DESIGNING EFFECTIVE STORE-RELEASE COVERS FOR THE LONG-TERM CONTAINMENT OF MINE WASTE – THE ROLE OF VEGETATION (STAGE 2)

Project summary report for the investigations at the trial sites Mt Isa and Cobar by:

Research team: The University of Queensland
Centre for Mined Land Rehabilitation
The University of Queensland

Contact:
Thomas Baumgartl  t.baumgartl@uq.edu.au
David Mulligan  d.mulligan@uq.edu.au
David Doley  d.doley@uq.edu.au

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The research team consisted of the following research groups and advisors:

*The University of Queensland*

Thomas Baumgartl, David Doley, David Mulligan, Anne Schneider (PhD student)

*The University of Western Australia*

Christoph Hinz, Erik Veneklaas, Tim Bleby, Willis Gwenzi (PhD student)

*The University of Technology Sydney*

Derek Eamus, Isa Yunusa (Postdoctoral fellow)

Advisors

Mike O’Kane (OKC)

Ward Wilson (UBC)
DESIGNING EFFECTIVE STORE-RELEASE COVERS FOR THE LONG-TERM CONTAINMENT OF MINE WASTE – THE ROLE OF VEGETATION (STAGE 2)

- Research outcomes from investigations at the trial sites Mt Isa and Cobar -

Executive Summary
In arid and semi-arid environments evapotranspiration (ET) cover systems are widely suggested as a viable method to mitigate the occurrence of (contaminated) seepage from hazardous mine waste into the adjacent environment. The theory of ET covers is based on the water balance equation with the aim of minimising seepage with the objective to influence the design of key parameters of the water balance equation. Vegetation can play an important role to influence the water balance and improve the performance of ET covers.

The performance of two ET cover trials constructed from benign waste rock in Mount Isa and Cobar has been investigated. The water balance equation parameters and their variability was analysed over a period of three years. The investigations showed, that seasonal and inter-annual variations in rainfall critically influence cover performance. For successful cover system operation, the return periods for higher than average rainfall must be taken into account. In addition, failure of ET covers is more likely in areas with marked rainfall seasonality. Water holding capacity and plant available water content are low in covers constructed from waste rock. Changes in water holding capacity due to variation in particle size distribution are likely and critically influence cover performance. The application of topsoil can be beneficial for water ingress control through runoff, but a balance has to be struck between runoff, erosion and plant available water. Changes in vegetation composition only influence evapotranspiration water losses at plant coverage exceeding 50 %, which is unrealistic in semi-arid areas.

The outcome of the project showed that the capacity of cover systems designed as evapotranspiration covers (also known as store-and-release covers) to hold and dispose of received rainfall is strongly dependent on materials and climate. Its function can be greatly affected by preferential water flow in cover materials which contain rocks, so their effectiveness can be limited, even in semi-arid and arid environments. Vegetation has a major impact on the extraction of water only in climatic settings where precipitation is sufficient
and relatively uniformly distributed, and where the cover material provides sufficient storage for successive precipitation events.

In order to improve the reliability of long term cover performance, the variability of rainfall and water holding capacity of the cover have to be analysed carefully through water balance analysis and numerical modelling. Changes in cover properties over time are likely and only mid- to long-term monitoring can provide confidence in the performance of waste covers.

1.0 Introduction

Mining activities result in the production of waste rock materials and tailings materials, both of which, depending on geology and processing methodology, can be hazardous to the adjacent natural environment (Lottermoser, 2007). For mine site relinquishment, contamination of the natural environment by mining waste has to be prevented.

Common practice for the to minimisation of water ingress into hazardous waste, and consequent seepage of contaminated water into the environment, is to isolate the hazardous waste by enclosing it within a cover system (INAP: The International Network for Acid Prevention, 2011). In arid and semi-arid areas evapotranspiration cover systems are often proposed as a suitable method to minimise rainfall percolation into waste material (O'Kane Consultants Inc., 2004, Williams, 2011, Wilson et al., 2003).

Evapotranspiration cover designs are based on the principle of the water balance equation (Eq.1)

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

With \( L \) = seepage (mm), \( P \) = precipitation (mm), \( Q \) = runoff (mm), \( \Delta S \) = change in moisture storage (mm), \( EV \) = evaporation (mm) and \( T \) = transpiration (mm).

Evaporation and transpiration are often combined into the term evapotranspiration (ET), giving the cover type assessed in this project its name.

The evapotranspiration cover method was developed in the 1980’s with the first cover system trialled in Australia soon after (Taylor et al., 2003). Cover systems are now being tested on
mine sites in arid and semi-arid areas all over the world (Bohnhoff et al., 2009, Milczarek et al., 2003, O’Kane, 2011, Urrutia et al., 2011).

Water balance parameters measured in these small or medium scale cover trials are used to model long term cover performance. In recent years, attention has been drawn to the analysis of the variability of water balance parameters (Meiers et al., 2009, Schneider et al., 2010). However, up to date studies acknowledging the alteration of properties with time are limited and variability is widely ignored in cover performance modelling.

In this project report the results of investigations from the Stage 2 trial, East Coast sites (Cobar and Mt Isa) are summarised and discussed. Parameters of the water balance equation, their sensitivity to variability and their importance for successful cover performance are discussed in depth and recommendations for future cover design are suggested.

2.0 Material and Methods
For this project two field sites were selected, namely Mt Isa in Queensland and Cobar in New South Wales. Both sites are located in semi-arid Australia and have a similar long term annual rainfall of approximately 400 mm. The main climatic difference between the sites is that the Mt Isa site is situated in an area with distinct wet/dry seasonality, while at Cobar rainfall occurs without seasonal variation.

