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Evapotranspiration cover systems over hazardous mine waste should hold and evaporate all precipitation. Analysis of replicates of two cover designs showed heterogeneity in cover materials and hence water flow, which resulted in seepage into the hazardous material below, challenging the common assumption of hydrologic uniformity within covers.

Evaluation of the Heterogeneity of Constructed Landforms for Rehabilitation Using Lysimeters

Rainfall ingress into sulfidic rocks or tailings from metalliferous mining operations can result in acid mine drainage. Waste rock cover systems in semiarid areas are commonly designed to retain all precipitated water within benign material, from where it is removed by evapotranspiration. The long-term effectiveness of covers is often predicted from models that are based on data obtained from single trial plots assuming that the trials are homogeneous and representative of large areas. Two cover designs were tested in semiarid monsoonal northwest Queensland: (i) 1.5 m of unconsolidated waste rock overlying 0.5 m of consolidated waste rock; and (ii) 2.0 m of unconsolidated benign waste rock. Three identical plots comprised each treatment in which water balance equation parameters were estimated from meteorological measurements and vertical arrays of soil suction and moisture sensors and seepage collection using a 3-m-deep lysimeter inserted in the waste rock. In a wet season with 900 mm of precipitation, water movement through the covers was followed through changes in moisture content, suction, and seepage. Greater differences in these parameters occurred within than between cover treatments. Water retention and water movement varied substantially and seepage ranged from 2 to 80% of total rainfall. The internal heterogeneity of hydraulic properties had more effect on cover performance than did the initial cover design. Therefore, it is important to include internal heterogeneity in mine waste cover water balance models to improve their applicability.

Abbreviations: ET, evapotranspirative; NAF, non-acid-forming; PAF, potentially acid forming; PSD, particle size distribution; WRC, water retention curve.

Mining can often result in hazardous or potentially hazardous byproducts such as waste rock from the extraction of the ore and fine-grained residues (tailings) from the processing of the ore. The exposure of potentially acid-forming (PAF) sulfidic waste rock to O\(_2\) and water can result in acidic or metal-contaminated drainage waters. Tailings can contain high concentrations of heavy metals or sulfides and seepage from these systems can also be highly contaminated (Lottermoser, 2007). Infiltration of precipitation into the waste material can result in the leaching of hazardous substances into adjacent environments. For mine lease relinquishment, mining companies are required to prevent any potential contamination of the surrounding environment.

In semiarid environments, evapotranspirative covers (ET covers) have been proposed to prevent the ingress of water to hazardous mine wastes (Hauser et al., 2001; Mine Environment Neutral Drainage Program, 2004; Fourie and Tibbett, 2007). The aim of an ET cover system is to retain precipitation within the benign cover material, thus preventing it from either running off the surface or percolating through the base of the cover by deep drainage and reacting with the underlying hazardous waste. Stored rainwater is then removed from the cover through evaporation and transpiration (Mine Environment Neutral Drainage Program, 2004). Mine site cover systems generally consist of benign waste rock, which overlies waste rock dumps or tailings. The required thickness of the benign non-acid-forming (NAF) waste rock layer is largely determined by the site, climate (especially rainfall), and the particle size distribution of the cover material itself. Other design features of the cover may include a compacted layer directly overlying the hazardous waste. The theory of ET cover systems is based on the water balance equation:

\[
L = P - Q - \Delta S - (EV + T)
\]  

[1]
where \( L \) is seepage, \( P \) is precipitation, \( Q \) is runoff, \( \Delta S \) is the change in moisture content of the cover material, \( EV \) is evaporation, and \( T \) is transpiration.

**Cover performance** is the term used to reflect the success of the cover design, which may be expressed by evidence of minimal percolation of water through NAF material into PAF material. The effectiveness of ET covers is commonly tested by the installation of a range of sensors within the cover systems and monitoring of the sensor output (Mileczarek et al., 2003; O’Kane and Waters, 2003; Taylor et al., 2003; Meiers et al., 2009). Generally, the performances of different cover designs are compared by measuring \( L, P, Q, \) and \( \Delta S \) at one location per design type, assuming that the properties of the cover materials and the physical characteristics of each component of the cover system are uniform within each design under test. Information from such instrumented experimental trials serves as input data for models to predict long-term cover performance (Zornberg et al., 2003; Scanlon et al., 2005; Bohnhoff et al., 2009). While recent attempts have been made to introduce parametric uncertainties into models (Young et al., 2006), the spatial heterogeneity of material physical properties and water movement in cover systems has rarely been addressed in cover trials or models.

