# Evaluation of the Long-Term Performance of Dry Cover Systems

## Final Report

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**Prepared for:**

**International Network for Acid Prevention**

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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 two-phase project examining the long-term performance of dry covers for reactive mine waste. 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.

Summary of Phase 1 Final Report

- 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 degree of saturation, and the physical integrity of the cover system.
- A literature study was completed to identify numerical models capable of simulating 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.

## Summary of Phase 2 Final Report

*BHP Billiton Iron Pty Ltd., Mt. Whaleback Operations (Australia):*

- The mine site includes five cover system test plots incorporating run-of-mine moisture 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.

*Placer Dome Canada Ltd., Equity Silver Division (Canada):*

- Three full-scale cover systems were constructed with compacted and non-compacted till (glacial deposited earthen material) approximately 10 years ago. Performance monitoring data is collected at three automated monitoring stations on two of the full-scale cover systems at 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 x $10^{-5}$ cm/s in the upper 10 cm of the compacted barrier layer compared to a hydraulic conductivity of less than 5 x $10^{-7}$ 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., Mildred Lake Operations (Canada):*

- Three large, sloping cover systems were constructed at the Mildred Lake Operations 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.

*Teck Cominco Ltd., Kimberly Operations (Canada):*

- Three cover system field trials, 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 moisture store-and-release cover system field trials 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.

## Project Summary

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.

## ACKNOWLEDGEMENTS

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. Peter Waters, BHP Billiton Iron Ore, Mr. Mike Aziz, Placer Dome Canada Ltd., Ms. Zoe Ramdin, Teck Cominco Ltd., Ms. Clara Qualizza and Dr. Gord McKenna, Syncrude Canada Ltd., and Dr. Stuart Jennings, Montana State University 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, Mr. Les Hulett, Inco Ltd., and Mr. Denis Kemp, Falconbridge Ltd.

Thank you to those who reviewed the draft version of the report, including Mr. Nick Currey, Placer Dome Asia Pacific, Mr. Rich Borden, Rio Tinto Technical Services, Mr. Peter Waters, and Mr. Mike Aziz.

Dr. Lee Barbour of the Department of Civil Engineering at the University of Saskatchewan provided invaluable insight and direction during this project. His contribution to the project and open approach to sharing ideas and expertise are gratefully acknowledged.

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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 Iron Ore Pty Ltd., Mt. Whaleback Operations (waste rock; arid tropical climate);

2) Placer Dome Canada Ltd., Equity Silver Division (waste rock; humid climate);

3) Syncrude Canada Ltd., Mildred Lake Operations (saline / sodic overburden; semi-arid climate);

4) Teck Cominco Ltd., Kimberley Operations (tailings; semi-arid / 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 and discussed in separate sections: the Mt. Whaleback site in Section 3; the Equity Silver Division in Section 4; the Mildred Lake Operations in Section 5; the Kimberley Operation in Section 6; and the historic reclamation site in the western United States in Section 7. 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

A 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.

Identification of Cover Performance Properties

- 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 it 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 MT. WHALEBACK OPERATIONS

## 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 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°. The objective was to quantify the difference in performance of the Mt. Whaleback moisture store-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 moisture 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.

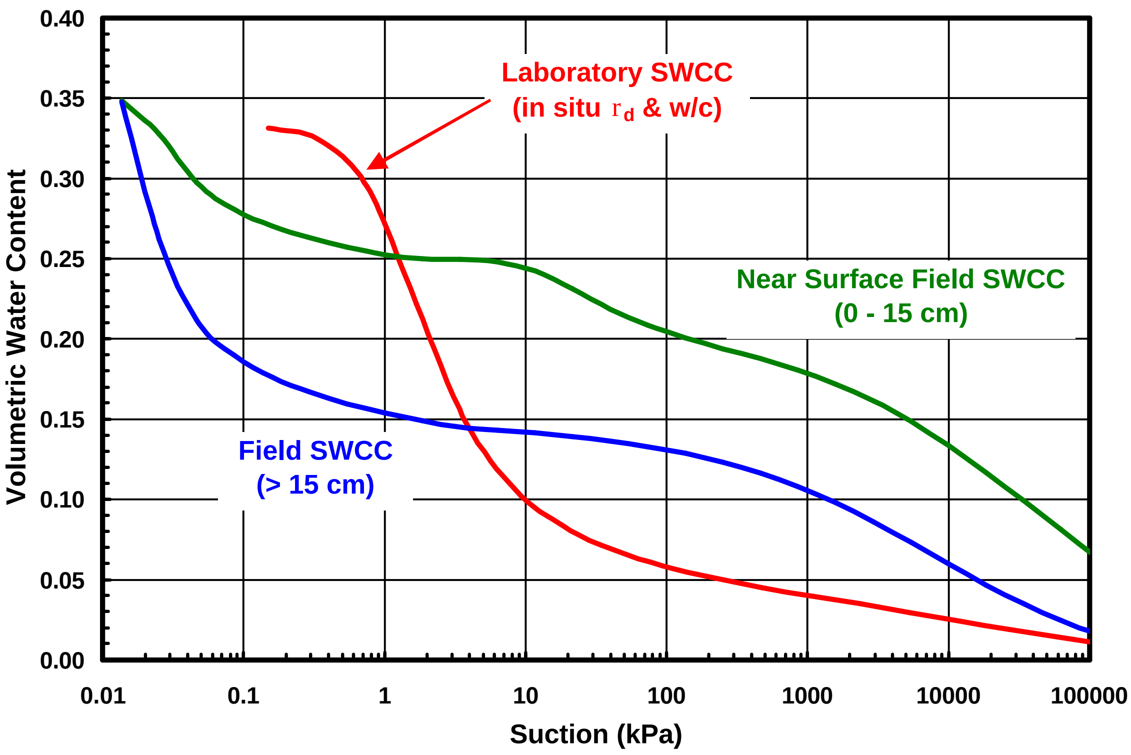

**Figure 3.1** Comparison of the laboratory and *in situ* field SWCCs for the BIF cover material.

### *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 shows 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 field SWCCs.

