Evaluation of the Long-Term Performance of Dry Cover Systems

Final Report

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EXECUTIVE SUMMARY

Construction of a dry cover system as a closure option for management and decommissioning of waste rock and tailings is a technique used at numerous mine sites around the world. The objectives of dry cover systems are to minimise the infiltration of water and provide an oxygen diffusion barrier to minimise the influx of oxygen. Apart from these functions, dry covers are expected to be resistant to erosion and provide support for vegetation.

Mining companies are developing new practices and technologies in the disposal of mine waste. Often the long-term viability of these new technologies must be demonstrated before they can be implemented with confidence within the mine closure process. There is a need to develop a well-researched predictive tool, or model, that is acceptable to all stakeholders for simulating long-term performance.

This report is the culmination of a project examining the long-term performance of dry covers for reactive mine waste. The project involved two phases; Phase 1 consisted primarily of a literature study. Information was compiled regarding; the processes affecting the long-term performance of dry cover systems, the numerical models capable of predicting long-term performance, laboratory characterisation of cover materials, and field performance monitoring practices. Phase 2 included collecting and analysing detailed performance monitoring data for five mine sites located in Canada, Australia, and the United States. Field saturated hydraulic conductivity tests were completed at the four North American sites to examine changes in saturated hydraulic conductivity of the cover system material with time. A calibrated numerical model, selected from the Phase 1 study, was developed for three of the five sites. The calibrated model allowed examination of cover system performance at these sites and provided information regarding key processes and characteristics that will control long-term performance.

The following is a non-technical summary of each section of this final report. The results from each of the five mine sites investigated in the INAP study are also summarised.

<u>Summary of Phase 1 Final Report</u>

- The processes affecting the long-term performance of a dry cover system were identified and were grouped into physical, chemical, and biological processes.
- Examination of the defined processes showed that each could be related to the change in four key cover performance properties; namely, the saturated hydraulic conductivity, the moisture retention characteristics of the cover materials, the relationship between oxygen diffusion and the degree of saturation, and the physical integrity of the cover system.
- A literature study was completed to identify numerical models capable of simulating the long-term performance of a dry cover system.
- A review of numerical models typically used to predict cover system performance was undertaken. The key thought process in reviewing the models was that modelling is about gaining a further understanding for processes and characteristics that influence and control performance, not about being able to develop a "better prediction". The VADOSE/W model was determined to be the most advanced model because it included more of the processes and characteristics that are important to cover system performance. Hence, it was determined that a user could better understand the impact of these processes and characteristics when conducting cover system design modelling.

BHP Billiton Mt. Whaleback

- The mine site includes five cover system test plots incorporating run-of-mine store and release dry cover systems. Performance monitoring data are recorded automatically at each of the test plots.
- Field performance monitoring and the measurement of *in situ* material properties were found to be essential in the calibration of a numerical model to site conditions. The calibrated numerical model showed good agreement with measured field conditions over a three-year period.
- The effect of extreme climate events on the performance of a cover system, such as the successive above average rainfall years experienced at the site from 1998 to 2001, was investigated with the calibrated model.
- In addition, the positive influence of vegetation on the performance of a dry cover system in semi-arid tropical climates was investigated with the calibrated numerical model.
- Cover system performance was evaluated for the adverse effect of segregation, which can occur during material placement.

Equity Silver Mine

- Three full-scale cover systems were constructed with compacted and non-compacted till approximately 10 years ago. Performance monitoring data is collected at three automated monitoring stations on two of the full-scale cover systems the site. In addition, manual measurement of *in situ* volumetric water content is measured at 14 locations.
- The field saturated hydraulic conductivity testing showed the importance of monitoring the evolution of the cover materials, including changes in the field saturated hydraulic conductivity. Field tests found an average saturated hydraulic conductivity of 1×10^{-5} cm/s in the upper 10 cm of the compacted barrier layer compared to a hydraulic conductivity of less than 5×10^{-7} cm/s at the base of the compacted layer.
- The study demonstrated the need to properly design the non-compacted growth medium layer within a cover system to protect the underlying compacted barrier layer.

Syncrude Canada Ltd.

- Three large, sloping cover systems were constructed at the Syncrude Canada Ltd. site that incorporate peat and till secondary materials. Performance monitoring data are collected from seven different instrumentation locations.
- The effect of slope micro-topography and small undulations on the performance of the cover system was demonstrated with a numerical model calibrated to site conditions.
- The results of a three-year field study evaluating the change in cover material saturated hydraulic conductivity were examined. The field study found significant increases in the saturated hydraulic conductivity from the first year to the second year and small increases from year two to year three.

TeckCominco Kimberly Operations

- Three test plots, which include performance monitoring systems, were constructed on the tailings facility at the mine site.
- The relative influence of snowfall and rainfall on cover system performance was analysed. A tendency for higher net percolation during years when snowfall was a large percentage of the total annual precipitation was identified.
- A field testing programme was completed to evaluate the changes in the field saturated hydraulic conductivity of the cover materials over time.

Historical Site in Western United States

- Four store and release test plots were evaluated at the site. Two of the cover systems have been in-place for 14 and 18 years, respectively, while the remaining two cover systems are three and six years old, respectively.
- The field testing programme found that each cover system had approximately the same average saturated hydraulic conductivity. These results were unexpected, as the recent cover systems were constructed with a finer-textured material to improve the performance of the cover system.

The INAP study was completed in two phases. Phase 1 identified the tools required to analyse specific mine site case studies. For example, the processes and key properties affecting long-term performance were studied. The list of physical, chemical, and biological processes affecting the key properties is meant to serve as a tool during the conceptual and detailed design of a cover system. The objective is to ensure that the cover system design addresses the site-specific processes, which have potential to impact on long-term performance of the cover system. The list of processes is meant to be complete; although clearly there will be processes for a particular site that have not been identified herein. However, the intent for listing the processes remains the same; namely, that it is fundamental to ensuring long-term performance that the potential impact of these site-specific processes are addressed.

Phase 2 analysed the practical issues occurring at the case study mine sites. The focus of the study was to identify the weakness in cover design or the natural event(s) that led to the change in cover system performance. These determinations and the identification of successful reclamation measures can lead to improved dry cover system design and long-term cover system performance.

ACKNOWLEDGEMENT

O'Kane Consultants Inc. would like to thank the International Network for Acid Prevention for the opportunity to assist with their dry cover system longevity project. It has been a tremendous opportunity to learn and develop further understanding for the long-term performance of dry cover systems. It is clear that further fundamental and applied research is required, but it is hoped that the "lessons learned" during completion of the project have been conveyed in this final report.

The contribution from the network of people who volunteered their time to the project is gratefully acknowledged. In particular, Dr. Mandy Agnew, formerly of Rio Tinto Technical Services, Mr. Pete Waters, BHP Billiton Iron Ore, Mr. Mike Aziz, Placer Dome Canada Ltd., Ms. Zoe Ramdin, TeckCominco Ltd., Ms. Clara Qualizza and Dr. Gord McKenna, Syncrude Canada Ltd., and Dr. Stuart Jennings, Montana State University who facilitated the completion of the project and provided valuable advice and direction on the scope of work. We also acknowledge the support for the project as a result of the enthusiasm and input provided by Mr. Ross Gallinger, BHP Billiton, Dr. Bruce Kelley, Rio Tinto Technical Services, Mt. Les Hulett, Inco Ltd., and Mr. Denis Kemp, Falconbridge Ltd.

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1 INTRODUCTION

Dry cover systems have been used as a closure option for the decommissioning of waste rock and tailings storage facilities at numerous mine sites around the world. The objectives of dry cover systems are to minimise the infiltration of water and provide an oxygen diffusion barrier to minimise the influx of oxygen. Apart from these functions, dry covers are expected to be resistant to erosion and provide support for vegetation.

Dry covers 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. Multi-layer cover systems often utilise the capillary barrier concept to keep one (or more) of its layers near saturation under all climatic conditions. This creates a “blanket” of water over the reactive waste material, which reduces the influx of atmospheric oxygen and subsequent sulphide mineral oxidation.

Over a long period of time the properties of the cover materials, the climate of the mine site, the vegetation cover, and the wildlife species within the mine site area will change. Prediction of the impact of these changes on the performance of the dry cover system is extremely difficult, yet regulating agencies often require it.

Mining companies are developing new practices and technologies in the disposal of mining waste. The long-term viability of these new technologies must be demonstrated before they can be implemented with confidence within the mine closure process. There is a need to develop a well-researched prediction model acceptable to all stakeholders to simulate long-term performance.

This report is the culmination of a project examining the long-term performance of dry cover systems for mine waste. The project is funded by the International Network for Acid Prevention (INAP), a consortium of some of the larger mining companies in the world. The project consisted of two phases. The Phase 1 Final report was submitted to the INAP committee in October 2002. This Phase 2 report documents the second and final phase of the project.

1.1 Project Objectives and Scope

Phase 2 focused on analysing cover system performance monitoring data from five sites in Australia, Canada, and the United States. The specific activities of this phase of the project are:

- “Mining” the collected performance monitoring data to identify changes in cover system performance;
- Analysing the performance monitoring data to determine the possible physical, chemical, or biological processes that occurred to cause a change in cover system performance;
- Conducting field *in situ* saturated hydraulic conductivity tests to examine the evolution of the cover system materials over time;
- Calibrating a numerical model to site-specific measured field conditions; and
- Predicting the performance of the in-place dry cover systems and examine their long-term cover performance.

1.2 Sites Selected for Phase 2 Analysis

Several criteria were utilised while selecting the mine sites for inclusion in Phase 2 of the project. Ideally the sites should be owned or operated by an INAP member company and distributed to include a wide range of climates, from humid to arid conditions. The sites would preferably possess five to ten years of detailed cover system performance monitoring data. Finally, two to three sites should be located in the western United States or Canada to allow for a field testing programme. The following five sites were selected for analysis in the Phase 2 study.

1) BHP Billiton, Mt. Whaleback (waste rock; arid tropical climate);
2) Equity Silver Mine (waste rock; humid climate);
3) Syncrude Canada Ltd. (saline / sodic overburden; semi-arid climate);
4) TeckCominco, Kimberley Operations (tailings; semi-arid to semi-humid climate); and
5) Historic reclamation site in the western United States (Note: In order to gain access to the site and the associated performance monitoring data, OKC cannot disclose the specific site).

1.3 Organisation of Report

This report summarises Phase 1 and Phase 2 tasks completed to examine the long-term performance of dry cover systems for reactive mine waste. Section 2 of this report presents a summary of the Phase 1 Final report submitted to the INAP committee in October 2002. The results from each of the selected mine sites are presented in separate sections. The BHP Billiton, Mt. Whaleback site are summarised in Section 3 while Section 4 includes the analysis of the Equity Silver Mine. The discussion of the Syncrude Canada Ltd. site, TeckCominco, Kimberley Operations, and the historic reclamation site in the western United States are contained in Sections 5, 6, and 7, respectively. The final section of this report summarises the key findings from completion of the INAP project work tasks. Recommendation for future research were not within the scope of this project, but were submitted to INAP separate from this report.

Note that in order to reduce the size of the main document much of the supporting documentation and details on each case study have been placed into appendices.

2 SUMMARY OF THE PHASE 1 FINAL REPORT

The summary of the Phase 1 Final report is presented below. Appendices A1 through A4 contain the entire Phase 1 Final report document.

Phase 1 of this project included identification of the key properties affecting long-term cover performance, a comparison of the available numerical models for evaluating the performance of cover systems, and a discussion of laboratory testing and field performance monitoring methodologies.

The following is a non-technical summary of each section of this Phase 1 final report.

<u>Identification of Cover Performance Properties</u>

- The processes affecting the long-term performance of a dry cover system were identified through discussion with mine site personnel and the completion of an informal questionnaire.
- Examination of the defined processes showed that each could be related to the change in four key cover performance properties; namely, the saturated hydraulic conductivity and moisture retention characteristics of the cover materials, the relationship between oxygen diffusion and the degree of saturation, and the physical integrity of the cover system.
- The processes were grouped into physical, chemical, and biological processes. A short definition and literature study was completed for each process listed in Table 2.1.

Table 2.1

Summary of the physical, chemical, and biological processes defined in the Phase 1 study.

Physical Processes	**Chemical Processes**	**Biological Processes**
Erosion	Osmotic Consolidation	Root Penetration
Slope Instability	Dispersion/Erosion	Burrowing Animals
Wet/Dry Cycles	Dissolution/Precipitation	Bioturbation
Freeze/Thaw Cycles	Acidic Hydrolysis	Human Intervention
Consolidation/Settlement	Mineralogical Consolidation	Bacterial Clogging
Extreme Climate Events	Sorption	Vegetation Establishment
Brushfires	Oxidation	
	Salinisation	

A key issue to note is that *in situ* evaluation (i.e. performance monitoring) is required to accurately define vegetation conditions, saturated hydraulic conductivity (and the hydraulic conductivity function), and moisture retention characteristics.

The list of processes identified in Table 2.1 likely excludes some processes that are important at a particular site. However, rather than focus on processes that may have been excluded, the rationale for listing and defining the processes as part of this project should not be overlooked. That is, it is fundamental that personnel responsible for designing, constructing, and maintaining cover systems for reactive mine waste understand the processes that will impact on long-term cover system performance for their sites.

Cover Performance Numerical Models

The advantage of numerical modelling is that allows for coalescing and evaluating a set of complex settings, processes, designs, and decisions into a comprehensive effort. The purpose for numerical modelling in general is threefold. First, modelling can be conducted to interpret a mechanism or process (e.g. to prove a hypothesis or to "train" our thinking), or to assist with interpretation of field data. Second, modelling can be used to evaluate the relative performance of alternate conditions. And finally, modelling can be used for predicting a final behaviour or impact. In general, the latter two aspects tend to be the focus of numerical modelling, when in fact the first rationale should be the foremost use of a numerical model. For example, numerical modelling is often dismissed as being "useless" due to a lack of predictive accuracy. However, the key advantage to numerical modelling is the ability to enhance judgment, not the ability to enhance predictive capabilities. In short, numerical modelling should focus on improving our ability to understand key processes and characteristics, as opposed to enhancing predictive capability. In addition, numerical modelling should be undertaken at all levels of the project (e.g. data gathering, interpretation, and design), and not just for predicting performance.

A review was completed to identify numerical models capable of simulating the long-term performance of a dry cover system. The following is a summary of the review.

- Seven numerical models were evaluated. Four of the models were one-dimensional (HELP, UNSAT-H, SWIM, SoilCover), while the remaining three were two-dimensional (VS-2D, HYDRUS-2D, VADOSE/W).
- The capabilities of the numerical models were compared for eight key functions, including formulation of the flow and transport numerical equations, boundary conditions, and the ease of using the pre- and post-processor interfaces.
- SoilCover and VADOSE/W were determined to be the best -suited numerical model for simulations to be completed during Phase 2 of this project.
- It was determined that VADOSE/W included more of the processes and characteristics that are important to cover system performance. Therefore, it was concluded that VADOSE/W, in comparison to the other models, was the most appropriate model for conducting cover system design because a user could better understand the impact of the processes and characteristics on long-term performance.

Desired Additions to the VADOSE/W Model

- Possible additions to the VADOSE/W model to improve its ability to predict long-term performance were identified. The proposed additions were an erosion and stability module, an expanded vegetation module, and a hydraulic conductivity and SWCC evolution module.
- The value of a climate change model and site-specific wildlife database is discussed as part of the review.

Laboratory Characterisation Programme

- A suggested protocol for the collection of representative material samples for characterisation in the laboratory is provided.
- A comprehensive geotechnical characterisation programme consists of laboratory tests to determine the following parameters: particle size distribution (PSD), Atterberg limits, clay mineralogy (i.e. X-ray diffraction), specific gravity, compaction curve (i.e. Proctor curve), shear strength, saturated hydraulic conductivity, consolidation-saturated hydraulic conductivity relationship; and soil water characteristic or moisture retention curve.

Cover Performance Monitoring

- Field performance monitoring can be implemented during the design stage with test cover plots or following construction of the full-scale cover.
- Field performance monitoring should include meteorological monitoring, monitoring of moisture storage changes, and monitoring of net percolation, surface runoff, vegetation, and erosion.
- The typical method of measurement for each component of a field performance monitoring system was summarised in the Phase 1 report (included as Appendix A).

Interpretation of Cover Performance Monitoring

- One of the simplest methods for evaluating cover performance is through the use of a surface water balance, and /or a water balance across the interface of the cover material and waste material. This can only be done properly by having access to data generated by the recommended performance monitoring sensors.
- Development of field SWCCs and unsaturated hydraulic conductivity functions are key inputs to models developed to predict long-term performance. In addition, the change in these relationships over time assist with interpretation of field data and provide insight to the key processes and characteristics that are controlling long-term performance.