The Alternative Cover Assessment Program (ACAP) in the United States compares runoff, lateral drainage, and percolation of different municipal waste landfill cover designs across a range of climatic conditions. At each site, however, only one cover of a specific design is tested (Albright et al., 2004). Material commonly used for landfill covers is relatively fine grained, with a narrow particle size distribution compared with the material used for waste rock cover systems. Therefore, landfill cover material is likely to be relatively homogenous and does not result in significant structural differences within a cover. The water-holding capacities of covers compared by Scanlon et al. (2005) varied only slightly and Fayer and Gee (2006) found differences in seepage only through unvegetated covers under irrigation that simulated increased precipitation.

In contrast to cover materials used for municipal waste landfills, the materials used to construct covers for mine wastes are much more heterogeneous. Because benign waste rock is commonly used as cover material, its material size distribution depends strongly on the blasting force and state of weathering of the bedrock. Furthermore, the coarse nature of the material is likely to result in high heterogeneity of soil physical properties within a cover system, even if a consistent construction technique is used. Research in natural or agricultural environments has shown the ambivalent influence of stones in soils. The amount of rainfall that infiltrates into a soil depends strongly on the stone cover percentage and the position of stones in the cover, i.e., embedded, partly embedded, or lying on the surface (Poesen et al., 1990; Abrahams and Parsons, 1991; Poesen and Ingelmo-Sanchez, 1992; Poesen and Lavee, 1994; Ma and Shao, 2008). Saturated hydraulic conductivity is generally enhanced by increased stone content (Sauer and Logsdon, 2002; Verbist et al., 2009); however, above a certain percentage of stones, the reduction of total fine earth and the increase in tortuosity can result in a decreasing saturated hydraulic conductivity (Verbist et al., 2009). The water-holding capacity can be enhanced or reduced by stones, depending on the bulk density, the percentage of fine earth, and the moisture contents of the material (Magier and Ravina, 1984; Kosmas et al., 1994; Oyonarte et al., 1998; Fies et al., 2002; Baetens et al., 2009). On the other hand, the presence of stones will increase the macroporosity and therefore decrease the water-holding capacity, especially at low water potentials (van Wesemael et al., 1996). Generally, the presence of stones inhibits evaporation due to the sheltering of fine earth from solar radiation and wind and by creating macro pores that inhibit unsaturated water transport to the soil surface (Kosmas et al., 1994; Poesen and Lavee, 1994; Sauer and Logsdon, 2002; Katra et al., 2008; Verbist et al., 2009). The influence of stones on the soil surface on evaporation is in essence identical to the effects of a typical stone mulch layer (Danalatos et al., 1995).

Considering the broad variety of effects that stones can have on hydraulic properties, it is likely that the varying contribution of stones in mining waste covers will lead to high variability in the physical properties of the cover material. This will result in variation in the storage capacity and hydraulic conductivity. Despite this, the performances of different cover designs have commonly been compared using single-point measurements and it has been assumed that the trial covers are structurally homogeneous within any one design (Madalinski et al., 2003; O’Kane and Waters, 2003; Williams et al., 2003; O’Kane et al., 2006). Only recently, Meiers et al. (2009) recognized the problem of heterogeneity in mine waste covers. Rohde and Williams (2009) observed highly variable infiltration on an uncovered waste rock dump. These results are applicable to substrates with similar origin, such as material for waste rock cover systems. To achieve a greater certainty of the success from extensive cover systems, the problem of heterogeneity should be addressed in initial trials of intended ET cover designs.

The aim of the current study was to compare the variation in cover performance both within and between two ET cover designs during a period of unusually high wet-season rainfall in semiarid northern Australia.

**Material and Methods Field Site**

The study site is located at Mt. Isa in northwest Queensland, Australia (20°44′ S, 139°30′ E). The area is classified as BSh (B = arid, S = steppe, h = hot arid) in the Köppen–Geiger classification (Kottek et al., 2006). The mean annual minimum and maximum temperatures are 11.6°C and 37.3°C, respectively (Bureau of Meteorology, 2009b). The long-term average annual rainfall of the area is 420 mm, but rainfall is highly erratic. During 77 yr of
records since 1932, the annual rainfall fluctuated between 105 mm in 1970 and 871 mm in 1950. Three-quarters of the annual precipitation occurs in the summer, mainly between December and March, but varies greatly, from 78.0 mm in 1985–1986 to 798.3 mm in 1996–1997. Most summer rainfall events are high-intensity storms (Bureau of Meteorology, 2009b).

