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Predicting Field Performance of Lysimeters Used to Evaluate Cover Systems for Mine Waste

M O'Kane[1] and S L Barbour[2]

ABSTRACT

Measurement of the net percolation from the base of a cover system into the underlying waste material is a key component of a cover system monitoring program. The units of measure (ie a percentage of precipitation or rainfall) are simple to understand for all stakeholders, 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; however, the design of lysimeters for cover system monitoring programs in the mining industry have typically not considered fundamental aspects of lysimeter design. 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.

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. Finally, the performance of lysimeter designs previously installed in the field at sites in Australia, Canada, and the United States are subjected to numerical modelling to determine whether net percolation is being measured properly.

INTRODUCTION

Cover systems are a common prevention and control strategy for potentially reactive mine waste. The purpose of a cover system is to limit contaminant release to the receiving environment following closure of the mine waste storage facility. This cover system must therefore provide long-term control of the quality of surface run-off 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 that is consistent with the current and final land use of the area.

The two principal objectives of a soil cover system are to control or limit the ingress of oxygen and meteoric waters to the underlying reactive mine waste. Additional objectives may include: control of consolidation and differential settlement; oxygen consumption (ie organic cover materials); reaction inhibition (ie incorporate limestone at the surface which does not prevent oxidation but can control the rate of acid generation); and control of upward capillary movement of process water constituents/oxidation products.

For the purpose of this paper, net percolation, as shown conceptually in Figure 1, is defined as the net transmission of meteoric water across the cover material surface. Meteoric water will either be intercepted by vegetation, run-off, or infiltrate into the surface. Water that infiltrates will be stored in the 'active zone' and a large majority will then subsequently be 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.

Control of net percolation is required for essentially all cover systems for reactive mine waste and is an essential component of the water balance for a mine waste storage facility. In many cases, the long-term net percolation from a cover system to the underlying waste storage facility will control the predicted concentration and contaminant load to the receiving environment.

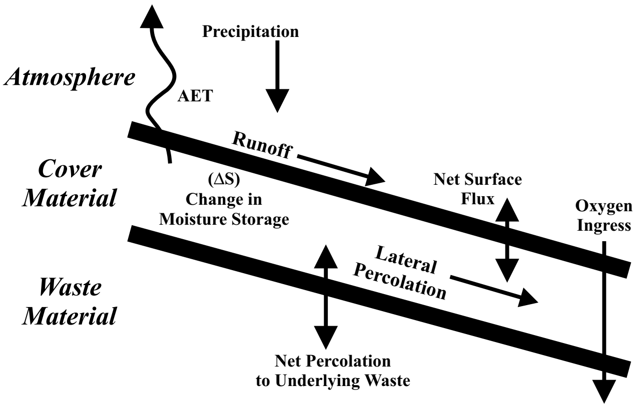

FIG 1 - Water balance of a typical cover system.

Predictions of the net percolation for a particular cover system design are typically based on soil-atmosphere numerical cover design models. Significant advances in the ability to predict net percolation have been realised in recent years; however, it is essential that predictions of performance be validated through field measurements, whether it is on a field trial scale basis (eg cover system test plots), or on a full-scale basis (eg construction of the entire cover system).

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

UNSATURATED ZONE HYDROLOGY CONCEPTS FOR LYSIMETER DESIGN

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:

$$q = -k\,i \tag{1}$$

where:

q	is the Darcy flux (L/T)
k	is the hydraulic conductivity (L/T)
i	is the hydraulic gradient

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[1] Senior Geotechnical Engineer, O'Kane Consultants Inc, 134 – 335 Packham Avenue, Saskatoon SK S7N 4S1, Canada.

[2] Department of Civil Engineering, University of Saskatchewan, Saskatoon SK S7N 5A9, Canada.

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 (ie 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 (ie 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 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 (ie $q = -k$).

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 (eg a sand as compared to a silt, or an increase in fines content). However, in the case of typical field conditions at mine sites, a different hydraulic conductivity function may result simply from a difference with respect to *in situ* density conditions.

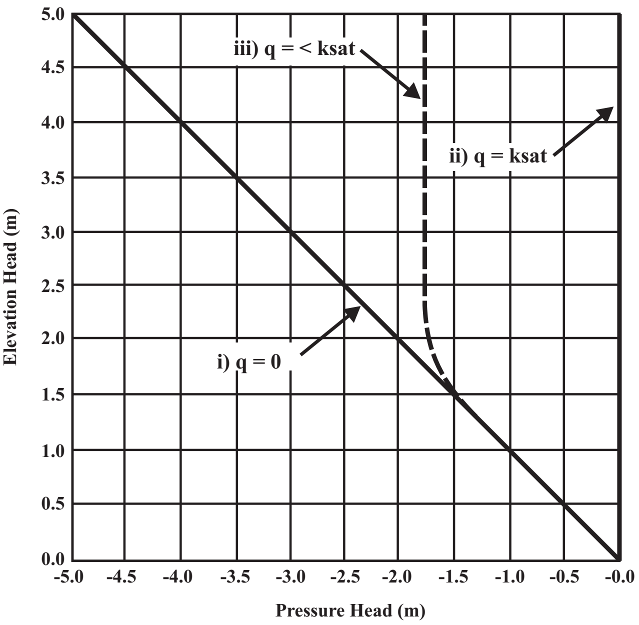

FIG 2 - Relationship between pressure and elevation head for three different applied percolation rates.

The influence on the pressure head profile due to the presence of a lysimeter

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, condition within the lysimeter below the cover material-waste material interface. 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 (ie P_{in}) as compared to outside the lysimeter (ie 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 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 (ie 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 depth is sufficiently deep so the presence of the water table does not influence the net percolation condition. The pressure head developed is a function of the net percolation rate from the base of the cover layer and the hydraulic conductivity function of the underlying waste material.

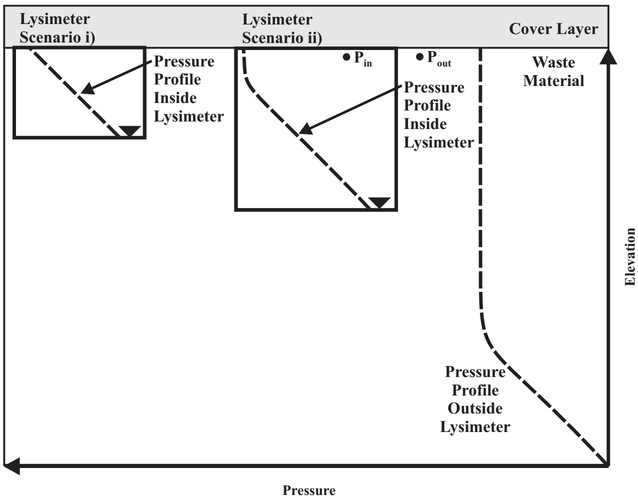

FIG 3 - Pressure head profiles for two lysimeter depths compared to the *in situ* material.

