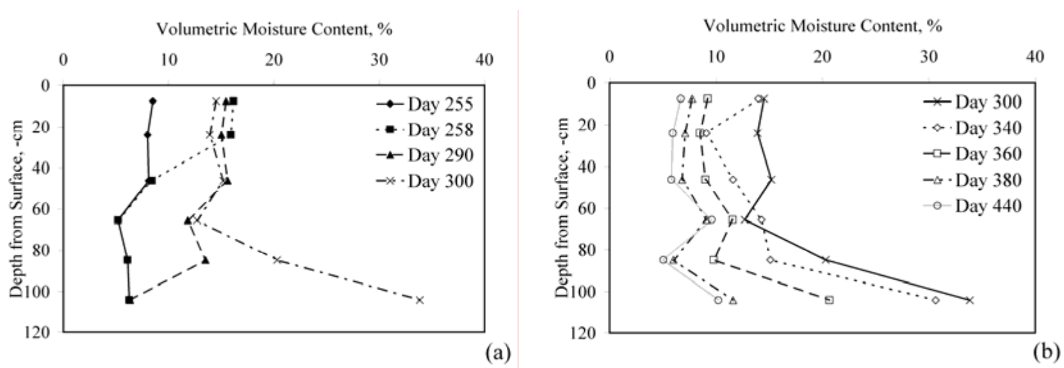

Figure 5: Evidence of ponding in cover A: (a) Moisture front advance; (b) Moisture front retreat

4.3 *Analysis of Preferential Flow*

The percolation for cover D shown in Figure 4(a) is relatively higher than cover A (which has a different soil type but a similar thickness) and test plots B and C (which have the same soil type but different depths). Based on the design of cover D, one would not expect that a higher percolation would occur. It was also observed that percolation recorded by the lysimeter for covers B, C and D was greater than that predicted by the numerical model. Visual observation of the covers shows defects in cover D, such as surface depressions and animal burrows, indicating that the recorded lysimeter percolation may have been due to preferential flow through these defects. It is likely that the lysimeter was able to capture percolation traveling through preferential flow channels which are often at near-saturation during infiltration events, allowing breakthrough of the capillary break. The flow channels may bypass the TDR locations, giving no immediate indication of the poor performance of the cover. The moisture storage (calculated from the TDR moisture content values) for cover D, shown in Figure 6, follows similar trends to the other three covers, and is also consistently higher than that of cover A, which showed no percolation. This indicates that the soil column near the vertical array of TDR probes is performing as expected, while percolation occurs through unmonitored preferential flow paths. Despite the disadvantages of capillary break formation, lysimeters should still be used in tandem with moisture profile monitoring to monitor all flow mechanisms.

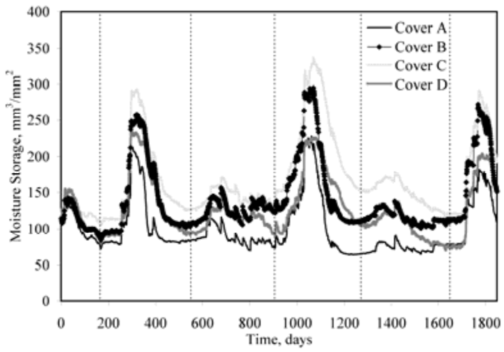

Figure 6: Comparison of moisture storage the in the four covers

5 USE OF MOISTURE PROFILES TO COMPLEMENT LYSIMETRY

5.1 *Qualitative Analysis of Moisture Profiles*

Although moisture profiles cannot provide a direct evaluation of percolation, especially when the moisture profile is distorted by a lysimeter, they can still provide several assessment tools to complement lysimetry. A representative set of TDR probe θ measurements for cover A is shown in Figure 7(a), which is useful to consider θ trends with depth in the cover over time to assess the movement of moisture fronts through the cover. Figure 7(a) indicates that the surface probe shows an erratic response corresponding to daily meteorological effects, while the lower probes are only affected by larger precipitation events. The lower probes occasionally become wetter than the surface probe, indicating that infiltration from the surface reached the base of the cover, an event that may indicate percolation. This behavior is consistent for all covers. The degree of saturation (i.e. $\theta/\theta_{saturated}$) at the base of each cover is shown in Figure 7(b). This figure indicates that the base of the covers reaches high saturation values (greater than 50%) on three occasions, corresponding to the high precipitation in 1999, 2001 and 2003, and the ponding events observed in Section 4.2. Although percolation recorded by the lysimeter indicates that cover A performed the best, this figure indicates that it may be the worst when compared to the moisture that reaches the base of the other three covers.