Test Plot Description

Test Plot Design

The test plots were constructed of NAF material on top of a 10-m-high, traffic-compacted, PAF waste rock dump. A nested design used two cover treatments, each with three replicates. The cover treatments were 20- by 60-m areas constructed from: (i) 0.5 m of compacted NAF material, overlaid by 1.5 m of uncompacted NAF material (Treatment C); and (ii) 2.0 m of uncompacted NAF material (Treatment U).

The treatment plots were built in the same way as a large-scale cover system for a waste rock dump or tailings facility. Compaction of the 0.5-m layer in Treatment C was achieved by the passage of a bulldozer (Caterpillar D10, Caterpillar Inc., East Peoria, IL) until a sufficiently even surface was obtained. The cover material was applied in one lift through paddock dumping with haul trucks (Caterpillar 777D and 785C). Thereafter, the material was leveled out by an excavator (Hitachi ZX330LC, Hitachi Construction Machinery, Tsuchiura City, Japan) and the sides of the plots were brought to an even slope. All the waste rock originated from 300 m below the surface. Because only 12.2 mm of rainfall was received in the 7 mo before construction of the plots (Bureau of Meteorology, 2010), similar initial moisture conditions of the cover material for all treatment plots could be assumed.

Material Characterization

The particle size distribution (PSD) for the NAF material was determined on five and six samples from the compacted and uncompacted treatment plots, respectively. In the laboratory, the PSD was determined as percentages by weight of the material fractions. The PAF material had a higher content of finer material, but still consisted of almost 60% of gravel. The cover material (NAF) had a fraction of coarse material (>2 mm) of approximately 75% (Table 1).

The water retention curve (WRC) was determined using representative samples from subsamples of all treatments. Only fine material (<2 mm) was used for the tests in the laboratory. For this purpose, the NAF waste was sieved (<2 mm) and a soil water retention curve was established from this fraction. Soil suction values between 1 and 3 kPa were measured by gravitational drainage on a sand bath; vacuum pressure plates were used between 10 and 50 kPa, and one desiccation value (1000 kPa) was determined with a pressure pot (Klute, 1986).

<table>
<thead>
<tr>
<th>Particle size</th>
<th>PAF ($n=5$)</th>
<th>C ($n=5$)</th>
<th>U ($n=6$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silt and clay (&lt;0.075 mm)</td>
<td>14.4</td>
<td>7.5</td>
<td>2.8</td>
</tr>
<tr>
<td>Sand (0.075–2.00 mm)</td>
<td>27.0</td>
<td>8.0</td>
<td>22.2</td>
</tr>
<tr>
<td>Gravel (&gt;2.00 mm)</td>
<td>58.6</td>
<td>15.2</td>
<td>75.0</td>
</tr>
</tbody>
</table>

Coarse waste rock cover material is characterized by two independent pore systems. One is determined by the textural pore system of the fine material and its particle size distribution. The other is strongly characterized by particles >2 mm, their percentage contribution to the total material volume, and their size distribution and shape. In particular, at rock contents where the packing density is determined by the number of possible contact points between the rocks, compared with rocks embedded in fine material, a macropore system unrelated to the fine material pore system will be typical. This will lead to a heterogeneous pore size distribution with distinctively different pore size classes. The WRC of a stony soil may not be described correctly by the unimodal van Genuchten function, which was developed for soils with a normally distributed PSD (Durner, 1994). A bimodal WRC function (Durner, 1994; Zhang and Fredlund, 2003) can be more suitable to estimate water-holding characteristics in such cases. Durner (1994) suggested deriving a bimodal WRC through the weighted sum of WRCs for different pore systems. Based on the PSD and soil water retention, a bimodal water retention curve was established for the heterogeneous waste rock following Durner (1994).

Instrumentation

Each plot was subdivided into three identically instrumented 20-by 20-m subplots (Fig. 1). The treatment areas were constructed...
and lysimeters and most sensor arrays were installed in October 2008 and additional sensors were installed in early December 2008.