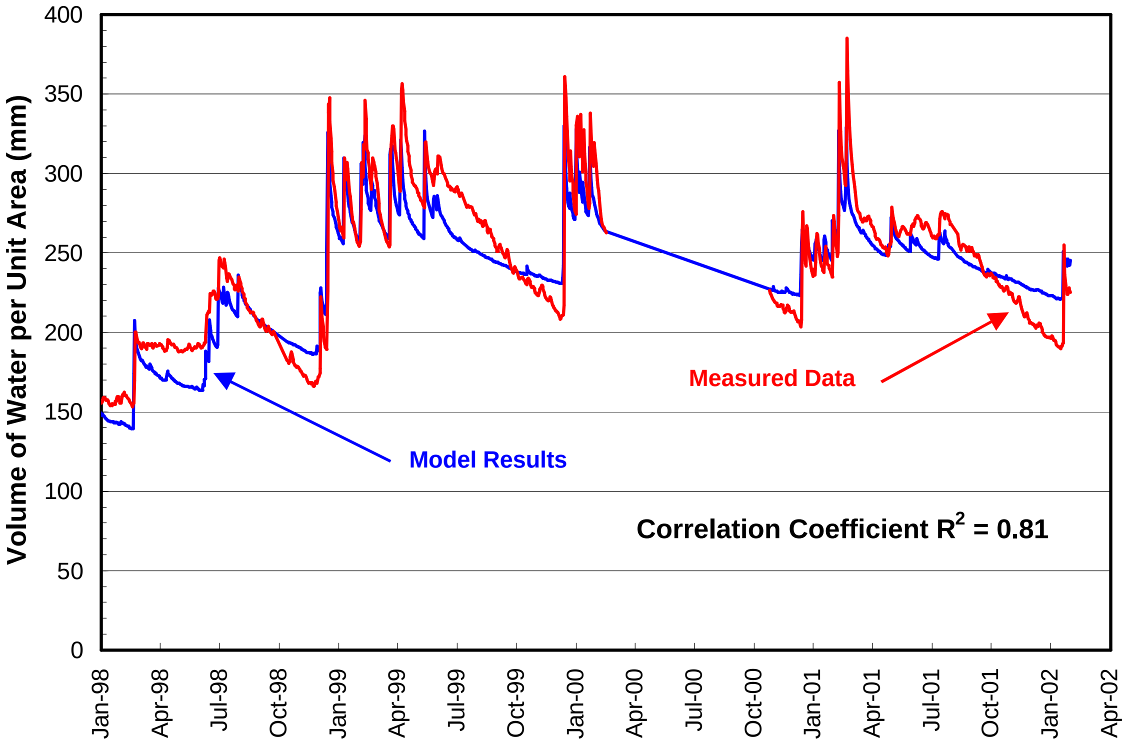

**Figure 3.2** Comparison of the calibrated numerical model results to actual measured field data covering the period from January 1998 to February 2002.

### *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.

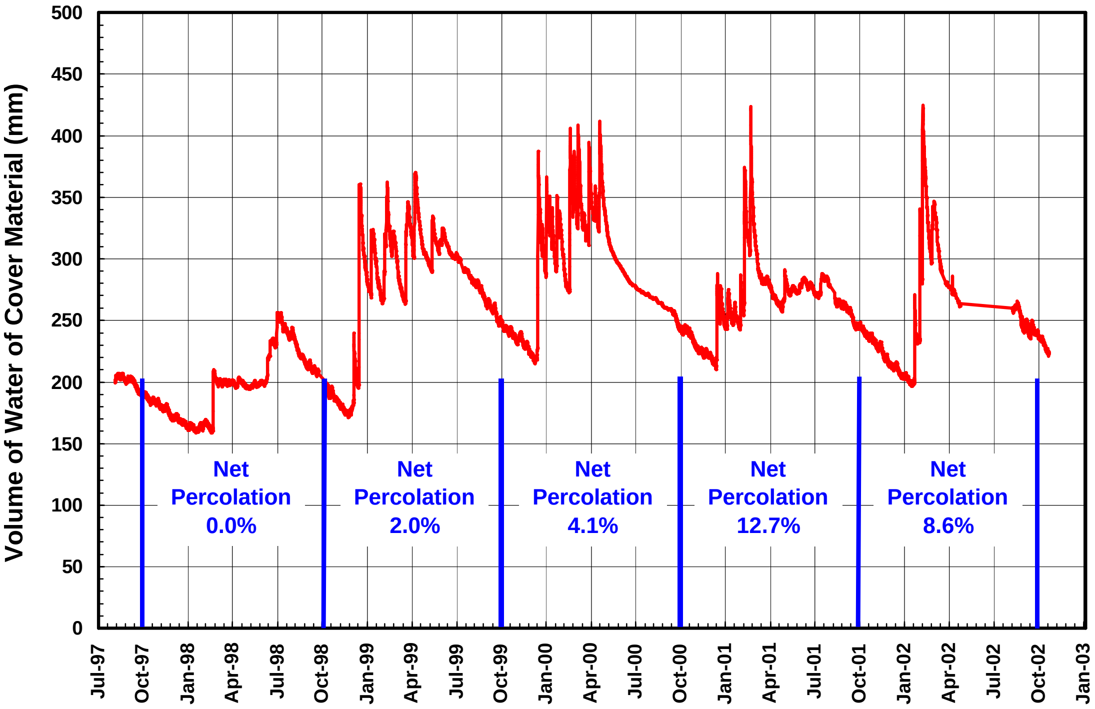

**Figure 3.3** Net percolation and change in cover material storage at Test Plot 1.

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 1999-00, 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.

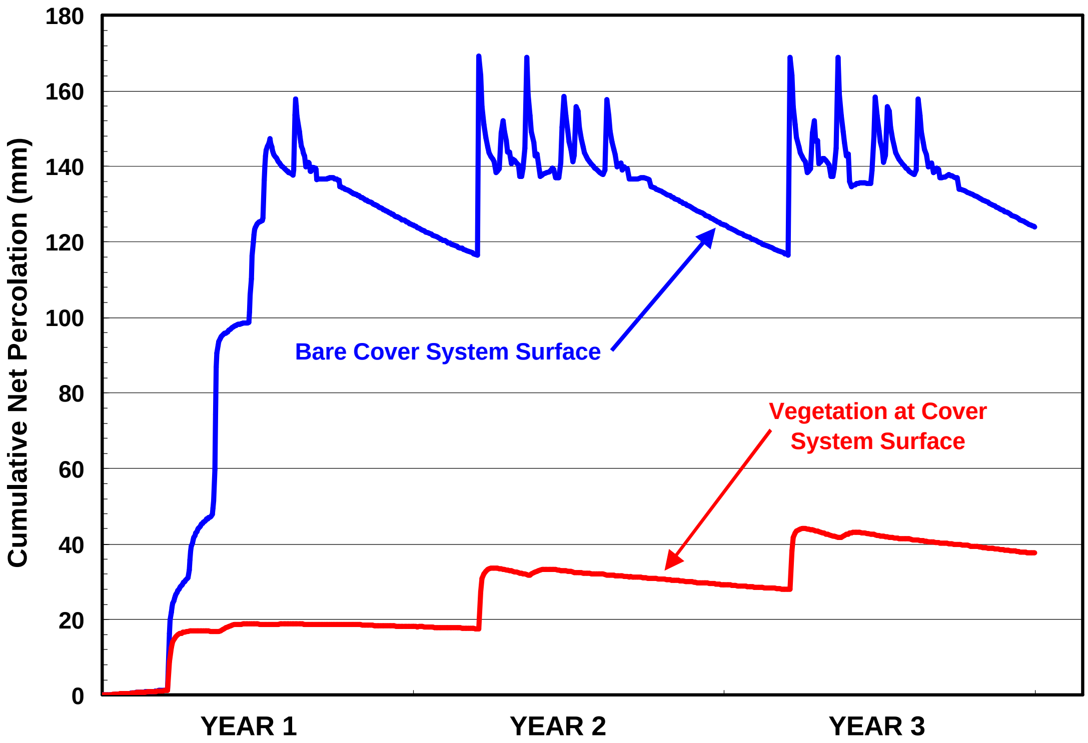

**Figure 3.4** Net percolation predicted for consecutive wet year simulations.

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, moisture 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 3.5b).