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 hydraulic conductivity 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 (ie 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 hydraulic conductivity function of the waste material, the maximum negative pressure head that can develop is known, and the required lysimeter depth can be estimated.

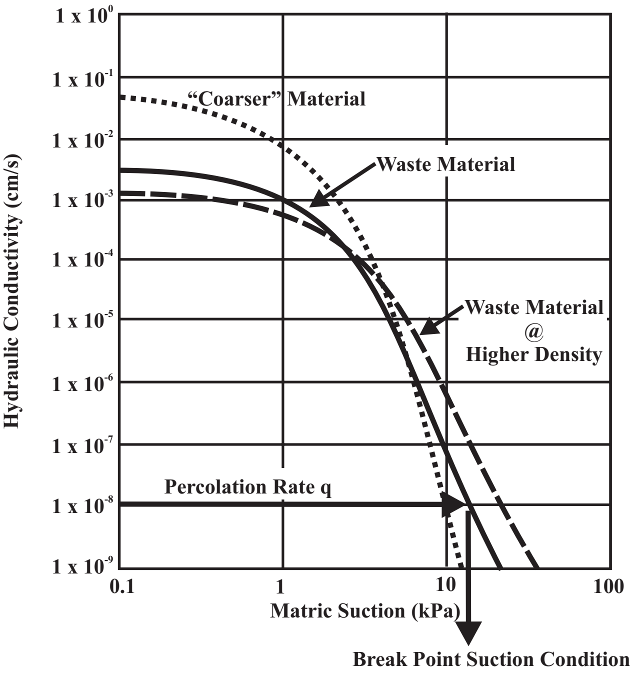

FIG 4 - Unsaturated hydraulic conductivity functions illustrating the method of determining the maximum negative pressure head that can develop below the cover/waste interface.

Note that Figure 4 also shows the hydraulic conductivity 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 only slightly, the slope of the hydraulic conductivity 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 on the lysimeter wall height

The discussion above focused on the influence of the depth of 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. Bews *et al* (1997) modelled 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 (ie 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.

DETAILED LYSIMETER DESIGN MODELLING

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 modelling program should be undertaken, with the estimated depth used as a starting point for the modelling program.

The numerical modelling of the lysimeter designs discussed in this paper was completed with the VADOSE/W model (Geo-Slope, 2002). 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 vapour 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/run-off, ground water seepage, ground freezing and thawing, ground vapour 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 two-dimensional, transient evaluation of lysimeter performance.

Development of a lysimeter to measure net percolation under field conditions

Figure 5 (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 measured 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 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 accurate results. 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 (ie suction is not changing with depth). It should be emphasised that the suction

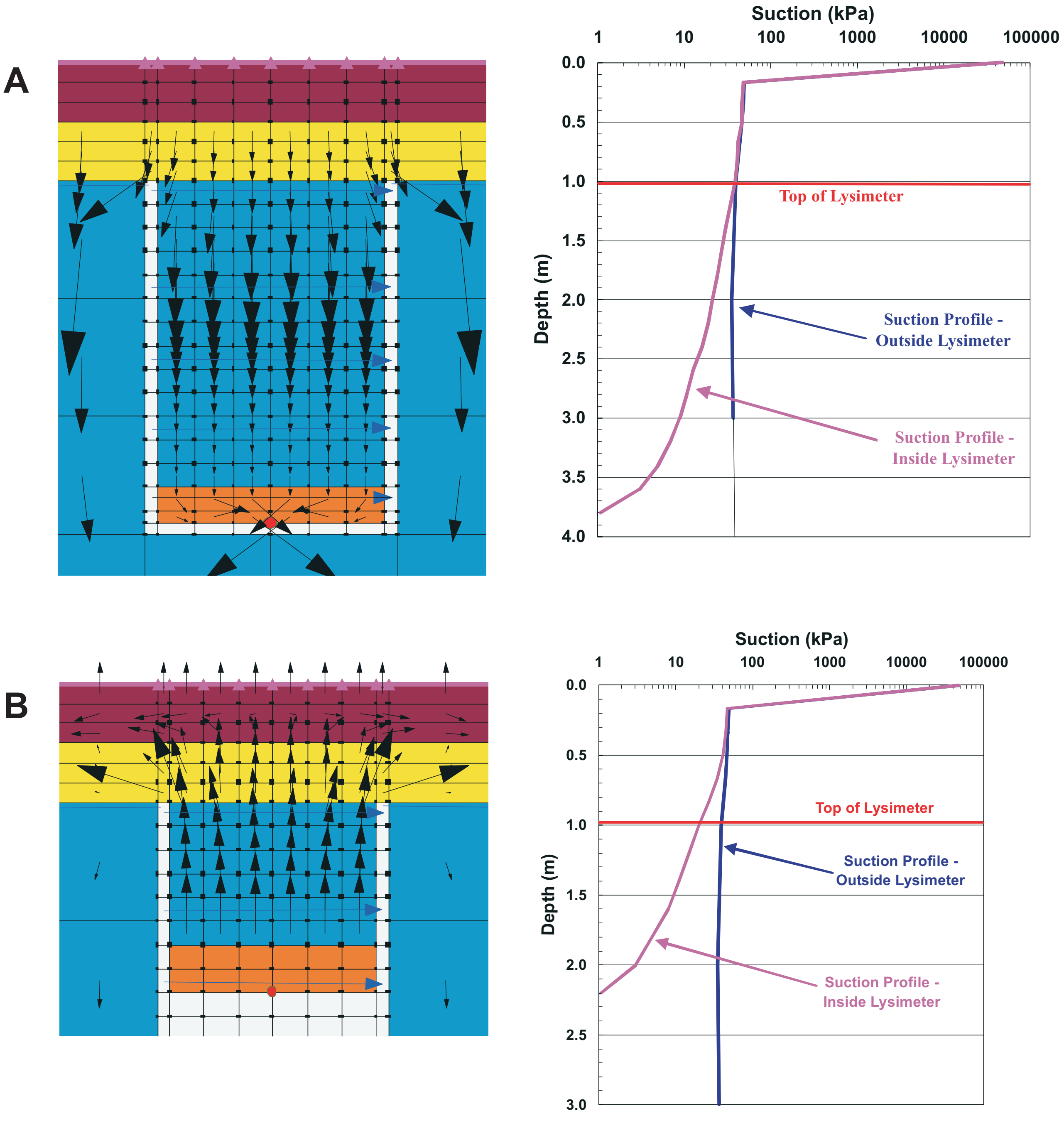

FIG 5 - VADOSE/W modelling results for **(a)** a 3.0 m deep lysimeter and **(b)** a 1.5 m deep lysimeter.