Each subplot was instrumented identically. A lysimeter, consisting of an open-top rainwater tank (3.0-m height, 3.0-m diameter), was placed in the PAF waste, approximately at the center of each subplot. The top of the lysimeter was level with the PAF surface (Fig. 2). A biaxial drainage net (Flownet, Geofabrics Australasia Pty Ltd, North Albury, NSW) was placed at the bottom of the lysimeter, covered by a geotextile liner (bidim, Geofabrics Australasia Pty Ltd) and a thin layer of washed sand. Thereafter, the lysimeter was backfilled with PAF material in approximately 0.5-m lifts. After each lift, the material was leveled by hand and compacted with a vibrating plate compactor (MVC 82 Mikasa Plate Compactor, Multiquip Inc., Carson, CA) to achieve the same bulk density as before the excavation. The outside and inside of the lysimeter were backfilled alternately. The discharge point from each lysimeter was connected to a calibrated tipping bucket flow gauge (Model 6506G, Unidata Pty Ltd, Perth, WA, Australia) through a polyvinyl chloride pipe with a slope of approximately 2%.

Six water content reflectometers (Model CS616, Campbell Scientific, Logan, UT) and 16 matric water potential sensors (229-L, Campbell Scientific) were installed from the bottom of each lysimeter (approximately 4.8 m below the final surface) to approximately 0.5 m beneath the NAF cover surface during the process of backfilling. Sensors were placed to provide detailed data at the boundaries of the cover, compacted layer, and waste material (Fig. 2).

To ensure optimal contact between the sensors and the waste material, the matric water potential sensors were placed in sieved waste material (<4 mm). Water content reflectometers were precalibrated for waste rock material and installed so as to avoid cavities between the sensor and the material. In some cases, this led to finer material around the sensors compared with the particle size distribution of the waste. Additional sensors were installed in early December 2008, requiring localized disturbance to approximately the 1.0-m depth.

A weather station measuring rainfall (Campbell Scientific CS 700-L), air temperature, and humidity (Vaisala Model HMP45C, Vaisala Oyi, Helsinki), wind speed (Wind Sentry Anemometer 03101-L, R.M. Young Co., Traverse City, MI) and net radiation (NR-Lite-L, Kipp and Zonen, Delft, the Netherlands) was located 500 m from the experimental area (Fig. 1). All sensors and the datalogger were acquired from Campbell Scientific.

**Calibration of Matric Potential Sensors**

The matric potential sensors operate on the principle of heat dissipation, which is an indirect method to establish soil suction. The sensors consist of a porous ceramic medium that encloses a heating element and a thermocouple. The ceramic medium is in moisture equilibrium with the soil. A heat pulse is sent to the heating element and the increase in temperature for a given time step is recorded. The temperature increase ($\Delta Temp$) is determined by the moisture content of the ceramic, which influences its thermal conductivity.

To transform the recorded change in temperature ($\Delta Temp$) to soil suction, each sensor has to be calibrated individually and basically reflect the water retention curve of the sensor related to heat dissipation. Calibration curves have a shape similar to the algorithms describing the functional relationships of soil water retention curves. For this purpose, the Fredlund equation (Fredlund and Xing, 1994) was used, substituting soil moisture with soil temperature values:

$$\Delta Temp = \Delta Temp_{\text{Min}} - \Delta Temp_{\text{Max}} - \Delta Temp_{\text{Min}} \ln \left( e + \left( \frac{\psi}{\alpha} \right)^n \right)^m$$

[2]

where $\Delta Temp$ is the change in soil temperature, $\Delta Temp_{\text{Max}}$ is the maximum point on the calibration curve, $\Delta Temp_{\text{Min}}$ is the minimum point on the calibration curve, $\psi$ is soil suction, and $\alpha$, $n$, and $m$ are curve-fitting parameters.

This can be solved for soil suction:

$$\psi = \alpha \left( \exp \left( \frac{\Delta Temp_{\text{Max}} - \Delta Temp_{\text{Min}}}{\Delta Temp - \Delta Temp_{\text{Min}}} \right)^{1/m} - e \right)^{1/n}$$

[3]

The parameters $\alpha$, $n$, and $m$ were derived iteratively with the SOLVER procedure in Microsoft Excel 2007 using Eq. [2]. Modeled and measured calibration curves were in close agreement.
(Fig. 3), which allows the assumption of accurately calculated soil suction values. This algorithm has the advantage of being asymmetrical, resulting in an improved fitted curve compared with the van Genuchten equation (van Genuchten, 1980).

