Lysimeter Field Performance:
Design and Installation Factors for Representative Cover Systems Evaluations

Mark A. Phillip
O'Kane ConsultantsUSA, Inc.
Anaconda, MT

Mike A. O'Kane
O'Kane Consultants, Inc.
Calgary, Alberta
Canada

ABSTRACT

Measurement of net percolation from the base of a cover system into the underlying waste material is very often a key component of a cover system monitoring program. The units of measure (i.e. a percentage of precipitation or rainfall) are simple to understand, which increases the importance of obtaining representative net percolation values. In general, lysimeters are used to measure net percolation across the cover material-waste material interface. Lysimeter design is typically thought of as being conceptually simple, when in reality the design, installation, and operation of lysimeters is often counter-intuitive, due to the complexities of flow through unsaturated soil systems. In general, the design, installation, and operation of lysimeters for measurement of net percolation from landfill covers is one of the most poorly understood facets of monitoring in the landfill industry.

This paper puts forward a methodology for lysimeter design while also presenting the fundamental design variables that should be considered. Lysimeter design for differing climates, cover materials, and waste materials is discussed. The performance of lysimeter designs previously installed in the field at sites in a variety of climatic conditions are subjected to numerical modeling to determine whether net percolation is being measured properly.

INTRODUCTION

Cover systems are a mandated prevention and control strategy for landfills. The principal objective of a cover system is to control or limit the ingress of meteoric waters to the underlying waste. The purpose of a cover system is to limit contaminant release to the receiving environment. The cover system must therefore provide long-term control of the quality of surface runoff and seepage waters from the waste storage facility to protect adjacent surface and groundwater systems. They also provide a medium for establishing a sustainable vegetation cover.

Of all the industries that utilize cover systems, the mining industry may utilize lysimeters to the greatest extent to evaluate field performance and measure net percolation. The cover and liner systems prescribed in United States regulations for the landfill and hazardous waste repository industries have generally limited the need to measure net percolation. However, lysimeters have been used in landfill research studies (ITRC, 2003, Albright *et al*, 2006, Benson *et al*, 2007) and the application of alternative covers may increase both the use of lysimeters and the need to understand their design and performance.

For the purpose of this paper, net percolation, as shown conceptually in Figure 1, is defined as the net transmission of meteoric water through the cover material. Meteoric water will either be intercepted by vegetation, runoff, or infiltrate into the surface. Water that infiltrates will be stored in the "active zone" and a large majority will then subsequently removed by surface evaporation or transpiration, or move laterally within the cover system. A percentage of the infiltrating meteoric water will migrate beyond the active zone as a result of gravity drainage, and produce a net percolation to the underlying waste.

Predictions of net percolation for a particular cover system design are typically based on soil-atmosphere numerical cover design models. While net percolation can be predicted, it is common for predictions of performance to be validated through field measurements, whether it is on a field trial scale basis (e.g. cover system test plots), or on a full-scale basis (e.g. construction of the entire cover system).

Together with monitoring site-specific climate conditions, *in situ* moisture and temperature conditions, runoff, and lateral percolation, monitoring net percolation is a key aspect of validating predicted cover system performance.

UNSATURATED ZONE HYDROLOGY CONCEPTS FOR LYSIMETER DESIGN AND PERFORMANCE

Barbour (1990) illustrated how the suction and water content profile through a deep profile of unsaturated soil under a steady state percolation rate applied to the top of the column could be predicted using a method originally proposed by Kisch (1959). Darcy's Law governs the flow of water through the column:

$$q = -k\ i \qquad [1]$$

where q is the Darcy flux (L/T), k is the hydraulic conductivity (L/T), and i is the hydraulic gradient. The hydraulic gradient consists of the elevation gradient, which is equal to one in the case of vertical flow, and the pressure gradient. Darcy's Law was developed for saturated flow, where the hydraulic gradient is a constant value (i.e. the saturated hydraulic conductivity); however, the hydraulic conductivity of an unsaturated soil is a function of the negative pressure head of a soil.

Three percolation scenarios are presented in Figure 2 to illustrate the pressure profile developed as a function of the applied percolation. In the case of the soil column discussed above, if the percolation rate at the top of the column is zero (i.e. scenario (i) in Figure 2), the pressure head will decrease hydrostatically for each increment of elevation above the water table. The pressure head remains zero, as shown in Figure 2 (Scenario (ii)), if the flux applied to the top of the column is equal to the saturated hydraulic conductivity of the soil.

If the steady state percolation rate applied to the top of the column is some value less than the saturated hydraulic conductivity of the soil, then the vertical hydraulic gradient will become equal to one at some elevation above the water table, as shown in Figure 2 with scenario (iii). The elevation at which the pressure head gradient becomes equal to zero and the hydraulic gradient is equal to one, is a function of the applied percolation rate and the hydraulic conductivity function (k-function) of the soil. For percolation rates higher than that illustrated for scenario (iii) in Figure 2, but still less than the saturated hydraulic conductivity of the soil, the "break" from the hydrostatic line will occur at a more negative pressure head; and vice versa for higher percolation rates. Under these conditions the unsaturated hydraulic conductivity in the upper portion of the profile is equal to the applied percolation rate (i.e. q = -k).

A key concept from this simple illustration is that under the same percolation conditions, but for a different material within the column, the break from the hydrostatic line will occur at a different point because the hydraulic conductivity function will vary from one material to the next. The variance between hydraulic conductivity functions is most commonly a result of differences in texture (e.g. texture of the waste and/or daily cover (interim cover) below the cover system). A different k-function may also result simply from a difference with respect to *in situ* density conditions.

<u>The Influence on the Pressure Head Profile due to the Presence of a Lysimeter</u>

A fundamental design feature of a lysimeter installed to measure net percolation for unsaturated conditions is that the presence of the lysimeter must not influence the net percolation being measured. The presence of a lysimeter creates an "artificial" pressure equal to zero, or water table (phreatic surface), condition within the lysimeter below the cover material-waste material interface, which does not exist outside the confines of the lysimeter. Figure 3 illustrates two scenarios, which expand on the concepts presented in Figure 2. The pressure head profile shown in Figure 3 for the waste material underlying the cover layer is for a steady state percolation rate from the base of the cover material, which is less than the saturated hydraulic conductivity of the waste material, similar to that presented in Figure 2. In scenario (i) of Figure 3, the break in the pressure head profile does not occur within the backfilled lysimeter, which results in a different pressure head condition inside the lysimeter (i.e. P_{in}) as compared to outside the lysimeter (i.e. P_{out}). The impact of this condition is that preferential flow will occur, and the lysimeter will not measure the “true” net percolation condition due to flow bypassing around the lysimeter. In addition, moisture within the shallower lysimeter may wick out of the lysimeter.

In scenario (ii) of Figure 3, the break in the pressure head profile occurs within the confines of the lysimeter because the base of the lysimeter (i.e. the depth of the artificial water table) is at a depth that allows for this condition to develop within the lysimeter backfill. In this scenario the pressure head at the top of the lysimeter within the confines of the lysimeter is equal to that outside the confines of the lysimeter, and the lysimeter is sufficiently deep so the presence of the zero pressure condition at the base of the lysimeter (i.e. water table) does not influence the net percolation being measured. The pressure head developed is a function of the net percolation rate from the base of the cover layer and the k-function of the underlying waste material.

A simple “back-of-the-envelope” methodology can be used for determining the maximum negative pressure head that can potentially develop within the waste material just below the cover material-waste material interface. The methodology is illustrated in Figure 4, where the k-function of the underlying waste material is presented as a function of matric suction (the difference between pore-air pressure and pore-water pressure), along with the steady state percolation rate from the base of the cover layer. In Figure 4, the steady state percolation rate is 1×10^{-8} cm/s. Note that the break from hydrostatic conditions of the pressure head profile under steady state conditions will occur when the percolation rate is equal to the hydraulic conductivity. The pressure head developed under these conditions would be approximately 2 m (i.e. 20 kPa suction). In order for the break in the pressure head to occur within the confines of the lysimeter, the depth of the base of the lysimeter below the cover material-waste material interface should be greater than 2 m. Therefore, by using the predicted net percolation rate for a given cover system design, as well as the k-function of the waste material, the maximum negative pressure head that can develop is known, and the required lysimeter depth can be estimated.

Note that Figure 4 also shows the k-function for a material that is coarser than the waste material discussed above. In his case, the depth of the lysimeter could be reduced to approximately 1.0 m because the suction at the break point of the pressure profile would be approximately 10 kPa. Figure 4 also shows a hydraulic conductivity function for waste material placed at a slightly higher density condition. In this case, while the saturated hydraulic conductivity of the waste material has likely decreased slightly, the slope of the k-function has also decreased, thus leading to a condition where the estimated depth required for a lysimeter would be approximately 3.0 m.

Note that the discussion provided above assumes that the waste material properties inside the lysimeter are the same as the material properties outside the lysimeter. In an ideal situation, this would be the case; however, the discussion above provides the necessary basis for understanding the implications to performance if the lysimeter backfill material was not the same as the surrounding material.

The Influence of the Lysimeter Wall Height

The discussion above focused on the influence of the depth to the base of the lysimeter below the base of the cover layer. However, it should be noted, that the height of the lysimeter walls is equally important. In general, the lysimeter wall height should be the same as the depth of the base of the lysimeter below the cover material–waste material interface in order to prevent wicking of moisture out of the lysimeter, which has percolated to the base of the lysimeter. Barone *et al.* (1999) modeled the performance of a “pan” type lysimeter located at the theoretically proper depth below the cover material–waste material interface, but which would not measure the proper net percolation rate. Moisture entering the pan causes a decrease in suction within the pan. A lateral hydraulic gradient then develops because the suction outside the confines of the pan remains a function of the steady state percolation rate (i.e. is constant). The moisture collected by the pan then “wicks” out of the shallow pan, with the result being a lysimeter that consistently measures the incorrect percolation rate. Figure 5 shows flow velocity vectors for a “pan” type lysimeter modeled using a saturated-unsaturated seepage model (after Berone *et al.*, 1999).

DETAILED LYSIMETER DESIGN MODELING

The depth of the lysimeter required for steady state conditions could be estimated using the methodology presented in this paper. However, in order to design the lysimeter for the wide variety of conditions that will likely be encountered in the field, a detailed modeling program should be undertaken, with the estimated depth used as a starting point for the modeling program.

Numerical modeling of the lysimeter designs discussed in this paper was completed with the VADOSE/W 2007 (Geo-Slope International, 2008). VADOSE/W is a two-dimensional (2D) model, which uses numerical solutions of Darcy's Law and Fick's Law to simulate water, heat, and solute transport through variably saturated media. VADOSE/W uses the Penman-Wilson method (Wilson *et al.* 1994) for computing actual evaporation (AE) at the soil surface such that AE is computed as a varying function of potential evaporation dependent on soil pore-water pressure and temperature conditions. The coupled heat and mass transport equations with vapor flow in VADOSE/W permit the necessary parameters at the soil surface to be available for use in the Penman-Wilson method of estimating evaporation.

