STATE-OF-THE-ART PERFORMANCE MONITORING OF COVER SYSTEMS – MOVING FROM POINT SCALE TO MACRO SCALE APPROACHES

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ABSTRACT

Closure plans for mine waste possessing the potential to generate acid and metalliferous drainage (AMD) often requires implementing a system to control percolation of meteoric waters and/or ingress of oxygen to the underlying waste. Soil, or “dry”, cover systems are an accepted prevention and control alternative to meet these objectives. Full-scale cover system performance is often evaluated by water quality analyses of seepage discharged from the waste storage facility. The disadvantage of this monitoring technique is that it may take tens of years before a considerable change is measured inside or downstream of the waste storage facility.

Direct measurement of cover system field performance is the state-of-the-art methodology for measuring performance of a cover system. The objective is to develop understanding with respect to a water balance for the cover system itself, as well as for the waste storage facility. A challenge with direct measurement of cover systems is in addressing the gap between point-scale and macro-scale areal performance. This paper describes an emerging approach to cover system performance monitoring, which relies on a watershed based approach. Hilbert-Huang transform is employed to demonstrate how instrumentation and monitoring can be transferred from a point-scale cover system monitoring perspective to using that system to understand macro-scale cover system performance.

1.0 INTRODUCTION

Closure plans for mine waste possessing the potential to generate acid and metalliferous drainage (AMD) often requires strict management to mitigate or minimise the effect of AMD on surrounding the environment including surface water and groundwater. Soil, or “dry”, cover systems, is an accepted prevention and control alternative, and have been successfully used at numerous sites around the world for AMD management. The two principal objectives of a cover system are to control the ingress of oxygen to the underlying reactive mine waste and/or to control infiltration of meteoric waters to the underlying waste. These objectives are achieved through cover system design by providing a barrier layer in the cover system. This barrier layer usually maintains low hydraulic conductivity and high water saturation. The high water saturation in the barrier layer can minimise the oxygen ingress into the underlying waste rock because the oxygen diffusion coefficient in water is several orders of magnitude less than in atmosphere (Fredlund and Rahardjo 1993). Cover systems can also take advantage of the moisture retention of the cover layer (or layers) to store infiltration, and then release that moisture back to the atmosphere through evapotranspiration such that acceptable levels of control on percolation rates to the underlying waste are achieved with the presence of a ‘barrier’ layer.
Cover systems can be simple or complex, ranging from a single layer of earthen material to several layers of different material types, including native soils, non-reactive tailings and/or waste rock, geosynthetic materials, and oxygen consuming organic materials (MEND 2001).

There are two main disadvantages to cover systems for mine wastes: cost and the uncertainty with respect to long-term performance (Yanful et al. 2006). Implementing a cover system typically represents a substantial component of mine closure costs. However, the costs associated with the environmental liability from not having a well-designed cover system are typically much more significant from a mine-life cycle perspective. Therefore, the cover systems should be designed on the basis of the best available information. Models and field test trials (pilot-scale) are often used to guide design due to their low cost and shorter timelines as compared to full-scale cover systems (MEND 2004). However, use of the pilot-scale results to predict full-scale (e.g. watershed) cover performance can be problematic due to an inherent disconnect in measurement scales (Robinson et al. 2008). In general, the mining industry's knowledge and confidence with respect to long-term performance is limited because there is a lack of appropriate performance monitoring for cover systems over an extended time frame.

Full-scale cover system performance is often evaluated by water quality analyses of seepage discharged from the waste storage facility. This approach empirically describes a waste storage facility through monitoring of its cumulative effect at the base. The merits of this monitoring technique are that: (1) it can sometimes use available drainage outlets (e.g. a river, a lake, or a groundwater well), hence simplifying monitoring and optimising costs; and (2) the measured results provide direct information for comparison with the design criteria or other water quality guidelines. However, monitoring of the cumulative effect at the base of the waste storage facility has two major disadvantages. The first is that it may take tens if not hundreds of years before a considerable change is measured inside or downstream of the waste storage facility due to, for example, drain-down effects, complete oxidation of sulphidic minerals, and/or mixing with groundwater. The second disadvantage is that without additional forms of monitoring, there will not be enough information to explain the results if they do not meet expectations. The understanding for measured water quality at the base of a waste storage facility requires some fundamental parameters, including precipitation, runoff, soil water storage change, etc. Therefore, this monitoring approach on its own does not provide enough information for understanding and predicting performance of a cover system placed on the waste storage facility to mitigate AMD.