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 modelled 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 tailings material located within a semi-arid site is shown in Figure 6. It is assumed that the site has an average annual rainfall of 400 mm and three per cent to 20 per cent 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 tailings profile is 4.0×10^{-8} cm/s to 2.5×10^{-7} cm/s. During low net percolation periods (three per cent of annual rainfall) the suction within the tailings profile will be approximately 70 kPa; high net percolation periods will decrease the tailings 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.

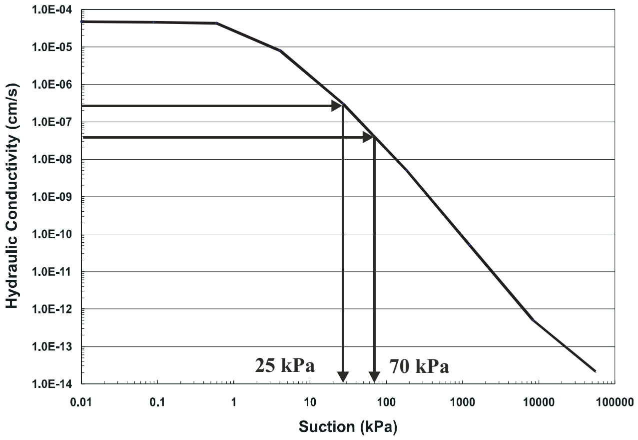

FIG 6 - Hydraulic conductivity function for a tailings material.

A 7 m deep lysimeter may not be economically nor technically feasible to construct in the field. When it is not feasible to construct the lysimeter at the base of the cover system, the top edge of the lysimeter must 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 metres of the underlying waste material (ie a 2.0 m deep lysimeter could be used for a 1.0 m cover over tailings or waste rock).

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 should 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 field conditions (ie field hydraulic properties are developed), the actual lower boundary condition, as measured with instrumentation outside the lysimeter, is substituted into the model to determine the 'actual' net percolation from the cover system to the underlying waste material.

EVALUATION AND DISCUSSION OF TYPICAL COVER SYSTEM MONITORING LYSIMETER DESIGNS UTILISED IN THE MINING INDUSTRY

A review of literature with respect to monitoring cover system performance in the mining industry provides a general frame of reference for 'typical' mining industry lysimeter designs. This paper evaluates the performance and functionality of several different types of documented lysimeters. In all, three types of lysimeters were evaluated including short, barrel-type lysimeters, long, shallow pan lysimeters, and coarse material filled barrel lysimeters. 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 presents 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 outside the confines of the lysimeter.

Short barrel lysimeters

Short barrel lysimeters refer to the small (usually less than 1 m in diameter and depth) containers buried within the soil profile to collect net percolation. Most often these lysimeters are constructed from 225 L (45 gallon) barrels that are open at one end. Measurement of the 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 an automatic drainage collection system to record net flow out of the lysimeter.

The objectives of the short barrel lysimeter numerical modelling 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 short barrel lysimeter under varying net percolation measurement schedules including daily collection, monthly collection, and annual collection.

Description of cover system and short barrel lysimeter

The dry cover system utilised in the modelling demonstration, shown in Figure 7, was generalised, as opposed to a site-specific cover system design. However, the cover design selected is typical of a dry cover system in a semi-humid to humid climate. The cover system includes a low hydraulic conductivity compacted barrier layer, with an overlying protection/growth medium layer. A horizontal cover system was simulated in the modelling demonstration as lysimeters are most often placed beneath flat cover surfaces such as at the top of waste rock dumps. The cover system consisted of a 0.25 m compacted clay barrier layer placed directly on the waste rock 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 rock 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 phreatic

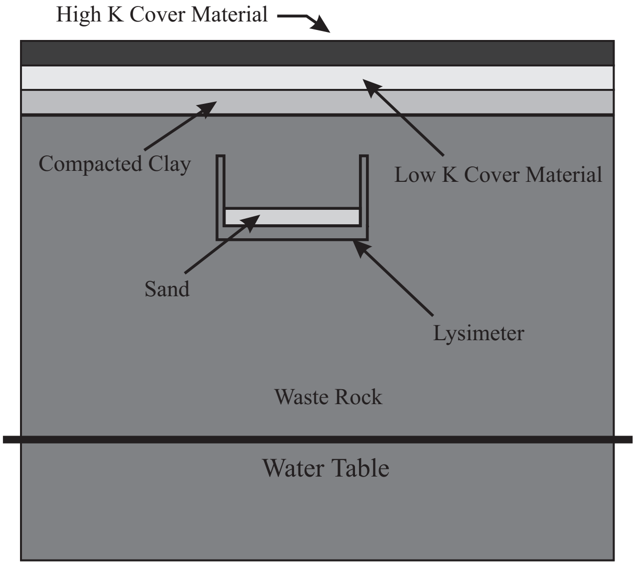

FIG 7 - Dry cover system used for modelling the short barrel lysimeter.

surface was placed three metres below the base of the lysimeter. The physical properties of the cover and waste materials were based on typical materials used in dry cover system design. Figures 8 and 9 present the soil water characteristic curves (SWCC) and hydraulic conductivity functions of the materials used for the modelling.

The climate year used in the modelling program was adapted from climate data collected at a site in northern Australia. 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 from October to September to place the summer season at the beginning of the simulation, 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 (m/s).

Short barrel lysimeter modelling program

The performance of the short barrel lysimeter was examined under a number of different percolation collection and measurement schedules. Simulations were completed assuming that the net percolation was collected and measured on a daily, monthly, and annual basis. 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 summarises the eight numerical simulations completed for the short barrel lysimeter modelling program.