3 BHP-BILLITON, MT. WHALEBACK

3.1 Background

The Mt. Whaleback iron ore mine is located in the Hamersley Iron Province in the northwest of Australia, approximately 1,200 km north-northeast of Perth, WA. The mine was started in 1968 with the first railing of iron ore in 1969. The mine currently produces approximately 18 million wet tonnes (Mt) and moves approximately 53 Mt of overburden per annum. The current projected life of the mine is approximately 25 years.

The Mt. Whaleback mine is the largest known continuous high-grade iron ore deposit in the world and originally contained over 1.7 billion tonnes of iron ore and nearly 4 billion tonnes of overburden (van der Hayden, 1993). The ore consists mainly of the mineral hematite, an iron oxide containing up to 70% iron. Overburden materials at the mine consist primarily of Banded Iron Formations (BIF) and shales, but also small amounts of chert and dolerite.

The climate of the Pilbara region is semi-arid, tropical with a mean annual rainfall of approximately 320 mm. There are two distinct seasons, a hot, wet summer (December to April), and the rest of the year, which is more temperate and generally has lower rainfall. Typically, rainfall occurs in high intensity, short duration events, usually associated with cyclonic events during the summer. The annual potential evaporation typically exceeds 3,000 mm (O'Kane *et al.* 2000).

3.2 Summary of Cover System Test Plots

BHP Billiton Iron Ore (BHPBIO) has installed five acid rock drainage field test plot performance monitoring systems for cover systems placed over overburden material at their Mt. Whaleback operation. Details of the test plots are summarised below.

Test Plot 1 and Test Plot 2:

- Surface area: ˜ 1 ha each
- Location: W22 overburden storage area
- Constructed: January 1997
- Performance monitoring started: August 1997
- Surface characteristics: no vegetation, generally horizontal with block dumped hummocks

Test Plot No. 3:

- Surface area: ˜ 0.75 ha
- Location: W31 overburden storage area (south slope)
- Constructed: January 1998
- Performance monitoring started: January 1998
- Surface characteristics: minimal vegetation, sloping surface (˜ 3.3H:1V)

Test Plot 4 and Test Plot 5:

- Surface area: ˜ 0.25 ha each
- Location: W29 overburden storage area
- Constructed: June 2001
- Performance monitoring started: June 2001
- Surface characteristics: approximately 20 cm of topsoil placed and seeded late 2001, relatively horizontal surface (˜ 2%), paddock area created using large bund walls

Test Plot 1 and Test Plot 2 are constructed immediately adjacent to each other on a horizontal overburden storage area (OSA) surface at W22. Well-graded run-of-mine overburden material with little or no potential to consume or produce acid was used as the cover material. The cover material was block dumped on the surface of W22 creating an undulating surface with low and high points as well as short surface runoff paths to reduce erosion during the life of the test plots. Test Plot 1 had a minimum of 2 m of cover material at the aforementioned low points while Test Plot 2 was constructed in two lifts with a minimum of 4 m of cover material at the low points. The performance of the two horizontal surface field test plots is monitored using a system designed to measure climate conditions at the test plot area (rainfall, potential evaporation, and actual evaporation), moisture and temperature conditions within the cover and waste material, and net percolation from the base of the cover layer into the underlying overburden material.

Test Plot 3 was constructed on a historic OSA sloped to approximately 17^{o}. The objective was to quantify the difference in performance of the Mt. Whaleback moisture storage and release cover system design constructed on a sloping surface as compared to a horizontal surface. Test Plot 3 was created by battering down a 45 m wide historic reclaimed area to a uniform surface extending approximately 160 m from the crest to the toe of the slope. Sensors extending laterally from six instrument access culverts monitor the performance of the sloped surface field test plot. The objective of the patterned instrument nests was to replicate monitoring laterally and longitudinally to the sloped surface.

Test Plot 4 and Test Plot 5 are located on the re-vegetated surface of the W29 OSA. Both of these test plots are located entirely within the run-of-mine banded iron formation (BIF) material. The objective of the test plots is to quantify the effect of vegetation on the cover system water balance in comparison to the bare surface cover system water balance measured at the W22 test plots.

3.2.1 Overview of the Field Performance Monitoring Systems

State-of-the-art monitoring systems were installed to monitor various parameters that will influence the field performance of each test plot cover systems. Climatic data collected at the central mine weather station includes: rainfall, wind speed and direction, temperature, pan evaporation, relative humidity, and net radiation. Tipping bucket rain gauges were installed at the W22 OSA, which is adjacent to W29, as well as at the W31 OSA. The lysimeters at Test Plot 1 and Test Plot 2 are being monitored manually to record the quantity of net percolation through each cover system field trial. The *in situ* moisture and temperature conditions within the cover and waste materials at each test plot are being monitored with thermal conductivity and volumetric water content sensors. These sensors are connected to automated data acquisition systems powered by solar panel/rechargeable battery sources. The parameters monitored by the

Bowen ratio station installed at W29 provide an assessment of evapotranspiration rates from the vegetated surface. Prior to construction of the W29 field trials, the Bowen ratio station was set up at the W22 field trial area to monitor bare surface evaporation.

3.3 Analysis of the Mt. Whaleback Site

The cover system test plots installed at the BHP Billiton Mt. Whaleback site have information for characterising one-dimensional (1-D) and two-dimensional (2-D) flow within the cover system, as well as the effect of vegetation on cover system performance. Analysis of the performance monitoring data has led to insights or "lessons learned" pertaining to the long-term performance of the cover system. The "lessons learned" at the Mt. Whaleback site include:

- The effect of extreme climate events, such as successive above average rainfall years, on the performance of a cover system;
- The importance of field performance monitoring and the measurement of *in situ* material properties in the calibration of a numerical model to site conditions;
- The positive influence of vegetation on the performance of a dry cover system in semi-arid tropical climates; and
- The adverse effect of segregation, which can occur during material placement, on cover system performance.

Phase 1 of the INAP study identified extreme climate events as one of the physical processes that can affect the long-term performance of the cover system (see Appendix A). The Mt. Whaleback site experienced three consecutive years in which the total annual rainfall was equal to or greater than the annual rainfall recorded at the site in the previous 30 years. The performance of the cover system during this period was not as originally predicted, which at first glance could be attributed to the consecutive periods of extreme rainfall (that were not modelled during the Mt. Whaleback test plot design phase). This aspect of the performance of the Mt. Whaleback store and release cover system field trials is discussed below, and clearly has led to higher net percolation than predicted. However, a contributing factor could also be the use of the laboratory SWCC during the design phase of the field trials, which is often a poor representation of field conditions. The propensity for segregation of well-graded run-of-mine cover material to occur during cover material placement is also discussed as a potential reason for net percolation being higher than predicted.

3.3.1 Measurement of In Situ Material Properties

In situ field properties of the BIF cover material at the Mt. Whaleback site were developed using the field performance monitoring data. *In situ* temperature, matric suction, and volumetric water content are measured at each test plot using sensors connected to an automated data acquisition system. The sensors are located at the same depth (up to 4 m deep) in close proximity to each other. In addition, sensor measurements are taken at the same interval.

For the purposes of this case study, the *in situ* suction and volumetric water content readings are of primary interest. Simultaneous measurement of these parameters produces the field soil-water characteristic curve (SWCC), which details the moisture retention characteristics of the BIF cover material. The moisture retention characteristics of the cover material are vital to the performance of the "store and release" cover system constructed at Mt. Whaleback, which relies upon storing meteoric waters during the wet season rainfall events for release during subsequent prolonged dry periods.

The SWCC and the hydraulic conductivity functions are the most important functions in a soil-atmosphere numerical model. Figure 3.1 compares the *in situ* SWCC measured in the field at the W22 OSA (Test Plot 1) to the SWCC measured in the laboratory prior to construction of the test plots. The field SWCCs show a “double hump”, or are bi-modal, which is typical of field SWCCs. The bi-modal SWCC is indicative of a gap-graded material in which the coarse materials de-saturate first at a low suction value producing the function’s first steep downward slope. The second hump is produced when the finer-textured materials start to de-saturate. This point is rarely well defined in field measurements due to the inherent heterogeneity of the cover materials. Figure 3.1 shows that there was a significant difference between the shape of the laboratory and field SWCCs, even though the laboratory test was completed on a sample prepared to *in situ* density and moisture content conditions, which were measured during the potential cover material sample collection phase of the project.

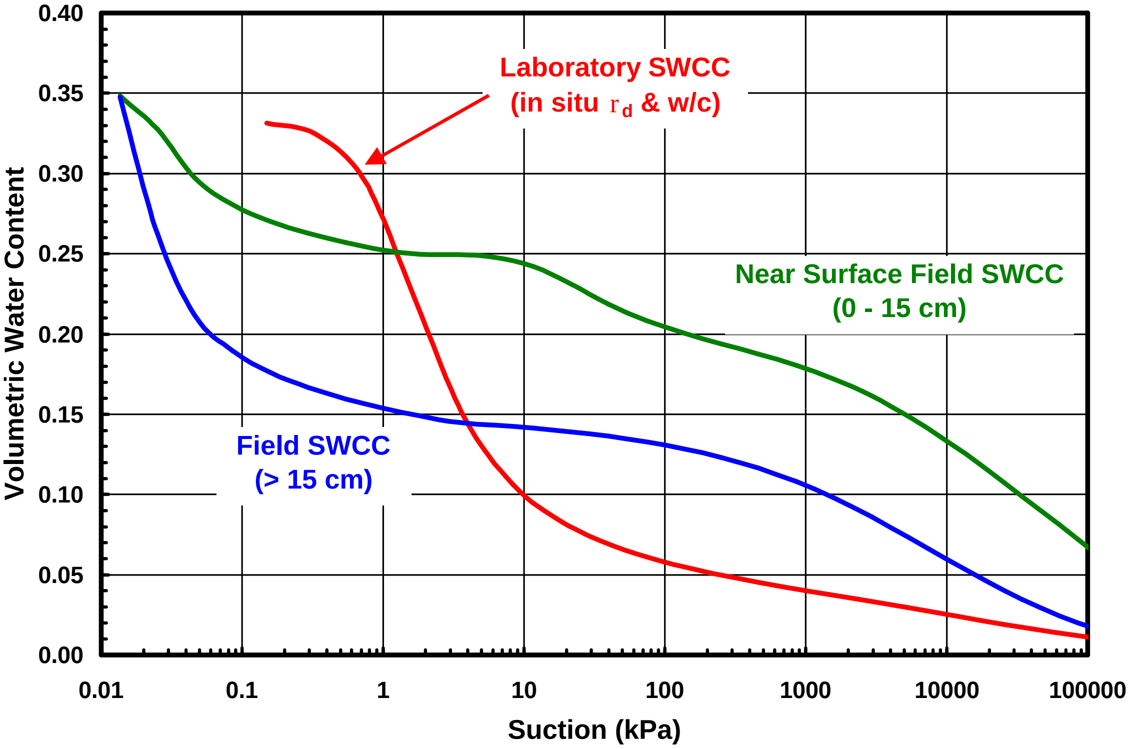

Figure 3.1 Comparison of the laboratory and *in situ* field SWCCs for the BIF cover material.

3.3.2 *Calibration of the Numerical Model*

The 1-D SoilCover soil-atmosphere model was calibrated to a set of field conditions measured at Test Plot 1 at the Mt. Whaleback site. Appendix B1 contains the methodology employed to complete the numerical model calibration. Figure 3.2 shows the results from the calibrated SoilCover model compared to the actual measured field data.

The correlation coefficient between the measured field data and the model results are relatively high for the monitoring period. The numerical model responded at the same time and with a similar magnitude to the measured field conditions, which is critical in the calibration of a numerical model. Future performance of the in-place cover system or alternative cover system designs can be predicted with reasonable confidence with the calibrated numerical model.

It is important to note that the results shown in Figure 3.2 and discussed above were generated on the first attempt of the numerical simulation with minimal changes to the numerical model. The field SWCCs were input to the model as well as estimated hydraulic conductivity functions based on the field SWCCs and field saturated hydraulic conductivity testing. Very few of the model inputs were "tweaked" or varied in successive model runs to better fit the data. This exercise showed the value of field-based material properties such as the SWCC and the value of accurate, detailed performance monitoring systems, which are used to generate the field SWCC.

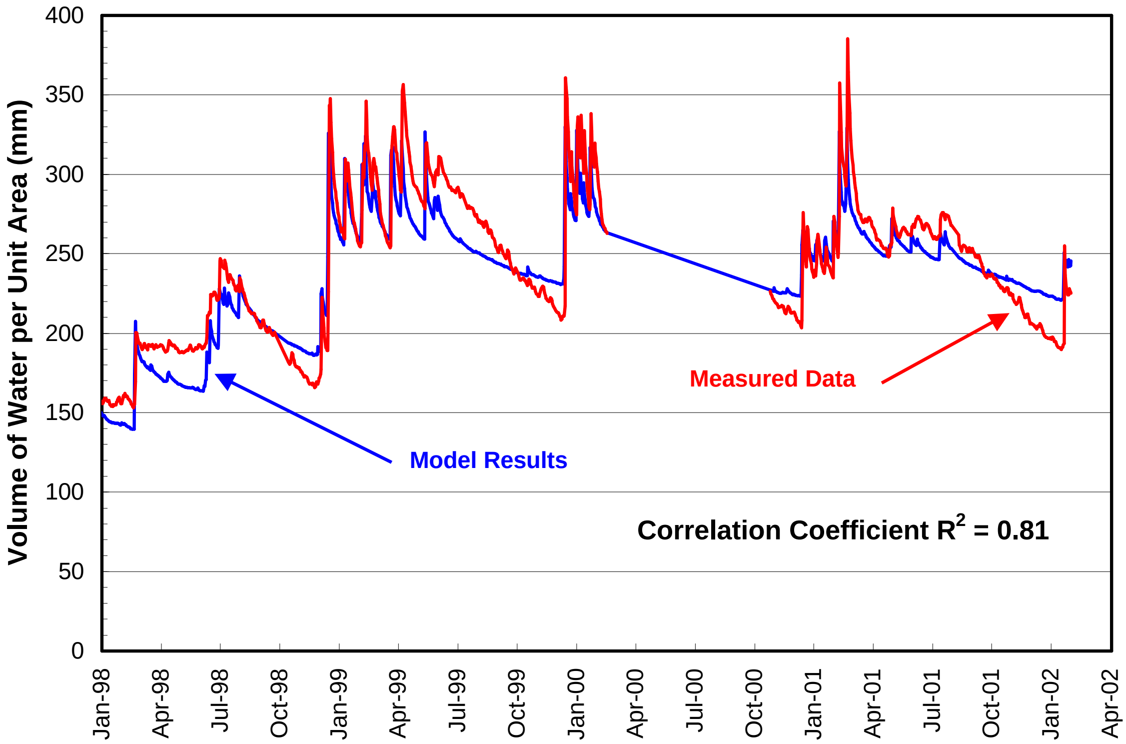

Figure 3.2 Comparison of the calibrated numerical model results to actual measured field data covering the period from January 1998 to February 2002.

3.3.3 Effect of Extreme Climate Events

The original modelling of the Mt. Whaleback cover system used 300 mm for the average annual rainfall based on 30 years of climate data for the site. No net percolation into the underlying waste was predicted using this annual rainfall data. The highest recorded annual rainfall in the 30 year database was approximately 500 mm, which when modelled in 1996 (before construction of the field trials) indicated that net percolation in the 2.0 m BIF cover system would be less than 1% of annual rainfall.

The annual rainfall for the first year of monitoring (October 1997 to September 1998) at Test Plot 1 was 295 mm. No net percolation was recorded during this monitoring period. Rainfall was significantly higher in the next three years with 870 mm recorded in 1998-99, 1,160 mm in 1999-2000, and 497 mm in 2000-01. Net percolation through the cover system was recorded because the storage capacity of the cover system was exceeded by the successive wet years. Figure 3.3 shows the calculated volume of water within the cover system, as well as the net percolation recorded in each year, expressed as a percentage of annual rainfall.