VADOSE/W accounts for precipitation, evaporation, snow accumulation / melt / runoff, ground water seepage, ground freezing and thawing, ground vapor flow, and actual transpiration from plants. All parameters can be applied in unique ways dependent on site requirements. Site-specific climate data can be entered.

The use of VADOSE/W to simulate the moisture flow in and around the installed lysimeter allows a 2D, transient evaluation of lysimeter performance.

Development of a Lysimeter to Measure Net Percolation Under Field Conditions

Figure 6 (a and b) shows a 3.0 m deep lysimeter and a 1.5 m deep lysimeter, respectively. The percolating flow through the lysimeter is close to vertical in the 3.0 m deep lysimeter. The only deviation in the vertical flow is due to the slight diversion of flow around the lysimeter wall. The near vertical percolation across the cover/lysimeter interface is a result of the pressure, or suction, profile within the lysimeter being nearly identical to the suction profile predicted outside the lysimeter. At the top of lysimeter tank (depth = 1.0 m), the suction inside and outside the lysimeter is 39 kPa.

The 1.5 m lysimeter (Figure 6b) shows upward net percolation due to the increased suction condition outside the lysimeter (39 kPa) as compared to inside the lysimeter (20 kPa). For the net percolation rate used in this simulation, a 1.5 m lysimeter does not provide representative results. For a lysimeter installed with this design, and for the flux conditions and material properties modeled, the presence of the lysimeter itself would influence the net percolation being measured. The suction profile within the lysimeter is still increasing at the top of the lysimeter tank. In comparison, the suction profile for the 3.0 m lysimeter is almost vertical at the top of the lysimeter tank (i.e. suction is not changing with depth). It should be emphasized that the suction profiles inside and outside of the lysimeter would change with a change in the net percolation rate through the base of the cover system. Increased net percolation might decrease the suction profile outside the 1.5 m lysimeter tank to a point where the suction profiles match at the top of the lysimeter tank and the lysimeter would begin to collect water at an appropriate rate. The key point is that field conditions that result in this scenario can be easily modeled using the methodology presented.

Alternative lysimeter installation techniques are required when the combination of the cover and waste materials, as well as the site-specific climate conditions make the proper function of a lysimeter unlikely. For example, the hydraulic conductivity function for a waste material located within a semi-arid site is shown in Figure 7. It is assumed that the site has an average annual rainfall of 400 mm and 3% to 20% net percolation as a percentage of annual rainfall is expected through the cover system. Converting these potential percolation rates, the expected range of downward percolation within the cover system and waste profile is 4.0×10^{-8} cm/s to 2.5×10^{-7} cm/s. During low net percolation periods (3% of annual rainfall) the suction within the tailings profile will be approximately 70 kPa; high net percolation periods will decrease the waste material suction to approximately 25 kPa. In order for the lysimeter to function properly during high net percolation conditions the lysimeter walls will have to be approximately 2.5 m in height to ensure the suction condition inside the lysimeter will match the suction condition outside the lysimeter. During low net percolation conditions, the lysimeter would have to be approximately 7 m deep to produce a suitable suction condition within the lysimeter.

A 7 m deep lysimeter may not be economically feasible, nor technically feasible to construct in the field (due to practical and safety issues). When it is not feasible to construct the lysimeter at the base of the cover system, the top edge of the lysimeter can be raised to the cover system surface, creating a lysimeter isolated from the surrounding cover system. The lysimeter should be deep enough to accommodate the full thickness of the cover system and approximately one to two meters of the underlying waste material (i.e. a 2.0 m deep lysimeter could be used for a 1.0 m cover over waste material).

It should be noted that a lysimeter that extends to the cover system surface will not measure the actual net percolation rate because the artificial water table created at the base of the lysimeter will influence the net percolation measured. To address this issue, moisture conditions inside and outside the confines of the lysimeter must be measured. Following a period of monitoring, a numerical model must be calibrated to the net percolation measured by the lysimeter and the moisture conditions measured within the lysimeter. After calibration of the numerical model to the lysimeter field conditions (i.e. field hydraulic properties are developed), the actual lower boundary condition, as measured with instrumentation outside the lysimeter, is substituted into the model. The model is then re-run, and the "actual" net percolation from the cover system to the underlying waste material is determined based on the model results evaluated at the interface of the cover and waste material.

EVALUATION AND DISCUSSION OF TYPICAL COVER SYSTEM MONITORING LYSIMETER DESIGNS

This paper evaluates the performance and functionality of several different types of lysimeters. Three types of lysimeters are evaluated including shallow lysimeters, long, pan lysimeters, and lysimeters backfilled with coarse-textured material. Each lysimeter design is discussed in separate sections of this paper. The inputs to the numerical model, which include material properties, climate data, and model geometry are presented first, followed by a discussion on the performance, advantages, and disadvantages of the particular lysimeter design.

Lysimeter Collection Ratio

This paper utilizes the concept of the "Lysimeter Collection Ratio", or LCR, as a means of evaluating performance of the typical lysimeter designs. LCR is defined as the ratio of the net percolation that would be measured by a lysimeter, as predicted by the model, to the net percolation predicted for if the lysimeter were not present.

Shallow Lysimeters

Shallow lysimeters in this paper refer to the small (usually less than 1 m in diameter and depth) containers buried within the soil profile to collect net percolation. These lysimeters are commonly constructed from 225 L (45 gallon) barrels that are open at one end, but in general could be constructed from any material. The basic premise though is that they are relatively shallow. Measurement of net percolation is often completed through collection ports that are pumped out at specified intervals. Other net percolation measurement techniques include a piezometer to measure water levels within the lysimeter, or drainage collection system that uses an automated system record net flow out of the lysimeter.

The objectives of the shallow lysimeter numerical modeling program were to evaluate the effectiveness of the lysimeter in collecting and providing measurements of net percolation through a cover system. The performance of the lysimeter was defined by the LCR. The LCR was measured for a shallow lysimeter under varying net percolation measurement schedules including daily collection, monthly collection, and annual collection.

Description of Cover System and Shallow Lysimeter: The cover system utilized in the modeling demonstration, shown in Figure 8, was generalized, as opposed to a site-specific cover system design. The cover system includes a low hydraulic conductivity compacted barrier layer, with an overlying protection / growth medium layer. For the simplification of a one-dimensional (1D) system, a horizontal cover system was simulated in the modeling demonstration. The cover system consists of a 0.25 m compacted clay barrier layer placed directly on the waste material surface, with an overlying 0.4 m thick non-compacted, well-graded growth medium material. The growth medium material was split into two 0.2 m layers with the upper layer having a slightly higher saturated hydraulic conductivity. The lysimeter was placed 0.5 m below the dry cover / waste material interface. The lysimeter used in the numerical simulations was 0.8 m deep and included a 0.2 m thick layer of sand at the base to collect the percolation water. The lysimeter was 2.0 m wide to reduce the influence of the 0.1 m thick lysimeter walls used in the simulation. The physical properties of the cover and waste materials were based on typical materials. Figures 9 and 10 present the moisture retention curves (MRCs) and k-functions of the materials used for the modeling.

The climate year used in the modeling program was adapted from climate data collected at a site in the southern hemisphere, which is characterized as being semi-humid to humid. The climate year is strongly seasonal featuring a hot, wet summer season and a warm, dry winter season. A full year simulation period of 365 days was selected to examine the net percolation of meteoric waters through the cover system and into the lysimeter. The climate year was run to place the summer season at the beginning of the simulation when the wet season commenced, eliminating the influence of lysimeter lag time on the yearly results. The climate data model included daily rainfall, potential evaporation, air temperature, relative humidity, and wind speed.

Shallow Lysimeter Modeling Program: The performance of the shallow lysimeter was examined under a number of different percolation collection and measurement schedules. Simulations were completed assuming that the lysimeter was drained at the base such that net percolation was collected and measured on a daily basis. In addition, simulations were completed assuming the lysimeter was not drained, and monthly and annual collection periods occurred. An automatic collection system would be required to measure the daily percolation rates. Measurements completed on a monthly or annual basis would allow ponding of the net percolation collected within the lysimeter, and then collection with a pump via a perforated pipe at the base of the lysimeter, which is connected to a flexible hose extending to the surface. Table 1 summarizes the numerical simulations completed for the shallow lysimeter modeling program.

TABLE 1. SUMMARY OF NUMERICAL SIMULATIONS COMPLETED FOR THE SHALLOW LYSIMETER MODELING PROGRAM.

Collection and Measurement Schedule	Measurement Date
Daily (Continuous)	N/A
Monthly	End of calendar month
Every Four Months	March 1 June 1 September 30
Annually	March 31 April 30 May 31 June 30 August 15 September 30

Shallow Lysimeter Modeling Results: The boundary condition in the continuous simulation represents collection and measurement of the lysimeter drainage each day of the simulation. These results are shown in Figure 11. Meteoric water began to percolate through the cover system on January 25th of the simulation year. The lysimeter began to record net percolation at its base on February 15th, which means the lag time for response of the lysimeter was approximately 20 days. The lysimeter collected approximately 58 mm of net percolation during the simulation period, while approximately 91 mm of net percolation was predicted across the cover system and waste material interface outside the confines of the shallow lysimeter. Therefore, the LCR of the shallow lysimeter for the continuous simulation was approximately 0.64 (i.e. the ratio of 58 mm to 91 mm). An LCR of 0.64 indicates that the lysimeter does not accurately predict the net percolation through the cover system.

The low LCR is a result of the insufficient depth of the shallow lysimeter. Figure 12 shows the suction at the cover system-waste material interface immediately above the shallow lysimeter, as well as outside of the shallow lysimeter. The LCR of a lysimeter will be highest when the pressure profile within the lysimeter is close to or equal to the pressure profile measured outside the lysimeter. Figure 13 shows that the pressure profiles are fairly similar during the April to July period, which coincides with the period that had the highest LCR shown in Figure 11.

The performance of the shallow lysimeter for the scenario when the lysimeter is pumped out once per month and at the end of each month of the year, is shown in Figure 13. The LCR peaks at 0.38 at the end of February and is only 0.11 for the entire one-year monitoring period. The lower LCR, as compared to the value of 0.64 predicted for the continuous collection scenario, is caused by "ponding" within the lysimeter during the high percolation months of February and March. As water collects in the lysimeter during the month, the perched water table within the lysimeter increases in height, which decreases the suction at the cover system / waste material interface above the lysimeter. This increases the propensity for bypass flow around the lysimeter because the suction conditions outside of the lysimeter are greater than inside the lysimeter, effectively pulling, or wicking, water around the lysimeter. Figure 14 compares the flow vectors predicted for the shallow lysimeter on March 1st, one day after the lysimeter was pumped out, to the flow regime on March 31st, just prior to the next pumping event. The flow vectors are not vertical at the end of March, indicating that there is bypass flow occurring around the shallow lysimeter.

The pressure profile at the cover system / waste material interface above the lysimeter is shown in Figure 15 for the simulation representing the once per month pumping schedule. The suction condition for the once per month collection simulation is lower than that predicted for the continuous collection simulation. The disparity in suction conditions outside and inside the shallow lysimeter is greater for the once per month collection simulation, which results in a lower LCR.