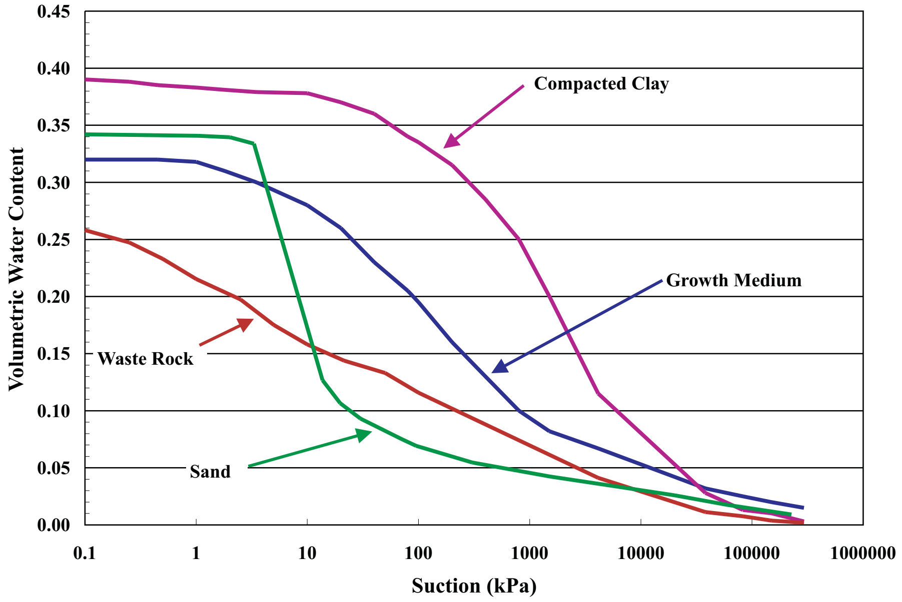

FIG 8 - Soil water characteristic curves of materials used for modelling the short barrel lysimeter.

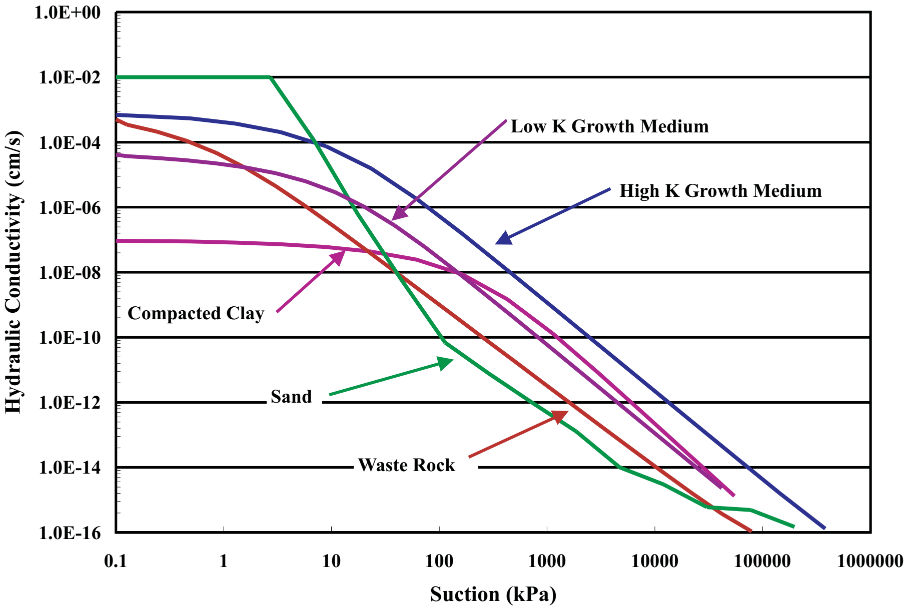

FIG 9 - Hydraulic conductivity functions of materials used for modelling the short barrel lysimeter.

Short barrel lysimeter modelling 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 10. Meteoric water began to percolate through the cover system on 25 January of the simulation year. The lysimeter began to record net percolation at its base on 15 February, which means the lag time 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, waste rock interface outside the confines of the short barrel lysimeter. Therefore, the LCR of the short barrel lysimeter for the continuous simulation was approximately 0.64 (ie 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.

TABLE 1

Summary of numerical simulations completed for the short barrel lysimeter modelling 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

The low LCR is a result of the shallow depth of the short barrel lysimeter. Figure 11 shows the suction at the cover system-waste material interface immediately above the short barrel lysimeter, as well as outside of the short barrel 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 12 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 10.

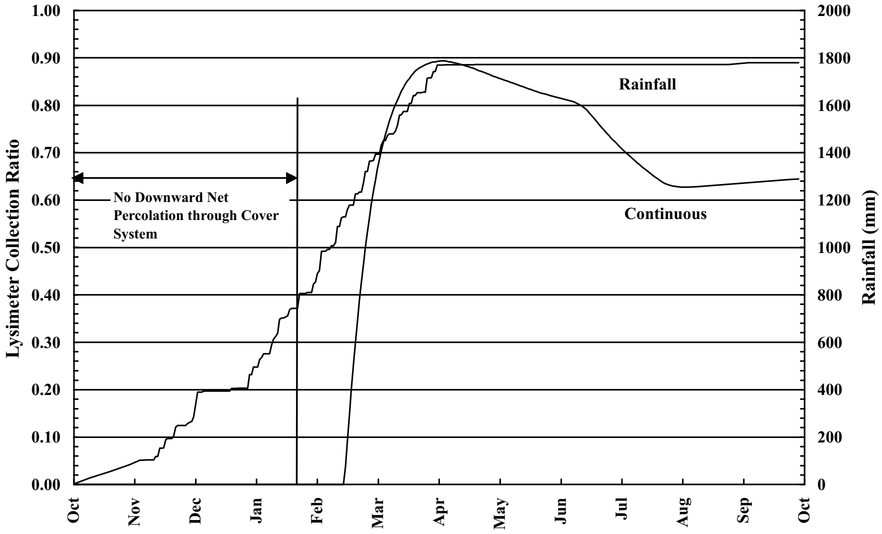

FIG 10 - Variations in lysimeter collection ratio for short barrel lysimeter modelling results when pumped continuously.

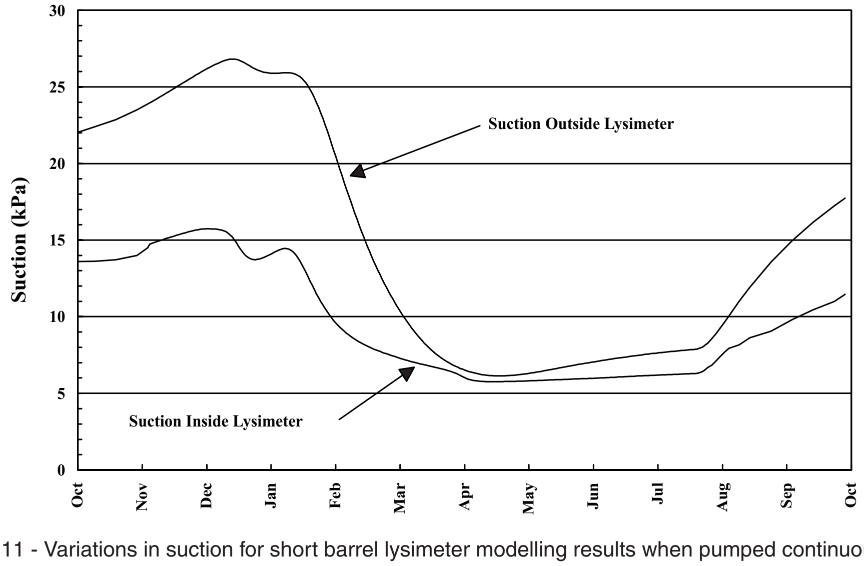

FIG 11 - Variations in suction for short barrel lysimeter modelling results when pumped continuously.