Results and Discussion

Field Data Recovery

Data were collected for the time period 5 Dec. 2008 to 25 Mar. 2009. Two of the six subplots (C1 and U2) encountered initial problems with recharging of the datalogger battery and hence the data from these two were only recorded when sufficient solar radiation was received by the solar panels. The results from these plots were not taken into account in the following analyses because data were not recorded at times of heavy rainfall events. At the four remaining subplots, soil suction and soil moisture data were logged every 4 h. Lysimeter drainage was recorded as the sum of tips per day and was recorded at midnight.

No seepage was recorded on any subplot from 13 to 24 Jan. 2009. During these 10 d, a total of 253 mm of rainfall was recorded, with daily rainfall of 37, 48, and 50 mm on 20, 21, and 22 January, respectively. As the soil suction and soil moisture sensors were operating satisfactorily during this time, we concluded that the tipping buckets were not functioning correctly, the cause being unknown.

Precipitation

The wet season of 2008–2009 started in early December 2008 and ended in the second week of February 2009. No significant precipitation was received in March 2009. In total, 916 mm of rainfall was recorded during 67 d. This total was higher than that for the Bureau of Meteorology Mt. Isa site located 3 km away, which recorded 668 mm. The Bureau of Meteorology rainfall for January 2009 was the highest for that month since measurements commenced in 1932. Overall, the wet season of 2008–2009 was the third wettest recorded at Mt. Isa (Bureau of Meteorology, 2009a).

The right skewness of Fig. 4 reflects the slightly higher probability that wet seasons will have a total rainfall below than above 300 mm. In 13% of years, however, it is probable that the rainfall for the months from December to March inclusive will exceed the long-term annual average rainfall of 420 mm (Fig. 4).

Soil Water Retention Curve

Water retention curves of substrates with a high proportion of stones and coarse pores are difficult to determine. An approximation of the total pore volume was used by differentiating between fine material (<2 mm) and stones. For the NAF material, the WRC of the material <2 mm was measured as described above. The shape of the WRC resembles that of a silty sand, with a total pore volume of approximately 35% (v/v) and a field capacity (at 10-kPa desiccation) of approximately 17% (v/v). Drying of the laboratory-filled soil cores after saturation of the sample caused shrinkage and a reduction of the total pore volume by approximately 5% (v/v). The van Genuchten parameters \( \alpha \) and \( n \) were determined to be 0.106 and 1.28, respectively. The approximation of the actual WRC of the bulk material (consisting of stones (>2 mm)) and fine material (<2 mm) is based on the ratio of the mass of fine material (<2 mm) to the mass of coarse rocks (>2 mm), which has a ratio of approximately 1:3 (from Table 1). It was assumed that only the fine material proportion was able to store water, while the rest consisted of competent rocks with no significant capacity to take up

Fig. 3. Experimental calibration data for Campbell Scientific Model 229-L matric potential sensors (solid circles) and a calibration curve modeled with the Fredlund and Xing (1994) equation (open circles).

Fig. 4. Frequency distribution of wet season rainfall (December–April) from 77 yr of records at Mt. Isa, Queensland, Australia (data from Bureau of Meteorology, 2009a).
and store water other than as superficial water films. A number of nuclear densitometer tests indicated that the bulk density of the material was 1.9 Mg/m³. Hence, the total pore volume of the bulk material of the NAF was calculated to be approximately 27% (v/v) based on the assumption that the porphyry-rich waste rock had a particle density of approximately 2.6 Mg/m³. For each fraction of the fine and coarse solids, the relative volume was calculated using the particle density. The ratio of the unknown relative pore volume ($r_{PV}$) to the total volume, i.e., the sum of the solid volumes ($V_c$ and $V_f$), and the unknown $r_{PV}$ was calculated using

$$PV_t = \frac{r_{PV}}{V_c + V_f + r_{PV}}$$  \[4\]

and resulted in a total pore volume ($PV_t$) of 27%. The value of $PV_t$ was calculated from the bulk density measurements with the densitometer.