Direct measurement of cover system field performance is the state-of-the-art methodology for measuring performance of a cover system. The objective of the method is to develop understanding with respect to a water balance for the cover system itself, as well as for the waste storage facility. This is achieved through monitoring multiple components of the water balance such that key indicators of cover system performance (e.g. net percolation) can be understood with the highest level of confidence possible. A challenge with direct measurement of cover systems is in addressing the gap between point-scale (such as a test plot or field trial) and macro-scale (such as watershed) areal performance. For example, the measurement gap when applying measurements or predictions taken at the point-scale to predict cover system performance on the macro-scale (watershed-scale) results in predictions that may not be valid for the intended purpose (Robinson et al. 2008). Hence, as part of a natural progression of cover monitoring, and in order to increase confidence with cover systems as an AMD prevention and control alternative, there is a need to account for spatial variability within the system in the design process.

Several methods have been proposed to address cover system field performance on a macro-scale level. For example, a system dynamics watershed model was proposed by
Elshorbagy et al. (2007) to gain a better understanding of the hydraulic performance of a reconstructed watershed and to optimise the cover design. Tallon et al. (2009) used the hydro-pedotransfer functions (HPTFs) as a novel method to upscale net percolation predictions for closure planning and reclamation on a landscape scale. It is possible to use point-scale measurements and other assistance (e.g. model predictions) for predicting the performance of a macro-scale cover system because spatial variations in soil properties are not random. Of course the most appropriate approach to gaining understanding for this variability is through performance monitoring. Myriad analysis techniques, including geostatistics, spectral and coherency analyses, fractals/multi-fractals, wavelets and wavelet coherency, have been developed to understand soil spatial variability. The common feature of these techniques is that they assume the spatial series to be linear. However, the cover system can seldom be explained by a linear equation in practice. Hilbert-Huang transform (HHT) is a new method that has been developed to simultaneously deal with both non-linear and non-stationary data series (Huang et al. 1998). An advantage of the HHT method is that it does not impose any mathematical rule in the analysis, but instead explains the hidden physical mechanisms directly from the data (Huang and Wu 2008). Unlike other data analysis methods, there is not a priori basis in HHT; rather it is adaptive and derived from the data (Huang et al. 1998).

This paper describes an emerging approach to cover system performance monitoring, which relies on a watershed based approach. A case study employing HHT to demonstrate temporal variability of measured water content is presented. Considering temporal and spatial variability of cover system performance will be a trend of cover system monitoring on a macro-scale basis.

2.0 MACRO-SCALE MONITORING METHODS

Direct measurement of cover system field performance is achieved through monitoring multiple components of the water balance such that key indicators of cover system performance (e.g. net percolation) can be understood with the highest level of confidence possible. In essence, one should attempt to develop multiple lines of evidence to develop the cover system water balance. Macro-scale (watershed-scale) monitoring is multi-dimensional with abundant spatial and temporal variation, and this is inherently more challenging than point-scale monitoring. Although instrumentation may set up at certain points in a watershed, the understanding of data obtained from different parts of a watershed should be linked. This section focuses on the direct hydrologic aspects monitoring, which includes surface and sub-surface hydrologic monitoring as well as monitoring location guidelines (MEND 2007).

2.1 Surface Hydrologic Monitoring

Hydrologic monitoring involves measuring and tracking the movement of water in the watershed. Surface hydrologic monitoring includes precipitation, runoff, pond monitoring, and evapotranspiration.

Precipitation Precipitation includes rainfall and snowfall. Rainfall should be measured at several locations on a watershed to quantify spatial differences in rainfall depth and intensity. Snowfall should be measured with an all-season precipitation gauge and in addition, regular depth/density measurements of the snowpack should be collected with increasing frequency as spring freshet approaches. The three most common methods for the measurement of precipitation are: 1) non-recording gauges; 2) recording gauges; and 3) the snow survey method.
Runoff  A watershed is an area of land that contributes runoff to a single outlet location; hence, runoff can be determined by measuring stream flow from the outlet of a watershed. Stream flow is typically measured using either velocity measurement or stage measurement (McCuen 1989). Velocity measurement is best suited to large rivers or permanent streams in which the flow rates are more constant. Stage measurement can either use the natural streambed, or it can involve the construction of measurement structures. Flow rate measurement structures are the most common method used for measuring flow rates in small, ephemeral streams and are therefore the most practical method for measuring runoff from small watersheds. These structures have a known stage-discharge relationship, which can be applied without detailed measurement of the stream flow. Weirs and flumes are those most commonly used structures in runoff measurement applications.