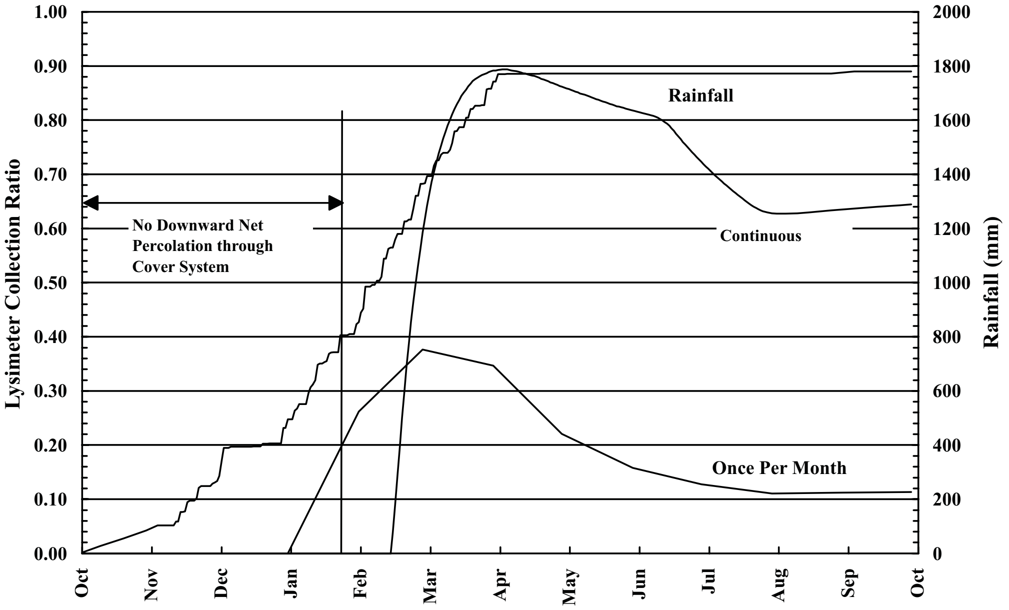

FIG 12 - Variations in lysimeter collection ratio for short barrel lysimeter modelling results when pumped monthly.

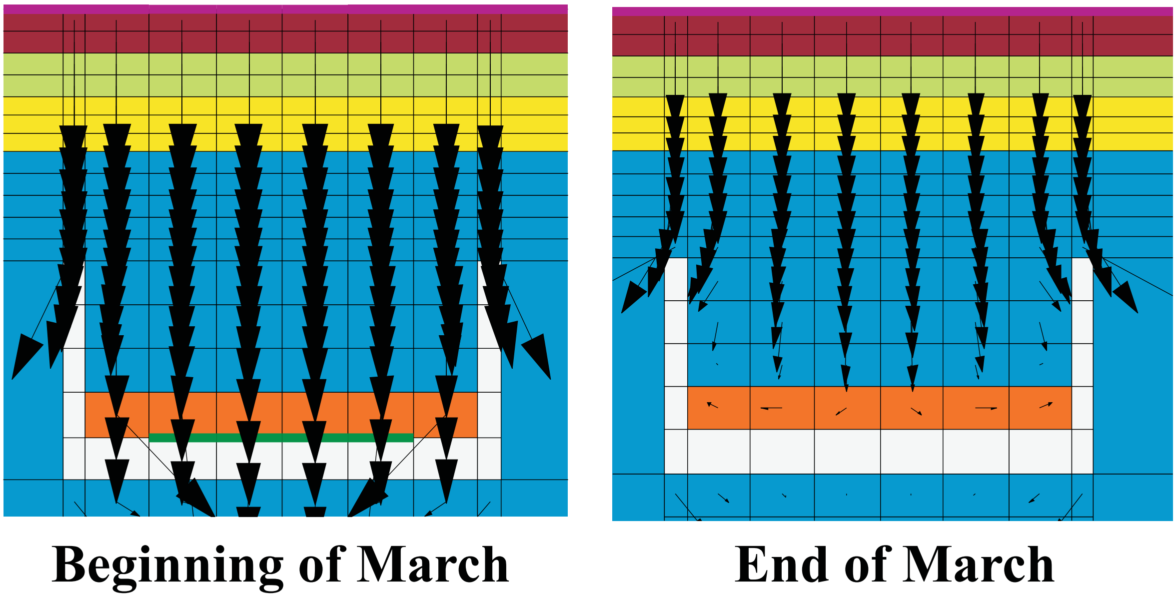

FIG 13 - Comparison of the flow vectors predicted for the short barrel lysimeter modelling one day after pumping (1 March) and one month after pumping (31 March).

The performance of the short barrel lysimeter for the scenario when the lysimeter is pumped out once per month, at the end of each month of the year, is shown in Figure 12. 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 percolated 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 13 compares the flow vectors predicted for the short barrel lysimeter on 1 March, one day after the lysimeter was pumped out, to the flow regime on 31 March, 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 short barrel lysimeter.

The pressure profile at the cover system/waste material interface above the lysimeter is shown in Figure 14 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 short barrel 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 15. 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 15 represents an individual model simulation.

Figure 15 clearly indicates that the net percolation measured by the short barrel lysimeter is highly dependent on which month percolation was collected from the short barrel 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 the cause of the disparity between the different LCR values. If the 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 short barrel lysimeters are installed in seasonal climates with well defined wet and dry seasons. In addition to the fact that short barrel lysimeter are simply not deep enough for any waste material encountered in the mining industry, short barrel 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.