Numerical simulations were also completed assuming the lysimeter was pumped out three times per year and once annually at different times of the year. The results are presented in Figure 16. A total net percolation of 8 mm (LCR of approximately 0.09) was predicted if the net percolation was collected and measured three times per year. Each of the once per year symbols on Figure 16 represents an individual model simulation.

Figure 16 clearly indicates that net percolation measured by the shallow lysimeter is highly dependent on which month percolation was collected from the shallow lysimeter. For example, if the measurement was completed at the end of May approximately 17 mm of net percolation would be collected (LCR = 0.17). If the measurement was not completed until the end of September, which is near the end of the dry season, the net percolation would be approximately 1 mm, which corresponds to an LCR of approximately 0.02. Significant wicking of percolation collected at the base of the lysimeter up and over the lysimeter walls is the primary cause of the disparity between the different LCR values. If net percolation is not measured as soon as it reaches the base of the lysimeter, significant potential exists for the collected moisture to wick out of the lysimeter during the dry season.

Numerous shallow lysimeters are installed in seasonal climates with well defined wet and dry seasons. In addition to the fact that some shallow lysimeter are simply not deep enough, shallow lysimeters will always be subject to variances in measurement if the net percolation is not measured as soon as percolation reaches the base of the lysimeter. Any collection or pooling of percolated water will result in wicking and a loss of percolated water during dry periods of the year when strong unsaturated conditions dominate the cover / waste material profile.

Sensitivity Analysis of the Shallow Lysimeter: The design and performance of a lysimeter is specific to the material properties and climate conditions of a site. Sensitivity analysis was completed for the continuous drainage simulation by varying the k-function of the waste material and the annual rainfall. The saturated hydraulic conductivity of the waste material for the shallow lysimeter modeling results presented in the previous section was 1 x 10^{-3} cm/s. The saturated hydraulic conductivity was adjusted to 1 x 10^{-2} cm/s in the high hydraulic conductivity simulation and 1 x 10^{-4} cm/s for the low hydraulic conductivity simulation. These conditions would reflect different waste material back-filled into the shallow lysimeter during installation, or the same material, but placed at lower and higher density conditions, respectively. The rainfall was adjusted from 1780 mm for the average year to 1122 mm and 2547 mm for the low rainfall and high rainfall simulations, respectively.

Figure 17 shows the influence of changing the saturated hydraulic conductivity of the waste rock by one order of magnitude. The timing of the response of the shallow lysimeter to the meteoric waters is similar for each of the three simulations. The LCR is highest for the high conductivity simulation (LCR = 0.94) and lowest for the low conductivity simulation (LCR = 0.33). The increased LCR for the high conductivity simulation is a result of the high percolation rates during the wet season. The meteoric waters were able to reach the base of the shallow lysimeter where it was removed from the numerical model as net percolation. The increased rate of percolation reduced the amount of water available to be “pulled” back out of the shallow lysimeter during the dry season. Conversely, less water was able to percolate through the waste to the base of the lysimeter in the low hydraulic conductivity simulation.

The effect on the LCR as a result of increasing or decreasing the total annual rainfall is shown in Figure 18. The most obvious effect is the timing of the initial breakthrough of percolation to the base of the shallow lysimeter. In the high rainfall simulation, net percolation was first recorded on December 23rd, as compared to February 15th and April 18th for the average rainfall and low rainfall simulations, respectively. The LCR is highest for the high rainfall simulation (LCR = 0.85) and lowest for the low conductivity simulation (LCR = 0.26).

In all modeled scenarios of hydraulic conductivity or rainfall, the shallow lysimeter did not provide a proper measure of net percolation, even though the model assumed that percolation collected at the base of the shallow lysimeter was removed from the model. In the case of monthly, quarterly, or annual collection of percolation, the disparity between the sensitivity analyses would be significantly increased.

The performance of a shallow lysimeter will be sensitive to both the saturated hydraulic conductivity and site climate conditions. Variations of saturated hydraulic conductivity are likely the cause of different percolation results often reported for clusters of shallow lysimeters installed next to each other and at the same time. A difference in one order of magnitude in saturated hydraulic conductivity for typical waste material can be achieved with only a moderate increase, or decrease, in density. It would be difficult to backfill the lysimeters to the same density condition, even assuming the same material was used for each lysimeter. Hence, it is not surprising that pairs of shallow lysimeters, which are generally thought to be duplicates, do not measure the same net percolation.

Correction for Wicking from Shallow Lysimeters: It has been reported that net percolation measured by shallow lysimeters can be “corrected” for the wicking that will occur (e.g. Timms and Bennett 2000). However, Figures 16 and 18 demonstrate that this is not possible.

The amount of wicking is strongly dependent on *in situ* lysimeter backfill conditions, precipitation conditions, and the shallow lysimeter pumping schedule. All these conditions can be highly variable, even for a single site. In terms of precipitation conditions, whether the same rainfall occurs over a one-hour or 24-hour period would have a strong influence on net percolation and the amount of wicking that occurs once dry conditions are prevalent.

In short, it is not possible to back-calculate, or "back-simulate" the amount of wicking that has occurred because the "true", or actual net percolation is not known. In addition, a wide variety of additional scenarios (e.g. hydraulic conductivity of the lysimeter backfill) would make each lysimeter at a particular site subject to a different rate of wicking. The only approach that is feasible to "correct" for the presence of a shallow lysimeter is to install moisture and suction sensors within and outside the confines of the lysimeter.

Lysimeters with Coarse-Textured Backfill

A lysimeter with coarse-textured backfill is often quite similar to the shallow lysimeter. The shallow lysimeter incorporates a waste material backfill with a thin layer of sand at the base to represent the *in situ* conditions of the waste material. The common rationale behind using a coarse-textured material is to facilitate quick infiltration and collection of net percolation water after it crosses the cover system-waste material interface.

Description of Cover System and Coarse-Textured Backfill Lysimeter: The cover system utilized in the modeling demonstration, shown in Figure 19, was also generalized. The cover system consisted of a 1.0 m well graded glacial till material silty/clayey matrix) placed over a fine-textured waste material. The lysimeter was placed directly below the cover material and fine-textured waste material interface. The lysimeter used in the numerical simulations was 0.4 m deep and 0.5 m wide. The backfill material is a coarse-textured, poorly graded gravel material (e.g. pea gravel). Figures 20 and 21 show the MRCs and k-functions, respectively, for the materials modeled.

Coarse-Textured Backfill Lysimeter Modeling Program: Steady state numerical simulations were used to analyze the coarse-textured backfill lysimeter design. A steady state flux was applied to the surface of the cover system and then flow within the coarse-textured backfill of the lysimeter was compared to the flow in the waste material outside the lysimeter to calculate the LCR. Four steady state infiltration rates were applied to the cover surface. The first was 5 x 10^{-7} cm/s, equivalent to the saturated hydraulic conductivity of the cover material. Under this infiltration rate the cover system remained saturated and kept suction conditions within the lysimeter and waste material profile close to zero. The infiltration rate was reduced to 1 x 10^{-7} cm/s, 5 x 10^{-8} cm/s, and 5 x 10^{-9} cm/s in subsequent simulations. The performance of the coarse-textured backfill lysimeter under the reduced infiltration rates (resulting in increased suction pressures within the lysimeter and fine-textured waste material) was examined.

Coarse-Textured Backfill Lysimeter Modeling Results: The results of the four steady-state models are shown in Figure 22. The lysimeter performed well (LCR = 1.0) under the near saturated conditions created by the 5 x 10^{-7} cm/s infiltration rate. The LCR dropped to approximately 0.78 when the infiltration rate dropped to 1 x 10^{-7} cm/s. Further reduction in the infiltration rate to 5 x 10^{-8} cm/s and 5 x 10^{-9} cm/s resulted in LCR values of 0.08 and less than 0.01, respectively. The decrease in LCR with infiltration rate is due to the fine-textured waste material becoming the preferential flow path for infiltrating water at the increased suction condition. Under near saturated conditions of the high infiltration rate, the suction condition in the lysimeter and waste profile was close to zero. As shown in Figure 21, the hydraulic conductivity of the coarse material is greater than the waste material at suctions close to zero. This situation is reversed at suctions greater than approximately 20 kPa when the hydraulic conductivity of the fine-textured waste material is greater than the coarse material. In essence, the coarse textured material within the lysimeter creates a capillary break condition, leading to significant bypass flow around the lysimeter. The infiltration rate of 1 x 10^{-7} cm/s creates suction values close to 20 kPa within the lysimeter and waste material, producing some bypass flow from the lysimeter to the fine-textured waste material. At the two lowest infiltration rates, suction values within the fine-textured waste material profile are much greater than 20 kPa resulting in little flow into the lysimeter and low LCR values.

The poor performance of a coarse-textured backfill lysimeter is recognized in the literature but often disregarded (e.g. Woyshner and Swarbick 1997). The rationale is that the majority of net percolation will occur when the cover system is saturated and the net percolation "missed" during the remaining periods of the year is insignificant. However, modeling illustrates that a small increase in the suction condition below the cover system will result in bypass flow and inaccurate net percolation measurements. In addition, this rationale incorrectly presumes that the conditions overlying the lysimeter are the key issue. The key issue is the suction profile generated in the fine-textured waste material and coarse-textured lysimeter backfill material below the cover layers. It should also be noted that unsaturated conditions are predominant in almost all cover systems. Saturated conditions occur for only very brief periods of time, most often at the end of the wet season, as well as during the period following snowmelt in colder climates. Hence, a significant amount of net percolation will not be collected by a lysimeter installed to monitor net percolation to finer-textured waste material if the lysimeter is backfilled with coarse-textured material. In general, all lysimeters should be backfilled with the waste material itself.

Wide / Shallow Pan Lysimeters

The impact of installing a wide shallow pan lysimeter was discussed earlier in this paper. Bews *et al* (1997) demonstrated that this type of lysimeter design does not properly measure net percolation. A common rationale, which is thought to reduce the amount of wicking from pan type lysimeters, is to increase the spatial area of the lysimeter such that a large wide area is monitored. However, Barone *et al* (1999) reported that shallow (approximately 0.25 m wall height) and wide (approximately 15 m x 15 m) lysimeters installed in the unsaturated zone below a landfill cover system to measure net percolation did not collect any seepage after fifteen years of monitoring. In contrast, lysimeters installed further up in the profile within the landfill liner material have reported seepage flow rates in the range of 1 L/day to 12 L/day. Barone *et al* (1999) modeled the shallow and wide pan lysimeters in a similar manner as described within this paper (see Figure 5). The results indicate that wicking of seepage water out of the 15 m x 15 m lysimeter was a result of negative pore-water pressures in the surrounding unsaturated material, which extend laterally beyond the confines of the lysimeter.

A great deal of caution is required when installing a pan lysimeter with a large spatial area. While it seems conceptually simple, there remains significant potential for wicking to occur, thus creating a situation where low or zero net percolation conditions are assumed to be occurring, when in fact the low or zero net percolation conditions are a direct result of poor lysimeter design.