2.1 Mt Isa
2.1.1 Climate
The study site was located at Mt Isa in north-west Queensland, Australia (20°44’S 139°30’E). The area is classified as BSh (B=arid, S=steppe, h=hot arid) in the Köppen and 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, 2012). The long-term average annual rainfall of the area is 420 mm but rainfall is highly erratic. Three-quarters of the annual precipitation occurs in summer, mainly between December and March but varies greatly, from 78.0 mm in 1985/86 to 798.3 mm in 1996/1997. Most summer rainfall events are high intensity storms (Bureau of Meteorology, 2012).

2.1.2 Test plot description and instrumentation
The test plots were constructed in September 2008 and commissioned in December 2008. They were constructed of non acid forming (NAF) material on top of a 10 m high traffic-compacted potentially acid forming (PAF) waste rock dump. A nested design used two cover
treatments, each with three replicates. The cover treatments were 20 m x 60 m areas constructed from: (1) 0.5 m compacted non-acid-forming (NAF) material, overlaid by 1.5 m uncompacted NAF material (Treatment C) and (2) 2.0 m 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) until a sufficiently even surface was obtained. The cover material was applied in one lift through paddock dumping with haul trucks (Caterpillar 777D, 785C). Thereafter, the material was levelled out by an excavator (Hitachi ZX330LC) and the sides of the plots were brought to an even slope. All waste rock originated from 300 m below the surface.

Particle size distribution (PSD) for the NAF material was determined on five and six samples (excluding boulders) from the compacted and uncompacted treatment plot, respectively (Fig. 1). In the laboratory, PSD was determined as percentages by weight of the material fractions. The potentially acid forming (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 ca. 75 %.
To determine the water storage capacity of the Mt Isa cover system a water retention curve (WRC) was established. Based on the characteristic of the material, i.e. high rock content, and data interpretation a bimodal water retention curve (Durner, 1994) was chosen. The WRCs for cover material and underlying pyritic waste were derived by direct measurements of saturated/unsaturated hydraulic conductivity close to saturation using a HOOD-infiltrometer (Schwärzel and Punzel, 2007) and modelling with HYDRUS 1-D. The interpretation of the data required weighting of fine and coarse material according to PSD.

**Instrumentation**

Each plot was subdivided into three identically instrumented 20 m x 20 m subplots. 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 (see appendix A). Each subplot was instrumented identically.
A lysimeter, consisting of an open-top rain water tank (3.0 m height, 3.0 m diameter), was placed in the PAF waste, approximately at the centre of each subplot. The top of the lysimeter was level with the PAF surface. A biaxial drainage net (Flownet™, Geofabrics Australasia Pty Ltd) was placed at the bottom of the lysimeter, covered by a geotextile liner (Filter Wrap - 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 levelled by hand and compacted with a vibrating plate compactor (MVC 82 Mikasa Plate Compactor, Multiquip Inc.) to achieve the same bulk density as prior to 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) through a PVC pipe with a slope of ca. 2 %.

Six water content reflectometers (Model CS616, Campbell Scientific, Inc®) and 16 matric water potential sensors (229-L, Campbell Scientific, Inc®) were installed from the bottom of each lysimeter (approximately 4.8 m below final surface) to approximately 0.5 m beneath the NAF cover surface during the process of backfilling.

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 pre-calibrated for waste rock material and installed so as to avoid cavities between sensor and material. In some cases, this led to finer material around the sensors compared to the particle size distribution of the waste. Additional sensors were installed in early December 2008, requiring localised disturbance to approximately 1.0 m depth.

A weather station measuring rainfall (Campbell Scientific CS 700-L), air temperature and humidity (Vaisala Model HMP45C), wind speed (R.M. Young Wind Sentry Anemometer 03101-L) and net radiation (NR-Lite-L) was located 500 m from the experimental area. All sensors and the logger were acquired from Campbell Scientific, Inc.

2.2 Cobar

2.2.1 Climate
This field site was located near Cobar, in central west New South Wales, Australia (31°33’S, 145°52’E). The climate of this area is described as BSh (B= arid, S= steppe, h= hot) in the Köppen and Geiger climate classification (Kottek et al., 2006). The long term average annual rainfall of the region is approximately 400 mm per year, the mean annual minimum and
maximum temperature are recorded to be 12.8 °C and 25.2 °C, respectively (Bureau of Meteorology, 2011b). Rainfall distribution does not follow a seasonal pattern but tends to be uniformly distributed throughout the year. However, rainfall can be highly variable, especially in early spring and summer (Bureau of Meteorology, 2011a).

2.2.2 Test plot description and instrumentation
Two evapotranspiration covers were built on the tailings dam facility from benign, oxidised waste rock in 2002 by O’Kane Consultancy Ltd. The covers were designed to test the performance of two different material thicknesses, namely 1.5 m uncompacted material and 2.0 m uncompacted material (hereafter TP1.5 and TP2.0, respectively). Cover trial dimensions were approximately 35 x 35 m.

Covers were instrumented with heat-dissipation sensors (CS 229-L) and moisture probes (EnviroSCAN®, Sentek, Stepney, Australia), a runoff gauge and a lysimeter (diameter 2.4 m, height 2.5 m TP1.5 and 3.0 m TP2.0). On each plot the lysimeter, consisting of an open-top rainwater tank, was installed one metre into the underlying tailings material, while the lysimeter top was flush with the surface of the cover system. The lysimeter drain was covered with a geotextile, over which 0.15 m of washed sand was placed. Unfortunately, no further details about the sand or geotextile were available.