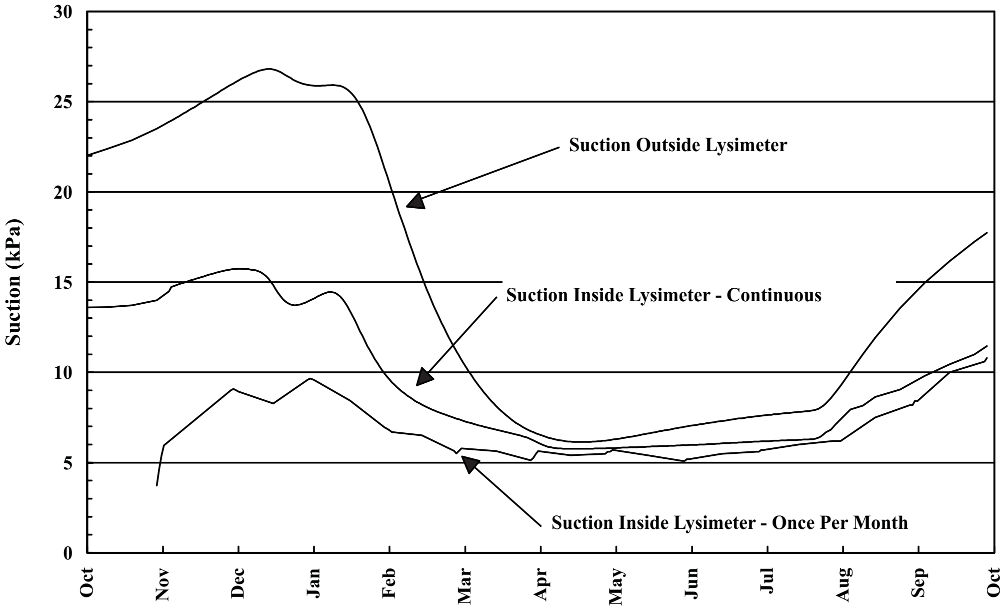

FIG 14 - Variations in suction for short barrel lysimeter modelling results when pumped monthly.

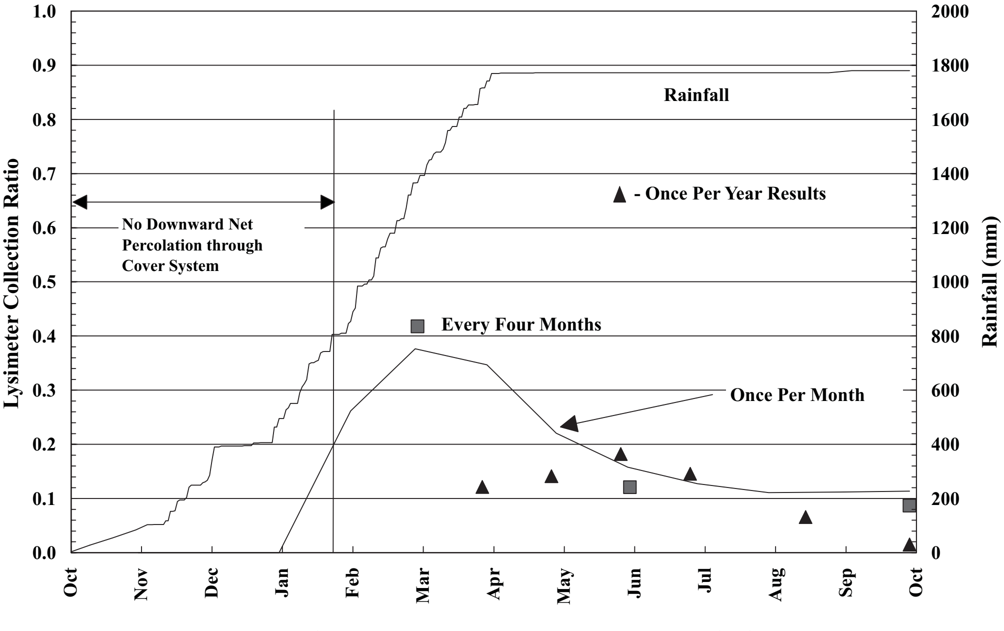

FIG 15 - Variations in lysimeter collection ratio for short barrel lysimeter modelling results for four month and annual pumping periods.

Sensitivity analysis of the short barrel 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 hydraulic conductivity function of the waste rock material and the annual rainfall. The saturated hydraulic conductivity of the waste rock material for the short barrel lysimeter modelling results presented in the previous section was 1×10^{-3} cm/s. The saturated hydraulic conductivity was adjusted to 1×10^{-2} cm/s in the high hydraulic conductivity simulation and 1×10^{-4} cm/s for the low hydraulic conductivity simulation. These conditions would reflect different waste rock material back-filled into the short barrel 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 16 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 short barrel 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 short barrel 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 short barrel lysimeter during the dry season. Conversely, less water was able to percolate through the waste rock 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 17. The most obvious effect is the timing of the initial breakthrough of percolation to the base of the short barrel lysimeter. In the high rainfall simulation, net percolation was first recorded on 23 December, as compared to 15 February and 18 April 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).

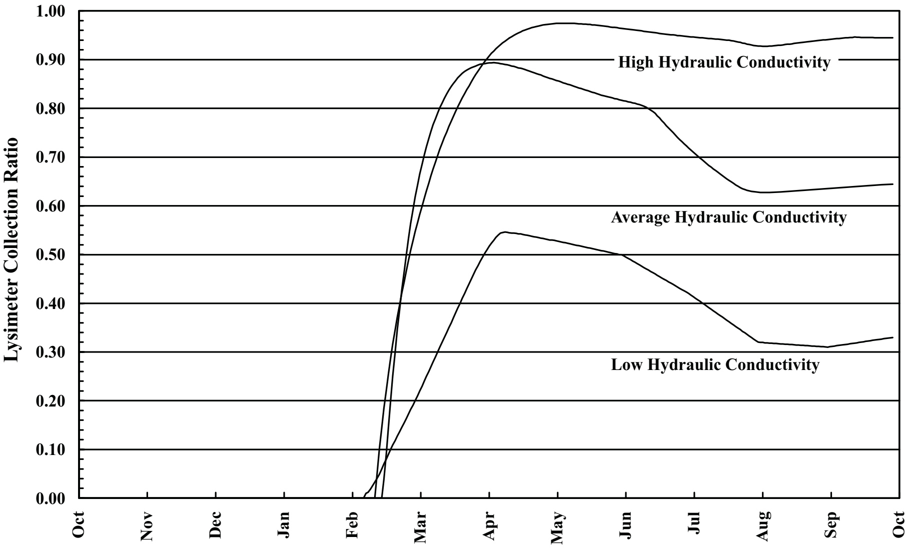

FIG 16 - Comparison of the lysimeter collection ratio for three materials with different hydraulic conductivity functions.