Monolith Wide / Shallow Pan Lysimeters

In addition to the above issues associated with wicking of from pan lysimeters, large pan monolith lysimeters that are constructed such that the entire monitored profile are contained within the lysimeter can also be problematic. Albright *et al* (2006) present a lysimeter installed in subtropical Georgia, seasonal and humid Iowa, and arid southeastern California to evaluate the field hydrology of compacted clay covers for final closure of landfills. Water balance of the covers was monitored over two to four year periods using large (10 m by 20 m) instrumented drainage lysimeters (Albright *et al.*, 2006), as shown in Figure 23.

Albright *et al* (2006) report that the geometric mean for measurements of saturated hydraulic conductivity for the interim cover material at the three sites ranged from 2×10^{-6} cm/s to 3×10^{-7} cm/s. These material characteristics, combined with the plasticity index (PI) for the interim cover material reported by Albright *et al* (2006) (e.g. 10 to 12), as well as the reported clay size content (18% to 31%), suggest that the moisture retention capability of the interim cover material is relatively substantial. The thickness of interim cover at the three sites ranged from 15 cm at the Georgia site, to 30 cm at the Iowa site, and to 60 cm at the California site. At these thicknesses, and given the substantial moisture retention characteristics of the interim cover material, it is not reasonable to assume that the interim cover layer would be at a drained condition at any location under the barrier layer (see Figure 23).

It can be argued then, that the Albright *et al* (2006) pan lysimeter shown in Figure 23 is too shallow given the thickness of the interim cover and its hydraulic material properties. In other words, the presence of the confining geomembrane at the base of the lysimeter, combined with the interim cover's hydraulic characteristics, is influencing moisture conditions within the lysimeter. One may argue that the fact that the drainage point is at the far end of the lysimeter allows for the interim cover to be drained. However, this is not likely the case given the thickness of the material and its hydraulic characteristics. At the very least, this would not be the case for the entire length of the lysimeter.

The impact on measured performance of the shallow lysimeter is transmitted vertically and laterally in the case of the Albright *et al* (2006) pan type lysimeter. For example, given the scenario described above, it can be argued that the negative pore-water pressure conditions would not be as high as that which would occur if the geomembrane at the base of the lysimeter were not present. This pore-water condition would then be transmitted vertically within the overlying barrier layer, as well as the surface layer. For lower negative pore-water conditions (as compared to if the geomembrane were not present), hydraulic conductivity would be higher, and moisture storage capacity (particularly in the surface layer) would be lower. Hence, for any given precipitation event, the response of the lysimeter, in terms of runoff, infiltration, moisture storage, percolation, timing of freezing and thawing, impact of wet-dry cycling, etc. will be influenced by the presence of the geomembrane at the base of the lysimeter (i.e. the presence of the lysimeter itself in comparison to the geomembrane not being present). Thus, one should question whether the "true" performance is actually being measured for monolith pan type lysimeters, such as that depicted in Figure 23 by Albright *et al* (2006). In short, it is fundamental to understand whether or not the presence of the lysimeter, and particularly the depth to the base of the lysimeter is influencing not only the net percolation rates being measured, but also the *in situ* moisture and temperature conditions.

Effect on Lysimeter Performance due to the Presence of Sloping Lysimeter Walls

It is common for lysimeters to be installed with sloping walls. Benson *et al.* (2007) provide an example, as shown in Figure 24. Ideally however, a lysimeter should have vertical walls because the presence of sloping walls results in a percentage of the lysimeter footprint with insufficient depth, even though the base of the lysimeter might be the required depth. For example, for a lysimeter with 2 m deep walls constructed at 1H:1V, which has dimensions of approximately 20 m long and 10 m wide, the base of the lysimeter would be approximately 16 m long and 6 m wide. Hence, if the required depth of the lysimeter were 2 m, less than 60% of the lysimeter footprint would be of sufficient depth. If the required depth of the lysimeter were 0.6 m, approximately 80% of the lysimeter footprint would be of sufficient depth.

Vertical lysimeter walls eliminate this issue; however, vertical lysimeter walls are generally challenging to construct, and more importantly introduce challenging safety issues during construction. Increasing the lysimeter footprint does increase the percentage of the footprint area that would be of sufficient depth, as would a reduction in the required depth of the lysimeter. However, there is a point where a significant increase in the footprint does not yield any appreciable increase in the percentage of the footprint that is of sufficient depth.

Caution is required when designing a lysimeter with sloping lysimeter walls because the representative area for surface infiltration can me much greater than the area for which the lysimeter is of sufficient depth, which can draw into question the validity of the net percolation being measured. Hence, care should be taken to conduct a 2D saturated-unsaturated soil-atmosphere model of the lysimeter such that a thorough understanding of the affect of the presence of the sloping lysimeter walls is understood for a variety of infiltration conditions. The model results will also assist with properly locating monitoring instruments within the lysimeter such that the appropriate understanding of the lysimeter's performance can be developed in the field, and data is available should it become apparent that the net percolation measurements must be corrected due to the presence of the sloping lysimeter walls.

Lysimeter Spatial Dimensions

A large lysimeter footprint addresses an additional issue that often arises with respect to lysimeter performance, albeit in a more qualitative manner. Heterogeneity will exist in a constructed cover system, whether a result of the cover and waste materials themselves, from placement of the materials, or following construction as a result of physical, chemical, and biological processes that alter as-built conditions. A larger lysimeter footprint will include, from a qualitative perspective, a greater level of heterogeneity inherent to the cover system, with the objective of constructing a lysimeter with a sufficient footprint such that a general "bulk" net percolation rate can be measured that is representative of the "true" net percolation rate.

An appropriate lysimeter footprint is site specific, given that factors influencing cover system heterogeneity are site specific. Furthermore, it is challenging to quantitatively determine an appropriate footprint to address this heterogeneity. In general, the appropriate lysimeter footprint will be a function of the cost of constructing the lysimeter balanced against a qualitative sense of a footprint that incorporates anticipated cover system heterogeneity.

SUMMARIZING DISCUSSION

This paper has presented the unsaturated zone hydrology background required to properly design a lysimeter to measure net percolation from the base of cover system to underlying waste material. A methodology is presented to estimate the required dimensions (i.e. depth) and installation technique of a lysimeter on the basis of site specific climate conditions and waste material properties. The concept of the lysimeter efficiency ratio, or LCR, was utilized as means of evaluating alternate lysimeter designs for a variety of climate, cover system, and waste material conditions. The LCR is the ratio of the net percolation measured or predicted inside the confines of the lysimeter, to that measured or predicted outside the confines of the lysimeter. An LCR of 1.0 indicates that the lysimeter is functioning properly. The modeling results presented in this paper demonstrate that shallow lysimeters will not measure the proper net percolation. The annual LCR ranged from approximately 0.02 to 0.64 for a wide variety of lysimeter pumping conditions, lysimeter backfill conditions, and rainfall (i.e. net percolation) conditions. Back-simulating wicking from a shallow lysimeters is demonstrated to be technically infeasible without the presence of an appropriate number of suction and water content sensors located within and outside the confines of the lysimeter.

The modeling also demonstrates how shallow, large surface area pan type lysimeters lead to similar wicking problems, and incorrect measurements of net percolation. Furthermore, the paper illustrates that a great deal of caution is required when interpreting results from large monolith lysimeters. The assumption that the monolith lysimeter has a drained condition at the base of the lysimeter is very often incorrect.

Lysimeters backfilled with coarse-textured material, which are installed to measure net percolation to fine-textured waste material, were shown to incorrectly measure net percolation for a large majority of typical field conditions. This was due to creation of a capillary break as a result of the presence of the coarse-textured lysimeter backfill material, which led to bypass flow around the lysimeter.

Details on the installation methodology for a properly designed lysimeter are not within the scope of this paper. However, it is paramount that those responsible for installing a lysimeter have a fundamental understanding for unsaturated zone hydrology. In situations where conditions are encountered in the field during installation, which differ from those conditions that were modeled, the correct decision must be made such that the lysimeter has the best opportunity to properly measure net percolation.

A lysimeter to measure net percolation from a waste cover system is conceptually simple. However, lysimeter design should be approached with a great deal of caution because lysimeters are part of unsaturated systems, where moisture flow and storage is often counter-intuitive. A fundamental design methodology, such as that presented in this paper, should be followed to ensure that the lysimeter has the best chance for properly measuring net percolation. Furthermore, it is fundamental to realize that a lysimeter design that is appropriate for one site is not necessarily appropriate for another site, because site specific conditions will differ from one site to the next. It is the design methodology that is transferable from one site to the next.
Net percolation must be measured properly because it is a key indicator of long-term cover system performance, and a measurement that can be understood conceptually by all stakeholders. The key question one should ask however is: given the background on unsaturated zone hydrology as applied to lysimeter design and performance, how the presence of a shallow lysimeter can affect its performance, and how sloping walls and the material inside a lysimeter can affect performance; is it intuitive that lysimeters, which the reader may have experience with, were designed properly, and are providing representative net percolation measurements? In most instances it is not intuitive that the lysimeter has been designed properly because the design depends on numerous factors as presented within this paper, many of which are counter-intuitive. Hence, a robust lysimeter design methodology that accounts for all the key design considerations is required, such as that presented in this paper, such that there is confidence with a particular lysimeter design, and thus confidence with net percolation measurements. In addition, the methodology can be used to evaluate current designs.

REFERENCES

Albright, W.H., Benson, C.H., Gee, G.W., Abichou, T., Tyler, S.W., and Rock, S.A., 2006. Field Performance of Three Compacted Clay Landfill Covers. Vadoze Zone Journal, 5:1157-1171.

Barbour, S.L., 1990. Reduction of acid generation in mine tailings through the use of moisture-retaining layers as oxygen barriers: Discussion. Canadian Geotechnical Journal. 27: 398-401.

Barone, F.S., Barbour, S.L., Bews, B.E., and Costa, J.M.A., 1999. Behaviour of lysimeters installed within and below a compacted clay liner underlain by unsaturated sand. In Proceedings of the 52nd Canadian Geotechnical Engineering Conference, Regina, Saskatchewan, Canada, pp. 367-372.

Benson, C.H., Thorstad, P.A., Jo, H., and Rock, S.A., 2007. Hydraulic Performance of Geosynthetic Clay Liners in a Landfill Final Cover. Journal of Geotechnical and Geoenvironmental Engineering, Vol. 133, No. 7, p. 814-827.

Bews, B.E., Barbour, S.L., Wilson, G.W., and O’Kane, M., 1997. The design of lysimeters for a low flux cover system over acid generating waste. Canadian Geotechnical Golden Jubilee Conference, Pre-print Vol. 1: 26-33.

Geo-Slope International Ltd. 2008. GeoStudio 2008. Version 7.11 Build 4199. Online: www.geo-slope.com.

Interstate Technology & Regulatory Council, 2003. Technology Overview Using Case Studies of Alternative Landfill Technologies and Associated Regulatory Topics

Kisch, M., 1959. The theory of seepage from clay-blanketed reservoirs. Géotechnique, 9:9-21.

Timms, G.P. and Bennett, J.W., 2000. The effectiveness of covers at Rum Jungle after fifteen years. In Proceedings from the Fifth International Conference on Acid Rock Drainage, Denver, Colorado, USA, pp. 813-818.