Rearrangement of Eq. [4] enabled calculation of the rPV. The average value of $V_f$ and its pore volume relative to the total volume was 0.32, which represented the proportional contribution of the <2-mm material, including pores, to the WRC as it was measured in the laboratory. This means that the WRC determined in the laboratory using the <2-mm fraction had to be normalized using this factor. The pore volume of approximately 35% from the laboratory tests was multiplied by 0.32 to obtain the fractional pore volume of approximately 12% (v/v) of the fines in relation to the total volume (see Fig. 5). The difference between this volume and the calculated pore volume from the densitometer tests was attributed to the coarse pore volume, which resulted from the combination of fines and coarse material. The significance of macropores in the NAF cover material is shown in Fig. 5 through the marked decrease in water content between saturation (in Fig. 5 equivalent to 10⁻² kPa) and 5 kPa. The water-holding capacity of the cover material was moderately low, with a volumetric soil moisture content at field capacity (10 kPa) of 6% (Fig. 5). Combining the WRCs of the macropores and fine pores yielded the actual total pore volume.

Based on Fig. 5, a theoretical maximum of 148 mm of water could be stored at field capacity in the 2.0-m cover system. Based on the PSDs of the NAF and PAF materials and the derived total pore volumes of approximately 25% for NAF and 38% (v/v) for PAF, it was assumed that approximately 50% more moisture could be stored in the PAF than the NAF. Therefore, a storage capacity of approximately 330 mm was assumed for the potentially hazardous waste, which means that the whole NAF and PAF system had a storage capacity of approximately 480 mm throughout the 5-m depth of the lysimeters.

**Soil Suction Measurements**

The first seasonal rain event occurred a few days after the installation of the sensors. The soil suction sensors responded quickly to the rainfall events. The first major rain event on 7 Dec. 2008 (27 mm) triggered different responses among the four subplots. Percolation of rainfall proceeded quickly and to approximately the same depth in the uncompacted treatment plots (U1, 1.0 m; U3, 1.1 m) (Fig. 6d and 6e). In the compacted treatment, however, the depth of percolation ranged from 1.1 m (C3) to 2.0 m (C2), which perhaps indicated a highly heterogeneous flow in this cover treatment (Fig. 6b and 6c).

The term heterogeneity refers to variation in material characteristics in a layer that should be identical to the same layer of the same cover design, e.g., between each of the 1.5 m of uncompacted material of the compacted treatment subplots.

Progressive drying from the surface followed this first rain event and there was no evidence of penetration of water into the underlying PAF waste material in either treatment.

A second rain event, with a total of about 20 mm during 2 d (25–26 Dec. 2008) (Fig. 6) resulted in rewetting of the top 1 m of cover in Subplot U1 (Fig. 6d) but to not much more than 0.5 m in the other three plots (Fig. 6b, 6c, and 6e).

Heavy rain commenced in early January (1–8 Jan. 2009) and the responses of the cover subplots varied widely. In the compacted treatment, rainwater percolated into the PAF material after 151 mm of cumulative rainfall at C2, whereas in Subplot C3 a pronounced decrease in soil suction was registered in the PAF material after 99 mm of cumulative rainfall (Fig. 6b and 6c). In the uncompacted treatment, water reached the PAF material.
after 108 and 140 mm of cumulative rainfall on Subplots U3 and U1, respectively (Fig. 6d and 6e). In addition, the advancement of moisture within the cover and waste systems varied distinctly. In Subplot C2, progressive wetting of the waste material can be seen from the beginning of January 2009 (Fig. 6a), while in Subplot C3 there was almost immediate wetting (within one 4-h measurement period) of the waste to the bottom of the lysimeter (Fig. 6b). Subplots U1 and U3 showed a progressive advance of the wetting fronts through the waste material but at different rates. Water was registered at the deepest suction sensor after 207 mm at C3 (3 Jan. 2009), 319 mm at U3 (11 Jan. 2009), 498 mm at C2 (21 Jan. 2009), and 505 mm at U1 (22 Jan. 2009) (Fig. 6d, 6c, 6d, and 6e).

The rapid advancement of water in Subplot C3 on 1 and 2 Jan. 2009 can be attributed to macropore flow. Indications of preferential flow paths can be seen in both subplots of the compacted treatment. The deepest suction sensor in Subplot C2 recorded the advancing moisture 3 d before the sensor immediately above it. The pronounced decrease in soil suction at 2.1 m in Subplot C3 in the absence of similar changes between 1.1 and 2.1 m (Fig. 6c) indicates preferential flow in this subplot.