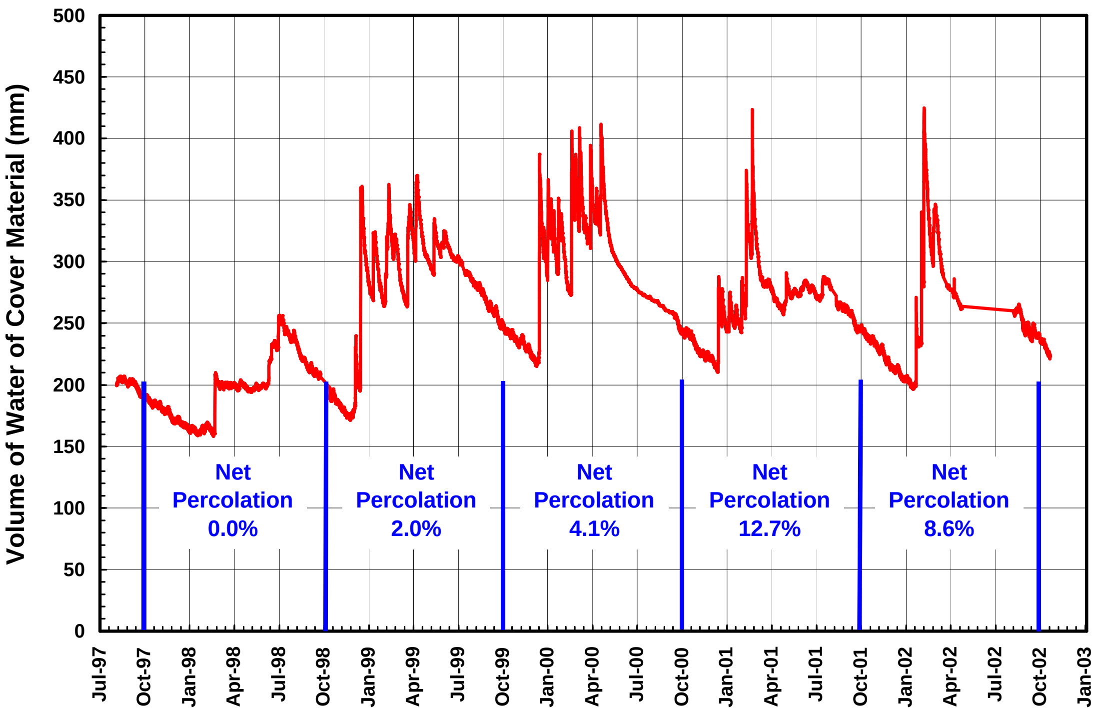

Figure 3.3 Net percolation and change in cover material storage at Test Plot 1.

Net percolation was greatest in 2000-01 when net percolation was approximately 13% of the annual rainfall. This is a significant amount of net percolation compared to the negligible net percolation predicted by the numerical model. The high net percolation in 2000-01 was likely due to the high rainfall in 1999-2000; as there is a lag time required for the infiltrating water to penetrate to the base of the cover system and further to the base of the lysimeter used to monitor net percolation. It is more appropriate to view net percolation over an extended time period to reduce the lag effects and develop an average net percolation value. The net percolation for the time period shown on Figure 3.3 was 5.0% of the rainfall recorded.

The fact that the 2 m of cover material was able to significantly buffer the extreme consecutive wet seasons is a positive aspect of the performance of the Mt. Whaleback field trials, particularly in light of the fact that bare surface conditions are being monitored (i.e. no transpiration). However, the results do illustrate an aspect of predicting cover system performance that was not included in the design phase of the Mt. Whaleback field trials. Typically, and certainly at the time the Mt. Whaleback field trials were designed, cover design modelling would only include modelling of a single extreme wet year. However, the Mt. Whaleback cover system field performance monitoring data clearly illustrate the importance of modelling consecutive extreme wet seasons to ensure that the impact of these conditions on long-term cover system performance is understood.

3.3.4 Effect of Vegetation on Cover System Performance

Vegetation provides the opportunity for a dry cover system to evapotranspirate moisture back to the atmosphere. Moisture stored within a cover system is “pulled” back to the surface through the vegetation root systems. The Mt. Whaleback site currently has two 1-D field plots (Test Plots 4 and 5) to examine the effects of native vegetation on cover system performance.

The calibrated SoilCover model was used to predict the effect of “poor” vegetation (in terms of transpiration rates), with root development to 1 m, on the performance of a 2 m thick layer of Mt. Whaleback run-of-mine cover material. The model was run for three consecutive years using the 1998-99 climate data. One set of simulations incorporated a bare cover system surface while another set of simulations added “poor” vegetation with root development to 1 m. A detailed explanation of the modelling process is contained in Appendix B1. The results of the modelling programme are shown in Figure 3.4.

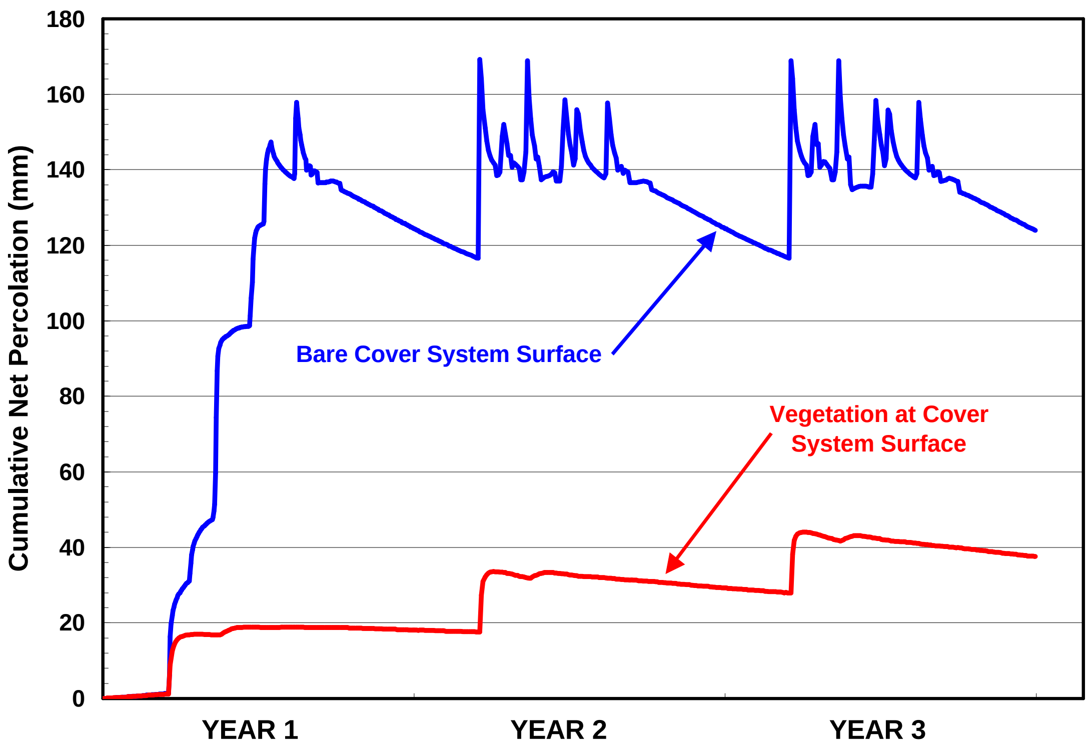

Figure 3.4 Net percolation predicted for consecutive wet year simulations.

The cumulative net percolation for the bare cover system simulations was 125 mm or 4.8% of the cumulative rainfall for the period. This percolation rate is similar to the 5.0% measured value at Test Plot 1 and discussed in Section 3.3.3. The net percolation predicted for a vegetated surface was 37 mm, or approximately 1.4% of the cumulative rainfall.

The presence of vegetation improves the performance of all dry cover systems and in particular, store and release cover systems. Vegetation increases evapotranspiration and "pulls" moisture back to the atmosphere that would otherwise report as net percolation. Once meteoric water infiltrates past the upper layers of the cover system (i.e. 30 cm), it takes prolonged dry periods to generate a sufficient suction gradient within the surface cover material to "pull" up the stored moisture to the surface by evaporation alone. Once a subsequent rainfall event occurs the suction gradient is reduced and infiltration from the first rainfall event cannot be removed from the cover system by evaporation. The rooting systems of most vegetation will develop to reach available moisture sources at depths greater than 30 cm, implying vegetation with a deep root system has a positive impact on cover performance. The modelling results shown in Figure 3.4 illustrate this impact. Test Plots 4 and 5 at Mt. Whaleback were implemented to quantify this effect for species native to the area.

3.3.5 The Effect of Segregation on Cover System Performance

The cover system at the Mt. Whaleback site was constructed by block dumping from large haul trucks to create a hummocky cover surface. Some segregation of the cover material is possible during placement due to the coarse nature of the material. Segregation of well-graded material, which describes most run-of–mine material, can lead to preferential flow paths, or macro-pore flow, within the cover system and possibly increase net percolation to the underlying waste material.

Macro-pore flow was observed in the field following a rainfall event where approximately 280 mm of rain was recorded over a 36-hour period. Sensors at a depth of 10 cm responded immediately following the start of the rainfall event. Sensors installed at 100 cm responded in the range of 36 to 48 hours after the start of the event, which was reasonable assuming flow through the matrix of the cover material. However, the sensors at a depth of 190 cm responded to the significant rainfall event less then six hours after the event started. This implies that a macro-pore flow path, which was not active for any other previous rainfall event, became a preferential flow path as a result of the extreme rainfall condition.

It was hypothesised that segregation of the cover material during placement caused a coarse textured zone, which only became active under high flow conditions (i.e. under all conditions before as well as after this event the preferred flow path was the finer textured matrix and homogeneous surrounding material). VADOSE/W, a 2-D soil-atmosphere numerical model, was used to verify this hypothesis while also illustrating the effects of segregation on performance of a store and release cover system.

The numerical simulation included an analysis of the net percolation of a 2.0 m BIF cover system with a hummocky surface, with the addition of a segregated layer within the cover system. Figure 3.5 shows the two meshes used in the numerical analysis. A detailed description of the modelling process is included in Appendix B1.

The results of the simulations are summarised in Figure 3.6. Minimal net percolation was predicted for the hummocky cover system with no segregation layers. Net percolation was highest (between 5 to 6 mm) below the depressions on the undulating surface. Surface runoff collected in these depressions during the high intensity rainfall events of the simulated climate year driving water into the cover system and resulting in the higher net percolation values. The average net percolation for the cover system was minimal. The cover system with segregation layers showed high net percolation in the two areas where the segregated layer connected with the surface of the overburden. Net percolation was approximately 180 mm in these areas, significantly increasing the average net percolation across the entire cover system modelled (i.e. the mesh shown in Figure 3.5).

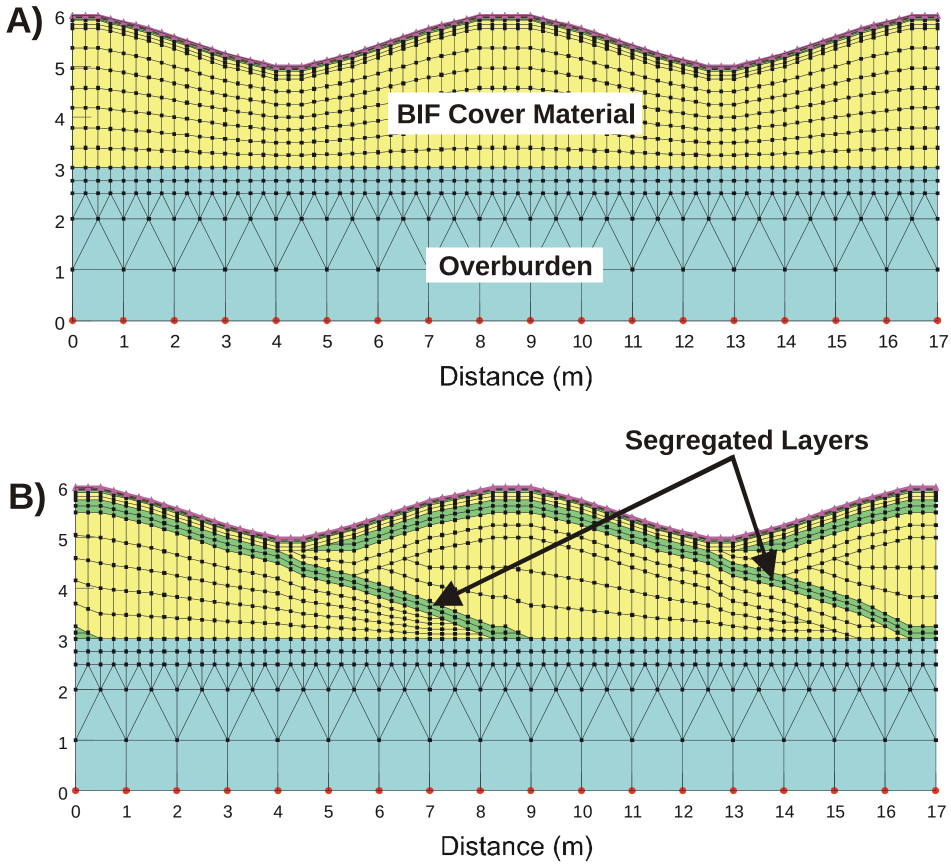

Figure 3.5 a) Mesh used in the 2-D analysis of the Mt. Whaleback hummocky cover system. b) Coarse-textured segregation layers added to the 2-D mesh.

The VADOSE/W model, together with the field performance monitoring data, illustrated a key characteristic with respect to the performance of a store and release cover system under high rainfall conditions. Namely; simply place cover material to the required depth is not sufficient. It is equally important to ensure that a homogeneous layer of material is placed to ensure that segregation of the cover material does not lead to near surface coarse zones, which have the potential to transmit infiltration deeper into the cover profile than would otherwise have occurred for a homogeneous layer of material.

Figure 3.6 Net percolation results predicted for the homogeneous and segregated cover systems.

The segregation layer produces a preferential, or macro-pore, flow path for meteoric waters to infiltrate to the underlying overburden material during extreme climate events. Macro-pore flow occurs in these areas resulting in high hydraulic conductivity rates causing rapid percolation to the underlying overburden material. The effects of segregation have also been observed at Test Plot 2 at the Mt. Whaleback site. Volumetric water content sensors will show quick responses to rainfall events at depths up to two or three metres, suggesting high hydraulic conductivity flow paths exist within the test plot. Note however that these flow paths only become “active” during the extreme rainfall events or when surface runoff promotes accumulated surface flow to the area of segregation. Once the meteoric waters percolate to depth, it is an extremely slow process to “pull” the moisture back to the surface because flow occurs in the matrix of the cover material. In addition, if rainfall events occur prior to exfiltration of the moisture to the surface (or transpiration of the moisture), then unsaturated “piston” flow will “push” the moisture deeper into the profile, and potentially to a depth where moisture cannot be removed as evapotranspiration. Segregation has an adverse effect on store and release cover systems because the macro-pore flow paths allow infiltration of moisture deep into the cover profile during the wet season where it might not be removed before the start of the next wet season. This can result in the deeper moisture reporting as net percolation.

3.4 Summary

The BHP Billiton Mt. Whaleback site possesses the second longest running performance monitoring system of the five sites examined in this study. Data has been collected at two of the test plots for more than five years, with little interruption in data due to equipment malfunction. The high data capture rates are a testament to the site’s commitment to the research project. The field data generated has allowed for the evaluation of the effects of extreme climate events on cover system performance, the definition of field material properties, the calibration of a numerical model to site conditions, an examination of the potential positive impacts of vegetation on cover system performance, and the assessment of the adverse effects of cover material segregation on cover system performance. It is expected that field performance monitoring data will continue to be collected for use in the development of a mine site closure plan.

The key lessons learned from the field performance monitoring are the impact of consecutive extreme climate events on cover system performance, the significant difference between field and laboratory cover material properties and the importance of limiting the segregation of cover material during placement. In short, for a store and release cover system, it is not sufficient to simply place the required thickness of a material with no quality control. This is particularly true for well-graded or gap-graded material, which describes most run-of-mine waste.

4 EQUITY SILVER MINE SITE

4.1 Background

Equity Silver Mines Ltd. is located in the Central Interior of British Columbia, within the Omineca Mining Division, 35 km southeast of Houston and approximately 575 km north northwest of Vancouver. During the life of the operation, copper, silver, and gold were mined within a window of interbedded volcanic and minor sedimentary rocks. Equity Silver Mines Ltd. is situated on an alpine plateau in a humid alpine environment. The average annual precipitation at Equity Silver Mines Ltd. is approximately 650 mm, with rainfall accounting for approximately 300 mm. Annual potential evaporation is approximately 500 mm.

Equity Silver Mines Ltd. worked an open pit mining operation from 1980 to the scheduled end of mining activities in the spring of 1992. Mining activities were continued past the scheduled closure date as underground mining was initiated to follow the ore body. A tailings facility containing waste from the milling operation and covering an area of 120 ha was constructed to the north of the mine plant site. In addition, three waste rock dumps were constructed during the life of the mine. Over 80 Mt of waste rock were placed in the Main dump, the Southern Tail dump, and the Bessemer dump. The final closure of the mine occurred in the spring of 1994.