Both, thermal conductivity and moisture sensors were installed outside the lysimeter. Thermal conductivity sensors were placed in vertical transects extending from a depth of 0.05 m to 2.40 m and 2.90 m in TP1.5 and TP2.0 respectively. For the installation of suction sensors two methods were used. The sensors in the tailings material were placed by excavating a trench and drilling into the trench wall. Sensors were then inserted and the drilled holes as well as the trench were backfilled with tailings material. The instruments within the cover system were installed during placement of the cover material, in a manner identical to the suction sensors in the Mt Isa cover trial (as described above) (O’Kane Consultants Inc., 2002). The calibration of thermal conductivity sensors were carried out as described above.

The installation of the moisture probes also followed two methods. For the underlying tailings material, a 56.5 mm diameter PVC tube enclosing the moisture probes was installed in an auger hole in the material. Thereafter, the waste rock cover material was placed around the tube by shovelling and a rubber-tyred backhoe until the final cover height was reached (O’Kane Consultants Inc., 2002).
Furthermore, a weather station with air temperature and relative humidity sensor (HMP45C, Vaisala, Inc., Helsinki, Finland), wind direction and wind speed sensor (Model 03101, R.M. Young Co., Traverse City, Michigan, USA), net radiometer (NR-Lite, Kipp and Zonen BV, Delft, Netherlands) and a rainfall gauge (CS700, Campbell Scientific, Logan, Utah, USA) was set up on TP2.0 (O'Kane Consultants Inc., 2002).

The particle size analysis, conducted after cover construction in 2002, showed that than at TP1.5 less than 25 % of the waste rock was smaller than 2 mm, while at TP2.0 25 % of the waste rock was classified as fine material (< 2 mm). Generally, waste rock from TP1.5 had a slightly higher percentage of coarse material (> 2 mm) (O'Kane Consultants Inc., 2002).

2.2.3 Vegetation
In March 2008 approximately 150 mm of topsoil was spread on the surface of both cover trials, ripped and seeded with a mixture of native grasses; re-seeding took place in April 2008. Vegetation establishment was low due to high grazing pressure from wild goats and kangaroos in the area, so the plots were fenced in June 2008. Additionally Atriplex nummilaria seedlings were planted in late 2008 and early 2009.

In April 2011 vegetation density was determined as foliage projective cover (FPC) (Specht, 1981). Two transects were run on each test trial, spanning the complete length of the plot, FPC was assessed every meter.

In addition, evapotranspiration measurements were conducted with a laboratory calibrated open top chamber (OTC), similar to the systems described by Hutley et al. (2000) and Zeppel et al. (2006). Two species, which were abundant on both plots, were selected, namely Senna artemisioides (DC. Randell) and Sclerolaena birchii (F. Muell). The OTC was provided by the project partner Prof Derek Eamus, UTS, Sydney, New South Wales.

On both cover trials, two plants of each species were selected, as well as a bare spot, resulting in five locations per cover plot. Measurements started at 6:30 hrs (sunrise), with one measurement round taking approximately 1.5 hrs. Measurements were repeated every two hours until 18:30 hrs (sunset). Each location was measured for 10 mins, after which the chamber was removed to minimise disturbance of the microclimate. Measurements alternated daily between TP1.5 and TP2.0.
3.0 Results

3.1 Precipitation
Precipitation was analysed from December 2008 through to April 2011, the period in which both cover trials were conducted. Data gaps resulting from instrument malfunction were filled with data from BoM weather station Mt Isa Mines (station number 029126 (Bureau of Meteorology, 2011d)) and Cobar MO (station number 048027 (Bureau of Meteorology, 2011c)). This was necessary from 26th March to 5th April 2009 for Mt Isa, as well as from 17th August to 18th November 2009, from 5th February to 10th March 2010 and 6th December to 31st December 2010 for the Cobar weather station.

In the period from December 2008 to April 2011 a total of 2375 mm and 1130 mm were recorded in Mt Isa and Cobar, respectively. While in Mt Isa the rainfall occurred in three distinct wet seasons, approximately from November to April, rainfall in Cobar was received all year round (Fig. 2).

![Graph of daily rainfall for Mt Isa (a) and Cobar (b) from 01/12/2008 until 13/03/2011.](image)

Fig. 2. Daily rainfall for Mt Isa (a) and Cobar (b) from 01/12/2008 until 13/03/2011.
The maximum daily rainfall recorded in Cobar was 57 mm. Daily precipitation exceeding 30 mm day$^{-1}$ was measured only on six occasions (Fig. 2 b). In Mt Isa maximum daily rainfall was 99 mm. Storm events above 30 mm day$^{-1}$ were measured on 24 days (Fig. 2 a).

On both field sites years with precipitation exceeding the long term annual average were recorded between 2008 and 2011. In Mt Isa 977 mm were recorded in 2009 and 564 mm in the following year, both exceeding the long term annual average of 420 mm year$^{-1}$. In Cobar 676 mm were recorded in 2010, exceeding the long term annual average of 400 mm year$^{-1}$.

For these three years an average return period was calculated, following the Food and Agriculture Organisation procedure (FAO) (Critchley and Siegert, 1991). Calculations were based on long term observational data from BoM station Mt Isa Mines (data range from 1932 to 2011, (Bureau of Meteorology, 2011d)) and Cobar MO (data range from 1962 to 2011, (Bureau of Meteorology, 2011c)).