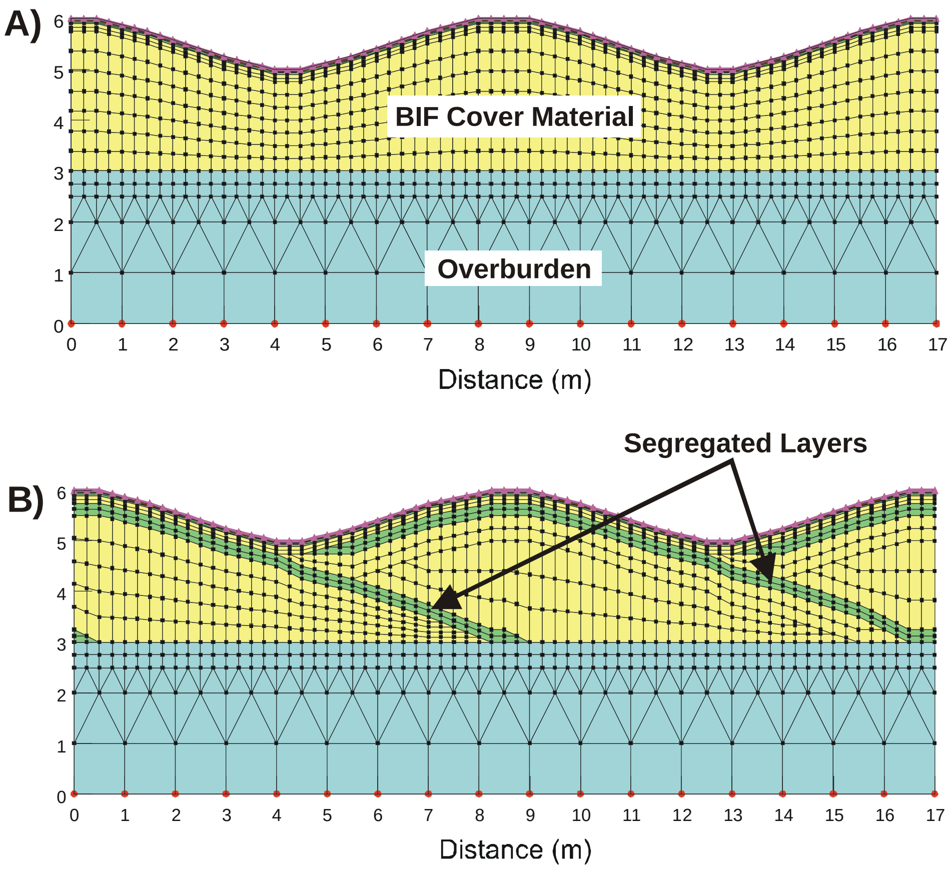

**Figure 3.5** a) Mesh used in the 2-D analysis of the Mt. Whaleback hummocky cover system. b) Coarse-textured segregation layers added to the 2-D mesh.

The VADOSE/W model, together with the field performance monitoring data, illustrated a key characteristic with respect to the performance of a moisture store-and-release cover system under high rainfall conditions. Namely, simply placing 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.

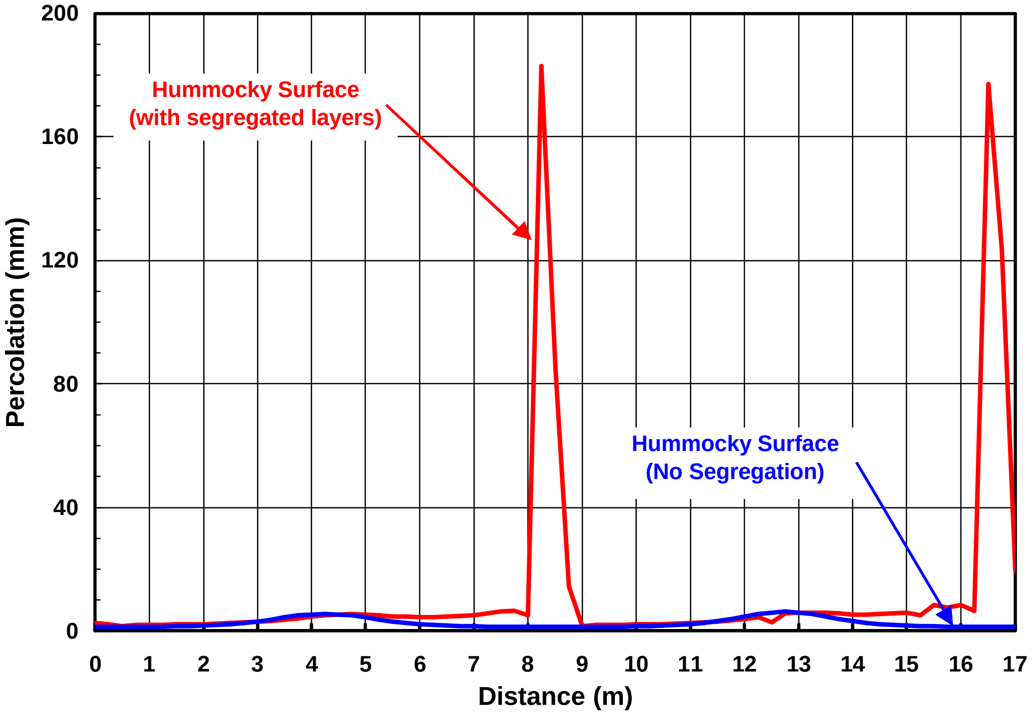

**Figure 3.6** Net percolation results predicted for the homogeneous and segregated cover systems.

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 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 Iron Pty Ltd., 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 moisture 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 DIVISION

## *4.1 Background*

Equity Silver 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 is situated on an alpine plateau in a humid alpine environment. The average annual precipitation at Equity Silver is approximately 650 mm, with rainfall accounting for approximately 300 mm. Annual potential evaporation is approximately 500 mm.

Equity Silver 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 metres to greater than 20 metres. 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 metres 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 realised 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 Equity Silver*

The full-scale cover systems installed at Equity Silver 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 Equity Silver 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 field 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 $1 \times 10^{-7}$ 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 Equity Silver
(geometric mean (M), standard deviation (σ), dry density ($\rho_d$)).

| **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 shows 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.