4.2 Summary of Full-Scale Cover System

The Main dump was constructed first by placing waste rock directly on the cleared ground surface. The natural ground surface consisted of a thin topsoil mantle over glacial till that varies in thickness from 2.5 meters to greater than 20 meters. The Main dump, which contains about 52 Mt of waste rock, has a surface area of approximately 41 ha. The Southern Tail dump, for which construction was started in 1985, contains approximately 18 Mt of waste rock. The surface area of the Southern Tail dump is approximately 31 ha. The Bessemer dump is the smallest of the three waste rock dumps and contains approximately 10 Mt of material. The Bessemer dump is located north of the Main dump between the mine plant site area and the Main dump. The surface area of the Bessemer dump is approximately 29 ha.

The cover system for the waste rock dumps was constructed over the period of 1990 to 1994, starting with the Southern Tail dump, followed by the Main dump, and finally the Bessemer dump. The side slopes of the Main dump were graded to a constant slope with a maximum grade of 21° (2.6H:1V). The entire Main dump was covered with a compacted till layer 0.5 meters thick. A non-compacted layer of till, 0.3 m thick, was placed over the compacted layer. The Southern Tail dump consists of two distinct sections, the northern flat portion which is directly east of the Main dump and the sloped and tiered southern section. Both dumps were covered with a layer of compacted till 0.5 m thick that was placed directly on the waste rock and overlain with a layer of non-compacted till 0.3 m thick. The Bessemer dump was active until final closure of the mine site. An engineered soil cover system similar to that placed on the Main dump and the Southern Tail dump was completed on the Bessemer dump.

The cover system was designed to limit net percolation of meteoric waters to the underlying waste, with any reduction in oxygen ingress seen as an additional benefit. Swanson *et al.* (2003) demonstrated that significant benefit was also realized in terms of controlling oxygen ingress due to the presence of the cover system. The compacted till barrier layer possesses a low hydraulic conductivity that limits the percolation of meteoric waters to the underlying waste material. The compacted barrier layer is also capable of maintaining a high degree of saturation to reduce the ingress of oxygen. The design takes advantage of the low diffusion coefficient of oxygen through water as compared to air. Maintaining a degree of saturation of approximately 85% ensures that diffusion through the cover system will be low.

4.2.1 Overview of the Field Performance Monitoring Systems

Performance monitoring systems were installed to monitor various parameters that will influence the performance of field-scale cover systems. A weather station on the top of the Main dump (TMD) collects rainfall, wind speed, temperature, relative humidity, and net radiation data. The *in situ* moisture and temperature conditions within the cover and waste materials are being monitored with thermal conductivity sensors at the TMD, southwest face of the Main dump (SWF), and at the Southern Tail dump (STD). These sensors are connected to automated data acquisition systems powered by solar panel/rechargeable battery sources. Volumetric water content is measured manually with a neutron water content probe. There are 14 neutron access tubes installed around the mine site with the majority clustered near the three automated monitoring sites.

4.3 Analysis of the Equity Silver Mine Site

The full-scale cover systems installed at Equity Silver Mine site have been in-place for approximately 10 years. The site has provided insight on the evolution of a full-scale cover system and the effects of changing cover material properties on cover system performance. The "lessons learned" at the Equity Silver site include:

- The importance of monitoring changes in the field saturated hydraulic conductivity of the cover materials;
- The proper design of the growth medium layer within a cover system to protect the compacted barrier layer; and
- The need to periodically re-evaluate the performance monitoring data and its value in developing a site-specific calibrated numerical model.

4.3.1 Evolution of Cover System Materials

Phase 1 of the INAP report summarised the physical, chemical, and biological processes that affect the long-term performance of a cover system (see Appendix A1). The processes were related to changes in the key properties of the cover materials such as hydraulic conductivity, the SWCC, and the physical integrity of the cover system. A field programme was completed as part of the INAP project at the Equity Silver Mine site to measure the *in situ* saturated hydraulic conductivity of both the compacted till barrier layer and the non-compacted till growth medium.

The objective of the field programme was to evaluate changes in hydraulic conductivity of cover material with time. Soil structure controls the hydraulic properties of well-graded and fine-grained materials. The alteration of soil structure with time can significantly change the hydraulic conductivity of the cover materials. The field programme was a unique opportunity to evaluate the change in hydraulic conductivity of the Equity Silver cover materials over time. This was possible because a consistent borrow source was used to construct the cover systems for three different waste dumps. The cover systems at the Main and Southern Tail dumps have been in-place for approximately 12 years while the Bessemer dump cover system has been in place for approximately nine years. The results of the field *in situ* saturated hydraulic conductivity test programme were compared to the as-built and laboratory material properties.

A detailed description of the measurement apparatus and the theory pertaining to the measurements is provided in Appendix C1. Twelve measurements of the *in situ* saturated hydraulic conductivity (K_{fs}) were made at a depth of 18 cm with the Guelph permeameter for each of the three cover systems at the site. In addition, three measurements of K_{fs} were obtained at depths of 2 cm, 30 cm, and 70 cm with a pressure infiltrometer. Four measurements of K_{fs} taken with the pressure infiltrometer at a depth of 70 cm “failed” indicating that the hydraulic conductivity of the material at 70 cm was less than the measurement limits of the instrument. The measurement limit of the instrument is 1 x 10^{-7} cm/s. Additional pits were excavated to a depth of 70 cm for hydraulic conductivity testing until three successful infiltration tests were completed. Lastly, dry density measurements were obtained with a sand cone at depths of 2 cm, 30 cm, and 70 cm. These measurements were taken in pits similar to the ones excavated for hydraulic conductivity testing. Table 4.1 summarises the results of the pressure infiltrometer and Guelph permeameter hydraulic conductivity tests.

Table 4.1
Summary of Guelph permeameter and pressure infiltrometer tests at the Equity Silver Mine (geometric mean (M), standard deviation (σ), dry density (ρ_d)).

Depth (cm)	**M (10^{-4} cm/s)**	**s (10^{-4} cm/s)**	**r_d (g/cm^3)**	**Failed Tests**	**M (10^{-4} cm/s)**	**s (10^{-4} cm/s)**	**r_d (g/cm^3)**	**Failed Tests**
	Southern Tail Dump (Slope)				Main Dump (Slope)			
18	0.28	0.62	Guelph Perm.		0.40	1.14	Guelph Perm.	
2	3.37	4.60	1.96	0	3.24	1.65	1.74	0
30	0.32	0.10	2.20	0	0.19	0.19	2.03	0
70	0.006	0.002	2.01	1	0.006	0.002	2.04	0
	Main Dump (Horizontal)				Bessemer Dump (Horizontal)			
18	0.49	0.46	Guelph Perm.		0.15	0.34	Guelph Perm.	
2	5.63	2.10	1.69	0	2.59	2.37	1.66	0
30	0.38	0.036	1.75	0	0.29	0.10	2.01	0
70	0.004	0.002	1.78	2	0.004	0.003	1.81	1

Note: M is the mean value of the field hydraulic conductivity tests conducted
s is the standard deviation of the field hydraulic conductivity tests conducted
r_d is the dry density measured at the same depth and location

Figure 4.1 show the field saturated hydraulic conductivity (geometric mean) and density as a function of depth for the sloped cover systems at the Main dump and the Southern Tail dump. Measurements of hydraulic conductivity taken at depths of 30 cm and 70 cm were within the compacted “barrier” layer. In general, the hydraulic conductivity decreased one order of magnitude from the 2 cm depth to 30 cm depth and decreased two additional orders of magnitude from 30 cm to 70 cm. The dry density was lowest at a depth of 2 cm and increased sharply at 30 cm. These results were anticipated as the 30 cm density measurements were made within the compacted layer. Dry density decreased marginally in the Southern Tail dump cover system as the depth increased to 70 cm. The density was fairly constant from 30 cm to 70 cm in the Main dump cover system.

Based on the relationship between density and hydraulic conductivity, it was anticipated that values of K_{fs} measured at 30 cm would be as low or lower than those at 70 cm due to the higher *in situ* density. However, values of K_{fs} at 30 cm were two orders of magnitude greater than at 70 cm. It would seem likely that the increase in hydraulic conductivity is a result of a change in soil structure. Two possible physical processes that could lead to a change in structure at the site are freeze/thaw cycling and wet/dry cycling. Temperature sensors installed in the compacted layer indicate that this region of each cover system is not undergoing freeze/thaw cycles at any of the automated monitoring locations.

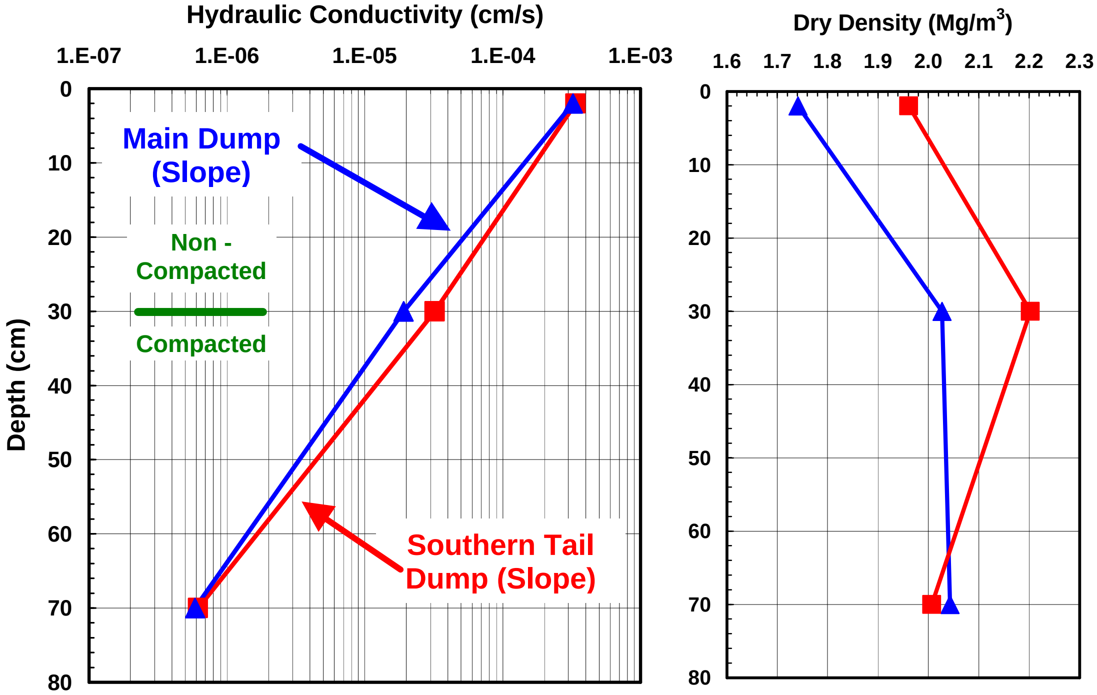

Figure 4.1 Saturated hydraulic conductivity and density measured for the sloping cover systems at the Equity Silver mine site.

The matric suction sensor data indicate that wet / dry cycles started occurring within the top 10 cm of the compacted material in approximately 1999 or 2000, and have continued in each subsequent summer. The increased levels of matric suction have only been recorded in the uppermost matric suction sensor in the compacted layer and were not experienced in the three sensors installed lower down in this layer. This suggests that only the top portion of the compacted layer has experienced wet / dry cycles, which might explain the increased field saturated hydraulic conductivity measured at the top of the layer, as compared to the lower values measured at a depth of 70 cm. Matric suction values measured by the uppermost sensor in the compacted layer during the summer have fluctuated between 400 kPa and 1,000 kPa, significantly higher than the AEV of the compacted cover material. The residual water content for this material likely corresponds to a suction higher than that measured, however, this level of suction would still represent significant drying conditions.

The field saturated hydraulic conductivity testing at the Equity Silver mine site found that the upper region of the compacted barrier layer (approximately 10 cm) possesses a field saturated hydraulic conductivity value more similar to the overlying growth medium. It is likely that the thickness of the growth medium at the Main and Southern Tail dumps was not sufficient to prevent evaporation of moisture from the underlying compacted layer (for the period commencing in 1999 or 2000). It is important to note, however, that the lower region of the compacted layer ($\approx$ 40 cm) appears to be "intact" in the sense that it is similar to as-built conditions and has not been affected by wet / dry cycling. In short, for the limited number of areas tested, it would appear that rather than the growth medium layer and compacted barrier layer having a thickness of 30 cm and 50 cm, respectively; the split is approximately 40 cm and 40 cm. Whether the cover system has come into equilibrium with its surroundings and the evolution of the upper region of the compacted barrier layer is complete (in terms of "changing" to become part of the growth medium); or whether the layers will continue to evolve, will require additional field performance monitoring to further understand the evolution of the cover system.

O'Kane (1996) reported that the laboratory measured saturated hydraulic conductivity values for the compacted till and non-compacted till used in the cover system design were 1×10^{-8} cm/s and 1×10^{-6} cm, respectively. Field measurements taken approximately 10 years later found the field saturated hydraulic conductivity of the growth medium in the range of 1×10^{-4} cm/s, which is a difference of two orders of magnitude. The upper region of the compacted till has a field saturated hydraulic conductivity of 2×10^{-5} cm/s while the lower depth of the compacted layer is 5×10^{-7} cm/s, or lower (recall the failed *in situ* K_{fs} tests, which indicate values less than 1×10^{-7} cm/s for the field saturated hydraulic conductivity of the lower region of the compacted layer).

As part of a cover system research programme undertaken by the site over the period covering approximately 1992 to 1995, Swanson *et al.* (2003) developed field calibrated model parameters that were similar to the laboratory values noted above. The numerical modelling completed for the Equity Silver cover system as part of the INAP project (refer to Appendix C2 for details) did not predict a higher net percolation, as compared to that predicted using the Swanson *et al.* (2003) field calibrated model parameters. This is despite using higher saturated hydraulic conductivity values, as compared to Swanson *et al.* (2003). The modelling comparison was completed for the period subsequent to the first occurrence of the wet/dry cycling measured in the upper 10 cm of the compacted layer (i.e. 1998 to 2002). One rationale for explaining this counter-intuitive result is the contrast between the growth medium and compacted layer, in terms of moisture retention and saturated hydraulic conductivity. This key aspect of the performance of the Equity Silver cover system exists, whether the material properties are as per that modelled by Swanson *et al.* (2003), or as utilised in the modelling completed for this INAP study. The higher saturated hydraulic conductivity and reduced moisture retention of the overlying growth medium (i.e. the non-compacted layer) increases the potential for atmospheric demand for moisture to be satisfied to a much greater extent by this layer, as compared to the underlying compacted material. In addition, the saturated hydraulic conductivity of the lower 40 cm of the compacted material appears to be sufficient to control net percolation for the period from 1998 to 2002 inclusive when evaporation was low (i.e. during late fall and spring freshet). Note also that while a higher saturated hydraulic conductivity for the growth medium increases surface infiltration, it should also imply that exfiltration rates would be higher.

The saturated hydraulic conductivity of a cover material is not the only material property likely to change with time; the SWCC will also likely change as the material evolves. The change in moisture retention characteristics of the material will affect the saturation levels of the cover system, which will, in turn, affect the rate of oxygen ingress to the underlying waste material. The modelling completed for this study predicted higher oxygen ingress for the hydraulic material properties assumed to represent current conditions, as compared to that predicted using the hydraulic material properties developed by Swanson *et al.* (2003).

Note that all numerical modelling on the Equity Silver cover system and reported herein was completed using the SoilCover model (Geo-Analysis 2000 Ltd., 2000).

4.3.2 Design of Growth Material Layer Thickness

Often in the design and construction of a compacted barrier layer – growth medium dry cover system the focus of the design is on the compacted barrier layer. Considerable attention is paid to the placement of the compacted layer, ensuring proper water content and compaction to produce a low hydraulic conductivity material. While the importance of the barrier should not be discounted, neither should the importance of the overlying growth medium. The growth medium layer serves as protection against physical processes, such as wet / dry cycling and freeze / thaw cycling, as well as chemical and biological processes. An inadequate growth medium layer will not properly protect the compacted barrier layer, leading to possible changes in the barrier layer performance. Concurrent to these considerations is that the growth medium must possess sufficient available water holding capacity to ensure a sustainable vegetation cover, which would be a function of the underlying material as well as the moisture retention and thickness of the growth medium.