Pond Monitoring  Typical hydrologic pond monitoring consists of water level measurement and seepage monitoring. Evaporation is usually evaluated based on information for the meteorological monitoring program. Water level measurement is typically done manually using a staff gauge or some other type of depth measurement. Seepage meters are the most commonly used method for direct measurement of seepage. Seepage meters range from simplistic manual devices to complex automated devices. In typical watershed pond applications, the simple barrel and bag-type seepage meter typically give suitable results for water balance determinations.

Evapotranspiration  Evapotranspiration is comprised of two components: evaporation and transpiration. A variety of methods are available for measuring evaporation and evapotranspiration rates from the ground surface. The most commonly utilised methods can be classified as direct measurement methods or micrometeorological methods. Atmometers, evaporation pans, and weighing lysimeters are the most widely used methods for direct measurement of evaporation and evapotranspiration. The most commonly used micrometeorological methods are the Bowen ratio energy balance method, the aerodynamic method, the mass transport method, and the Eddy covariance method. A review of the literature indicates that the three most popular methods of measuring evaporation and evapotranspiration rates are evaporation pans, weighing lysimeters, and the Bowen ratio energy balance method. However, this paper advocates that the most appropriate method for direct measurement of evapotranspiration for a cover system is the Eddy covariance method given that it is a micrometeorological method that provides a direct measurements of the evaporative flux from the surface.

2.2 Sub-Surface Hydrologic Monitoring

Sub-surface hydrologic monitoring involves measuring and tracking the movement of water through the various soil layers of the watershed, which includes measurements of soil moisture content, soil suction, net percolation, interflow, groundwater, soil temperature, and field hydraulic conductivity.

Soil Moisture Content  Measurements of soil moisture are fundamental to the development of a water balance for a watershed. Soil moisture profiles in the waste and cover layers allow the volume of water stored within the profile to be quantified, and can be interpreted to define the rates and direction of water movement in response to plant root uptake, evaporation, percolation, and interflow. The five most common methods of measuring in situ moisture content of soils are: gravimetric method; nuclear method; time domain reflectometry (TDR); frequency domain reflectometry (FDR); and electrical capacitance method. In the author’s experience, the latter three methods are preferable given that they can be automated and connected to a data acquisition system such that real time responses to field performance can be measured. Care must be taken to properly calibrate these sensors to field conditions
to ensure quantitative measurements are obtained. In addition, the response of these sensors to \textit{in situ} salinity conditions varies between different manufacturers, and therefore caution is required to ensure that the sensor chosen is compatible with the anticipated \textit{in situ} salinity conditions.

\textit{Soil Suction} The three most common methods used to measure soil suction in the field are tensiometers, thermal conductivity sensors (or heat dissipation sensors), and electrical resistance sensors (i.e. gypsum blocks). All three methods provide a field measurement of matric suction, which along with osmotic suction are the two components of total suction. In general, thermal conductivity sensors are most appropriate for cover system monitoring, based on the author’s experience. They are automated, robust and generally do not degrade over time. However, an understanding for anticipated \textit{in situ} matric suction conditions is required given the operating range of typical thermal conductivity sensors. In coarse textured materials, the use of tensiometers should be considered.

\textit{Net Percolation} Net percolation is a critical facet to understanding the water balance of a watershed. It is typically a key performance indicator for a cover system placed over reactive waste. In addition, owing to the simplicity of its application (i.e. as a percentage of precipitation), it is often a metric for stakeholder’s understanding of closure performance.