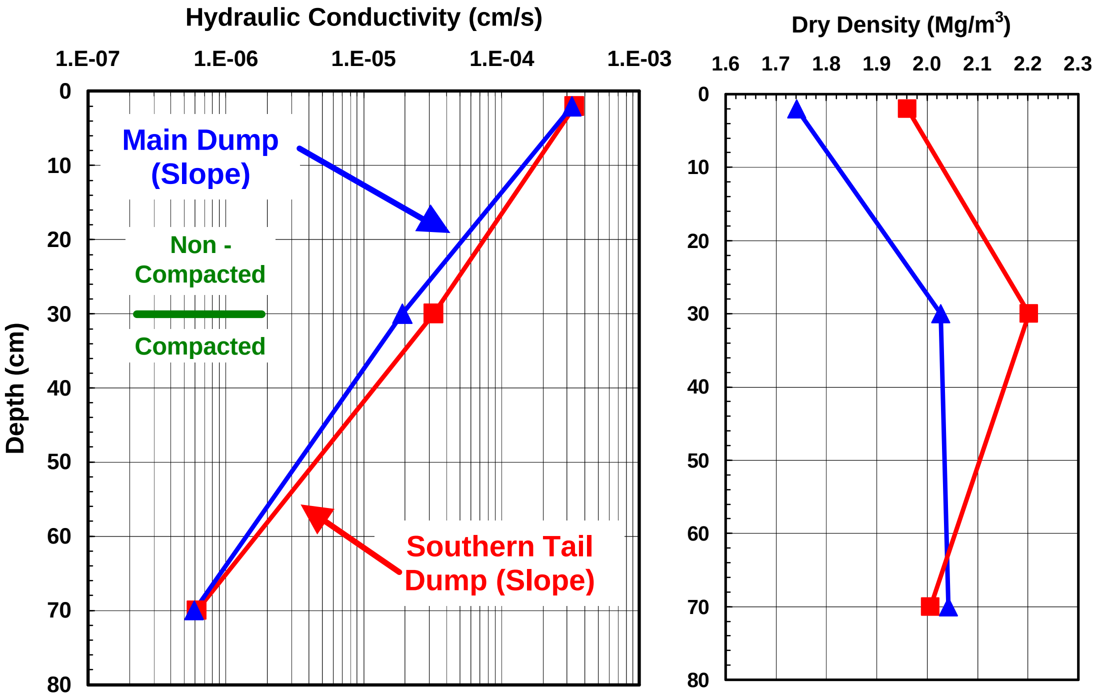

**Figure 4.1** Saturated hydraulic conductivity and density measured for the sloping cover systems at Equity Silver.

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 Equity Silver 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 (~ 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 *et al.* (1998) 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 x $10^{-8}$ cm/s and 1 x $10^{-6}$ cm, respectively. Field measurements taken approximately 10 years later found the field saturated hydraulic conductivity of the growth medium in the range of 1 x $10^{-4}$ 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 x $10^{-5}$ cm/s, while the lower depth of the compacted layer is 5 x $10^{-7}$ cm/s or lower (recall the failed *in situ* $K_{fs}$ tests, which indicate values less than 1 x $10^{-7}$ cm/s for 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 compared to that predicted using the Swanson *et al.* (2003) field calibrated model parameters. This is despite using higher saturated hydraulic conductivity values 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 Equity Silver 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.

Equity Silver 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 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 at Equity Silver 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. Equity Silver 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 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*

Equity Silver 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 Equity Silver 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 MILDRED LAKE OPERATIONS

## 5.1 Background

The Syncrude Canada Ltd. (SCL), Mildred Lake Operations located 40 km north of Fort McMurray, Alberta. The 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.

The Mildred Lake Operations use 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 oil 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 deposited materials and an overlying layer of peat.

## 5.2 Summary of Field Cover System Trials

Two large cover systems have been constructed at Mildred Lake Operations 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 the Mildred Lake Operations has not been determined.

The potential cover materials at the Mildred Lake Operations 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. This latter material is a glacial deposited material, otherwise referred to as till.

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 Mildred Lake Operations*

The oldest cover system installed at Mildred Lake Operations 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 INAP's dry cover system longevity research project reported herein, the "lessons learned" at Mildred Lake Operations 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 Mildred Lake Operations 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 Mildred Lake Operations. 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 Mildred Lake Operations' 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 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 during unfrozen conditions in 2000 compared 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.

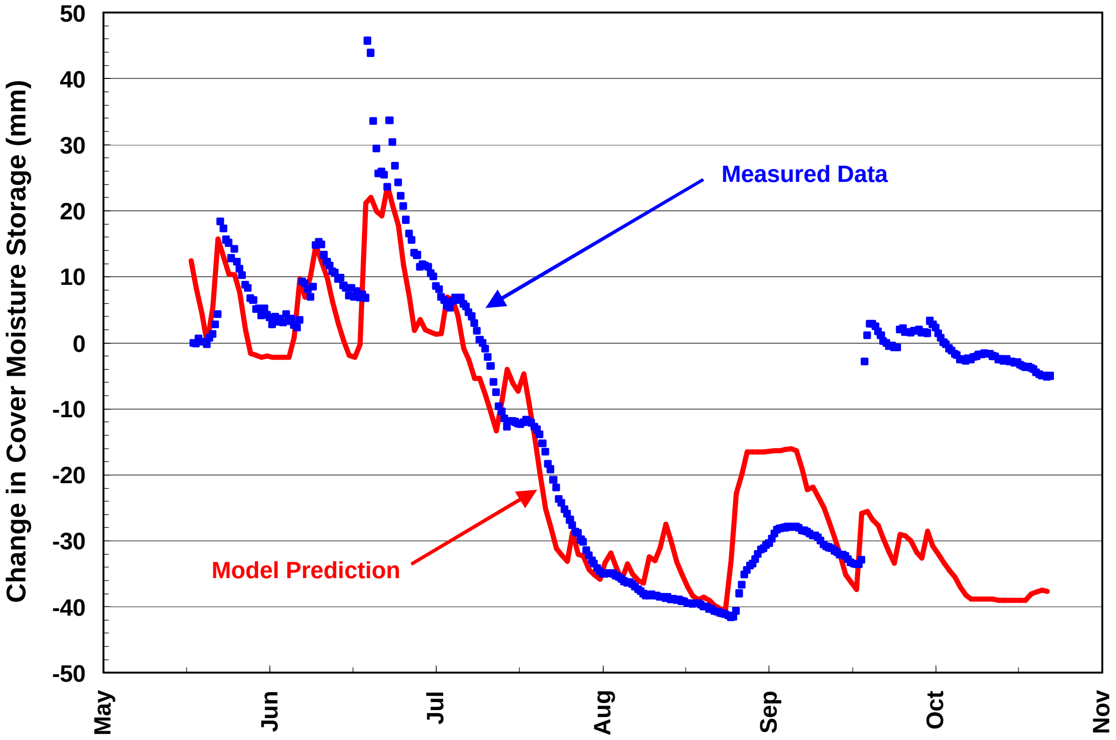

**Figure 5.1** Change in moisture storage predicted by SoilCover compared to actual measured field conditions at the D2 cover system for unfrozen conditions in 2000.