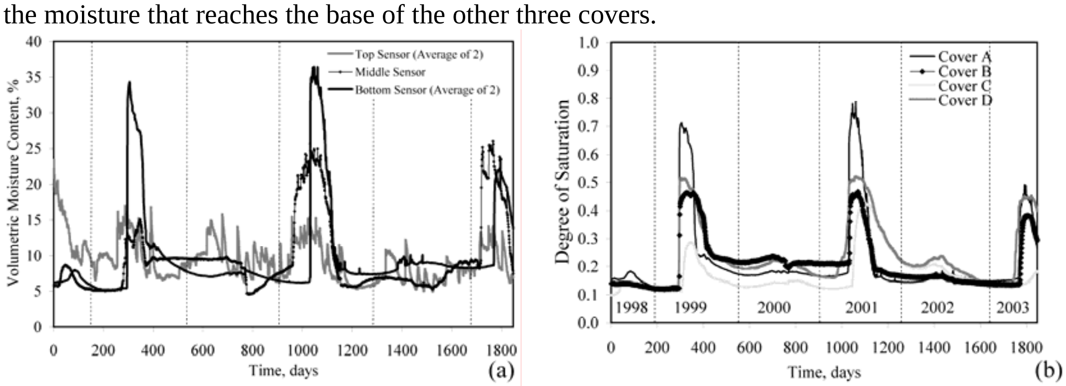

Figure 7: Variation in moisture content with time: (a) Depth variation; (b) Basal moisture contents

5.2 *Seasonal Recovery of Moisture Storage*

Evaluation of moisture storage defined using the θ profiles for the four covers shown in Figure 6 allows further assessment of evapotranspirative cover performance, notwithstanding the presence of preferential flow. As the ability of the cover to store water is one of the key performance requirements of an evapotranspirative cover, it should function as a sponge: the moisture storage should increase during wet seasons, but decrease back to a stable level during dry seasons. Figure 6 indicates that the different covers were able to recover after the wet seasons.

Figure 6 also indicates that moisture storage increases with the cover depth (cover C has greatest storage), and the amount of fine-grained particles (cover D has greater storage than cover A).

5.3 *Field Capacity Analysis*

There is a threshold moisture storage beyond which the soil cannot retain water by capillarity under the effects of gravity. Water added to the soil, exceeding this moisture storage, will lead to percolation. This moisture storage is referred to as the field capacity. For a silty soil, the field capacity is typically assumed to be the moisture storage of a soil with water content corresponding to a matric suction of -333 cm of water. When a capillary break occurs, the soil is likely to store more water than the field capacity, as capillary breakthrough will not occur until reaching a matric suction below -50 cm of water [5]. Figure 8 shows the moisture storage divided by the field capacity. The figure shows that the field capacity is exceeded (ratio above 1) three times coinciding with the ponding events. Cover A has the most water storage in excess of the field capacity during ponding, followed by cover D, B and then C, consistent with the previous analyses. In a cover assessment program, moisture storage exceeding the field capacity may indicate impending cover failure, allowing preventative cover maintenance.

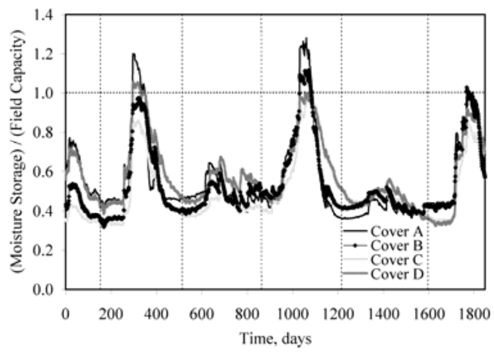

Figure 8: Ratio of moisture storage to the field capacity for each cover

6 CONCLUSIONS

This paper discusses the rationale in comparing monitored variables from evapotranspirative covers, specifically showing how moisture profiles measured using TDR probes can be used in tandem with lysimetry to assess evapotranspirative cover performance. Discrepancies between the percolation measured by a lysimeter and percolation calculated by a numerical model were observed. Moisture trends indicate that ponding occurred above the lysimeters, likely caused by a capillary break between the soil and the lysimeter. Although valuable for monitoring special infiltration events such as preferential flow, lysimeters were observed to create an unrealistic response in the cover they are meant to monitor. Thus, the utility of moisture profile monitoring and numerical modeling was stressed. Numerical modeling using boundary conditions from meteorological data and initial conditions from moisture profiles was found to provide a realistic base-case scenario for performance assessment. Moisture profiles were found to provide a continuous feedback of system performance and can provide early warning of cover failure.

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