Results showed that in Mt Isa a 977 mm annual rainfall had an average return period of 17 years, while 564 mm is likely to return every 4.5 years. On the other hand, the 676 mm annual precipitation measured in Cobar in the year 2010 had an estimated return period of 79 years.

### 3.2 Runoff

No runoff was detected at the Mt Isa site as the cover consisted of coarse waste rock without texture change towards or at the surface. For the calculation of the water balance this parameter was set to zero.

From the commencement of cover trials in Cobar in March 2002 until March 2008 the plot had a waste rock surface. In this time period a total of 71 mm runoff was measured on TP2.0, which equates to approximately 4 % of total rainfall (1697 mm) (Fig. 3 a). However, these numbers have to be interpreted as the minimum values as runoff was not collected in times with heavy rainfall due to logger malfunction.
Fig. 3. Runoff (red (TP2.0)/green (TP1.5) lines) occurring on the Cobar cover trial with waste rock surface from 23/03/2002 until 28/02/2008 (a) and with topsoil from 01/04/2008 until 13/03/2011 (b); rainfall: blue lines.
Runoff amounts after spreading of topsoil in March 2008 increased markedly. From 1 April 2008 until 13 March 2011 a total of 1025 mm of rainfall was recorded, of which 16 % (161 mm) was recorded as runoff (Fig. 3 b).

Figure 4 depicts the runoff coefficient, runoff divided by rainfall, for TP2.0 before and after topsoil application. The correlation between rainfall and runoff coefficient could be described with a three parameter power function, with a coefficient of determination ($R^2$) of 0.74 before topsoil application and 0.77 after topsoil application.

After application of topsoil the runoff coefficient markedly increased. The trendline after application of topsoil (dashed line) shows a logarithmic rise between 0-10 mm rainfall events, whereas the trendline of the waste rock surface (solid line) shows an exponential increase. Therefore lower rainfall events, i.e. below 10 mm, resulted in a higher runoff after the spreading of topsoil. Between 30 mm to 80 mm rainfall events the trendlines ran parallel, indicating a similar slope (Fig. 4).

![Figure 4](image-url)  
*Fig. 4. Runoff coefficient for cover trial with waste rock surface (23/05/2002 until 28/02/2008) (solid symbols) and runoff coefficient with topsoil surface (01/04/2008 until 13/03/2011) (open symbols). Runoff coefficient and rainfall relationships are modelled by a three parameter power function. Waste rock surface (solid circles, solid line) $R^2$ 0.74 and with topsoil surface (open circles, dashed line) $R^2$ 0.77.*
3.4 Change in moisture storage

The ability of material to store moisture is determined by its pore system, which depends on the particle size distribution of the material. The coarser the particles, the lesser is the likelihood that pores are formed which can hold water against gravity. The maximum pore size still able to store water is marked as field capacity (FC), which commonly occurs between 60 and 100 hPa, equivalent to a pore diameter of 50µm and 10µm, respectively (Hillel, 2004).

Precise identification of the change in storage is difficult for waste rock material. In natural and agricultural soils, volumetric moisture is measured through moisture sensors. However, due to the coarse nature of waste rock materials these sensors provide unreliable readings and suction sensors provide the highest precision when measuring changes in moisture in waste rock systems. Suction values can be converted to moisture values through water retention curves (WRC).

Appendices B and D show the distribution of water potentials over the depth of the lysimeters and for the period of measurement, appendices C and E the distribution of water contents (vol. 5) over the depth of the lysimeters and for the period of measurement.

The distributions of moisture over depth and time show that there is an immediate response of soil moisture to rainfall. In Mt Isa this response is not only restricted to the surface near depth of the cover, but occurs throughout the lysimeter. This direct response of water flow to precipitation and the immediate occurrence of water at greater depths under higher rainfall amounts/intensities clearly shows that water flow through the coarse waste rock cover occurs as preferential flow.

For modelling purposes and to characterise the hydraulic properties of the cover substrate, a water retention curve is required. To determine the WRC various approaches were used: theoretical, inverse modelling (using the numerical model HYDRUS-1D) of seepage based on moisture distribution over a period of time and by using point measurements of saturated/unsaturated hydraulic conductivity under different levels of tension (HOOD infiltrometer). All three methods resulted in a shape of a WRC as shown in Fig. 5. Common to all approaches for a successful solution of the problem was the requirement to describe the WRC not as a uni-modal pore size distribution, but as a pore size distribution with a distinct separation of a volume consisting of very coarse pores and a pore volume consisting of pores defined by fine textured material (e.g. <2mm), i.e. a bi-modal WRC.
Based on the WRC (Fig. 5) suction values were converted to volumetric moisture and stored water was calculated for the 2 m cover and the pyritic waste (Fig. 6).

![Bi-modal WRC for waste rock cover system in Mt Isa.](image)

Figure 6 shows the change in stored water for the treatment C2 and C3. While maximum amounts of stored water were similar, C3 showed a stronger desiccation between wet seasons and a faster decrease in stored water compared to C2. The dashed line indicates maximum storage capacity (280 mm) for the cover trials, calculated based on FC and cover thickness. Water exceeding this value will, over time, result in deep drainage (Fig. 6).
Fig. 6. Water storage [mm] within the cover with compaction layer (0-2m) (a) and in underlying pyritic waste rock (2-5m) (b) from 02/12/2008 until 01/08/2011. Subplot C2 black line, subplot C3 red line; dashed line maximum storage capacity of cover system.