There are numerous approaches for determining net percolation rates for a cover system, which can broadly be categorised into direct or indirect methodologies. A common indirect method is using the water balance approach. In this case, measurements of \textit{in situ} moisture conditions, surface runoff, and evapotranspiration are used to ‘back-calculate’ net percolation. A potential disadvantage to this approach is that the change in moisture storage measured at a single location will not be representative of the entire cover system. Differences will result due to the variability of the cover material itself, as well as the \textit{in situ} density conditions. The variability in meso-topographic and vegetation conditions across the cover system will also affect \textit{in situ} moisture conditions. In order to address this issue, multiple \textit{in situ} moisture profile monitoring locations should installed, such that the variability due to the above noted factors is understood, and the multiple lines of evidence are included for in the water balance calculation. In essence, two key components being measured, are being conducted on two different scales. Runoff is inherently a ‘macro-scale’, or watershed measurement, while, as alluded to above, measurements of \textit{in situ} moisture conditions are typically viewed as being a ‘micro-scale’, or point scale measurement. It can be challenging to resolve a cover system water balance when using a single moisture sensor profile within a watershed (i.e. the cover system) from which one is also measuring runoff. This issue is addressed by measuring \textit{in situ} moisture conditions at multiple locations within the watershed, such that the range of moisture conditions within the watershed (i.e. the cover system) is understood and can be incorporated into the water balance evaluation. An additional potential issue can arise given the challenges with measurement resolution of surface runoff. The other parameters can be measured, in comparison, with a relatively high level of resolution. Hence, if the measurement resolution of surface runoff is within the range of net percolation rates that one is attempting to back-calculate then it can be challenging to use the water balance method. In general, this may occur when dealing with cover systems that are designed for very low net percolation rates.

It is also possible to ‘back-calculate’ net percolation rates for a cover system by calibrating a soil-plant-atmosphere model to measured \textit{in situ} moisture conditions and surface runoff (using the measured climatic conditions as input to the model). The net percolation rate predicted by the model calibrated to field conditions can then be ‘measured’ by the model.
The preferred method for determining cover system net percolation rates is to directly measure it using a lysimeter. A lysimeter is a large tank (e.g. 2.5 m diameter by 3m deep), or lined facility (e.g. 10m x 10m) placed below the cover system within the underlying waste in which percolation is collected at the based, and then directed towards an underdrainage and measurement system. It can be challenging to install a lysimeter because, depending on anticipated net percolation rates and \textit{in situ} hydraulic properties of the waste material, the lysimeter may need to be constructed to a depth where it is unsafe and impractical to install the lysimeter. Placing a lysimeter on a steeply sloping surface introduces additional construction and safety challenges, which must be considered.

The areal extent required for a lysimeter is highly site-specific. For example, the size should allow for full-scale cover construction equipment to be utilised for placement of the overlying cover material. Abichou et al. (2006) argued that a lysimeter should be at least 7 m wide and possess a length twice the width. Abichou & Musagasa (2008) state that the length and width of a lysimeter should be five times larger than its depth. Benson et al. (2001) recommend that a lysimeter should be at least 10m wide and 10m long to account for the inherent variability in the overlying cover material and ensure a ‘bulk’ net percolation rate is measured. The primary rationale for a larger lysimeter is an attempt to address the inherent spatial variability of a cover system. This variability will result from construction (placement) of the cover material, which will affect the as-built hydraulic conditions (e.g. density, material characteristics etc.), as well as due to physical, chemical and biological process that influence performance of the cover system following construction (INAP, 2003). Examples include preferential flow (macro-features), vegetation, and material evolution.

In general for small-scale lysimeters (e.g. \~ 0.3m in diameter), one should expect high variability in the net percolation measured. If one were to increase the number of these small-scale lysimeters, it would provide an understanding for the variability of cover performance, which is a positive aspect for understanding performance, but does result in challenges with determining a representative net percolation rates. A larger-scale lysimeter will reduce the variability being measured with the objective being to obtain a measure of the bulk net percolation for the cover system. As noted above, it will be site-specific as to whether the variability has been captured. In general, the areal extent of a lysimeter is often a function of constructability (practicality and cost), coupled with the level of ‘comfort’ required to capture the inherent cover material variability.

In general, while the measurement principal of a lysimeter is conceptually simple (i.e. collect water at a depth below the cover system and compare that to precipitation), properly designing installing, and operating a lysimeter is in fact very complex. For this reason, it is the author’s experience that lysimeters for measuring net percolation from a cover system often do not provide a representative measure of field performance. The most common reason is that the depth of the lysimeter, and as a result the lower boundary condition at this depth below the cover system influences the net percolation rate being measured because the same pore-water pressure regime within the lysimeter does not reflect that outside the lysimeter.

Detailed discussion on addressing the above noted issue with respect to lysimeters is not within the scope of this paper. O’Kane and Barbour (2003) provide discussion on the above noted issue, as well as put forth a methodology for properly designing a lysimeter to ensure the presence of the lysimeter does influence the net percolation being measured.