Wilson, G.W., Fredlund, D.G., and Barbour, S.L., 1994. Coupled soil-atmosphere modelling for soil evaporation. Canadian Geotechnical Journal, Volume 31, 1994, pp.151-161.

Woyshner, M. and Swarbrick, B., 1997. Proper reference to be included in final version.

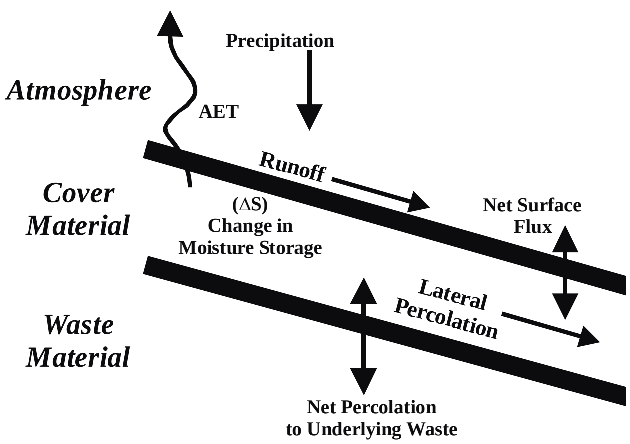

FIGURE 1. WATER BALANCE COMPONENTS OF A TYPICAL COVER SYSTEM.

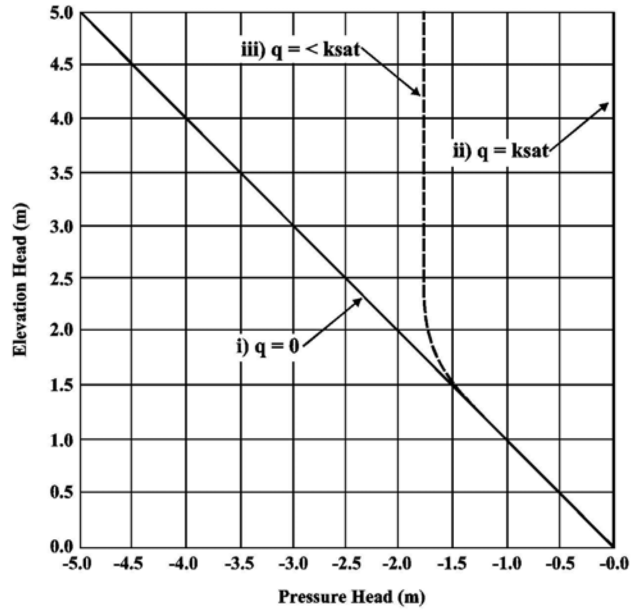

FIGURE 2. RELATIONSHIP BETWEEN PRESSURE AND ELEVATION HEAD FOR THREE DIFFERENT APPLIED PERCOLATION RATES.

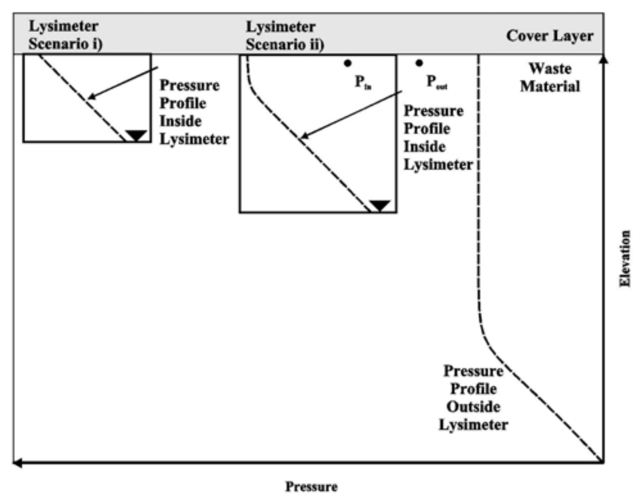

FIGURE 3. PRESSURE HEAD PROFILES FOR TWO LYSIMETER DEPTHS COMPARED TO THE *IN SITU* MATERIAL.

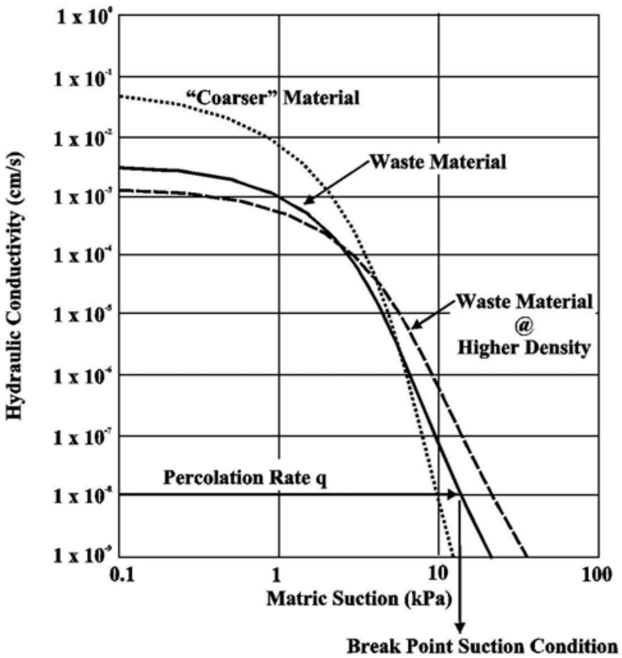

FIGURE 4. HYDRAULIC CONDUCTIVITY FUNCTIONS ILLUSTRATING THE METHOD OF DETERMINING THE MAXIMUM NEGATIVE PRESSURE HEAD THAT CAN DEVELOP BELOW THE COVER/WASTE INTERFACE.

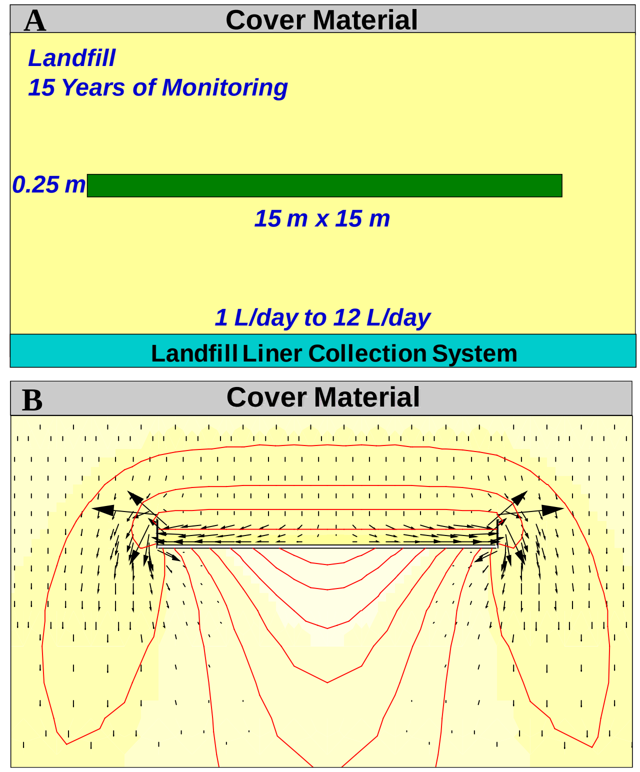

FIGURE 5. A) ILLUSTRATION OF PERFORMANCE OF A "PAN" TYPE LYSIMETER, AND B) RESULTING PREDICTED FLOW VELOCITY VECTORS FROM A SATURATED-UNSATURATED MODEL USED TO EVALUATE PERFORMANCE OF THE LYSIMETER (AFTER BERONE *ET AL.*, 1999).

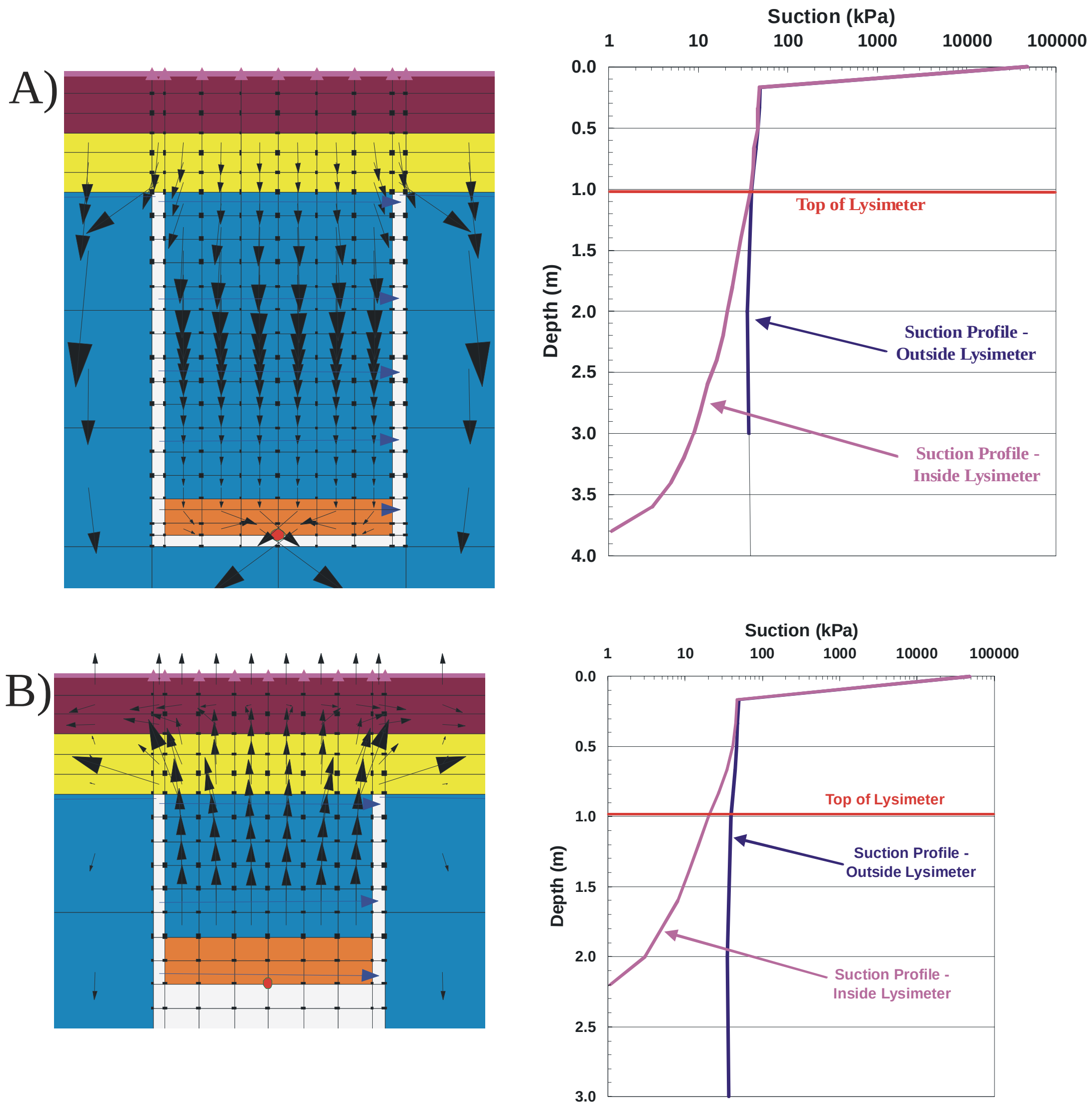

FIGURE 6. VADOSE/W MODELING RESULTS FOR A) A 3.0 M DEEP LYSIMETER AND B) A 1.5 M DEEP LYSIMETER.