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 regions.

The VADOSE/W model was used during the INAP project with respect to the Mildred Lake Operations 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.

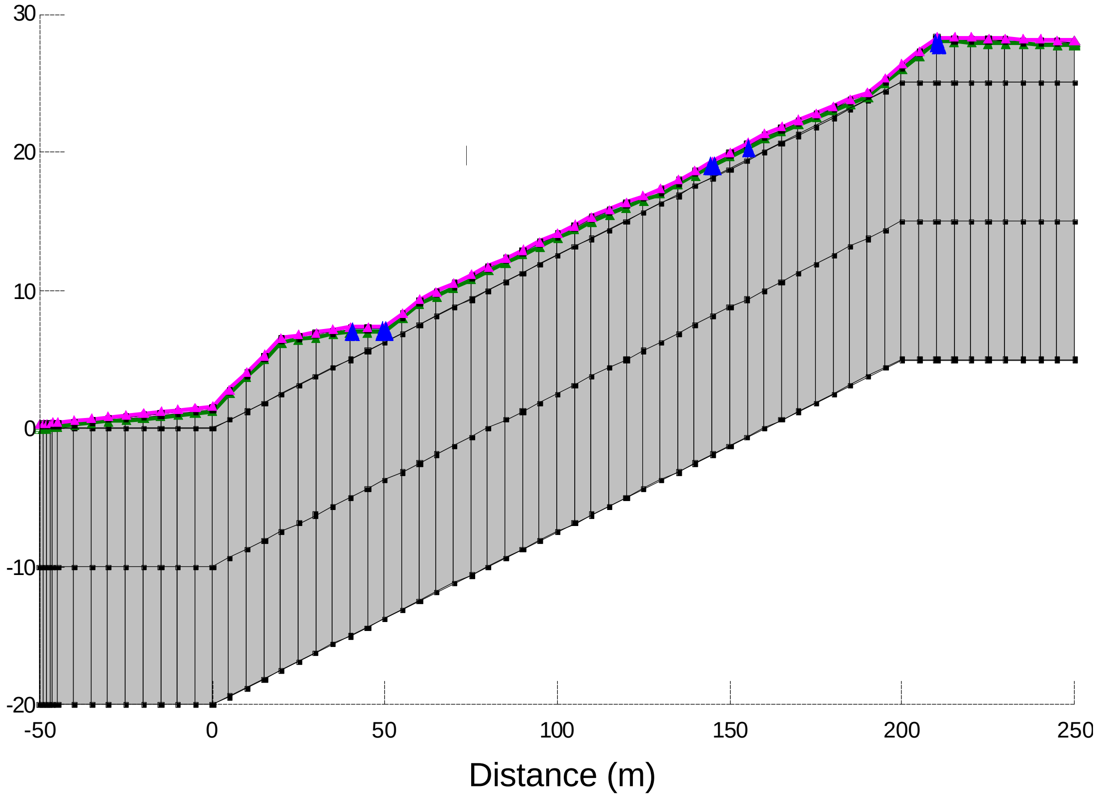

**Figure 5.2** The 2-D numerical mesh used in the VADOSE/W simulation.

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. 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 other locations along the slope.

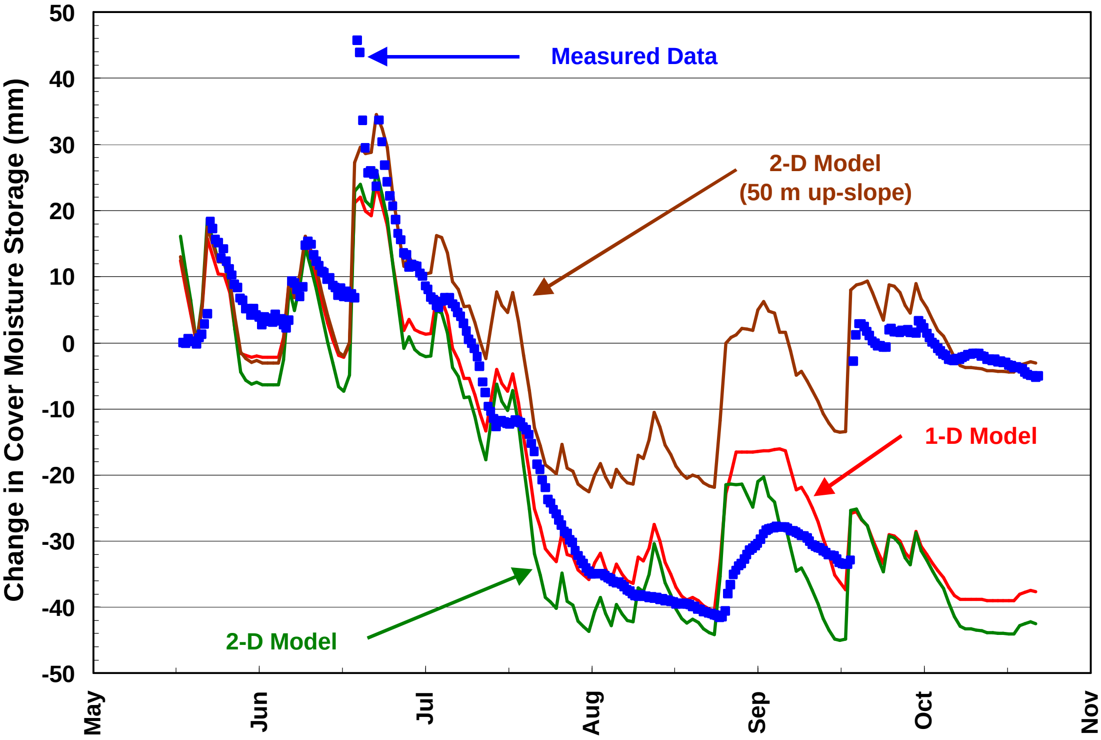

**Figure 5.3** Comparison of actual field conditions to predicted change in storage for 1-D and 2-D soil atmosphere numerical models.

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 trends. It was possible to verify the revised hypothesis regarding the processes and characteristics that led to the observed field performance, by “matching” the trend predicted by VADOSE/W when modelling the Mildred Lake Operations 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 field hydraulic conductivity testing programme completed at Equity Silver and described in Section 4.3.1 was based on the methodology described by Meiers (2002) for the Mildred Lake Operations. 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 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 field saturated 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 field saturated hydraulic conductivity of the cover and waste materials (from Meiers, 2002).