Preferential macropore flow is a common problem in covers constructed from benign waste rock, and its likelihood increases with an increasing percentage of large rocks and boulders (O’Kane Consultants, 2003). Furthermore, the different behaviors of fine material and stones in the wetting and drying processes can lead to detachment of fine particles from rocks and result in macropore creation (Poesen and Lavee, 1994). In the current study, mobilized particles could potentially be transported without undue inhibition into the coarse-pored underlying PAF waste rock. Initial shrinkage of the fines in the unconsolidated substrate after the first saturation may result in a reorganization of pores within the material, leading to a higher proportion of coarse pores and a decrease in the proportion of medium pores. An increase in the proportion of coarse pores under these conditions is not unlikely because only the fines between the rocks can change in volume while the rocks remain in their initial position, which is determined by the number of possible contact points. The development of preferential flow paths is an undesired occurrence and needs to be considered when assessing cover performance. The porosity of rocks used for the cover material was very low and it was a valid assumption that water storage within the rocks was low. In view of the above findings and interpretation, it is not unlikely that the differences in water storage and the rate of water movement in

Fig. 6. (a) Cumulative rainfall and time courses of soil suction (log_{10} kPa) profiles during the course of the wet season December 2008 to March 2009 on Subplots (b) C2, (c) C3, (d) U1, and (e) U3. The color scale bar at the right indicates the logarithm of soil suction.
the other three subplots (C2, U1, and U3) were also contributed to by small-scale differences in the amount of fine earth and the bulk density of the fine earth, the uniformity of PSDs, and hence the pore size distribution.

**Soil Moisture**

As with soil suction, soil moisture content readings generally responded promptly to advancing wetting fronts (Fig. 7). Water content reflectometers have been found to overestimate moisture because the electromagnetic field tends to preferentially penetrate moister areas (Logsdon, 2009). Therefore, moisture readings after a daily rain event of >35 mm were excluded from the analysis. These time periods are indicated by striped bars in Fig. 7.

The existence of preferential flow paths is also evident from the soil moisture readings. In Subplot C3 (Fig. 7c) following the first rain event on 7 Dec. 2008, rapid moisture content increases occurred at the 0.2-, 0.7-, and 2.1-m depths, whereas at 1.5 m, an increase in moisture was not recorded until the beginning of January 2009 (Fig. 7c). As with the suction readings, the lowest moisture sensor at C2 (4.8 m) recorded an increase in water content before the nearest overlying sensor at 3.8 m (Fig. 7b).

Like the soil suction values, soil moisture contents varied substantially between subplots, and the time when water reached a particular depth varied (Fig. 6). For both characteristics, this variation might be due to differences between subplots in the proportions of fine material or differences in bulk density despite the attention to placement of material.

The water contents at saturation slightly exceeded 40%, compared with the previously calculated maximum value of approximately 25%. This higher value was probably due to the positioning of the water content sensors in mainly finer material. As the laboratory WRC showed, the porosity for the finer material was approximately 35% and within the range of the measured water contents.
Seepage

The seepage rates from the four lysimeters were quite different (Fig. 8). Cumulative seepage totals to the end of March 2009 ranged from 21 mm (U1) to 736 mm (C3). Seepage from both of the covers incorporating a 0.5-m compacted layer was greater than from the plots without a compaction zone; however, the differences among the subplots within the same cover design were also very pronounced. Differences in seepage between the pairs of treatment plots were approximately 310 mm for the compacted and almost 200 mm for the uncompacted treatment (Fig. 8). Given the same boundary conditions of the treatments, this result indicates clearly that seepage is an important quantifying indicator for the description of material physical heterogeneity within the cover systems.

The amount of rainfall stored within the combined NAF cover and PAF waste material before the occurrence of seepage ranged from 207 mm (C3) to 505 mm (U1) (Fig. 8). From the four subplots under consideration, only U1 showed drainage from the lysimeter of <5% of rainfall. The amount of water seeping out of the remaining three plots (25, 47, and 80% from Subplots U3, C2, and C3, respectively) exceeded values usually accepted by stakeholders by a large margin. High seepage from C3 can be attributed to macropore flow through the cover, as discussed above (Fig. 8). Seepage was first registered after 236 mm of cumulative rainfall, whereas the storage capacity of the whole system, NAF and PAF material combined, was estimated at 480 mm, supporting this assumed attribution. After the wet season, this subplot showed a very pronounced concave depression at the surface, which is a visual indication of the existence of a number of macropores that partly consolidated. Because seepage continued to be exceptionally high in this subplot throughout the whole wet season (Fig. 8), it can be assumed that besides the consolidation, macropore flow constituted an important factor in this subplot. Preferential flow in the hazardous waste of Subplot C2 may have resulted in higher seepage than in the subplots of the uncompacted treatment. Figure 6d indicates an additional barrier at the 1.1-m depth for Subplot U1. The material between 1.1 and 2.5 m was considerably drier than the layers above or below. After the storm events in early January 2009, no additional water seemed to percolate through the layer at the 1.1 m in Subplot U1, which resulted in no further seepage even though the PAF waste material between 2.5 and 5.0 m was at or close to field capacity (Fig. 6c).