An increase of the amount of water in the pyritic waste often occurred before the cover system had reached its nominal water storage capacity of 268 mm (dashed line in Fig. 6a), indicating preferential water flow into the hazardous waste. Furthermore, the different maximum and minimum water storage values within the hazardous waste indicate a different porosity of the pyritic waste (Fig 6). Again, the dashed line indicates the amount of water in the waste at field capacity (558 mm). While the amount of water in the PAF beneath C2 decreased to approximately 558 mm between the wet seasons, the amount of water beneath C3 constantly exceeded calculated field capacity (Fig. 6b).
For modelling the bimodal WRC a weighting of coarse to fine material of 60:40 was assumed
and derived from the particle size distribution. Table 1 presents calculated moisture values
and maximum storage capacity for varying coarse to fine ratios. In addition the volumetric
moisture, corresponding stored water for plant wilting point (PWP, assumed to be 15000 hPa)
and plant available water (storage at FC – storage at PWP) are presented.

Table 1. Volumetric moisture [%] and stored water [mm] for a 2 m waste rock
evapotranspiration cover with varying percentages of coarse (> 2mm) to fine (< 2 mm)
material at field capacity (FC, 65 hPa) and permanent wilting point (PWP, 15 000 hPa) and
according plant available water (PAW) [mm].

<table>
<thead>
<tr>
<th>Ratio</th>
<th>moisture at FC [ % ]</th>
<th>water storage at FC [mm]</th>
<th>moisture at PWP [ % ]</th>
<th>water storage at PWP [mm]</th>
<th>PAW [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>30:70</td>
<td>20</td>
<td>400</td>
<td>13</td>
<td>260</td>
<td>140</td>
</tr>
<tr>
<td>50:50</td>
<td>16</td>
<td>320</td>
<td>10</td>
<td>200</td>
<td>120</td>
</tr>
<tr>
<td>60:40</td>
<td>14</td>
<td>280</td>
<td>9</td>
<td>180</td>
<td>100</td>
</tr>
<tr>
<td>70:30</td>
<td>11</td>
<td>220</td>
<td>8</td>
<td>160</td>
<td>60</td>
</tr>
</tbody>
</table>

For covers with 50 to 70 % coarse material, maximum water storage varies from 320 to 220
mm, respectively. A cover system with 70 % of the material smaller 2 mm could potentially
store 400 mm water. Moisture content at PWP varies over a range of 5 vol. % with variation
in fine material fraction froom 30 % and 70 %. Plant available water is low for all scenarios
(Table 1).

3.5 Seepage
Seepage was measured on both cover designs and all subplots of Mt Isa, no seepage data are
available for Cobar due to instrument failure. Total amount of generated seepage varied
greatly and no trend in seepage formation in one cover design over the other was apparent
(Fig. 7).
Seepage as percentage of rainfall was highly variable and ranged between approximately 20% (U3) to as high as 90% (C3) (Fig. 7). The plots C2 and U2 had no seepage recorded after the first major rain event, while U1 and U2 had no seepage initially, but recorded relatively high amounts from the second trial year onwards.

Table 2 shows the seepage recorded through tipping bucket devices and the calculated minimum seepage. The latter value is based upon the amount of rainfall occurring when the subplot was at field capacity. Field capacity describes the state in which no seepage occurs but all pores, which are physically able to hold water against the force of gravity are filled. Therefore, any additional water entering the system must result in the generation of seepage. In general, field capacity lay between 7 and 16 kPa, depending on material properties. For the cover trial, field capacity was assumed to be 8 kPa.
Table 2. Measured and calculated minimum seepage [mm], based on cumulative rainfall received when suction values were below field capacity (8 kPa)

<table>
<thead>
<tr>
<th>Subplot</th>
<th>Measured seepage [mm]</th>
<th>Calculated minimum seepage [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1Va</td>
<td>4</td>
<td>264 (21/12/10)</td>
</tr>
<tr>
<td>1Vb</td>
<td>434</td>
<td>816</td>
</tr>
<tr>
<td>1Vc</td>
<td>2160</td>
<td>1390</td>
</tr>
<tr>
<td>2Va</td>
<td>805</td>
<td>1085</td>
</tr>
<tr>
<td>2Vb</td>
<td>1264</td>
<td>801</td>
</tr>
<tr>
<td>2Vc</td>
<td>250</td>
<td>974</td>
</tr>
</tbody>
</table>

Table 2 shows that in four out of six cases seepage was underestimated by tipping bucket devices. This could be due to several reasons. The calibration tipping buckets could be inaccurate and therefore the transformation of recorded tips into seepage values in millimetres underestimates the true value of seepage. However, this is not likely to be the case as the differences between measured and calculated values are too substantial and tipping buckets were re-calibrated throughout the trial period.

Another explanation for the underestimation of seepage could be damage of the tipping bucket devices due to salt accumulation as seen in Fig. 8. Finally, substantial downtimes for some subplots (e.g. C1, U2) will have led to underestimation of seepage values (for more information see Appendix B).
In two of the six subplots, C3 and U2, seepage calculated from field capacity and rainfall resulted in an underestimation of percolation compared to the measured values. Both of these subplots had high measured seepage. The discrepancy between the two values could be due to preferential flow, resulting in the generation of seepage before the cover material had reached field capacity. Another explanation could be gravitational water movement to the seepage outlet point after the cessation of precipitation.