The full-scale cover system design at the Equity Silver mine site incorporated a 0.5 m compacted till barrier layer with a 0.3 m overlying non-compacted till growth medium layer. As discussed in the previous section, the compacted barrier layer has experienced an increase in saturated hydraulic conductivity resulting from a change in soil structure, which in turn was caused by wet/dry moisture cycling. This suggests that the growth medium layer did not provide adequate protection for the upper region of the underlying barrier layer in terms of ensuring that atmospheric demand for moisture was limited to the growth medium layer. The emergence of different vegetation species and changes in the moisture requirements of the vegetation would likely have also influenced the measured performance.

The performance monitoring data collected at the site suggests that the 0.3 m growth medium layer does adequately protect the compacted layer from freeze / thaw cycling, when combined with the insulating effects of the winter snowpack at the site. Suction data recorded within the compacted layer does show moisture cycling with elevated suctions being measured in the summer season and low suctions during the winter and spring. This indicates wet / dry cycling, most likely driven by the vegetation established on the cover system.

It is generally thought, that plants do not establish their rooting systems in barrier layers due to the high density conditions within the layer, although this report does not make that contention. An alternate hypothesis (Barbour, 2003) might be that root development does not extend into these layers due to the low oxygen levels within the compacted layer because these layers are most often compacted wet of optimum, which corresponds to a high saturation level. If the growth medium does not possess the capacity to supply the moisture required to meet vegetation and atmospheric demand throughout the summer season, this demand for moisture will extend to the barrier layer. The moisture condition of the upper region of the barrier layer will be reduced, which will increase oxygen concentration in the pore space. It is hypothesised that the vegetation could then establish a "toe-hold" within the barrier layer and continue to penetrate to the depth required to satisfy its moisture demands.

The Equity Silver site is an example of the importance of the design of the growth medium layer to long-term performance. The upper 10 cm of the compacted barrier layer functions in a similar manner to a growth medium layer rather than a compacted barrier layer. It is possible that a thicker growth medium layer, which would appear to be the direction in which the cover system is evolving, may provide better protection for the barrier layer and limit the evolution of the material within the barrier layer.

4.3.3 Periodic Evaluation of Performance Monitoring Data

The operational status of the performance monitoring system should be reviewed annually to ensure that it is still meeting its objectives with respect to the long-term closure plan. The objectives of field performance monitoring are to:

1. Develop an understanding for key processes and characteristics that control performance;
2. Verify the predicted performance of the cover system;
3. Develop credibility and confidence with respect to performance of the proposed cover system from a closure perspective; and
4. Develop a database with which to calibrate numerical modelling tools and optimise the cover system design.

For example, if one of the objectives of the performance monitoring programme at the mine site is to collect *in situ* field measurements for the calibration of a site-specific numerical model then the automated instrumentation must be maintained to ensure that the required data is collected. There is minimal value in maintaining a performance monitoring system that does not suit the closure objectives of the mine site.

Field performance monitoring systems were installed at three locations on the Equity Silver mine site in 1993. Data has been collected continuously since the onset of monitoring with automated temperature and matric suction readings and periodic manual measurements of volumetric water content. Gradually, over the 10 years of operation, some sensors have stopped operating or do not record accurate data. For example, only one of the original eight suction sensors at the top of the Main dump monitoring location is currently providing useful data. Note, however, that this is a function of the quality of the sensors installed. At the time of installation the sensors installed were state-of-the-art. More robust sensors are now available, which were not available at the time of installation of the monitoring system.

One of the work tasks of the Phase 2 study was to complete numerical modelling on selected mine sites. The Equity Silver mine site was one of the selected sites and time was spent to create a database of *in situ* conditions, material properties, and climate data. The soil-atmosphere model was calibrated to the field data, as noted in Section 4.3.1, and appendix C2. However, it should be noted that it was more difficult to calibrate the model to the site's field performance monitoring data (i.e. *in situ* suction), as compared to the BHP Billiton Mt. Whaleback site.

The difficulty in calibrating the model to the Equity Silver mine site field performance monitoring data is due in part to the lack of a continuous record of *in situ* conditions, as discussed above. An additional issue associated with the difficulty in developing the calibrated cover system model for the site was the manual, periodic measurements of volumetric water content. Neutron probe water content measurement was the state-of-the-art technology at the time of installation. However, recent research has shown that manual monitoring does not provide timely enough measurements for use in model calibration nor provide the required "real-time" data to develop a thorough understanding for the response of the cover system to precipitation and evaporation at the site. Volumetric water content should be measured automatically at the same intervals as soil suction. As discussed in the previous section, this would allow determination of the *in situ* field SWCC, which significantly enhances the ability to develop a calibrated numerical model.

4.4 Summary

The Equity Silver mine site possesses the oldest, in-place full-scale cover systems of the five sites examined in the study. Data has been collected at three monitoring stations for approximately ten years; however, there have been considerable interruptions in data collection due to equipment malfunction.

A field testing programme conducted as part of this study found that the saturated hydraulic conductivity of the non-compacted till growth medium material and the upper 10 cm of the compacted till barrier layer are higher than the laboratory measured values used in the numerical modelling completed by Swanson *et al.* (2003) and the original design work completed for the cover system. Examination of the field data collected found that wet / dry cycling is likely occurring in the upper 10 cm of the compacted layer and might be a possible cause of the change in cover material properties. This study highlighted the importance of a properly designed growth medium cover layer and the value of accurate, automated, and continuous cover system performance monitoring data.

The key lessons learned from the field performance monitoring and field testing completed at the Equity Silver mine site are the significant difference between the current saturated hydraulic conductivity of the cover materials and the original laboratory tests (i.e. the evolution of the cover material); and the importance of timely, accurate performance monitoring data. This includes the collection of automated volumetric water content data. The site's historical data and research work on cover system design at the site represents a tremendous opportunity to evaluate the long-term performance of dry cover systems.

5 SYNCRUDE CANADA LTD.

5.1 Background

The Syncrude Canada Ltd. (SCL) mine site is located 40 km north of Fort McMurray, Alberta. The northern Alberta climate at the site consists of cold winters and temperate summers, with an approximate average annual temperature of -1°C (Shurniak, 2003). The average annual precipitation recorded between 1994 and 1999 was 392 mm; the 40-year annual average precipitation measured at the Fort McMurray station (1953-1993) is 460 mm. The average annual potential evaporation for the period is 670 mm.

SCL uses open-pit mining methods to extract the Athabasca oil sand. Both post-glacial and glacial deposits as well as saline sodic shale must be removed to access the oils sands. The overburden piles are constructed by first placing the saline sodic shale on cleared ground. The overburden is then typically re-contoured shortly thereafter, and covered with glacial deposit materials and an overlying layer of peat.

5.2 Summary of Field Cover System Trials

Two large cover systems have been constructed at SCL at the 30-Dump Overburden Area (including Bill's Lake and Peter Pond) and the Southwest Sands Storage Area (SWSS). The cover systems are monitored and maintained as part of SCL's Watershed Monitoring Group. The cover systems are larger than conventional field test plots; however, they are considered to be cover system trials because the final cover system design at SCL has not been determined.

The potential cover materials at the SCL site include a peat / mineral mix and a secondary unit comprised of a mixture of reclaimed mineral soil, glacial till or glaciolacustrine clay. The 30-Dump cover system is placed over the saline sodic shale overburden while the SWSS cover system overlies tailings material. Each of the cover systems incorporates a mixture of the peat / mineral mix and the secondary unit.

The 30-Dump Overburden Area includes five different cover system trials. The cover system located on the top of the 30-Dump was constructed in 2001 and consists of 20 cm of peat / mineral mix overlying 80 cm of secondary. Three cover system trials (D1, D2, and D3) are located on the sloping surface of the 30-Dump Overburden area. The cover systems were constructed in 1999 and are approximately 150 m long and 50 m wide with slopes at approximately 8H:1V. The D1 cover system incorporates 20 cm of peat / mineral mix over 30 cm of secondary material while the D2 cover system includes 15 cm of peat / mineral mix overlying 20 cm of secondary. D3 has a cover system design similar to the top of the 30-Dump with 20 cm of peat / mineral mix overlying 80 cm of secondary. The oldest cover system in the 30-Dump area was constructed in 1996 near Bill's Lake. The Bill's Lake cover system incorporates a peat / secondary mix placed over the sloping shale overburden surface. The thickness of the cover material ranges from 30 cm at the toe of the slope to 155 cm at the crest, although the thickness is approximately 100 cm at the location of the performance monitoring system.

The cover system within the SWSS consists of a 45 cm thick peat / secondary cover material overlying the tailings sand. Detailed monitoring is conducted at two locations on the cover system at Cell 32 and Cell 46 on the sloping outer face of the facility, and are orientated in an easterly and westerly direction, respectively.

5.2.1 Overview of the Field Performance Monitoring Systems

Monitoring systems were installed to measure various parameters that influence the performance of the cover systems. Each monitoring location (i.e. D1, D2, D3, Top of the 30-Dump, Bill's Lake, Cell 32, and Cell 46) includes sensors to monitor in situ temperature, suction, and volumetric water content. Meiers (2002) and Boese (2003) provide further information on field performance monitoring of the 30-Dump, and Shurniak (2003) contains additional details regarding field response numerical modelling of the 30-Dump cover systems.

5.3 Analysis of the Syncrude Canada Ltd. Site

The oldest cover system installed at the SCL site has been in-place for approximately seven years while the most recent cover system has been in-place for two years. The site has provided insight to the performance of a relatively thin cover system on a sloping surface, the evolution of a dry cover system, and the effects of changing cover material properties on cover system performance. For the purposes of the INAP's dry cover system longevity research project reported herein, the "lessons learned" at the Syncrude Canada Ltd. site include:

- The importance of *in situ* monitoring at upper and lower locations on the cover system slope;
- The effect of slope micro-topography and small undulations on the performance of the cover system; and
- The importance of monitoring the evolution in the key cover material properties, which in particular at SCL is the field saturated hydraulic conductivity.

5.3.1 Performance Monitoring at Multiple Locations on the Cover System Slope

The effects of surface runoff and lateral percolation within the cover materials impact the performance of a sloping 2-D cover system. Enhanced field performance monitoring is required to characterise the 2-D performance. For example, the cover materials may divert flow within the cover system reducing the net percolation through to the underlying waste in the upper areas of the slope. However, the water being diverted down the slope will slowly increase the pore-water pressure condition of the cover materials until a breakthrough occurs and water percolates into the waste material at the lower areas of the slope. The measured net percolation below the breakthrough point would be higher (laterally) than above the breakthrough point (the difference between the values being a function of climate, material properties, and slope angle). This "build-up" of infiltration water within the cover materials has been observed at the SCL site. Alternatively, the performance of the upper area of the slope will also be impacted by lateral percolation. It will lead to a reduced degree of saturation within the cover materials that can lead to an increase in the rate of oxygen ingress across the cover system. While this is not a design objective for the SCL cover system, this is a concern if one of the main objectives of a cover system for reactive mine waste is to minimise oxygen ingress. In addition, there may be an impact on vegetation conditions (species, sustainability, etc.) as a result of potentially differing moisture regimes at the upslope and downslope conditions.

If one monitoring location is used to characterise the performance of the sloping cover system, it is likely that it will not reflect the actual average performance of the cover system at locations with seasonally humid to humid climate conditions. Two monitoring locations (up-slope and down-slope) can often be installed on the cover system slope and connected to the same datalogger. This produces more appropriate field performance monitoring data and allows analysis of lateral percolation flow gradients, as well as enhanced characterisation of the performance of the cover system on a sloping surface.

5.3.2 Effect of Micro-Topography and Undulations on Cover System Performance

The development of 2-D soil-atmosphere models has improved the understanding of moisture flow within dry cover systems. While previous studies have examined the 1-D performance of the cover system, state-of-the-art numerical models, such as VADOSE/W, can evaluate the performance of constant or concave slope cover systems, or the effects of small undulations or micro-topography.

The 1-D SoilCover model was calibrated as part of a University of Saskatchewan research programme funded by SCL to match the field conditions measured at the 30-Dump D1, D2, and D3 overburden cover systems (Shurniak, 2003). Note however, modelling information reported herein from Shurniak's (2003) research focuses on the D2 field trial. For further details the reader is referred to Shurniak (2003), or encouraged to contact SCL site personnel or Dr. Lee Barbour at the University of Saskatchewan. Appendix D1 contains a complete summary of the numerical modelling completed for the INAP project

While calibration of the model was successful, an almost identical match between the model and field conditions was not possible. Figure 5.1 shows the change in moisture storage measured in the D2 cover to the predicted results from the calibrated SoilCover model. It was hypothesised that the lack of complete agreement between the numerical model and field conditions was a result of 2-D lateral percolation within the cover system.

The reader is referred to Shurniak (2003) for further details with respect to the field calibrated model developed for the D2 cover system. In summary however, Shurniak (2003) utilised the field performance monitoring data to define the layering and *in situ* material properties (moisture retention and hydraulic conductivity) of the cover systems. In addition, species specific information was input to model vegetation.

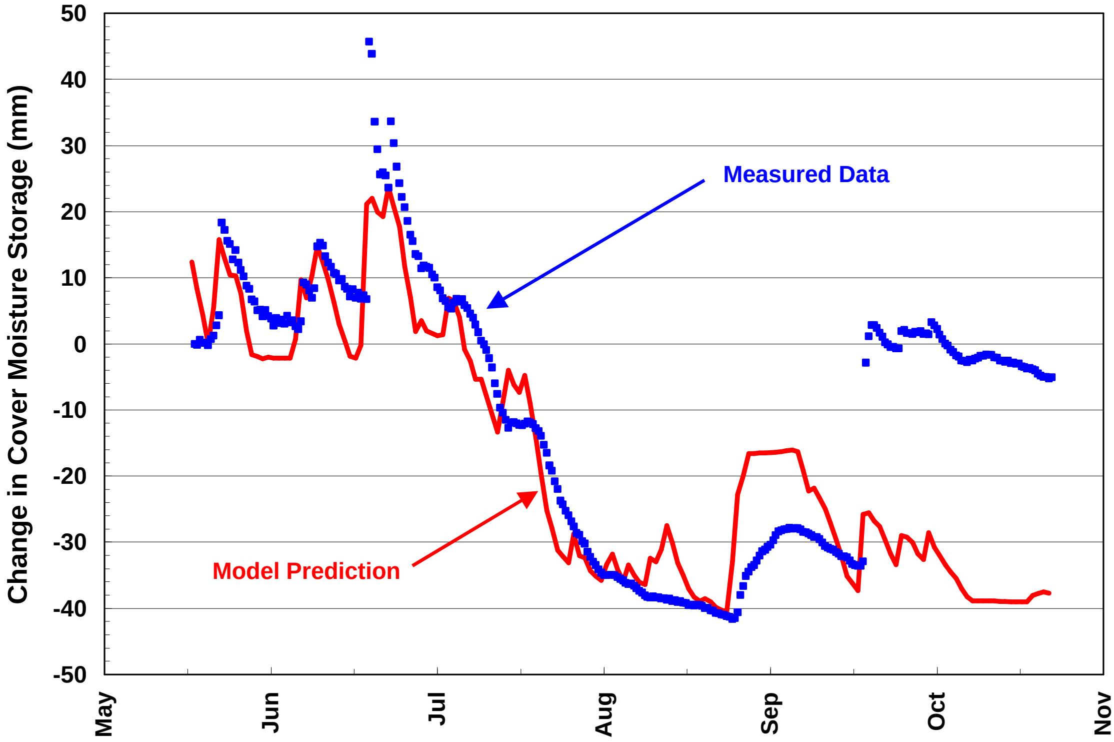

Figure 5.1 Change in storage predicted by SoilCover compared to actual measured field conditions at the D2 cover system.

In general, the change in moisture storage predicted by the SoilCover model reflects the actual conditions measured at the D2 monitoring site. The major disparities between the results are in early September when SoilCover predicted an increase in cover storage that was not measured in the field and on September 28, 2000 when a large increase in storage was measured in the field and not reflected in the model. Approximately 22 mm of rainfall was recorded during a late September 2000 storm event, while an increase in storage of 32 mm was measured in the field. It was hypothesised by Shurniak (2003) that the "extra" water storage (i.e. 10 mm greater than rainfall) measured at the monitoring site is a result of lateral percolation of infiltration water from up-slope.

The VADOSE/W model was used during the INAP project with respect to the Syncrude case study as a tool to better understand the processes and / or characteristics that led the SoilCover model (as well as intuition) to diverge from the field performance monitoring data. The first thought was that the 8H:1V sloping surface resulted in lateral flow, and hence a diversion from 1-D conditions. As part of the INAP project the VADOSE/W model was used to model this sloping condition to further understand and verify the hypothesis. The material properties from the calibrated SoilCover model were input to a 2-D VADOSE/W numerical model.