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

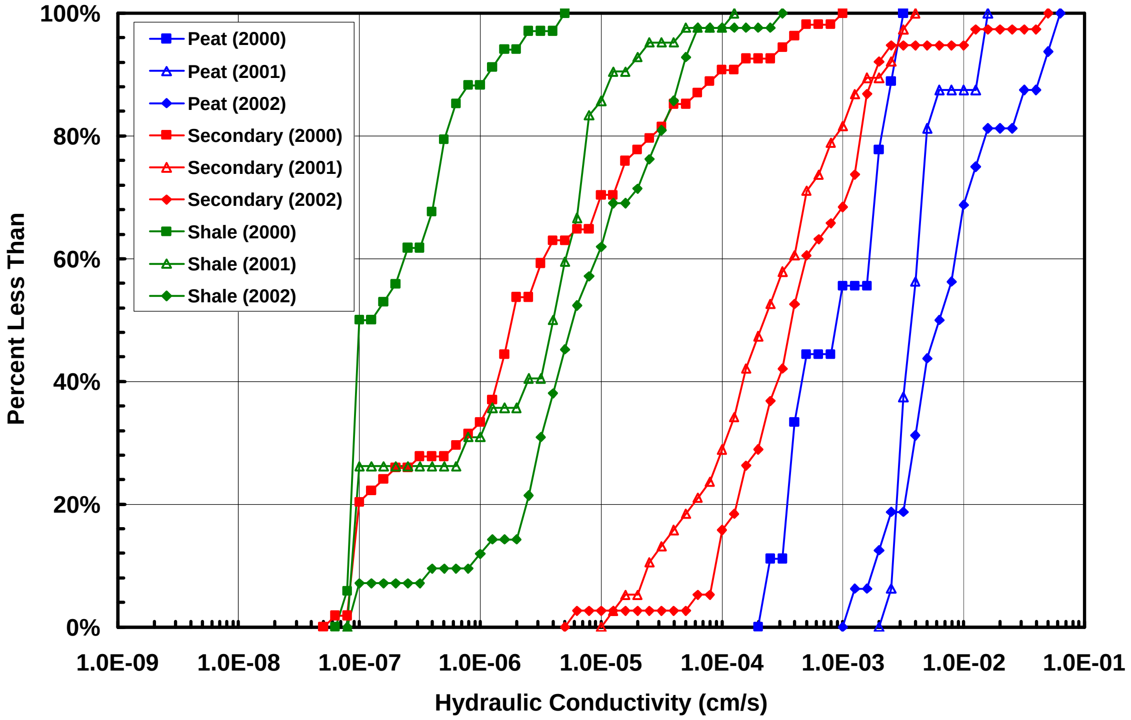

**Figure 5.4** *In situ* saturated hydraulic conductivity results from the 2000, 2001, and 2002 testing programme (from Meiers, 2002).

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 Mildred Lake Operations 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 Mildred Lake Operations 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 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*

Syncrude Canada Ltd., Mildred Lake Operations have 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 long-term performance of dry cover systems.

The key lessons learned from field performance monitoring and field testing at the Mildred Lake Operations 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 TECK COMINCO KIMBERLY OPERATIONS

## *6.1 Background*

The Teck Cominco Kimberly Operations mine site is located in Kimberley, British Columbia, within the Purcell range of the Rocky Mountains. Iron, lead, and zinc were mined from the underground ore body, during the life of the operation. The climate at the Teck Cominco 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 bedrock / till.

## *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 moisture 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 $1 \times 10^{-6}$ cm/s and $1 \times 10^{-3}$ 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 performance of the cover system field trials.

### 6.3 Analysis of the Teck Cominco Kimberly Operations Mine Site Test Plots

The cover system test plots installed at Teck Cominco 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 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 Teck Cominco 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 Influence of Precipitation Distribution on Cover System Performance

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.

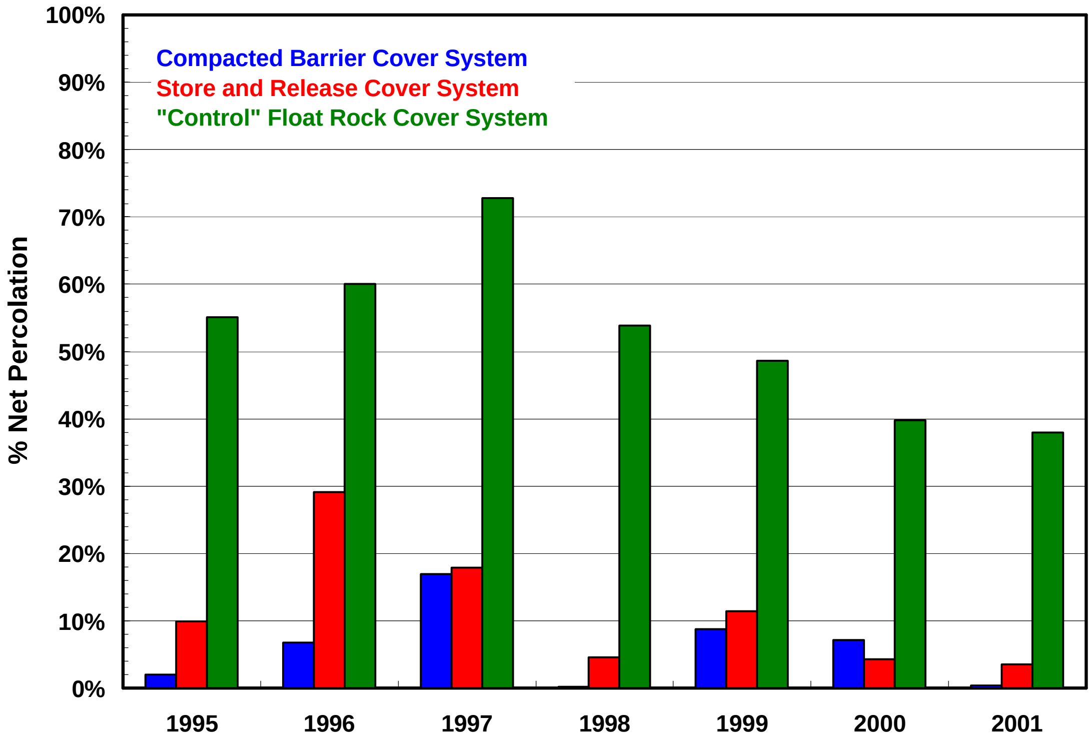

**Figure 6.1** Comparison of performance of the cover system test plots at the Teck Cominco Kimberly Operations site (1995-2001).