The discrepancy between measured and actual seepage for C3 and U2 emphasises that the calculated seepage values are minimum seepage values as it is likely that percolation will have occurred after precipitation and that preferential flow will have occurred on all plots. Furthermore, it emphasises the need to compare measurements of measured seepage values with suction values and the importance of regular maintenance of tipping buckets when seepage waters are highly acidic.

3.6 Evapotranspiration and evaporation
In general vegetation coverage on the Cobar test plots was relatively low, the line intercept method resulting in an average of 19 % vegetation cover on TP1.5 and 26 % vegetation cover on TP2.0.

Measured evapotranspiration varied from a maximum 4.2 mm day$^{-1}$ to a minimum of 1.0 mm day$^{-1}$ with *Senna artemisioides* generally showing a higher ET compared to *Sclerolaena birchii*. Evaporation rates from bare soil were distinctly lower than ET rates, varying between 0.9 to 0.7 mm day$^{-1}$ (Fig. 9).
Fig. 9. Daily evapotranspiration for four individuals of *Senna artemisioides* (Sa) and *Sclerolaena birchii* (Sb), and two bare locations (bare) on evapotranspiration cover trials in Cobar.

Extrapolation of measured chamber ET to whole plot ET has to take vegetation coverage as well as plant composition into account. Therefore, plot ET was calculated as a weighted average of bare soil evaporation and plant evapotranspiration.

To assess the influence of vegetation composition, plot ET was calculated according to three scenarios. Firstly, the vegetation coverage was allocated equally (50:50) to the two investigated species. Secondly, the more dominant species, *Sclerolaena birchii*, was assumed to form 70% of the vegetation coverage; thirdly, the more dominant species was allocated 80% of plant coverage.
Fig. 10. Calculated plot ET based on vegetation coverage, with no weighing of plant component between plant species (black), 70 % of plant component formed by dominant species *Sclerolaena birchii* (light grey) and 80 % of plant component formed by dominant species *Sclerolaena birchii* (dark grey).

Differences between the three scenarios for plot ET were small, with values ranging from 1.1 mm day\(^{-1}\) to 1.00 mm day\(^{-1}\) at TP1.5 and from 0.94 mm day\(^{-1}\) to 0.87 mm day\(^{-1}\) for TP2. (Fig. 10).

To determine the threshold when vegetation composition influences plot ET three scenarios, (I) no weighing of vegetation for plant component, (II) 70% of plant component taken up by species with higher water use and (III) 70% of plant component taken up by species with lower water use, was applied for increasing plant densities.

These scenarios suggest that for vegetation composition to substantially influence daily plot ET, a vegetation density of minimum 50 % coverage has to be achieved (Fig. 11)
Fig. 11. Increasing plot ET with increasing plot vegetation density for: no weighing of plant component between plant species (solid circle), 70 % of plant component formed by species with higher water use (solid triangle), 70 % of plant component formed by species with lower water use (open circle).

Water movement by evaporation only is an important factor for the water balance in semi-arid/arid environments. Soil sensor data for the derivation and interpretation of the evaporation characteristics were available only for the Mt Isa site (see water potential data in appendix B). From the water potential distribution and from the analysis of the depth distribution of the hydraulic gradient at various time steps, the maximum drying depth could be determined (Table 3).

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<th></th>
<th>C1</th>
<th>C2</th>
<th>C3</th>
<th>U1</th>
<th>U2</th>
<th>U3</th>
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</table>

The results show, that water loss to the atmosphere by evaporation affected the different covers to various degrees, reflecting the high heterogeneity of the material used in the trial. The maximum drying depth can be as little as 0.8m, but is not deeper than 2m. Specifically,
coarse pored substrates act as a kind of rock mulch and prevent the upward flow of water due to the lack of continuously filled small pores, which are able to conduct the water to the surface. At some point of drying, water loss is only possible by water vapour diffusion. This further reduces the amounts of pore water which can be transported to the surface and evaporated.

4.0 Discussion

4.1 Precipitation

The presented precipitation data clearly highlights the need to thoroughly understand the climate of the location of the proposed cover system. While mean annual precipitation was very similar in the two presented case studies, daily rainfall amounts and precipitation frequencies differed substantially. The precipitation patterns of the site in north-west Queensland describe a climate in which a successful evapotranspiration cover is unlikely to be constructed.

Therefore, a generic categorisation into wet and semi-arid climates is insufficient. In general, semi-arid areas are characterised by a potential evaporation rate up to twice the precipitation rate (Christopherson, 1994). However, potential evaporation, or evapotranspiration (pET), is the water loss driven by climatic demands assuming a constant, non limiting, water supply from the soil or cover system (Allen et al., 1998). Markedly smaller actual evapotranspiration (aET) rates compared to pET rates have been commonly reported for natural semi-arid areas throughout the world (e.g. Baldocchi et al., 2004, Kurc and Small, 2004, Liu et al., 2010) and are likely to occur for most of the time.

The highly seasonal rainfall distribution in central-north Queensland results in an oversupply of moisture in the wet season, unlikely to be extracted through ET in the timeframes needed to inhibit water ingress into hazardous waste. This is especially so when rainfall reached up to 100 mm day$^{-1}$.

At the New South Wales site on the other hand, the relatively even distribution of rainfall throughout the year and cumulative rainfall seldom exceeding 50 mm day$^{-1}$ allowed the system to partially wet up, resulting in increased evapotranspiration. This climatic setting provides a higher probability of a successful evapotranspiration cover system, compared to central-north Queensland’s climate.
Rainfall in semi-arid areas is typically highly variable and erratic (D’Odorico and Porporato, 2006). However, the average return period for annual rainfall more than twice the amount of the long term average rainfall is less than 20 years for the central-north Queensland site. In this area, a successful cover should therefore not consider the long term annual rainfall as baseline rainfall but at least double the amount of the long term average precipitation.