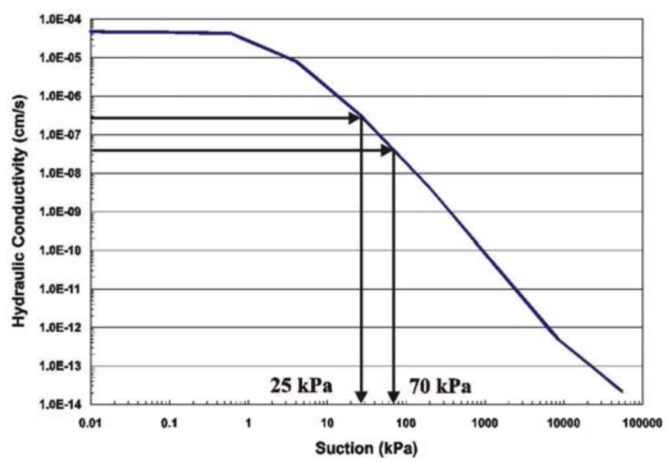

FIGURE 7. HYDRAULIC CONDUCTIVITY FUNCTION FOR A WASTE MATERIAL.

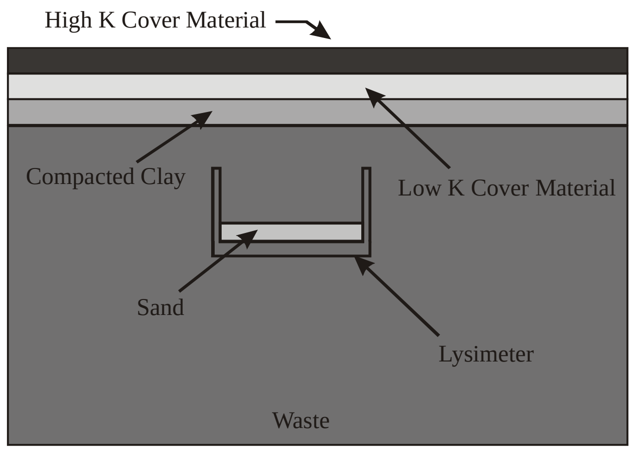

FIGURE 8. COVER SYSTEM CONFIGURATION USED FOR MODELING THE SHALLOW LYSIMETER

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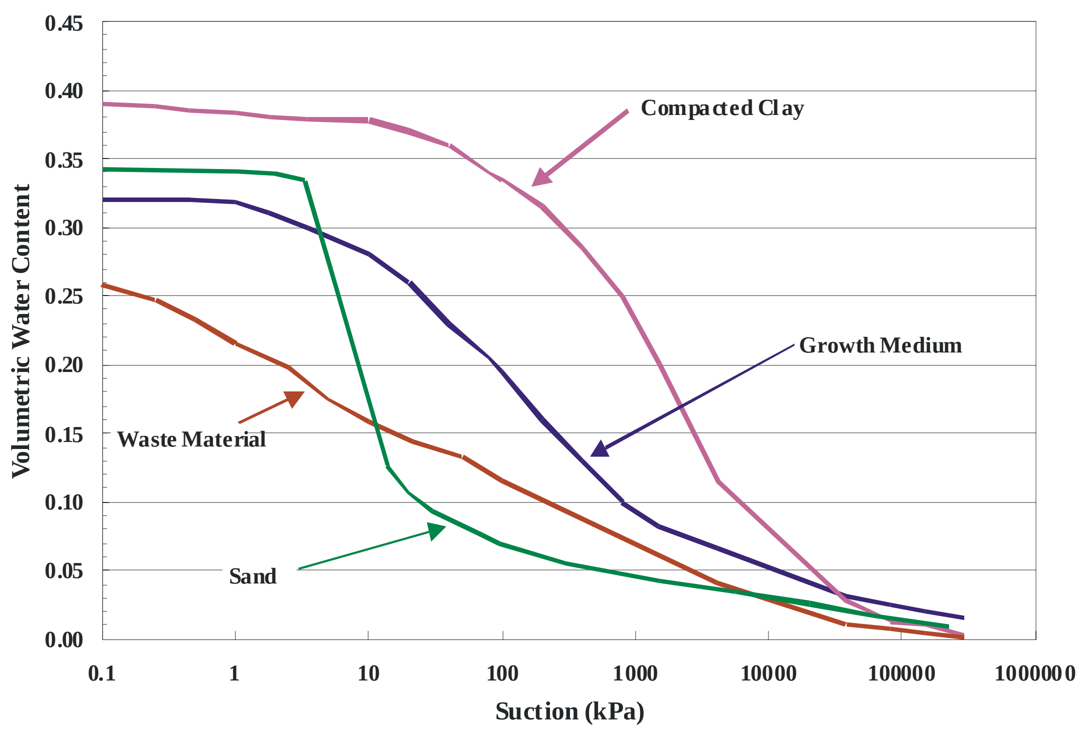

FIGURE 9. MOISTURE RETENTION CURVES OF MATERIALS USED FOR MODELING THE SHALLOW LYSIMETER.

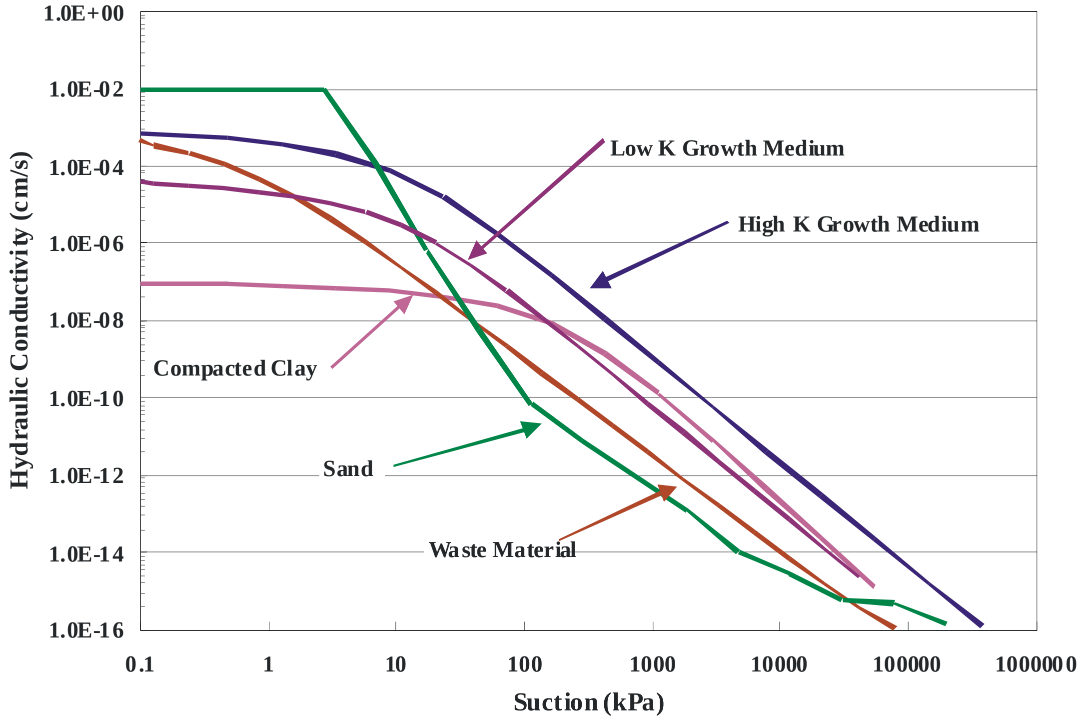

FIGURE 10. HYDRAULIC CONDUCTIVITY FUNCTIONS OF MATERIALS USED FOR MODELING THE SHALLOW LYSIMETER.

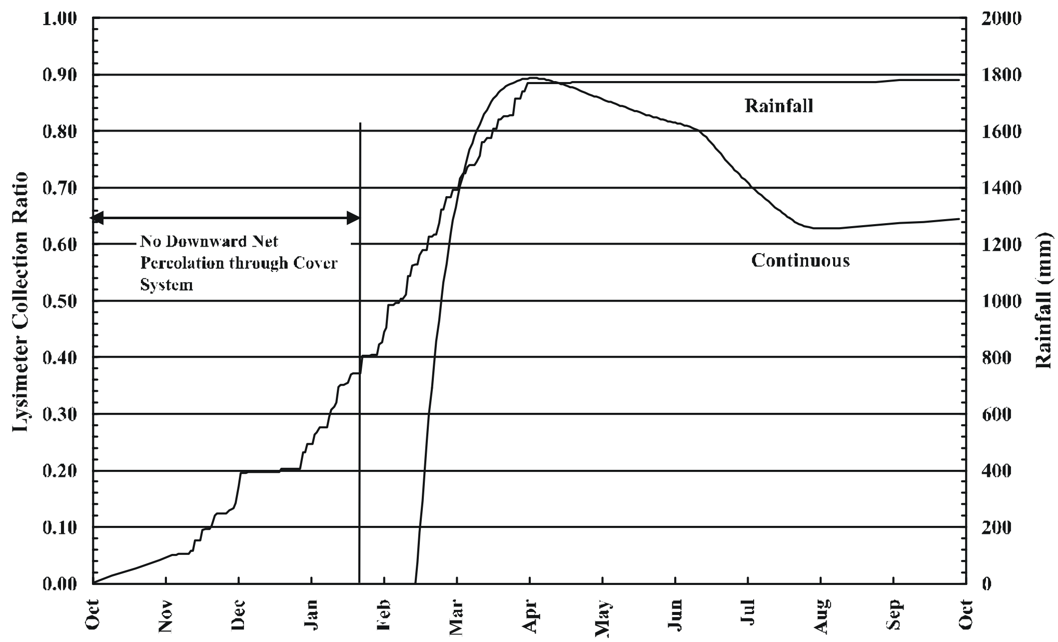

FIGURE 11. VARIATIONS IN LYSIMETER COLLECTION RATIO FOR SHALLOW LYSIMETER MODELING RESULTS WITH DRAINAGE.