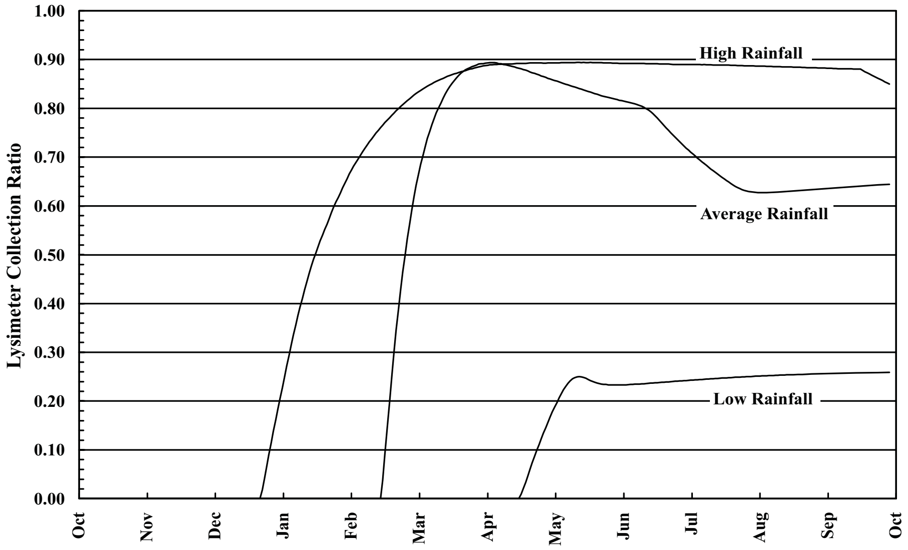

FIG 17 - Comparison of the lysimeter collection ratio for three variations in total annual rainfall.

In all modelled scenarios of hydraulic conductivity or rainfall, the short barrel lysimeter did not provide a proper measure of net percolation, even though the model assumed that percolation collected at the base of the short barrel 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 the short barrel lysimeter was sensitive to both the saturated hydraulic conductivity and the climate year rainfall conditions. Variations of saturated hydraulic conductivity are likely the cause of different percolation results often reported for clusters of short barrel lysimeters installed next to each other and at the same time. A difference in one order of magnitude in saturated hydraulic conductivity for typical mine waste rock 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 short barrel lysimeters, which are generally thought to be duplicates, do not measure the same net percolation.

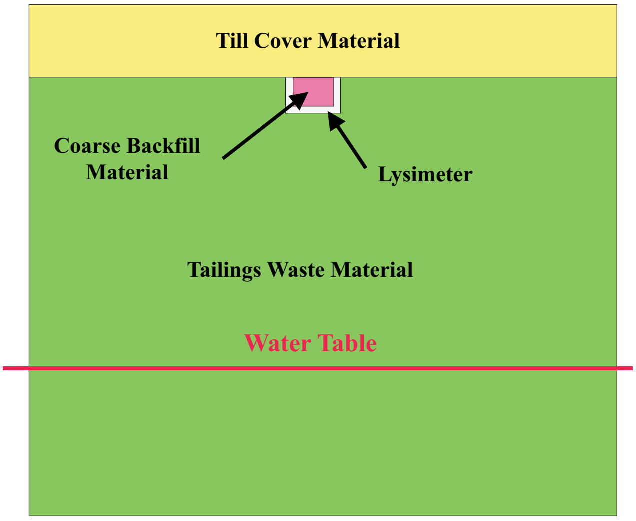

FIG 18 - Dry cover system used for modelling a shallow lysimeter.

Correction for wicking from short barrel lysimeters

It has been reported that net percolation measured by short barrel lysimeters can be 'corrected' for the wicking that will occur (eg Timms and Bennett, 2000). However, Figures 15 and 17 demonstrate that this is not possible. The amount of wicking is strongly dependent on the *in situ* lysimeter backfill conditions, the rainfall conditions, and the short barrel lysimeter pumping schedule. All these conditions can be highly variable, even for a single site. In terms of rainfall 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 (eg hydraulic conductivity of the lysimeter backfill) would make each lysimeter at a particular site subject to a different rate of wicking.

Shallow lysimeters with coarse-textured backfill

The shallow lysimeter with coarse-textured backfill is quite similar to the short barrel lysimeter. The short barrel lysimeter incorporates a waste rock backfill with a thin layer of sand at the base to represent the *in situ* conditions of the waste material. The 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 shallow lysimeter

The dry cover system utilised in the modelling demonstration, shown in Figure 19, was also generalised. The cover system consisted of a 1.0 m clayey layer placed directly on a tailings waste surface. The lysimeter was placed directly below the dry cover-tailings 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. The phreatic surface was placed five metres below the base of the lysimeter. The physical properties of the cover and waste materials were based on typical materials used in dry cover system design. Figures 19 and 20 show the SWCCs and hydraulic conductivity functions, respectively for the materials modelled.

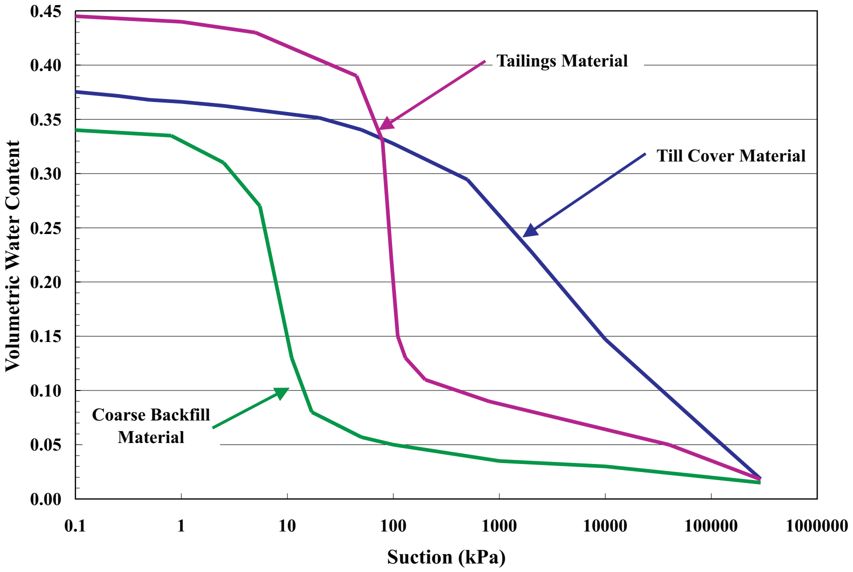

FIG 19 - Soil water characteristic curves of materials used for modelling the shallow lysimeter.