The VADOSE/W model demonstrated that the hypothesis, which assumed that lateral flow within the cover material resulted in the increase on moisture storage measured in the field, was incorrect. Hence, the understanding of the field condition was flawed. The modelling results predicted for the uniform 8H:1V sloping surface were similar to that predicted by SoilCover (see appendix D1).

Undulations in the surface of the field trials were observed, which had developed as a result of differential settlement of the cover material. It was also noted that the monitoring site was inadvertently located on a relatively shallower sloping area of the trial as compared to the rest of the slope. A detailed topographic survey was completed, and the topography input to the VADOSE/W model. Figure 5.2 shows the numerical mesh used in the 2-D simulation.

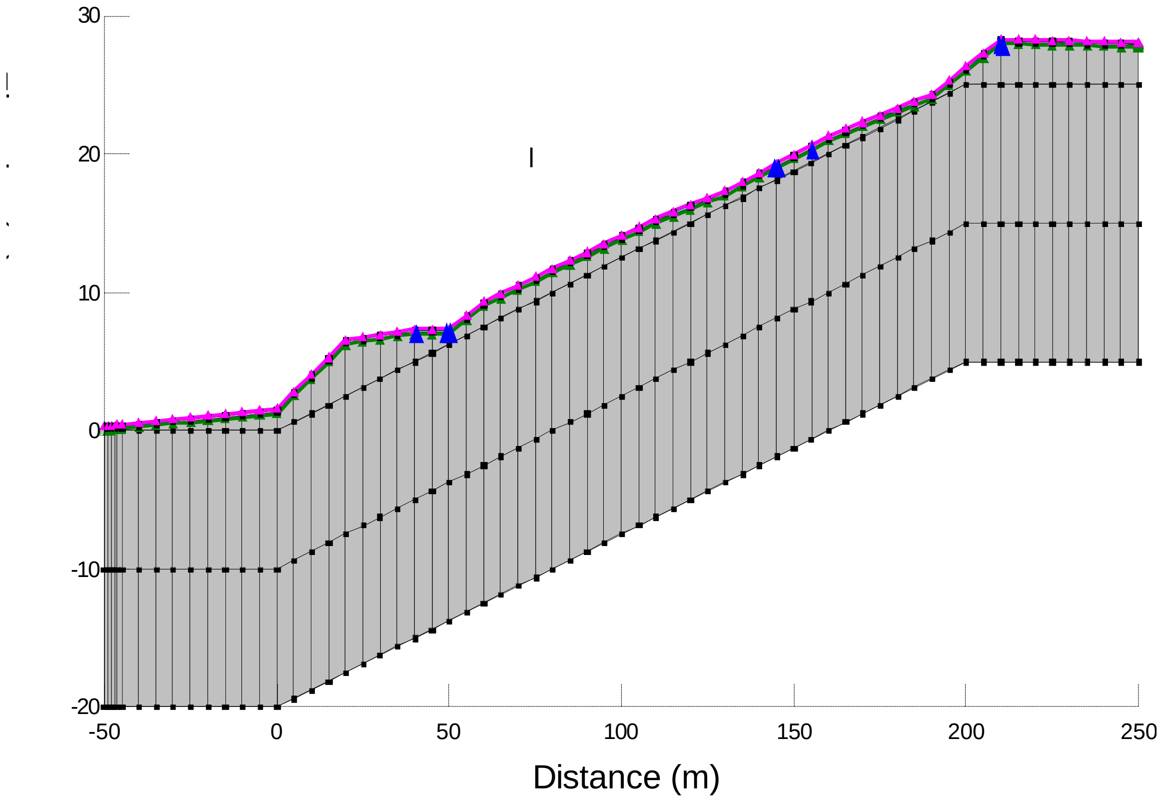

Figure 5.2 The 2-D numerical mesh used in the VADOSE/W simulation.

Figure 5.3 summarises the results of the 2-D simulation, including the results of the 1-D SoilCover simulation shown previously, the change in moisture storage for the entire cover system, and the change in moisture storage at a location 50 m up-slope of the toe of the slope. The predicted change in storage for the 2-D simulation for the entire cover system provides a reasonable match to measured field conditions and is an improvement over the 1-D simulation results. However, the 2-D model's response to the September 2000 rainfall event averaged over the entire slope is still not indicative of field conditions.

The change in storage at a position of 50 m up-slope of the toe is also shown on Figure 5.3. The predicted values do not match the field conditions well, however, the higher storage conditions measured at the site in late September and early October are reflected in the model results. The area 50 m up-slope of the toe is within a localised flattened section of the cover system. The break in the topography of the slope causes a "pooling" of water at the surface generating increased water storage in the cover material as compared to the other locations along the slope.

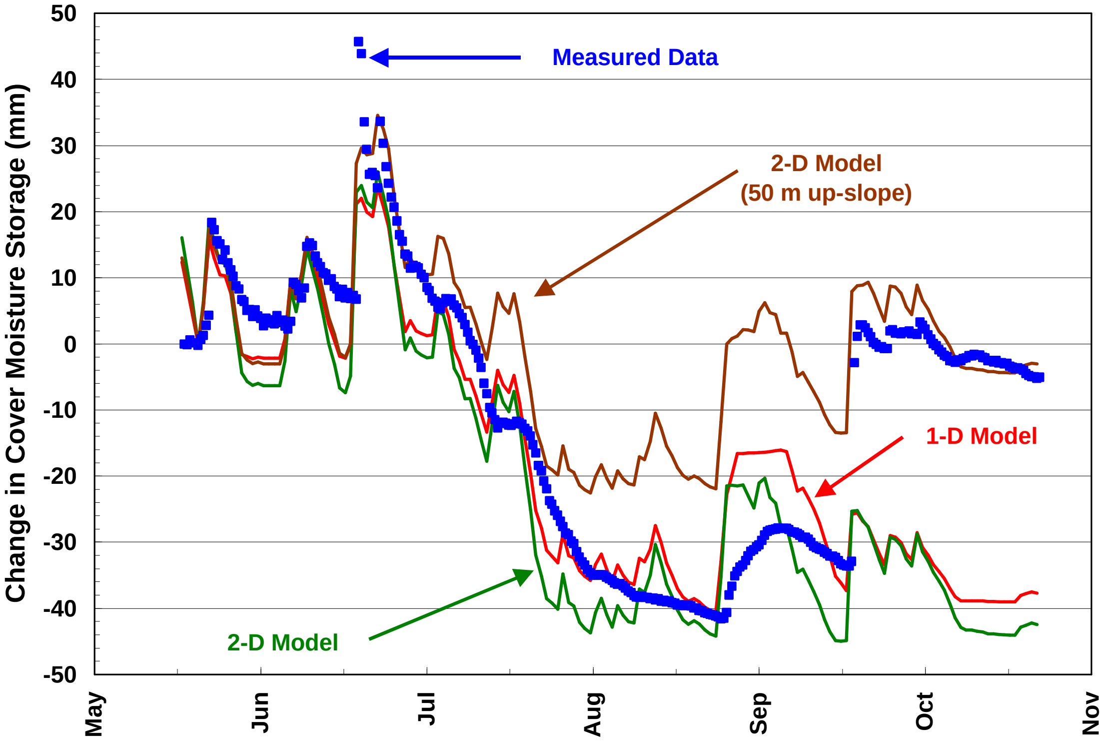

Figure 5.3 Comparison of actual field conditions to predicted change in storage for 1-D and 2-D soil atmosphere numerical models.

The numerical modelling shows the significant effect of these localised undulations in the slope on the cover system performance. In a 2-D system, runoff and lateral percolation "drive" net percolation by increasing water contents and pore-water pressures at the base of the slope. Localised undulations in the cover system slope "break up" the down-slope flow of water, which leads to higher saturation levels in the upper areas of the slope.

The D2 monitoring site is located on a shallower sloping area as compared to up-slope conditions. Knowledge of this, coupled with the results shown in Figures 5.2 and 5.3, allow for the development of a reasonable hypothesis for the increase in moisture storage measured at D2 in response to the September 2000 rainfall event. It would appear that undulations and depressions in the cover system led to an increase in moisture storage at the monitoring location, which otherwise would not have occurred for a uniform sloping surface.

The understanding developed with respect to the D2 cover system is a positive performance characteristic because it illustrates than an opportunity exists to engineer undulations and depressions in a sloping surface (rather than be caused by local settlement and heave). The result could be an increase in the capability of a cover system to control net percolation (by increasing ponding and moisture storage, and reducing runoff and associated erosion), by simply creating undulations and depressions using a dozer. Note however that the optimal depth and spatial extent of the undulations would be site-specific.

The fact that the VADOSE/W model results shown in Figure 5.3 do not perfectly "match" the Syncrude field data should not be the focus of discussion. With further refinements to the model an improved “match” to the field data could be achieved. However, field response modelling should not focus on numbers alone, but rather on patterns. It was possible to verify the revised hypothesis regarding the processes and characteristics that led to the observed field performance, by “matching” the pattern predicted by VADOSE/W when modelling the Syncrude field data. The result was that the model was able to "demonstrate" and educate, with respect to the significant influence on moisture storage in a cover material, and hence surface runoff and net percolation, due to seemingly insignificant changes in surface topography.

5.3.3 Evolution of Cover System Materials

The *in situ* field hydraulic conductivity testing programme completed at Equity Silver Mine and described in Section 4.3.1 was based on the methodology described by Meiers (2002) for the SCL site. The D1, D2, and D3 cover systems installed at the 30-Dump overburden area in 1999 were the focus of Meiers’ (2002) research programme. Field *in situ* hydraulic conductivity tests were completed on the peat and secondary cover materials and the underlying shale waste materials in the summers of 2000, 2001, and 2002. The measurements were obtained using a Guelph permeameter and a tension infiltrometer.

A summary of the results of the three-year testing programme is shown in the cumulative histogram in Figure 5.4. The cumulative histogram summarises the percentage of the total tests that produced a hydraulic conductivity greater or lesser than a specified hydraulic conductivity.

Table 5.1 summarises the mean saturated field hydraulic conductivity measured for the materials over the three-year period and includes the number of tests considered in the average. Each of the three materials tested shows a significant increase of *in situ* saturated hydraulic conductivity over the three-year period. The greatest increase was in the first year of study from 2000 to 2001 with a smaller increase occurring from 2001 to 2002.

Table 5.1
Summary of the mean saturated hydraulic conductivity of the cover and waste materials (from Meiers, 2002).

Year	Peat	Secondary	Shale
2000	8.0×10^{-4} cm/s (9 tests)	3.0×10^{-6} cm/ (54 tests)	2.0×10^{-7} cm/ (34 tests)
2001	4.0×10^{-3} cm/ (16 tests)	2.0×10^{-4} cm/s (38 tests)	2.0×10^{-6} cm/ (42 tests)
2002	6.0×10^{-3} cm/s (11 tests)	4.0×10^{-4} cm/s (29 tests)	6.0×10^{-6} cm/ (27 tests)

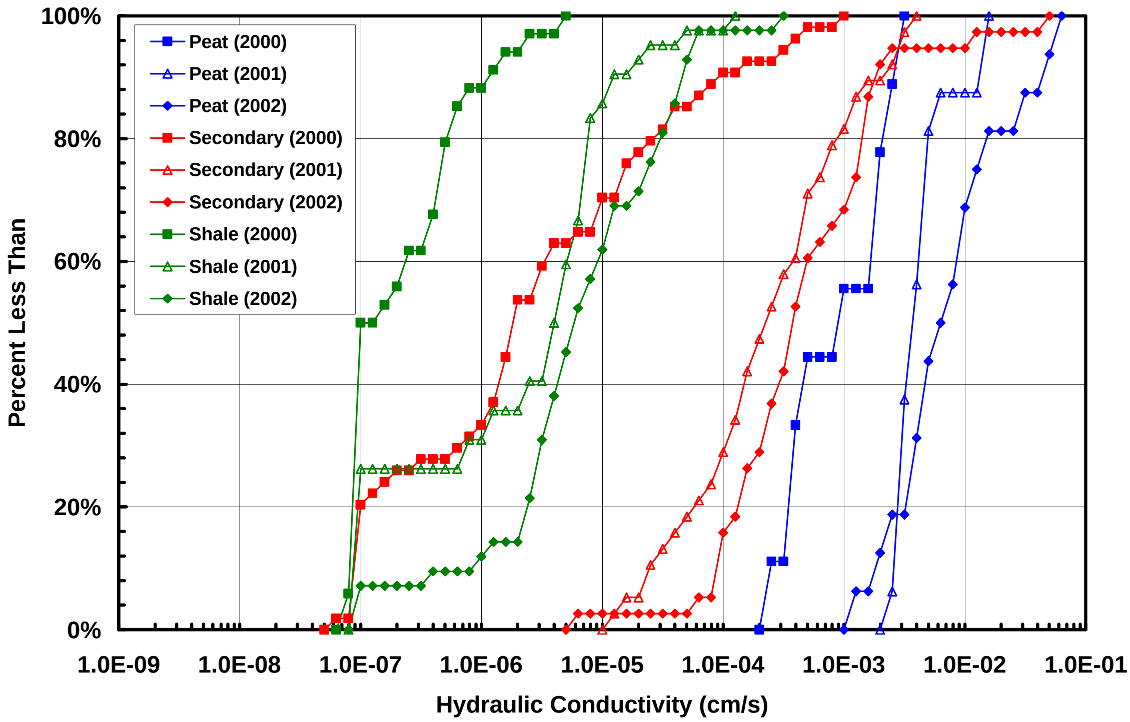

Figure 5.4 *In situ* saturated hydraulic conductivity results from the 2000, 2001, and 2002 testing programme (from Meiers, 2002).

The increase in the mean field saturated hydraulic conductivity of the peat material was less than one order of magnitude. The mean field hydraulic conductivity of the material was 8 x 10^{-4} cm/s in 2000 and increased to 4 x 10^{-3} cm/s and 6 x 10^{-3} cm/s in 2001 and 2002, respectively. The till secondary unit experienced the largest increase in field saturated hydraulic conductivity during the monitoring period. The field saturated hydraulic conductivity increased two orders of magnitude from 3 x 10^{-6} cm/s in 2000 to 2 x 10^{-4} cm/s in 2001. In 2002, the measured increase was comparatively small (4 x 10^{-4} cm/s). The increase in field saturated hydraulic conductivity in the shale waste material was one order of magnitude (2 x 10^{-7} cm/s to 2 x 10^{-6} cm/s) from 2000 to 2001. A smaller increase occurred in 2002 when the mean field saturated hydraulic conductivity was 6 x 10^{-6} cm/s.

The increase in field saturated hydraulic conductivity of the cover and waste materials at SCL will have a significant impact on the overall performance of the cover system. A small change in saturated hydraulic conductivity of the cover materials was measured between 2001 and 2002, as compared to the large increase measured in the previous year. This implies that the field saturated hydraulic conductivity of the cover material may be reaching an equilibrium condition. The exposure of the cover systems to freeze / thaw cycling was examined from the performance monitoring data, which shows that each cover system has frozen down to the underlying shale waste material during each winter. Hence, each cover system has undergone a single freeze / thaw cycle during the winter and subsequent summer, which led to the increase in the field saturated hydraulic conductivity. The first freeze / thaw cycle resulted in the greatest increase, while the impact of the subsequent freeze / thaw cycle was not as extensive. Further testing scheduled for the summer of 2003 will clarify whether the cover system materials are still evolving or whether they are approaching an equilibrium condition.

It is generally accepted that laboratory measurements of cover material properties are not representative of field conditions. However, field measurements of the as-built conditions may not be representative of the long-term field conditions either. This was illustrated for the SCL case study by the change in field saturated hydraulic conductivity of the cover materials resulting from freeze / thaw cycling. It is not a question of whether or not the site-specific processes will impact on the key material properties; rather, the issue is to what extent and over what time frame the key material properties will evolve such that the measured condition will be indicative of long-term performance.

5.4 Summary

The Syncrude Canada Ltd. site has large area field trials for examination of cover system performance in a cold, semi-arid environment. Data has been collected at the site's monitoring stations for approximately four years. A numerical modelling programme showed the importance of examining the 2-D effects of runoff and lateral percolation on cover system performance and the need for up-slope and down-slope field performance monitoring. A three-year field testing programme found that the field saturated hydraulic conductivity of the peat and secondary cover system materials has increased in each successive year since cover system construction at the 30-Dump site. The greatest increase in the field saturated hydraulic conductivity was observed between the first year and second year, with a smaller increase measured between the second and third years of monitoring. Field performance monitoring data shows that each of the D1, D2, and D3 cover systems is undergoing a single freeze/thaw cycle into the underlying waste material each year. SCL's commitment to understanding the performance of the cover system trials as part of a continuing effort to develop optimal operational scale reclamation methods presents an excellent opportunity to examine the long-term performance of dry cover systems.