\textbf{Interflow} \hspace{1cm} Quantification of the interflow is especially important for estimating percolation rates into underlying waste material, and it is also useful to understand the contribution of interflow as seepage into swales or ponds in the watershed. The layout of an interflow
monitoring system would be dependent on the topography and drainage patterns of the watershed. A single weeping tile drain may be installed in a given area. It is important to align the drain parallel to the topographic contour of the area, so that the drain runs perpendicular to the flow of water. Monitoring the interflow rate depends largely on the quantity of interflow and the resolution of measurements required.

**Groundwater** The interaction of surface water and groundwater is another important component of the watershed water balance. Perched water tables and groundwater flow add complexity to large-scale water balances. The most common method of monitoring groundwater levels is with a standpipe piezometer, usually constructed of PVC pipe with a lower screened or slotted portion that allows water to flow into the pipe. The difficulty associated with groundwater monitoring for watersheds on reclamation material is that significant changes in material layers can create a complex subsurface hydrology. Historic practices of disposing refuse or old equipment in pits or waste rock dumps can pose a problem when trying to drill through the material.

**Soil Temperature** The temperature of the soil profile defines the presence of freezing conditions, provides an indication of geochemical activity, and highlights critical temperatures for plant germination and growth. Measurement of soil temperature is relatively straightforward. A soil temperature sensor is either permanently buried or temporarily inserted in the soil at the depth of interest and a temperature is measured. The most commonly used sensors for measuring soil temperature are thermocouples or thermistors. For watershed temperature monitoring, the depths of the sensors depend on the information that is required and the materials and layers present in the profile. Shallow sensors are useful for evaluating biological and vegetation activity in the topsoil. Deeper sensors should be spaced according to material layers, such as in layered cover systems. The depth of the deepest sensor would most likely correspond to the average depth of frost penetration, or, if the waste is reactive, then deeper sensors may be required to monitor potential heating of the waste material (and also the impact of this heat source on cover performance).

**Field Hydraulic Conductivity** Determination of field hydraulic conductivity ($k_{fs}$) is fundamental for determining watershed performance because secondary structures in soil such as structural cracks, worm holes, root channels, and macropores can provide preferential flow paths in fine-textured materials. Freeze/thaw and wet/dry cycles, as well as biological activity all contribute to soil structure development. Field hydraulic conductivity measurements are a single point measurement. To determine a representative value for a material, it is important to do a number of measurements over a representative area. Various methods exist for measuring the $k_{fs}$ of soil including the double ring infiltrometer, a Guelph Permeameter (GP), a tension infiltrometer, etc. The different methods of determining $k_{fs}$ each have particular advantages and limitations. The selection of a method, therefore, should be based on the requirements of the specific application. *In situ* methods for determining the $k_{fs}$, which incorporate a large cross-sectional area, will tend to mask regions of low hydraulic conductivity. Values of $k_{fs}$ measured with the GP typically show relatively high coefficients of variation, indicating sensitivity to the heterogeneous hydraulic characteristics of soil.

### 2.3 Monitoring Locations and Sensor Placement

Reclamation landscapes, and the resulting watersheds, are topographically and geologically complex due to their very nature, and consequently can have complex hydrology. Soil moisture conditions, runoff rates, evaporation and transpiration rates, etc. may be strongly...
tied to slope position and aspect. The biggest challenge in watershed monitoring is determining where to monitor and how frequently to monitor.

In developing a monitoring plan, it is most helpful to first clearly define what the monitoring data will be used for. Generally, the following details should be taken into consideration when installing a watershed monitoring system.

1) *In situ* moisture content and soil suction sensors should be installed throughout the cover/waste profile, but should be concentrated around interfaces in the profile (e.g. cover-atmosphere interface, growth medium layer-barrier layer interface, barrier layer-waste material interface).

2) *In situ* moisture content and soil suction sensors should be installed adjacent to one another to facilitate the development of a ‘field-based’ moisture retention curves and hydraulic conductivity functions for each layer in the cover/waste profile.