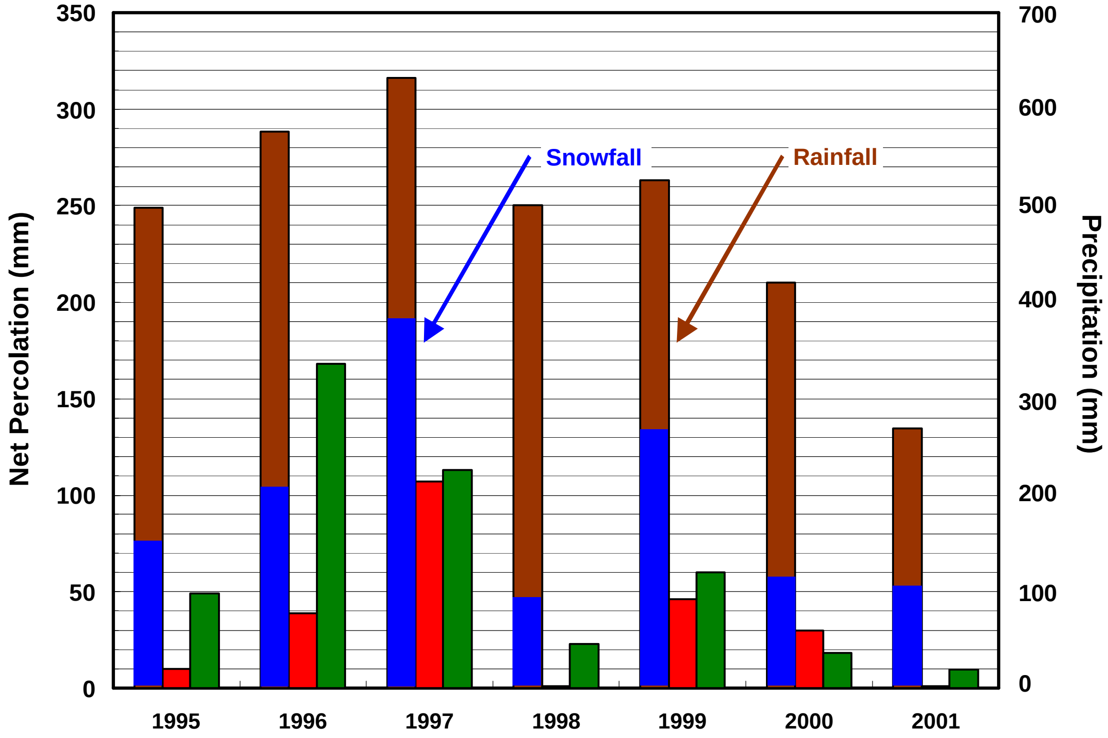

**Figure 6.2** Net percolation and precipitation recorded at the compacted barrier and store-and-release cover systems (1995-2001).

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 higher 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 saturated hydraulic conductivity testing programme was completed at Kimberly Operations in 2002 as part of the INAP study. The testing methodology was identical to the procedure incorporated at Equity Silver, 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 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 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.

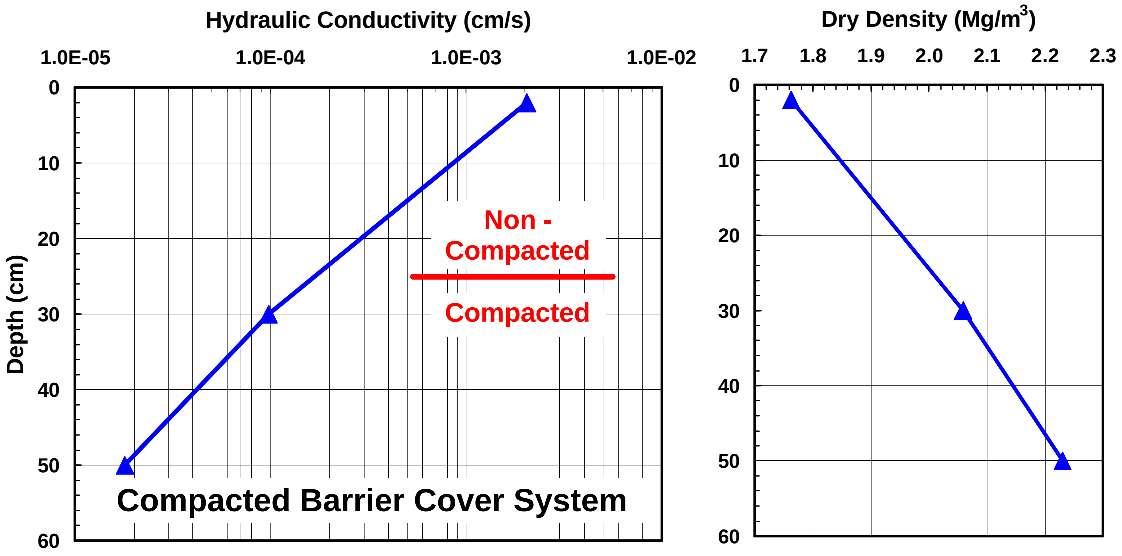

**Figure 6.3** Results of *in situ* saturated hydraulic conductivity tests on the compacted barrier cover system at Teck Cominco Kimberly Operation site.

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 field hydraulic conductivity testing at the Kimberley Operations 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. It remains to be seen 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). 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 Kimberley Operations field trials 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 laboratory saturated hydraulic conductivity values for the compacted till and non-compacted till used in cover system design were 1 x $10^{-6}$ cm/s and 1 x $10^{-3}$ 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 x $10^{-3}$ 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 x $10^{-4}$ cm/s while the lower depth of the compacted layer is approximately 2 x $10^{-5}$ 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 Teck Cominco Kimberly Operations mine site possesses one of the oldest (approximately nine years) instrumented test plots analysed in the study. 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 be 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 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 case 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 ($\sigma$), dry density ($\rho_d$)).

| **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 an 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 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).