The key lessons learned from the field performance monitoring and field testing at SCL are the significant effects of 2-D flow and small undulations in the sloping cover system surface on the performance of the cover system, and the increase in field saturated hydraulic conductivity of the cover materials following construction of the cover system.

6 TECKCOMINCO KIMBERLY OPERATIONS

6.1 Background

The TeckCominco Kimberly Operations mine site is located in Kimberley, British Columbia, within the Purcell range of the Rocky Mountains. During the life of the operation, iron, lead, and zinc were mined from the underground ore body. The climate at the TeckCominco Kimberly Operations is classified as semi-arid due to an annual moisture deficit, however the site typically experiences hot, dry summer conditions and can experience humid fall and winter conditions. The average annual precipitation at the site is 402 mm calculated from mill site weather records, with rainfall accounting for approximately 240 mm. The average annual potential evaporation for the site is approximately 700 mm.

The underground mining operation at the site ran continuously from 1909 until closure in 2001. A tailings facility was constructed in 1923 and contains 90 million tonnes of waste material within its 373 ha area. The tailings were deposited on a relatively flat area directly on a bedrock / till surface.

6.2 Summary of Cover System Test Plots

A total of seven test plots were constructed on the siliceous tailings storage facility. This study focuses on three test plots constructed in 1994; consisting of a compacted barrier cover system, a store and release cover system, and a coarse rock "control" cover system. The reader is referred to Gardiner *et al.* (1997) for additional details. The test plots were constructed using a coarse low-density reject rock from the mill (float rock) and a cobbly, non-plastic till. The float rock was originally placed on the tailings for dust suppression. However, as an understanding for the use of this material as a component of a cover system was developed, the float rock layer served as a capillary break to limit the upward movement of salts from the underlying tailings into the cover system materials. The depth of the float rock layer in the test plots ranges from 20 to 60 cm.

The compacted barrier cover system (Test Plot #2) included a 25 cm compacted till layer and an overlying 25 cm non-compacted till growth medium layer. The measured laboratory saturated hydraulic conductivity of the compacted and non-compacted till material was 1×10^{-6} cm/s and 1×10^{-3} cm/s, respectively. The store and release cover system (Test Plot #3) was constructed from 45 cm of non-compacted till over the float rock. The final "control" cover system consisted of the bare float rock material.

6.2.1 Overview of the Field Performance Monitoring Systems

Meteorological conditions monitored in the test plot area include air temperature, precipitation, and relative humidity. Information on global radiation and sunshine hours are recorded at nearby regional meteorological stations and was used to supplement site measurements. Snow depth measurements were obtained on the test plots subsequent to the onset of winter conditions and up to the spring freshet. The suction and temperature at the mid-depth of the non-compacted and compacted till layer of each test plot, as well as the underlying tailings, have been monitored since construction. Field lysimeters monitor net percolation into the underlying waste tailings material from the base of the cover systems and are used to evaluate the performance of the cover system field trials.

6.3 Analysis of the TeckCominco Kimberly Operations Mine Site Test Plots

The cover system test plots installed at TeckCominco Kimberly Operations Mine site have been in-place for approximately nine years. The site has provided insight on the relative influences of snow and rain on the performance of the cover systems, the evolution of cover system materials, and the effects of changing cover material properties on cover system performance. The "lessons learned" at the TeckCominco Kimberly Operations Mine include:

- The tendency for higher net percolation during years when snowfall is a large percentage of the total annual precipitation; and
- The importance of monitoring changes in the field saturated hydraulic conductivity of the cover materials.

6.3.1 The Influence of Precipitation Distribution on Cover System Performance

The comparative performance of the compacted barrier cover system and the store and release cover system has been evaluated at the site since 1994. Figure 6.1 summarises the performance of the three cover systems from 1995 to 2001. The average net percolation through the compacted barrier cover system was 6.6% of the average annual precipitation over the monitoring period, which is slightly less than the 8.8% average net percolation recorded at the store and release cover system. The performance of the "control" float rock cover system was distinctly higher; on average the control plot allowed 52% of the annual precipitation through as net percolation.

Further analysis of the precipitation and snow depth survey data was completed to examine the relative influence of snowfall and rainfall on cover system performance at the site. The timing of precipitation at the site is a significant factor on cover system performance due to the varying climate conditions at the site. For example, rainfall occurring during the hot, dry summers at the site is not likely to percolate through the cover systems. However, during the late fall, winter, and early spring, precipitation is more likely to result in net percolation. This is due to the low evaporative demand during these periods and the low storage capabilities of the cover systems. Freezing conditions do not usually develop within the cover system profile because of snow cover and climatic conditions, which allow net percolation into the underlying waste material during these periods.

Figure 6.2 separates the annual precipitation into rainfall and snowfall and includes the total net percolation recorded at the compacted barrier and store and release cover systems for each year of the monitoring period. In the first two years of monitoring, the compacted barrier cover system performed better than the store and release cover system allowing less net percolation. The increase in net percolation from 1995 to 1996 is comparable to the increase in total precipitation and snowfall for the two years. The highest total precipitation and snowfall was recorded in 1997, which led to the highest net percolations measured during the monitoring period, if the results for the two test plots are averaged. A significant increase in net percolation was recorded for the compacted barrier cover system while net percolation through the store and release cover system decreased. Minimal net percolation was measured at the test plots in 1998; this year had the lowest snowfall measured during the monitoring period. In the following year, snowfall and total precipitation increased leading to above average net percolation measured at the test plots. Finally, the net percolation recorded in 2000 and 2001 was low, with 2001 recording the lowest net percolation for the monitoring period.

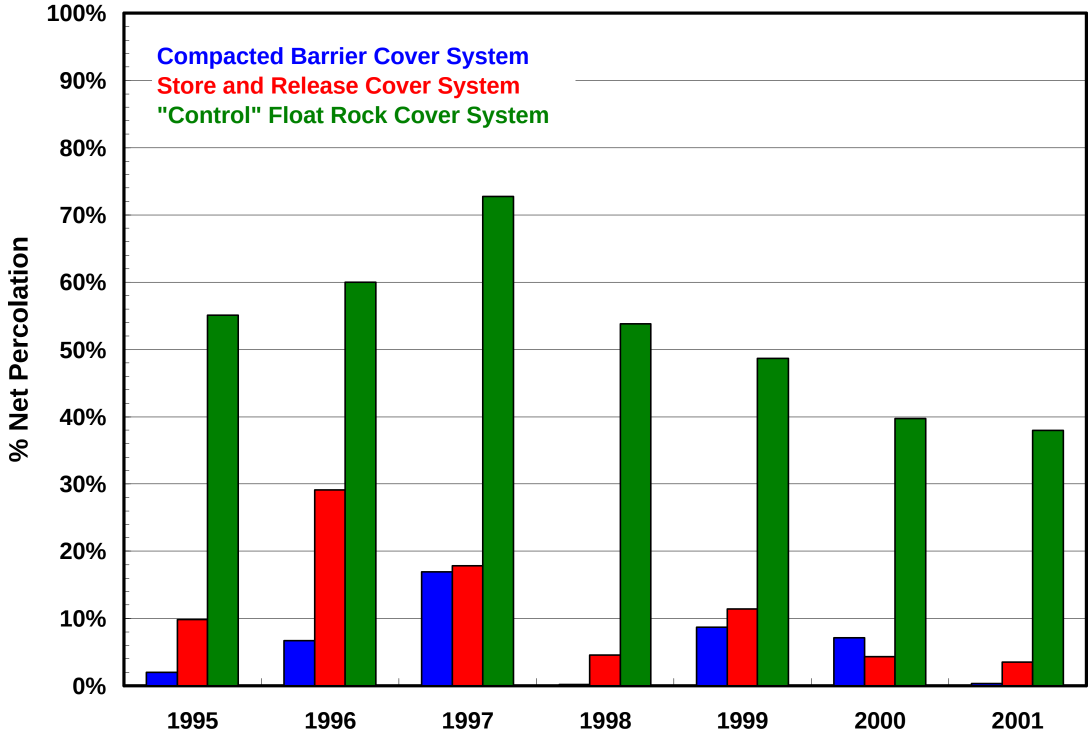

Figure 6.1 Comparison of the performance of the cover system test plots at the TeckCominco Kimberly Operations site (1995-2001).

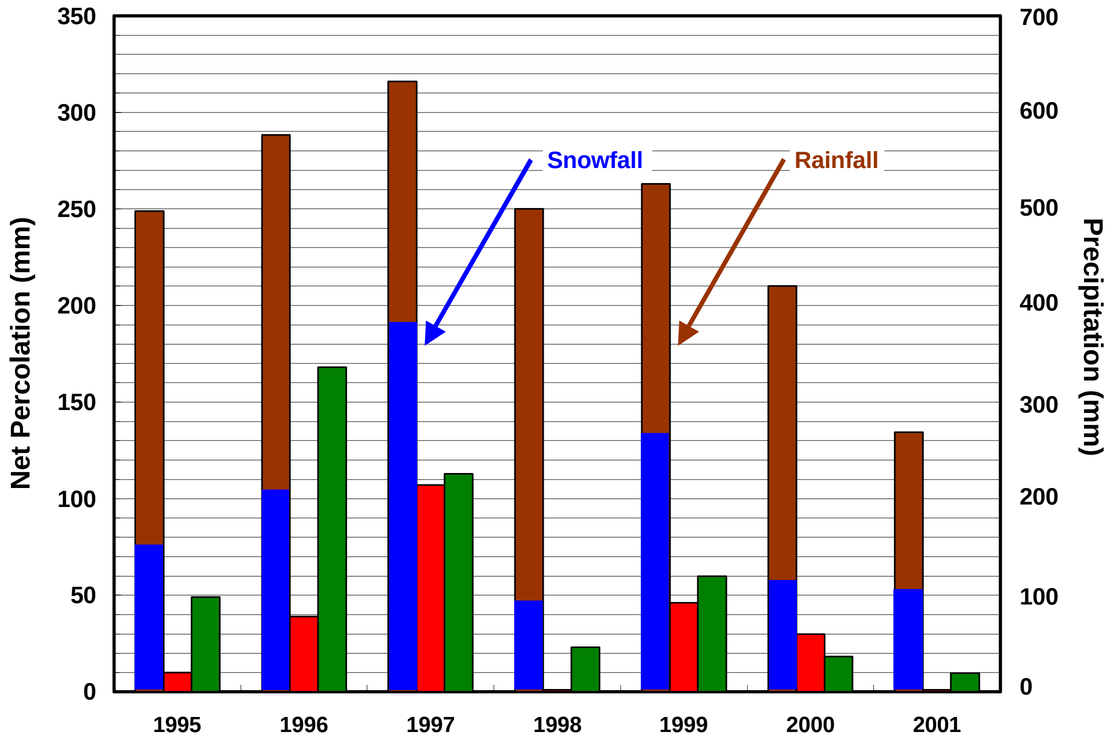

Figure 6.2 Net percolation and precipitation recorded at the compacted barrier and store and release cover systems (1995-2001).

It should be noted that precipitation was above the long-term average for the majority of the monitoring period. In the first five years (1995 to 1999), total precipitation was at least 100 mm greater than the long-term average. Precipitation recorded in 2000 was similar to normal conditions, and total precipitation was only 65% of the long-term annual average in 2001.

The best example of the relative influence of snowfall and rainfall is shown in the net percolation results measured in 1998 and 1999. These years had roughly equivalent total precipitation as approximately 25 mm more precipitation was recorded in 1999 (526 mm compared to 500 mm). However, net percolation during the two years was quite different. Less than 1 mm was measured at the compacted barrier cover system in 1998 with 23 mm recorded at the store and release cover system. In comparison, 46 mm and 60 mm were recorded at these test plots in 1999. The difference in performance is likely due to the precipitation that occurred as snowfall during the years. Only 90 mm of precipitation fell as snowfall in 1998 as compared to 270 mm in 1999. The results from 1995 are also similar to 1998 and 1999. Total precipitation was roughly equivalent and total snowfall was in between the results from 1998 and 1999. The net percolation measured at both test plots was also in between the values recorded in the other years.

Climate conditions appear to be the key factor controlling performance of the test plots. Higher annual incident precipitation will generally lead to an increase in percolation to the tailings underlying the test plots, which is intuitive, but often not appreciated when predicting long-term performance. However, not so intuitive is the influence on performance due to the time of year in which precipitation occurs and the form of precipitation (i.e. snow or rain). In general, precipitation that contributes to snowpack, or occurs during the winter, will increase net percolation to the underlying tailings material while summer rainfall is buffered by the presence of cover material and net percolation is reduced as a result of the hot dry conditions during this time. Hence, the impact on performance due to than average annual precipitation can only be properly understood within the context of whether the higher precipitation was due to rainfall, snowfall, or some combination of rainfall and snowfall.

6.3.2 Evolution of Cover System Materials

A field *in situ* saturated hydraulic conductivity testing programme was completed at the TeckCominco Kimberly Operations mine site in 2002 as part of the INAP study. The testing methodology was identical to the procedure incorporated at the Equity Silver mine site, as described in Section 4.3. A complete report of the hydraulic conductivity testing completed at the site is contained in Appendix E1. Figure 6.3 shows the field saturated hydraulic conductivity and density as a function of depth measured at the compacted barrier cover system (Test Plot #2). Measurements of field saturated hydraulic conductivity obtained at a depth of 30 cm and 50 cm were within the compacted barrier layer. In general, the hydraulic conductivity decreased one order of magnitude from the 2 cm depth to a depth of 30 cm, and decreased slightly less than one order of magnitude from 30 cm to 50 cm. The dry density was lowest at a depth of 2 cm and increased sharply at 30 cm. These results were anticipated as the 30 cm density measurements were obtained within the compacted layer. Dry density increased further as the depth increased to 50 cm. The results are similar to conditions measured at Equity Silver mine site with the upper 10-15 cm of the compacted barrier having higher field saturated hydraulic conductivity as compared to the lower region of the compacted layer.

The 25 cm compacted barrier layer at Test Plot #2 was constructed in two lifts. The same compaction procedure was used during construction making it unlikely that either the initial saturated hydraulic conductivity or initial density would differ between the layers. This suggests that a physical, chemical, or biological process has occurred at the site within the last nine years to alter the properties of the upper lift of the compacted barrier layer. Possible processes that could lead to a change in structure at the site are freeze / thaw cycling, wet / dry cycling, and the influence of plant roots identified from the performance monitoring data collected at the site. Temperature sensors installed in the compacted layer indicate that this region of the cover system is not undergoing freeze / thaw cycles.

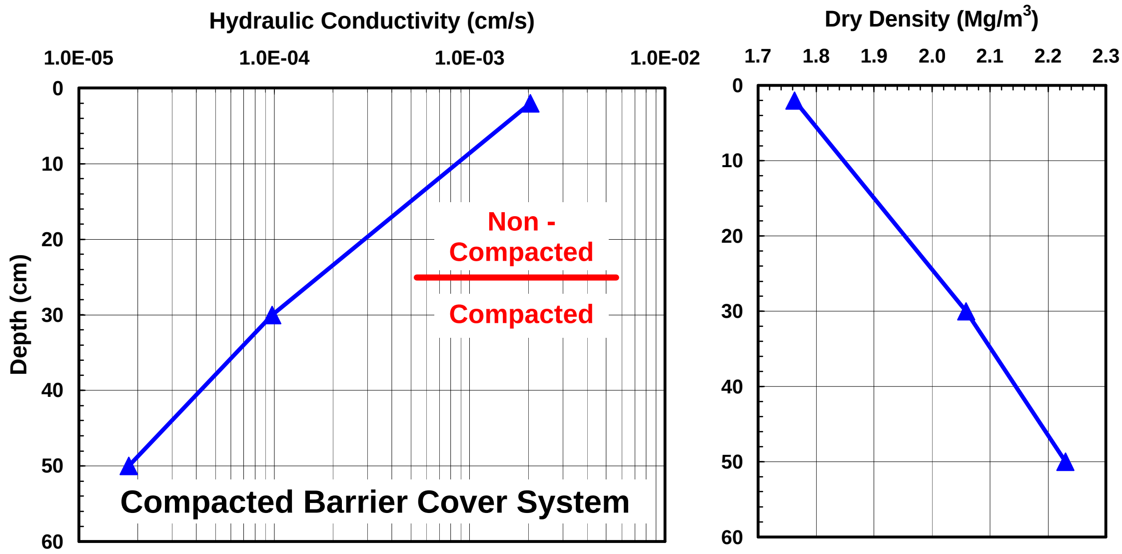

Figure 6.3 Results of *in situ* saturated hydraulic conductivity tests on the compacted barrier cover system at TeckCominco Kimberly Operation site.