3) A watershed monitoring program should have one or two detailed or primary instrumentation sites along with several secondary monitoring sites. For example, a primary instrumentation site may include automated *in situ* moisture content and suction sensors, an access tube for manual *in situ* moisture content measurements, *in situ* gas sampling ports, a lysimeter, and a fully automated meteorological station. A secondary monitoring site may only consist of a volumetric water content sensor profile, or at least an access tube for manual measurement of the *in situ* moisture conditions; however, this will at least give some indication of the potential spatial variability of conditions in the watershed. The primary and secondary instrumentation sites should be located such that they reflect the variable conditions influencing performance of the watershed. For example, if slope orientation is thought to strongly influence evaporation and vegetation conditions then more than one slope aspect should be monitored. Other factors that can influence the location of a monitoring site include slope angle, runoff and run-on conditions, slope length, elevation of the monitoring location, meso-topographic conditions, reactivity of the underlying material, and texture of the underlying material.

3.0 HIBERT-HUANG TRANSFORM AND APPLICATION (CASE STUDY)

3.1 Theory of Hilbert-Huang Transform

The Hilbert-Huang transform (HHT) separates different scale processes and identifies location specific scale variation of non-stationary and non-linear soil spatial variability. HHT is a two step method. The first step is empirical mode decomposition (EMD), which works directly in the spatial domain with the basis derived from data. EMD separates variations completely based on the frequencies present in a spatial dataset and decomposes a signal into a finite set of oscillatory modes. Each mode is represented by an intrinsic mode function (IMF). The decomposition to IMF is based on a simple assumption that at a given time or space, there may be different simple oscillatory modes of significantly different frequencies superimposing one other (Huang and Wu 2008). Each frequency is representative of one scale process. Defining modes or IMFs should satisfy the following conditions: 1) the mode may or may not be linear, but the number of extrema and zero crossings must either be equal or differ at most by one; and 2) at any data point, the average value of the envelopes defined by local maxima and local minima is zero. According to these definitions, IMFs can be obtained after decomposing any function through a sifting process.

Once the IMFs are separated, Hilbert transforms are easily applied to each IMF as the second step of HHT. Hilbert transform leads to an apparent space-frequency-energy description of a spatial series after separating into different scales, or IMFs, and thus will possess intrinsic physical meaning at every point. The energy of each IMF can be calculated
from the instantaneous amplitude, which is a function of space. The phase calculated from Hilbert transform is also converted to instantaneous frequency as a function of space. Unlike the fixed frequency band used in Fourier transform, Hilbert transform calculates frequency at every location. By examining the local frequency properties of a spatial series, the details of the nonlinear processes can be achieved. As the energy and the frequency are calculated separately as a function of space, the energy can be expressed as a combined function of space and frequency in Hilbert spectrum. The variable frequency resolution used in calculating the spectrum provides better spatial resolution than any other method based on uniform frequency.

The Hilbert spectrum provides instantaneous frequency information, which is representative of spatial scales of processes. The scale and location specific information of any soil process can be identified from Hilbert Spectral analyses. The total contribution of each frequency, or each scale, can be calculated by accumulating the energy over the entire data span from the construction of the marginal spectrum. A marginal spectrum can be calculated for each IMF, which is an alternative spectrum expression of the data to the traditional Fourier spectrum.

3.2 Case Study – Mt. Whaleback Mine, Western Australia, Australia

This case study demonstrates water flow mechanism in a field cover test plot (TP#1) and the response of sensor measured water content to precipitation events at the various depths for over 12 years. The Hilbert-Huang transform technique is employed to analyse water content variability with time. The data used in this case study is presented in Meiers et al (2010).

3.2.1 Site characterisation

The Mt. Whaleback iron ore mine is located in the Hamersley Iron Province in the northwestern corner (Pilbara Region) of Australia and situated adjacent to Newman, Western Australia (WA), approximately 1,200 km north-northeast of Perth. Development of the Mt. Whaleback mine commenced in 1968. The mine currently produces approximately 18 million wet tonnes of saleable product and 53 million tonnes of waste material annually. Ultimately, some 3.3 billion tonnes of waste rock will be mined and located into overburden storage areas (OSAs) in and around the final pit. Shale, strongly weathered as well as "un-oxidized", is a common type of waste rock at the Mt. Whaleback. Pyrite is the most common iron sulphide in the shale of the area, with average sulphide values less than 0.5%. The "un-oxidized" waste rock has varying acid generating potential. The nodular unit of the Mt. McRae Shale contains sulphide-S concentrations ranging from 1.7% to 20% and has a deficiency of carbonates. This unit is capable of producing up to one tonne of $H_2SO_4$ per tonne of waste rock. The disseminated unit of the Mt. McRae Shale, as well as additional shale units have the potential to produce in the range of 50 to 100 kg of $H_2SO_4$ per tonne of waste rock (Graeme Campbell & Associates 1996).