In central New South Wales on the other hand, the exceedance of the long term annual rainfall by 70 % showed an average return period of almost 80 years. This leads to the conclusion that in this region rainfall variability tends to result in lower than average annual rainfall.

It is therefore of utmost importance to analyse site specific long term rainfall data and to assess the likelihood of significant exceedance of long term average annual rainfall.

4.2 Runoff
The amount of runoff generated by a cover system affects the amount of water entering a the cover. If runoff generation is high, the probability of water ingress into the hazardous waste becomes lower. However, depending on the surface material, high amounts of runoff may result in high amounts of erosion leading to cover failure (Wilson et al., 2003). Another factor to consider is that reduced water ingress into the cover system results in a higher likelihood of plant water stress due to reduced plant available water in the system.

The potential of runoff generation from evapotranspiration cover system constructed from benign waste rock, without a layer of topsoil, is small. The coarse nature of waste rock material leads to high hydraulic conductivities (Smith et al., 1995) and therefore high infiltration rates and low runoff coefficients.

Topsoil on the other hand, generally shows lower infiltration rates. Plant establishment and pedogenetic processes may lead to an increase in hydraulic conductivity of topsoil over time and therefore a decrease in runoff generation (Benson et al., 2007).

Runoff coefficients in Cobar after topsoil application were, as expected, increased compared to the waste rock surface. However, no erosion gullies were visible and compared to other cover systems (Baumgartl and Mulligan, 2009), the runoff coefficient was moderate. While water ingress into the cover system was reduced, plant establishment, mainly by pioneer species, occurred after topsoil application, showing that the addition of topsoil benefited the hydraulic properties of the cover as well as plant communities.
Therefore, in the case of the Cobar site, the addition of 150 mm of topsoil led to an enhanced cover performance and a decreased likelihood of seepage generation.

4.3 Change in moisture storage
The more rapid and stronger decrease in water storage at C3 compared to C2 covers at Mt Isa indicates a lower water holding potential of the former cover trial. In addition, the higher and more frequent increase in water storage within the hazardous waste underlying C3 reflects a poor cover performance due to this water ingress. However, while percolation of water into the pyritic waste beneath C2 was less pronounced, it nevertheless occurred in every wet season. Therefore, neither subplot can be classified as a successful cover system.

Variability of water storage in the presented scenarios at Mt Isa ranged from 400 mm to 220 mm. As discussed above, a distinct wet dry seasonality exists in central north Queensland, represented by this cover trial. In general 75% of the annual rainfall is received in the wet season from November to March (Bureau of Meteorology, 2012). Long term average rainfall of the region is 420 mm, resulting in approximately 375 mm rainfall in an average wet season of an average year.

If a cover contained no stored moisture before the commencement of a wet season, which is technically unlikely, and if preferential flow could be excluded, only a cover with a ratio of 30:70 coarse (> 2 mm) to fine (< 2 mm) material would succeed in preventing water ingress into the underlying waste.

Particle size distributions of waste rock seldom provide a fine to coarse ratio above 30:70; in fact often the percentage of fines in waste generally does not exceed 30 to 40% (Smith et al., 1995). For this reason the water storage potential of cover systems constructed from benign waste rock is very likely to be low.

A slight variation in percentage of coarse to fine material resulted in a marked increase in water storage potential. A homogeneous distribution of coarse and fine material cannot be expected within an evapotranspiration cover system formed by benign waste rock, especially for a full scale cover. Commonly, cover material is paddock dumped by haul trucks during construction (O'Kane Consultants Inc., 2004). The particle size distribution of waste rock depends on the nature of the parent rock material and the powder factor resulting from blasting. As a result, it is highly probable that the particle size distribution of the waste...
carried by different haul trucks will be dissimilar. This inherent variability of PSD throughout the cover system must result in heterogeneous water flow through the system.

Plant available water for all scenarios was very low. Plants endemic to dry areas of the world are known to be able to extract water below 1500 kPa (Sharma, 1976, Winkworth, 1970). However, even if it is assumed that 30 % more moisture can be extracted than calculated as plant available water in the present study, the water stored for vegetation uptake is still low and varies from 78 mm to 182 mm.

4.4 Evaporation and Evapotranspiration
Foliage projective cover (FPC) values on both plots at Cobar were relatively low. However, no signs of erosion could be seen on the trials, so the combination of near-level surface vegetation and rocks on the surface seems to have resulted in a stable cover.

Daily ET rates lay well within values measured in semi-arid Australia (Pressland, 1978, Sharma, 1976, Winkworth, 1970). Bare soil evaporation rates were distinctly lower than evapotranspiration measured from the plant species.

Calculation of plot ET showed that the role of vegetation in the total water loss from the evapotranspiration cover was minimal, whereas bare soil evaporation was the main contributor in plot ET. This is reflected in the fact that the weighting of *Senna artemisioides* and *Sclerolaena birchii* evapotranspiration rates did not have a great effect on whole plot ET, even though their daily ET rates differed markedly. The reason for this lies in the high percentage of bare ground on the cover systems, as well found by Stannard and Weltz (2006) in a semi-arid shrubland in the United States.

While FPC values on the cover system were low, research has shown that in the long term the FPC can be expected to be in equilibrium with moisture availability, while fluctuations after rain or in drought will be the norm (Specht and Specht, 1999). Therefore, it can be expected that observed vegetation densities are representative for the cover system.