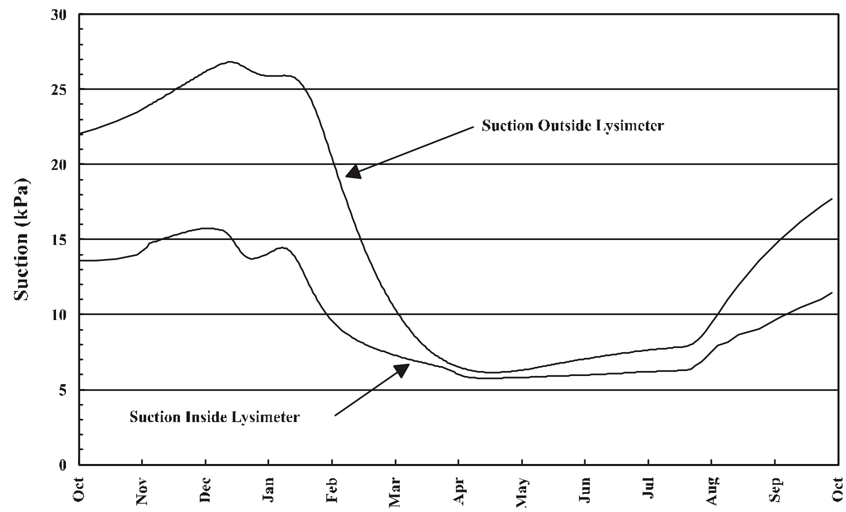

FIGURE 12. VARIATIONS IN SUCTION FOR SHALLOW LYSIMETER MODELLING RESULTS FOR A DRAINED LYSIMETER CONDITION.

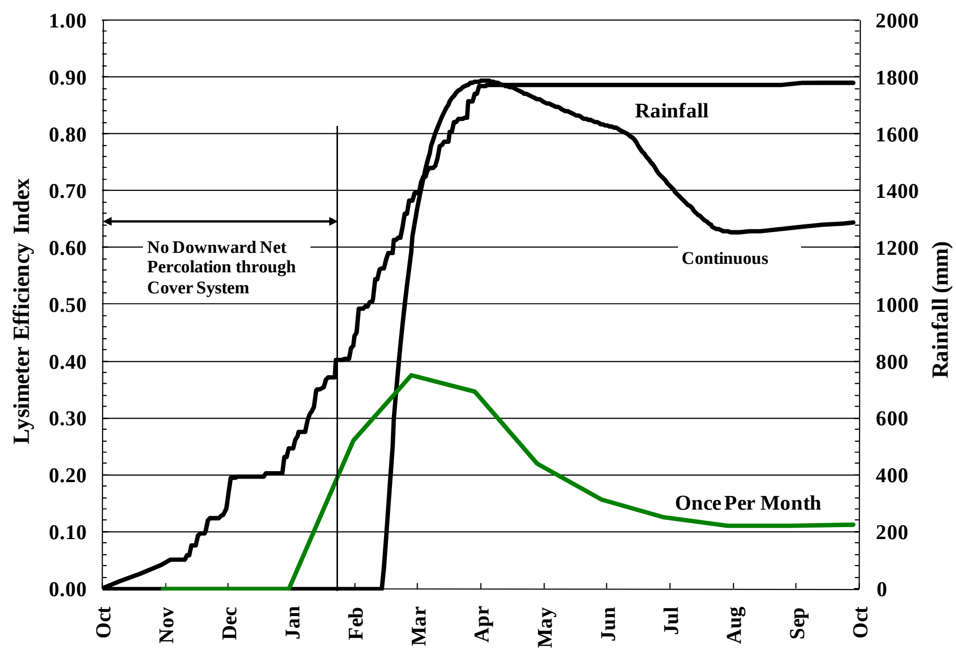

FIGURE 13. VARIATIONS IN LYSIMETER COLLECTION RATIO FOR SHALLOW LYSIMETER MODELLING RESULTS WHEN PUMPED MONTHLY.

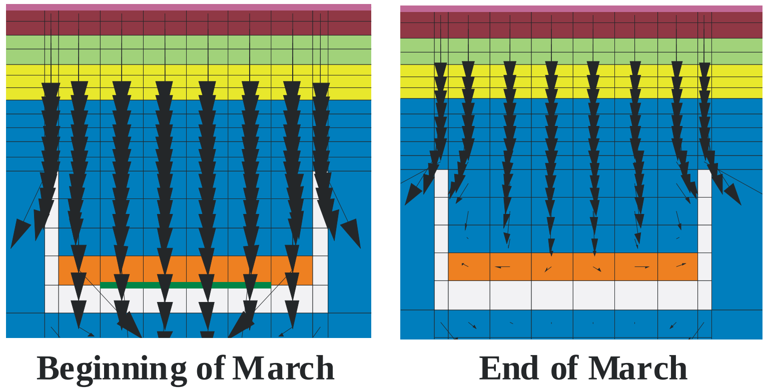

FIGURE 14. COMPARISON OF THE FLOW VECTORS PREDICTED FOR THE SHALLOW LYSIMETER MODELING ONE DAY AFTER PUMPING (MARCH 1ST) AND ONE MONTH AFTER PUMPING (MARCH 31ST).

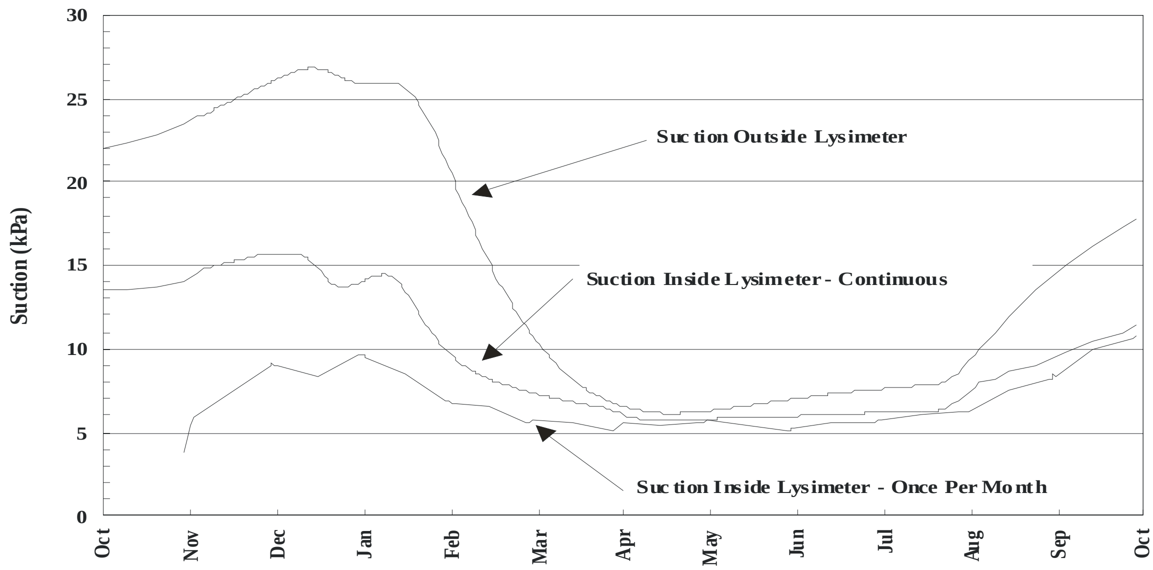

FIGURE 15. VARIATIONS IN SUCTION FOR SHALLOW LYSIMETER MODELING RESULTS WHEN PUMPED MONTHLY.

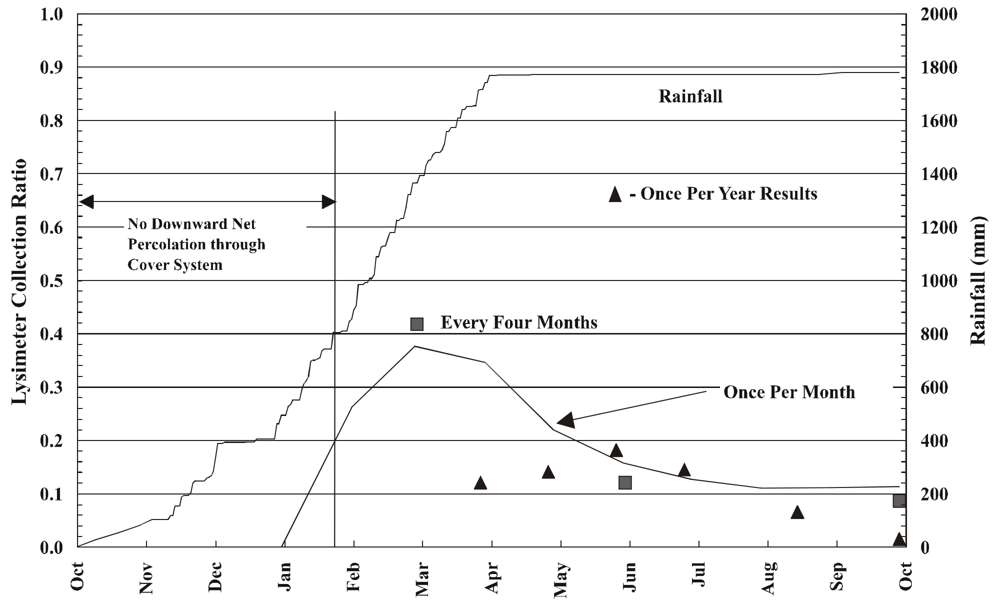

FIGURE 16. VARIATIONS IN LYSIMETER COLLECTION RATIO FOR SHALLOW LYSIMETER MODELING RESULTS FOR FOUR MONTH AND ANNUAL PUMPING PERIODS.

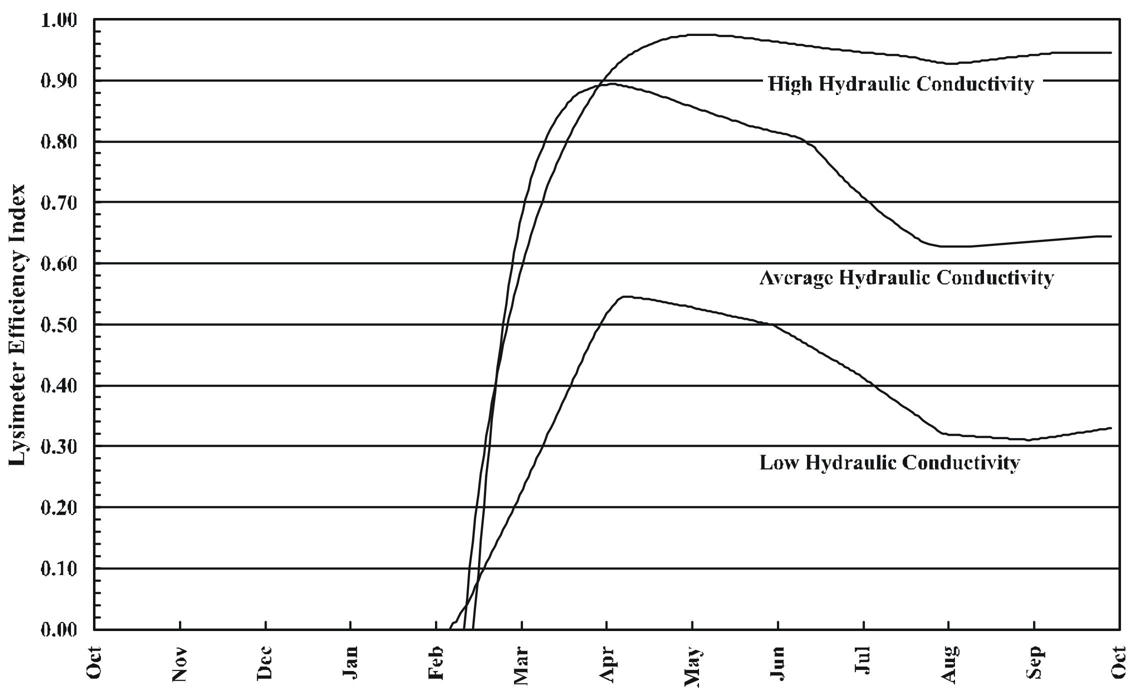

FIGURE 17. COMPARISON OF THE LYSIMETER COLLECTION RATIO FOR THREE MATERIALS WITH DIFFERENT K- FUNCTIONS.