The mine site is located in a semi-arid tropical region with a mean annual rainfall of approximately 320 mm. It is common for rainfall to occur over short periods and with high intensity. Annual potential evaporation typically exceeds 3,000 mm.

3.2.2 Cover design and instrumentation

In general, a cover system has three primary objectives; namely, limiting gaseous oxygen ingress and water infiltration in to the underlying reactive mine wastes, as well as providing support to the surface vegetation. However, it is not feasible to limit the ingress of oxygen to the potentially acid generating material at the Mt. Whaleback operation due to prolonged dry
periods. In addition, it is not practical to attempt to control the bacteriological activity within the waste material. The most promising closure option to control ARD at the Mt. Whaleback operation is the utilisation of a moisture “store-and-release” cover system, which takes advantage of the high evaporative conditions at the site. Therefore, the Mt. Whaleback cover system is designed to accept as much rainfall as possible, while minimising runoff and associated erosion, with all infiltration remaining within the cover material. The moisture is subsequently released to the atmosphere as evapotranspiration. The rationale of this cover system design is to control acid rock drainage as a result of controlling moisture movement into and through the waste rock material to an acceptable level.

Field test plot TP#1 with a surface area of 1 ha was constructed in February 1997 on a relatively horizontal surface to verify the results predicted by a soil-atmosphere model. TP#1 had a cover thickness of 2 m, and was left as ‘bare surface” (no vegetation) field trial in order to develop a conservative estimate of cover system performance at the site. Hence, moisture is only ‘removed’ from the cover profile through evaporation (i.e. there is no transpiration component).

A field performance monitoring system was installed to measure actual evaporation, potential evaporation, rainfall, net percolation (large-scale lysimeter), and in situ temperature and moisture (suction and volumetric water content) conditions. The sensors were installed at depths of 10, 20, 30, 45, 60, 75, 100, 188, and 218 cm in TP#1.

3.2.3 Field measured volumetric water content and data interpretation

Figure 2 shows the field measured volumetric water contents at the various depths in TP#1. The water content in the cover system shows two features. First, the measured volumetric water content (VWC) majorly changed with drying/wetting seasons, but were relatively stable on an annual basis with respect to each individual sensor depth. For example, the values of VWC at a depth of 10 cm is in the range from 0.13 to 0.28 each year for over 12 years. Second, in general, the range of sensor measured VWC changing with dry/wet seasons in one year decreases with increasing depths of the sensors. For instance, compared to the fluctuating range of VWC values (0.13 – 0.28) at 10 cm, the VWC values at 70 cm changed only between 0.09 and 0.15.

Fig. 2. Field measured volumetric water content in TP#1 at Mt. Whaleback

The variance contribution of measured VWC values for the all time scales over the entire 12 year monitoring period indicates that the small time scale variations decrease with increasing VWC measured depths (Figure 3). Above the monitoring depth of 75 cm, small time scale variations dominate, which means that water content sensors (i.e. the cover system) can respond to the low intensity rainfall events and short timeframe evaporation above this depth. Below this depth (75 cm) the annual signals of wetting and drying dominate. This is consistent with the measured VWC in Figure 2 and would be expected.
Fig. 3. Variance contribution of measured volumetric water content at the selected depths in the cover system (note: LT is long-term trend (>12 years))

The site measured rainfall intensity values between January 20 and March 13, 1999 and between January 19 and March 17, 2009 are presented in Figure 4, and corresponding variations of measured VWC at the selected depths in the cover system are presented in Figures 5 and 6, respectively. Figure 5 shows that the water content sensor at 10 cm reacted quickly to relatively minor events, while the sensors at depths greater than 75 cm responded primarily to more significant rainfall events (intensity > 15 mm/d). There is a complete dampening of the signal at 45 cm, which implies that water flow bypassed at this depth. Furthermore, the time scale of variation is between 10 to 16 hours ((1/0.2) x 2 hours = 10 hours) at a depth of 10 cm, and from 12 to 20 hours at a depth of 218 cm. These represent much shorter time frames than expected at the 218 cm depth if the wetting front was moving in a homogeneous, matrix flow type fashion. This implies that preferential flow occurred in the cover system.