When vegetation coverage reaches 50 % and above the role of vegetation for water loss from a cover system becomes more pronounced. If plant species with higher transpiration rates dominate the cover system this effect becomes more prominent. However, water supply to the plant will regulate water losses during times of sufficient moisture and plant densities in times of droughts. As demonstrated previously, water storage and plant available water in cover
systems from bening waste rock is limited. Therefore irrigation would be necessary to sustain vegetation densities above natural conditions.

The basic concept of an evapotranspiration cover makes this cover type only suitable for semi-arid and arid environments which are characterised through limited water availability to biological systems (D'Odorico and Porporato, 2006). As a sustainable vegetation community must be equilibrium with plant available water, vegetation densities on evapotranspiration cover systems must always be relatively low. Due to this very basic, concept the role of vegetation in an semi-arid evapotranspiration cover system must always be low.

Similarly, in instances where water loss to the atmosphere only occurs through evaporation (without influence of vegetation), the distribution of events of precipitation, their amount and intensity is critical for a successful performance of a cover.

Therefore it is of utmost importance that the remaining parameters of the water balance equation, climate, runoff, and moisture storage, have to be able to minimise water ingress into hazardous waste.

5.0 Conclusion
While the basic concept behind evapotranspiration cover system, the water balance equation, is relatively simple, parameters have to be considered carefully.

Changes in vegetation composition have less influence on cover performance as long as the total vegetation coverage is below 50 %. Given the characteristic of semi-arid environments and the low storage of plant available water in waste rock cover systems, vegetation densities are likely to not exceed 30 % coverage. Therefore, while vegetation is essential for successful waste facility rehabilitation, its role for water removal from an evapotranspiration cover system is limited.

Variations in runoff, and therefore water ingress into the cover, can partly be influenced through the application of topsoil to the waste rock surface. Runoff will minimise water infiltration into the cover and therefore the risk of water ingress into hazardous waste. A balance, site specific and climate specific, must be found between runoff and water ingress into the cover in order to avoid erosion and enable plant growth.
The probability of variations in rainfall regime in semi-arid environments is high. This can on the one hand lead to increased, high intensity storm events, resulting in deep drainage into hazardous waste. On the other hand, decreased precipitation rates may lead to temporary droughts and severe die back of vegetation.

The second water balance parameter highly prone to variability is change is storage capacity. Storage capacity is strongly affected by the type of material used and is respective pore size distribution/ water retention characteristic. In addition and related to the aforementioned property, the depth over which water can be stored and the maximum depth which can be affected by evaporative loss is critical for the quantification of precipitation which can be stored in a cover. Due to the variability of waste rock material, the storage capacity of a full scale cover is very likely to vary spatially. This variability challenges the precision of inputs to long term cover performance modelling and therefore the reliability of these model outcomes. An analysis of the climatic data (e.g. frequency, amount and intensity of precipitation) is therefore indispensable to minimise the risk of failure of a cover system prior to its design and installation.
References


O’KANE CONSULTANTS INC. 2002. As-built report for the Peak Gold Mine tailings dam cover system field trials. Saskatoon, Canada.


Published journal papers and refereed conference proceedings containing information from this project:


Schneider, A., Baumgartl, T., Doley, D., Mulligan, D. 2010. Store and release cover systems: A suitable preventive for acid mine drainage in semi-arid monsoonal Queensland? 19th World Congress of Soil Science, 1-6 August Brisbane, Australia

# Appendix A

## Sensor distribution Mt Isa

Depth distribution of sensors [m]

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The table above shows the depth distribution of sensors at Mt Isa, with columns for suction sensors and moisture sensors for different depths.
Appendix B: Water potential distribution trial site Mt Isa

App B.1. Cumulative rainfall (a) and logarithmic suction in subplots C1 (b), C2 (c), and C3 (d) of the cover design with a compacted layer from 4th December 2008 to 31st July 2011.
App B.2. Cumulative rainfall (a) and logarithmic suction in subplots U1 (b), U2 (c), and U3 (d) of the cover design without a compacted layer from 4\textsuperscript{th} December 2008 to 31\textsuperscript{st} July 2011).
Appendix C: Moisture content distribution trial site Mt Isa
Moisture profiles measured with CS616 sensors

App. C.1. Cumulative rainfall (a) and volumetric moisture for subplots C1 (b), C2 (c) and C3 (d) for cover with compacted layer from commencement of cover trial (04/12/2008) until decommission (31/07/2011).
App. C.2 Cumulative rainfall (a) and volumetric moisture for subplots U1 (b), U2 (c) and U3 (d) for cover without compacted layer from commencement of cover trial (04/12/2008) until decommission (31/07/2011).
### Appendix D

Downtime of seepage sensors (Mt Isa) and received precipitation in downtime from commencement of cover trials (04/12/2008) until decommission of cover trials (31/07/2011) for subplots (1, 2, 3) of treatment with compacted layer (C) and without compacted (U)

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Appendix E: Water potential distribution trial site Cobar

App. E. Cumulative rainfall (a) and logarithm of absolute value of matric potential for TP1.5 (b) and TP2.0 (c) after application of topsoil (01/04/2008) until termination of cover trials (14/02/2011).
Appendix F: Water potential distribution trial site Cobar

App. F. Cumulative rainfall (a) and moisture for TP1.5 (b) and TP2.0 (c) from commencement of cover trials (23/05/2002) until application of topsoil (28/02/2008).