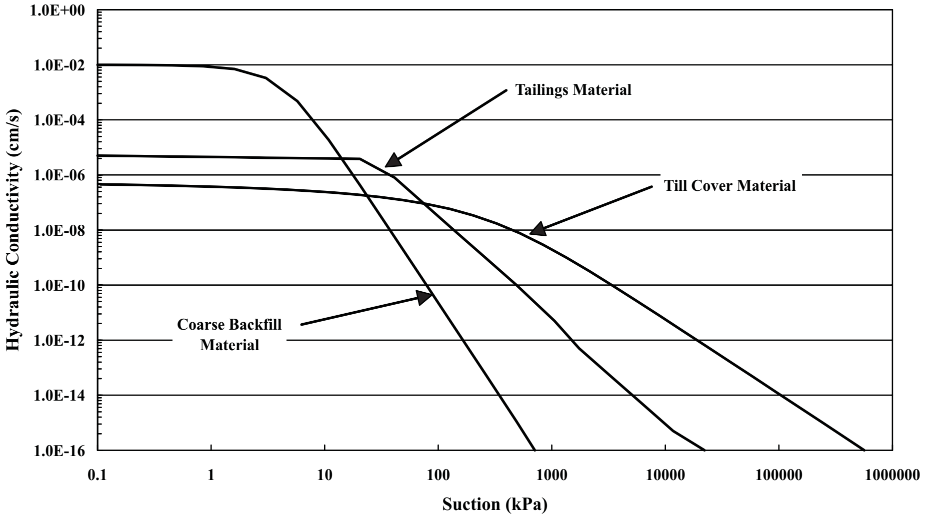

FIG 20 - Hydraulic conductivity functions of materials used for modelling the shallow lysimeter.

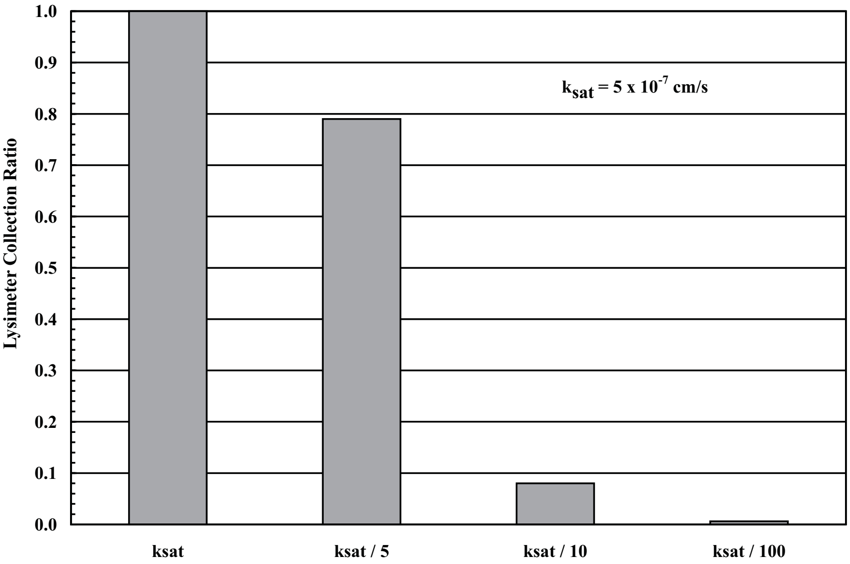

FIG 21 - Shallow lysimeter modelling results for four infiltration rates.

Shallow lysimeter modelling program

Steady state numerical simulations were used to analyse the 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 tailings material outside the lysimeter to calculate the LCR. Four steady state infiltration rates were applied to the cover surface. The first was 5×10^{-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 tailings profile close to zero. The infiltration rate was reduced to 1×10^{-7} cm/s, 5×10^{-8} cm/s, and 5×10^{-9} cm/s in subsequent simulations. The performance of the shallow lysimeter under the reduced infiltration rates (resulting in increased suction pressures within the lysimeter and tailings) was examined.

Shallow lysimeter modelling results

The results of the four steady-state models are shown in Figure 21. The lysimeter performed well (LCR = 1.0) under the near saturated conditions created by the 5×10^{-7} cm/s infiltration rate. The LCR dropped to approximately 0.78 when the infiltration rate dropped to 1×10^{-7} cm/s. Further reduction in the infiltration rate to 5×10^{-8} cm/s and 5×10^{-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 tailings 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 tailings profile was close to zero. As shown in Figure 20, the hydraulic conductivity of the coarse material is greater than the tailings material at suctions close to zero. This situation is reversed at suctions greater than approximately 20 kPa when the hydraulic conductivity of the tailings 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 1×10^{-7} cm/s creates suction values close to 20 kPa within the lysimeter and tailings material, producing some bypass flow from the lysimeter to the tailings. At the two lowest infiltration rates, suction values within the tailings profile are much greater than 20 kPa resulting in little flow into the lysimeter and low LCR values.

The poor performance of the shallow lysimeter with coarse backfill is recognised in the literature but often disregarded (eg Woyshner and Swarbick, 1997). The rationale is that the majority of the 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, modelling 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 tailings and lysimeter backfill material below the cover layers. It should also be noted that unsaturated conditions are predominant in almost all dry cover systems. Saturated conditions occur only for 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 tailings 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 × 15 m) lysimeters installed in the unsaturated zone below a landfill cover system to measure net percolation have yet to collect any seepage after 15 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) modelled the shallow and wide pan lysimeters in a similar manner as described within this paper. The results indicate that wicking of seepage water out of the 15 m × 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 shallow 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.

SUMMARY

This paper has illustrated the unsaturated zone hydrology background required to properly design a lysimeter to measure net percolation from the base of cover system to underlying mine waste material. A methodology was presented to estimate the required dimensions (ie depth) and installation technique of a lysimeter on the basis of site specific climate conditions and waste material properties.

The concept of the lysimeter collection ratio, or LCR, was introduced 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 modelling results presented in this paper demonstrated that shallow lysimeters constructed from 225 L barrels 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 (ie net percolation) conditions. Back-simulating wicking from the 225 L barrel lysimeters was demonstrated to be technically infeasible.

The modelling also demonstrated how shallow, large surface area pan type lysimeters lead to similar wicking problems, and incorrect measurements of net percolation. Finally, lysimeters installed to measure net percolation to tailings, and backfilled with coarse-textured material, were shown to incorrectly measure net percolation for a large majority of typical field conditions as a result of the creation of a capillary break by the 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 modelled, 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 mine 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. It is fundamental to realise 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.

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