Examination of matric suction sensor data indicates that wet / dry cycles have occurred in the compacted material in each summer since installation. Matric suction values measured during the summer in the compacted layer are typically greater than 1,000 kPa, significantly higher than the AEV of the compacted cover material and likely close to residual water content conditions. The dry conditions are typically experienced from June to October of each year. In the remainder of the year, the average suction condition in the compacted layer is approximately 30-40 kPa, but levels in 1998 and 1999 only dropped to 100 kPa. Matric suction is only measured at the center of the compacted layer so it is unclear whether the increased suction condition is typical of the entire compacted layer, but based on field observations, it is reasonable to assume this is the case.

Preparation of the test covers for *in situ* hydraulic conductivity testing at the TeckCominco site found that a large amount of plant roots extend into the upper lift of the compacted barrier layer. It is possible that plant roots have "broken up" the compacted layer and caused the increase in field saturated hydraulic conductivity and decrease in density. Very few traces of root development were found upon examination of the lower lift of the compacted layer, suggesting that the moisture demand resulting from vegetation is satisfied by the growth medium and upper compacted layer. It is also possible that the vegetation has not had sufficient time to fully penetrate the lower lift, which could be determined through monitoring during future growth seasons.

It is likely that the overlying growth medium of the cover system at the compacted barrier test plot was not sufficient to limit atmospheric demand for moisture from impacting on the underlying compacted layer. Whether or not the cover system has come into equilibrium with its surroundings and the evolution of the upper region of the compacted barrier layer is complete (in terms of "changing" to become part of the growth medium) remains to be seen. Additional field performance monitoring is required to further understand the evolution of the cover system.

Note that observations and measurements obtained during excavation of the TeckCominco test plots provide credence to the hypothesis presented earlier with respect to high density conditions and root development. It is clear that the upper lift of the compacted layer has not limited root development, and that this layer does possess low saturation conditions. This would theoretically provide for more suitable conditions for root development, in terms of oxygen concentration of the pore space, as compared to a tension saturated compacted barrier layer.

O'Kane *et al.* (1999) reported that the laboratory saturated hydraulic conductivity values for the compacted till and non-compacted till used in cover system design were 1×10^{-6} cm/s and 1×10^{-3} cm, respectively. Field measurements approximately nine years later indicate that the average field saturated hydraulic of the growth medium is approximately the same value (2×10^{-3} cm/s), which is an insignificant change from the initial measured value. It would appear that there is little difference between the laboratory and field based measurements, which could be a result of the non-plastic properties of the material. The upper area of the compacted till has a hydraulic conductivity of 1×10^{-4} cm/s while the lower depth of the compacted layer is approximately 2×10^{-5} cm/s. Both values represent higher field saturated hydraulic conductivity values as compared to laboratory measurements, and based on the results presented for previous case studies, it is also likely these values are higher than compared to the as-built conditions. It should be noted that the hydraulic conductivity of the material is not the only material property likely to change with time, the SWCC will also likely change with material evolution. The change in moisture retention characteristics of the materials will affect the saturation levels of the cover system, which will, in turn, affect the rate of oxygen ingress to the underlying waste material.

6.4 Summary

The TeckCominco Kimberly Operations mine site possesses one of the oldest (approximately nine years) instrumented test plots analysed in the study. The performance monitoring data collected at the site provides an opportunity to quantify the relative effects of snowfall and rainfall on cover system performance. The climate of the site is semi-arid, however, the winter season is cool and wet while hot and dry conditions persist in the summer. The analysis found that the amount of snowfall occurring during the year has the largest effect on cover performance. Field testing conducted as part of the INAP project found that the field saturated hydraulic conductivity of the compacted till barrier layer is higher than the original laboratory tested values used in the field response numerical modelling completed in 1996 and the original test plot design work. Examination of the field data collected found that wet / dry cycling is likely occurring in the compacted layer and might be a possible cause of the change in cover material properties. Also possible is the development of roots into the compacted barrier layer. The study also highlighted the importance of a properly designed growth medium cover layer to satisfy the demand for water by vegetation and ensure that root development does not extend into the underlying compacted layer.

In essence, if a significant effort is put forth to create an engineered compacted layer, then it is paramount that an appropriate growth medium layer is placed over the compacted layer. The objective is to ensure that the financial resources committed to creating the barrier layer are fully realised (in addition to the design objectives), and that the barrier layer does not evolve to a growth medium layer.

The key lessons learned from the field performance monitoring and field testing are the relative influence of snowfall and rainfall on cover system performance and the difference between current saturated hydraulic conductivity of the cover materials and the original laboratory tests.

7 HISTORICAL SITE IN WESTERN UNITED STATES

7.1 Background

A field testing programme was completed at a site in the western United States. In order to gain access to the site, an agreement was made to keep the site of the field tests anonymous.

7.2 Summary of Cover System Test Plots

Four cover systems were investigated at the historical site, each placed at different dates in a semi-arid environment. Generally, each cover system was constructed with the same design consisting of a single layer of non-compacted cover material. Cover systems #1 and #2 were constructed approximately 18 and 14 years ago, respectively, from coarse sand with trace amounts of silt and clay. Cover systems #3 and #4 were constructed using a material with a finer sand silt content and trace amounts of clay. Cover system #3 is approximately 6 years old while cover system #4 has been in place for 3 years. No automated field performance monitoring data is currently being collected at the site.

7.3 Analysis of the Historical Site

The site provides the opportunity to examine the field saturated hydraulic conductivity of comparatively older (to the other cast studies) cover systems. The waste material in the area was covered with a monolithic, variable thickness cover system. The “lesson learned” at the historical site was:

- The potential for large changes in field performance due to evolution of cover materials.

7.3.1 Evolution of the Cover System Materials

Sixteen measurements of K_{fs} were obtained with the Guelph permeameter at a depth of 12 cm for each of the four cover systems at the site. Table 7.1 summarises the average saturated hydraulic conductivity measured for each of the four cover systems.

Table 7.1

Summary of the average saturated hydraulic conductivity measured at the historical site (geometric mean (M), standard deviation (σ), dry density (ρ_d)).

Cover Designation	***M*** **(10^{-4} cm/s)**	s **(10^{-4} cm/s)**	**Cover Designation**	***M*** **(10^{-4} cm/s)**	s **(10^{-4} cm/s)**
Coarse Cover Material			*Fine Cover Material*		
#1	9.39	2.90	#3	7.37	2.61
#2	9.94	2.39	#4	4.89	2.08

Note: M is the mean value of the field hydraulic conductivity tests conducted
s is the standard deviation of the field hydraulic conductivity tests conducted
r_d is the dry density measured at the same depth and location

The coarse textured material cover systems were constructed in 1985 and 1989. The field saturated hydraulic conductivity measured at the site is approximately 1 x 10^{-3} cm/s for each cover system. The field saturated hydraulic conductivity measured for cover systems #3 and #4 are similar, which suggests that either the cover material has evolved to its final condition or that the material did not evolve any appreciable amount from the condition in which it was placed. The data collected in the field study programme cannot make this distinction, although it could be argued that based on the coarse texture of this cover material the latter hypothesis is more likely.

The newer cover systems were constructed in 1997 and 2000. The average hydraulic conductivity for each of these cover systems is within one-half of an order of magnitude of the coarse material cover systems at 7 x 10^{-4} cm/s and 5 x 10^{-4} cm/s for cover systems #3 and #4, respectively. Note that all field saturated hydraulic conductivity measurements at this site were obtained within the upper 20 cm of the surface of the cover systems.

Figure 7.1 is a cumulative histogram of the field saturated hydraulic conductivity values measured with the Guelph permeameter in the summer of 2002. There is a small difference in the field saturated hydraulic conductivity measured at the test plots. If the results of cover systems #3 and #4 are compared, it appears that the finer cover materials are evolving towards the older, coarser cover materials. In the long-term, there may be little difference in behavior of the cover materials. This is significant because effort was made in the newer cover systems to place a finer-textured material in order to improve cover system performance. The results suggest that in terms of field saturated hydraulic conductivity there will only be marginal difference in the performance of the newer cover systems (constructed with the finer textured material) as compared to the older cover systems (constructed with the coarser textured cover material).

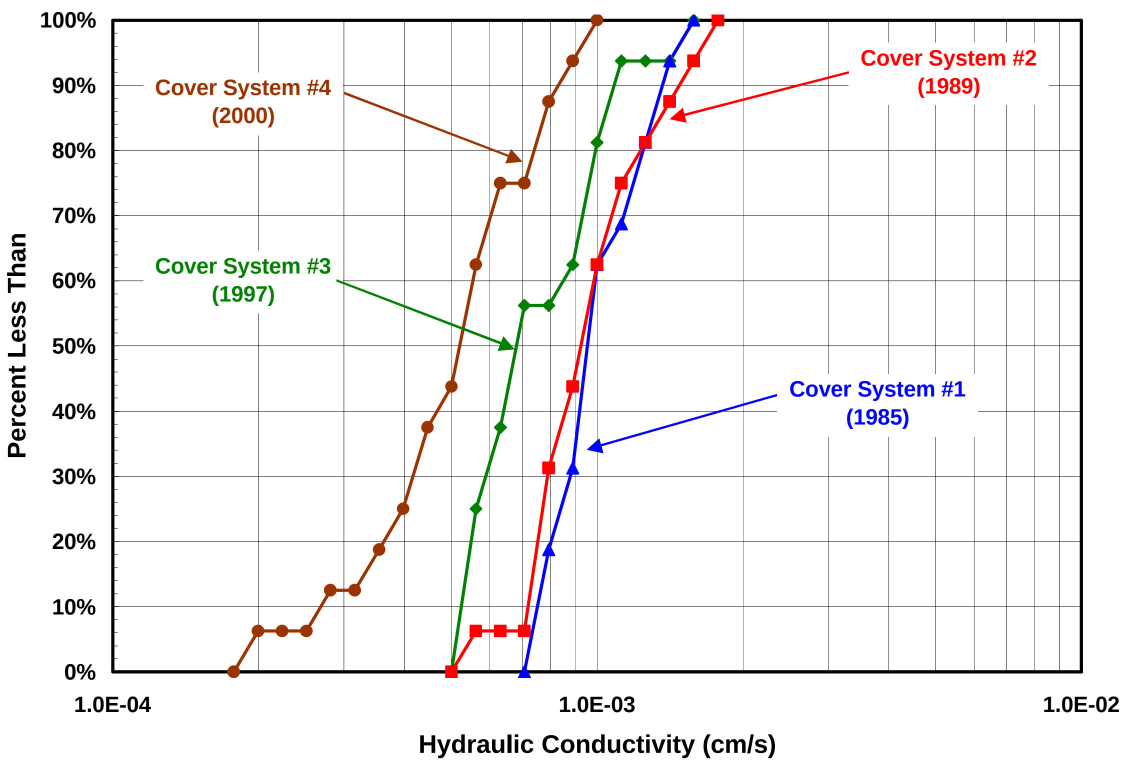

Figure 7.1 Cumulative histogram of the hydraulic conductivity results at the historical site.

The performance of each cover system since construction cannot be determined because no field performance monitoring data is available. However, it is likely that the evolution of the cover materials is a result of both wet / dry cycling and freeze / thaw cycling. It is reasonable to assume these processes would occur considering the general climate conditions at the site.

7.4 Summary

The historical site in the western United States provided the opportunity to examine older cover systems. The field *in situ* saturated hydraulic conductivity testing programme examined four cover systems of varying age. The two oldest test plots were constructed of a single layer of coarse textured cover material with low fines content. The newer cover systems, constructed in the late 1990's, incorporated a finer textured material to increase the performance of the cover system. However, field testing showed that at the current time there is less than one-half an order of magnitude between the cover material hydraulic conductivity values. This suggests that the additional expense taken to source, procure and construct a finer-textured cover system has probably not resulted in an increase in cover performance. It should be noted however that this statement is somewhat speculative, given that field performance is not being monitored at the site.

The key lesson learned from field testing at the historical site is the evolution of the two different cover materials to similar hydraulic properties and likely similar field performance. The impact of site specific physical, chemical, and biological processes on long-term performance should be considered when weighing the benefits of improving the as-built cover system design.

8 SUMMARY

The INAP project studying longevity of dry cover systems for reactive mine waste provided the opportunity to coalesce and define physical, chemical, and biological processes that impact on cover system performance, which can lead to an "evolution", or change, of key cover system performance indicators. Ideally, the list of processes developed as part of this study should be used by those responsible for designing, constructing, and maintaining cover systems to ensure that a thorough understanding is developed for those processes that could potentially impact on cover performance. This understanding should be developed in light of the potential changes in the four key cover performance properties; namely, the saturated hydraulic conductivity and moisture retention characteristics of the cover materials, the relationship between oxygen diffusion and the degree of saturation, and the physical integrity of the cover system.

The case studies were presented to highlight the "lessons learned" as a result of analysing the field performance monitoring data generated from the various full-scale and field trial cover systems, as opposed to simply presenting and discussing the field data. The objective was to determine whether one would have designed the cover systems differently (or utilised a different design methodology), if the knowledge gained through field performance monitoring was known at the time the cover systems were designed.

The specific "lessons learned" for each case study were presented and discussed in the corresponding section of this report, as well as in the Executive Summary. The "lessons learned", in a general sense, on the basis of evaluating the case studies are as follows.

- Above average and extreme wet climate years, particularly when they occur over successive years, can have a significant negative impact on the performance of a store and release cover system.
- Precipitation characteristics (duration, intensity, form (snow or rain), and timing (of the year) have a significant, if not controlling, influence on the annual performance of a cover system.
- Cover materials will evolve over time in response to site-specific physical, chemical, and biological processes such that as-built performance, and possibly performance after two or three years, does not represent long-term performance.
- That appropriate automated field performance monitoring is required, supplemented with manual *in situ* measurements, to properly understand the evolution of the cover materials and provide some sense of the time frame over which the cover system will "come into equilibrium" with its environmental setting;
- That the presence of vegetation provides a significant positive influence on the performance of a dry cover system, and therefore the design of a cover system should address the requirements of the vegetation that will ultimately exist as part of the cover system;
- The design of the non-compacted growth medium layer is as important, if not more important, to long-term cover system performance as the underlying compacted barrier layer.
- That segregation, which can occur during placement of run-of-mine material, can have a significant adverse effect on cover system performance.

The focus of this project was to develop further understanding for the factors and conditions impacting on the longevity of cover systems. The case studies clearly demonstrate, using field hydraulic conductivity as a surrogate, that evolution of a cover material is a major issue. With this evolution, performance will change. For example, if a full-scale cover system is designed with a compacted layer, and long-term performance is assumed / modelled / predicted based on this layer maintaining a certain saturated hydraulic conductivity, then a change in the saturated hydraulic conductivity of the compacted layer as a result of its evolution would be a major factor impacting the longevity of the cover system.

In addition to the evolution of the cover materials, site-specific rainfall and precipitation characteristics (duration, intensity, form (snow or rain), and timing (of the year) have a significant, if not controlling, influence on the annual performance of a cover system. More specifically, in terms of store and release cover systems, extreme climate events, particularly when they occur over successive years, can have a significant impact on cover system performance.

The issue of cover system construction was not discussed to any significant extent within this report because for the most part, none of the case studies could be used to highlight this issue. The possible exception is the Mt. Whaleback case study, where the importance of preventing segregation of the cover material for a store and release cover system is discussed. This is not meant to minimise the potential negative impact on long-term performance that will likely result from a poorly constructed cover system.

The impact of improper construction of a cover system, or poor quality assurance and control during construction, can have a significant, if not dominant influence of cover system longevity. In fact, it can be argued that poor construction of a cover system is the most important factor influencing long-term cover system performance.

If one were to assume that a cover system was designed appropriately (i.e. the design addressed site-specific chemical, physical, and biological processes that could impact on long-term performance), but the cover system was not constructed to specification, then there is no doubt that a failure to meet construction specifications can have a significant impact on long-term performance. For example, the thickness of a growth medium overlying a compacted layer may be appropriately designed and specified. However, if it is not constructed to the proper specifications, then significant potential exists for the saturated hydraulic conductivity of an underlying compacted layer to increase, which would result in a reduction in the long-term performance of the cover system.

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