Change in Storage

The change in storage for the subplots was determined through the water balance equation (Eq. [1]) with runoff assumed to be zero. Transpiration (T) was set to zero because the cover trials were devoid of vegetation. The change in soil moisture (\(\Delta S\)) was calculated from the total amount of water (S) in the whole system (5 m). For each consecutive day, the change in water storage (\(\Delta S\)) was determined as the difference between the total amounts of water on the day in question and on the previous day. As the deepest moisture sensor in Subplot C1 did not function, \(\Delta S\) could not be calculated satisfactorily for this subplot. Therefore, the water balance equation could not be adequately completed and the subplot was excluded from further consideration.

As mentioned above for the soil moisture content, reflectometers tend to overestimate moisture due to the preferential penetration of wet zones by the electromagnetic field (Logsdon, 2009). Therefore, moisture readings directly after a heavy rain event (>35 mm of daily rainfall) were eliminated (see striped bars in Fig. 9). Time periods when the change in storage could not be calculated due to deliberate elimination of moisture values or the failure of seepage recordings are marked with striped and dotted bars, respectively (Fig. 9).

Like the aforementioned parameters, the calculated evaporation illustrates the internal heterogeneity between the subplots (Fig. 9). This is especially evident in the time period from the end of February up to the end of March. In this month, only one minor rainfall event occurred (0.254 mm on 11 Mar. 2009), therefore providing an opportunity for continuous drying of the upper surface material. Furthermore, due to heavy rainfall at the end of February, moisture conditions near the surface should have been close to field capacity. Generally, evaporation at U3 exceeded that of the other two subplots (Fig. 9c) but was most different from U1, which had the lowest calculated evaporation of the three.
considered (Fig. 9b). Evaporation from the subplot with the 0.5-m compacted layer (C3) was between that recorded from the two subplots with 2.0 m of uncompacted material (Fig. 9a). Therefore, the different evaporation rates cannot be attributed to differences in cover design. It is more likely that different water retention curves resulting in different unsaturated hydraulic conductivities due to random distribution of fine material were the main drivers for evaporation from the subplots. For a macroporous material, it can be expected that the intensity and depth of drying will be reduced and the delivery of water for evaporation from lower depths will be limited. It is unclear, though, which role water vapor flow will play as a factor for evaporation under the prevailing climatic and soil physical conditions.

**Conclusions**

All of the monitored parameters clearly showed a high internal heterogeneity among all of the subplots. These differences have substantial effects on the water storage capacity and amounts of deep drainage.

The high variability of the material used on mine sites to construct barriers to minimize water ingress into hazardous waste creates a high level of uncertainty for predicting performance success. This uncertainty is very likely to be caused by macropore flow.

To be able to accurately predict long-term cover performance, a finer grained, more homogenous cover material needs to be sourced. For the success of the covers themselves, there needs to be a high degree of quality assurance in material selection and the way in which that material is used through the construction of the covers. This should lead to a design that minimizes both preferential flow and variations in water retention or hydraulic conductivity, and ultimately the risk of uncontrolled flow of contaminated drainage water off site. While the procurement, protection, and placement of the “ideal” cover material for many mine sites may not be seen as a financially feasible option in the short term, the cost of the consequences of not investing in such preventive measures...
approaches will, in the long term, be a far greater financial liability. Early characterization of potentially useful materials, early planning for closure, and efficient and rigorous separate management and stockpiling of appropriate and adequate cover materials throughout the mine life could result in the availability of more homogenous material with properties that would result in a more successful and lower risk outcome.

There is a question as to whether the current industry practice of testing cover designs by single installations and extrapolating the results through numerical modeling to landscape scales and long-term time periods is adequate for predicting water flow and water balance parameters. A statistical approach combined with a risk assessment of the likelihood and quantification of failure of a cover design might give a better understanding of the hydrologic behavior of covers. Further research is needed to attain a greater certainty in predicting long-term cover performance in order for mining companies to plan for safe and sustainable closure.

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