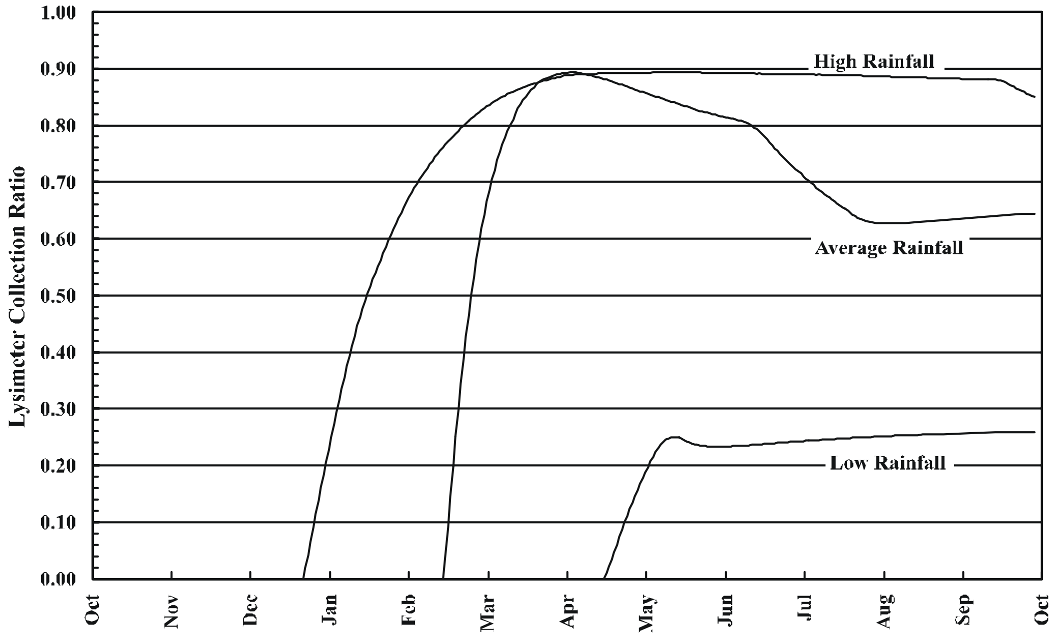

FIGURE 18. COMPARISON OF THE LYSIMETER COLLECTION RATIO FOR THREE VARIATIONS IN TOTAL ANNUAL RAINFALL.

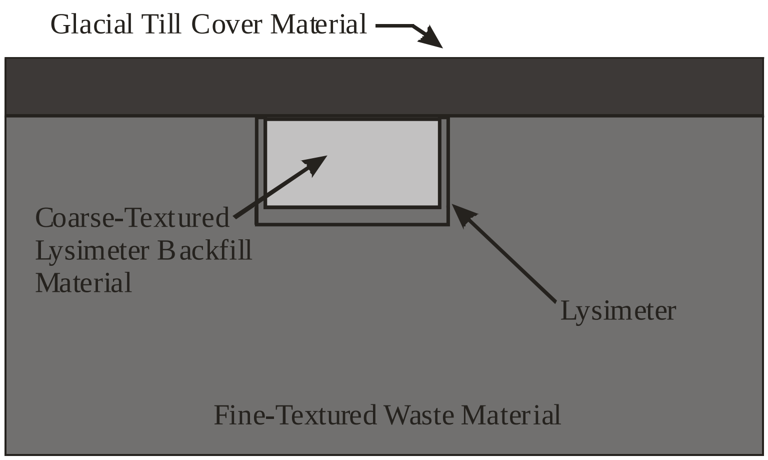

FIGURE 19. COVER SYSTEM USED FOR MODELLING A COARSE-TEXTURED BACKFILL LYSIMETER.

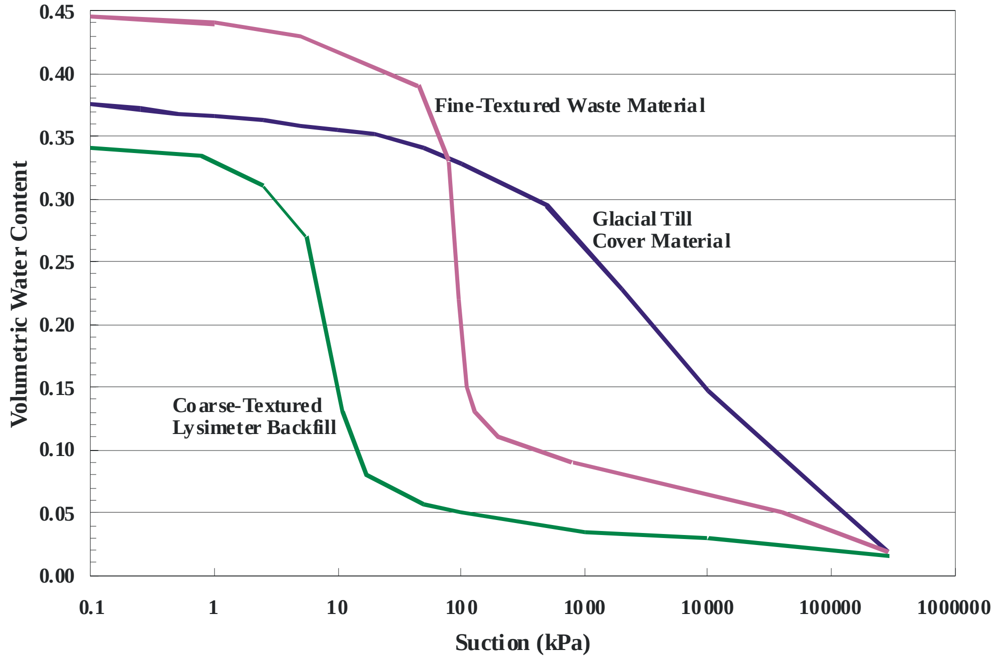

FIGURE 20. MOISTURE RETENTION CURVES OF MATERIALS USED FOR MODELING THE COARSE-TEXTURED BACKFILL LYSIMETER.

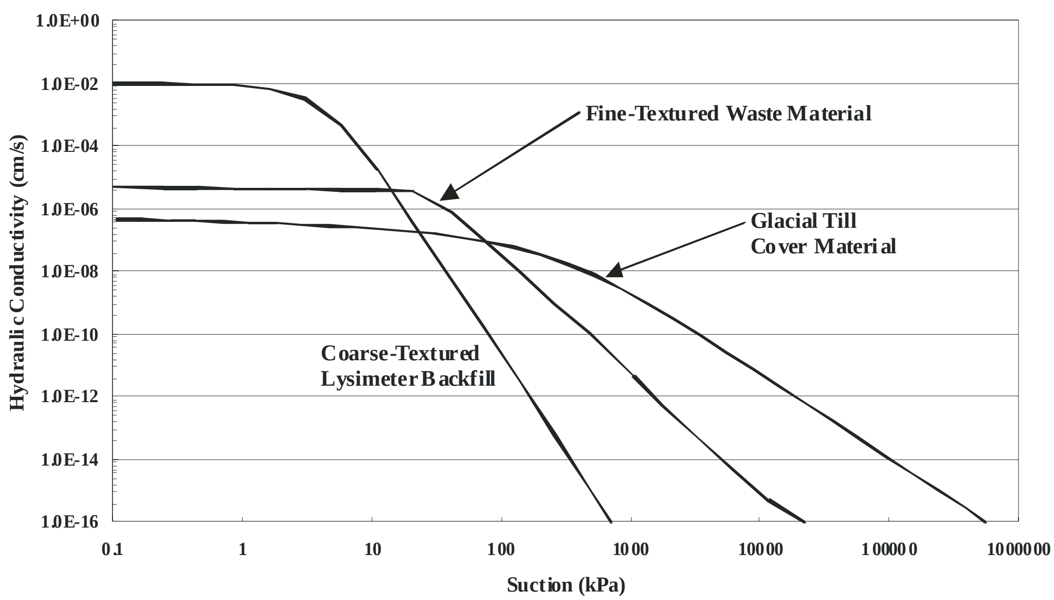

FIGURE 21. HYDRAULIC CONDUCTIVITY FUNCTIONS OF MATERIALS USED FOR MODELING THE COARSE-TEXTURED BACKFILL LYSIMETER.

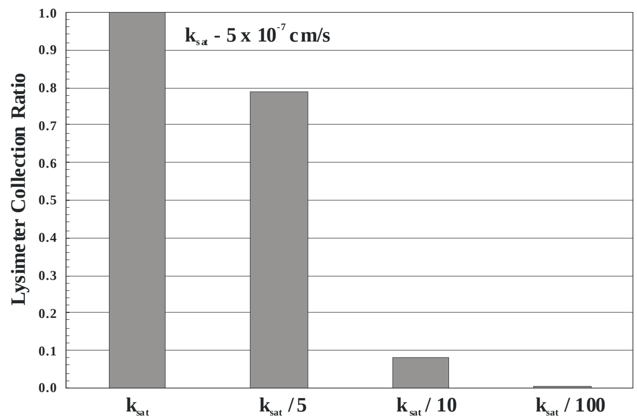

FIGURE 22. COARSE-TEXTURED BACKFILL LYSIMETER MODELING RESULTS FOR FOUR STEADY STATE INFILTRATION RATES.

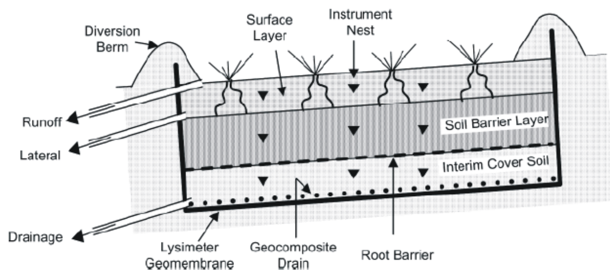

FIGURE 23. SCHEMATIC OF THE PAN TYPE DRAINAGE LYSIMETER USED BY ALBRIGHT *ET AL* (2006), TAKEN FROM ALBRIGHT *ET AL* (2006).

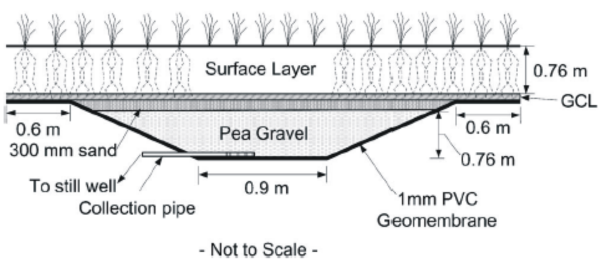

FIGURE 24. SCHEMATIC OF LYSIMETER WITH SLOPING LYSIMETER WALLS (FROM BENSON *ET AL*., 2007).