Fig. 4. Site measured rainfall intensity between (a) January 20 and March 13, 1999 and (b) between January 19 and March 17, 2009 (b) at Mt. Whaleback mine site

Three peaks at the 10 cm monitoring depth shown in Figure 6 correspond to rainfall intensities of 28 mm/d on January 25th, 38 mm/d on February 17th, and 108 mm/d on February 28th, 2009, respectively. Their time scales of variations are approximately 12 – 14 hours. Infiltration resulting from rainfall with an intensity of 108 mm/d reached depths greater than 10 cm. Similar to the water flow bypass at the depth of 45 cm in Figure 5, water flow also bypassed at a depth of 60 cm during the period of January 19 and March 17, 2009 (Figure 6). Again, this bypass water flow is assumed to be a result of preferential flow in the
cover system because this sharp response occurred very soon after the event began. Comparison of water flow in the cover system just after the cover was placed (Figure 5) and after over 12 years (Figure 6) illustrates the difference in performance as a result of evolution of the cover material because the general rainfall intensities less than 40 mm/d did not produce water infiltration deeper than 10 cm after the cover had been in place for 12 years, whereas a much lower rainfall intensity resulted in a response of the cover system at depth greater than 10 cm in the few years subsequent to construction of the cover system. It is hypothesised that the most likely reason for evolution of the cover materials is in response to wet-dry cycling leading to mechanical breakdown of the cover material, as well as settling of the cover material/surface.

Fig. 5. Spectra showing variance of measured water content at selected depths in the cover system during the period of January 20 and March 13, 1999

Fig. 6. Spectra showing variance of measured water content at selected depths in the cover system during the period of January 19 and March 17, 2009

3.3 Implications of HHT in Cover System Performance Monitoring

HHT can extract time scales from the filed measured datasets. The extracted time scales demonstrate what time scales dominates with respect to the datasets, and this performance of the cover system. From a cover system performance monitoring perspective, these prevailing time scales allude to the cover performance monitoring frequency, which is
associated with a specific cover system (materials and placement). Based on this approach, the time scales obtained from the datasets of monitoring a cover system can be extended to a macro-scale watershed cover system if the macro-scale and point-scale cover systems have the same design and placement approach.

A key question with monitoring of a full-scale cover system is the spatial extent of point scale measurements. In essence, how many locations does one need to monitor and at what scale to ensure that performance of the cover system as a whole is understood. HHT can also be used to analyse spatial variability of datasets obtained from a point-scale cover system monitoring. The application of HHT to the spatial variability analysis would require field measured data at the different locations. Alternatively, soil-plant-atmosphere modelling could be conducted with a sensitivity analysis conducted on key cover system conditions that would be expected to influence performance on a spatial scale (e.g. meso-topography, vegetation, in situ permeability, in situ moisture retential characteristics). Then, the HHT analyses could be conducted on the model outputs and once some understanding for spatial variability of the above noted cover conditions is developed, the scale over which monitoring of the full-scale cover system should occur can be determined.

It would be expected that the closer the monitoring locations, the more similar the datasets. Measurement of in situ moisture conditions in a cover system over these different scales can be achieved using VWC sensors, or through other geophysical techniques (e.g. ground penetrating radar). Once the dominating spatial scales are determined from analysis of the datasets obtained from a point-scale cover system, these spatial scales can be employed to guide and/or adjust the instrumentation of the performance monitoring in a macro-scale (full-scale) cover system such that it can be demonstrated that the field performance monitoring system deployed provides a representative measure of cover performance as a whole.

4.0 SUMMARY

The complexity and challenges of cover system performance monitoring are apparent given the scale increase of a cover system from a point-scale (e.g. a test plot) to a macro-scale (e.g. a watershed). Although most monitoring techniques used in point-scale cover system monitoring can be applied for macro-scale cover system monitoring, the extent of performance monitoring for a macro-scale cover system is much broader than that for a point-scale cover system. The performance monitoring and evaluation of a macro-scale cover system should consider the temporal and spatial variability of the field measured datasets. The monitoring frequency (scale) for obtaining sufficient data, which is associated with spatial instrumentation and temporal data acquisition, must be understood in order to deploy a cost-effective monitoring system. The Hilbert-Huang transform provides a promising analysis approach to assist in designing an appropriate full-scale cover system performance monitoring system, as well as for interpreting data from point-scale measurements and their validity in demonstrating macro-scale performance.

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