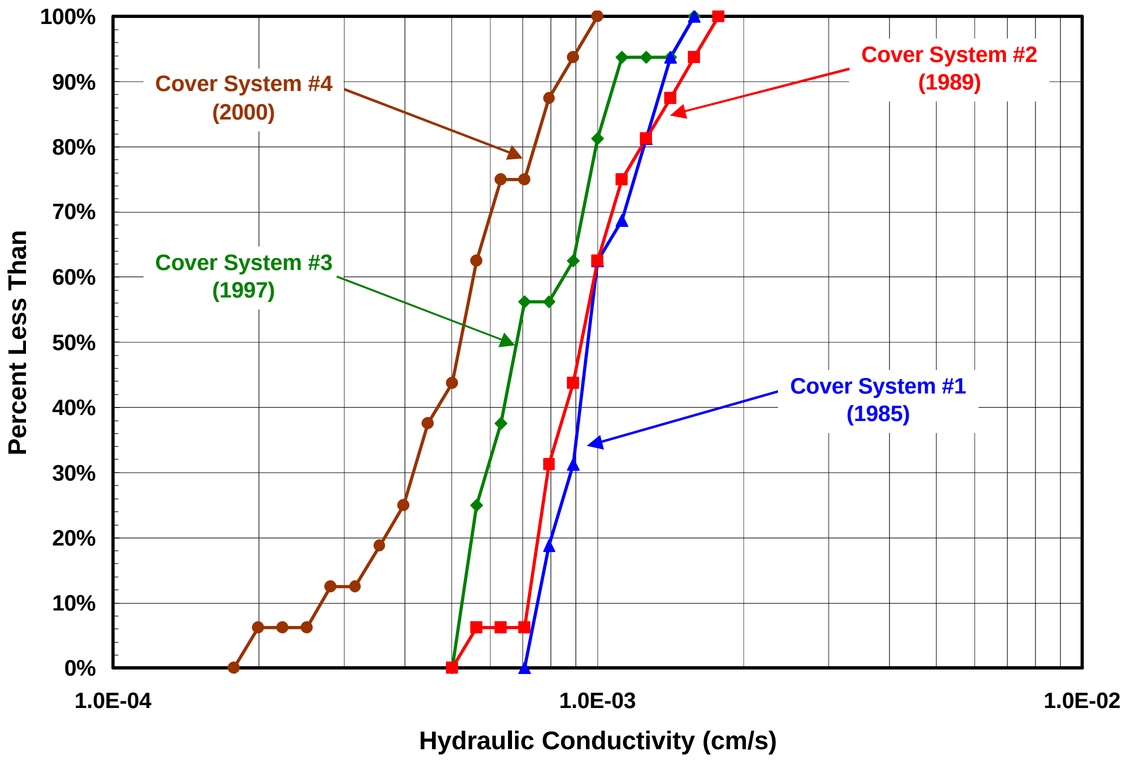

**Figure 7.1** Cumulative histogram of field hydraulic conductivity test results at the historical site.

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 saturated hydraulic conductivity testing programme examined four cover systems of varying age. The two oldest field trials 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 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 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 moisture 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.
- 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.
- 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.
- 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 moisture 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 moisture 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 on 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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# APPENDIX A1

## Evaluation of the Long-Term Performance of Dry Cover Systems

## (Phase 1 Final Report)

## 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 minimize the influx of water and provide an oxygen diffusion barrier to minimize 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 new technologies in the disposal of mining 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 new well-researched prediction model to simulate long-term performance. It must be acceptable to and trusted by all stakeholders, and lead to environmentally acceptable and economic decommissioning solutions.

This report is the culmination of Phase 1 of a project examining the long-term performance of dry covers for mine waste. The majority of the Phase 1 work involved a literature study, researching and compiling information about the processes affecting long-term dry cover system performance, available numerical models capable of predicting long-term performance, laboratory characterisation of cover materials, and field performance monitoring practices. The results of the Phase 1 work were incorporated into Phase 2 of this INAP project. Detailed performance monitoring data was collected and analysed for five mine sites located in Canada, Australia, and the United States. A calibrated numerical model, selected from the Phase 1 study, developed for three of the identified sites.

The following is a non-technical summary of each section of Phase 1 of the project.

Identification of Cover Performance Properties

- Discussion with mine site personnel and the completion of an informal questionnaire identified the processes affecting the long-term performance of a dry cover system. The processes were grouped into physical, chemical, and biological processes. A short definition and literature study was completed for each process

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 oxygen diffusion characteristics, and the physical integrity of the cover system.

## Cover Performance Numerical Models

- A literature study was completed to identify numerical models capable of simulating the long-term performance of a dry cover system.
- 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 use of the pre- and post-processor interfaces.
- 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.

## 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.

## Laboratory Characterisation Program

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

## Cover Performance Monitoring

- Field performance monitoring should include meteorological monitoring, monitoring of moisture storage changes, monitoring of net percolation, and vegetation monitoring. While difficult, it is often required that surface runoff and erosion monitoring is completed.

The Phase 2 work tasks, as outlined in OKC (2001), are currently being completed for the five sites identified in Phase 1. Detailed performance monitoring data for each site has been collected and the data is being “mined” for evidence of changes in the key cover performance properties.

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# 1.0 INTRODUCTION

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 minimize the influx of water and provide an oxygen diffusion barrier to minimize 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 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 production of acidic drainage.

It is recognized and expected that over a long period of time the properties of 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 new technologies in the disposal of mining 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 new well-researched prediction model to simulate long-term performance. It must be acceptable to and trusted by all stakeholders, and lead to environmentally acceptable and economic reclamation solutions.

This report is the culmination of Phase 1 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 largest mining companies in the world.

## 1.1 Project Objectives and Scope

A review of the processes influencing long-term performance of dry cover systems and the identification and research of the available numerical models were the focus of Phase 1 of this project. The specific objectives of this project phase are:

- Identifying the processes that affect long-term performance through a literature search and discussion with mine owners and designers;
- Evaluating models considered to be state-of-the-art tools for modelling dry cover systems;
- Defining the laboratory testing methodology required to properly design a cover system; and
- Determining the optimum method for integrating the required process fundamentals to existing models.

## 1.2 Organization of Report

Section 2 of this report defines the three key cover design properties influencing long-term performance and discusses the potential impact of physical, chemical, and biological processes on the long-term performance of dry cover systems. A review of the available numerical models capable of predicting the performance of dry cover systems is presented in Section 3. This section includes the selection of a numerical model and a summary of the modelling methodology to be undertaken during Phase 2 of the project. Section 4 of this report describes the additional modules that could possibly be added to the selected numerical model to improve its capabilities. Section 5 of this report defines the laboratory characterisation program required to properly design a cover system, while Section 6 summarises the field performance monitoring system required to evaluate the performance of a full scale or pilot scale dry cover system. The final section of this Phase 1 report summarises the key findings from completion of the Phase 1 work tasks.

## 2.0 IDENTIFICATION OF THE KEY COVER PERFORMANCE PROPERTIES

The first task completed within Phase 1 of this project was to identify the processes that could affect the long-term performance of a cover system. This task was completed through discussions with mine site personnel and completion of an informal questionnaire by practitioners and mine personnel. The results were grouped into three categories; namely the physical, chemical, and biological processes that affect dry cover system performance.

Examination of the identified processes showed that their effects could be related to the change in three key properties of the cover materials. These three key properties are the saturated hydraulic conductivity of the cover materials, the soil water characteristic curve (SWCC) of the cover materials, and the physical integrity of the cover system.

The change in each key property affects the performance of the cover system differently. In general, the change in saturated hydraulic conductivity will most greatly affect covers with a hydraulic barrier, such as compacted layer cover systems and capillary break cover systems. These cover systems rely on a low hydraulic conductivity layer to limit the percolation of infiltrated water through to the underlying waste material. Any change in the saturated hydraulic conductivity leads to a change in the percolation rate through the barrier layer. Barrier layers are normally constructed using the available materials best able to produce a low hydraulic conductivity layer. Therefore, it is likely that any change in hydraulic conductivity will lead to an increased saturated hydraulic conductivity of this layer. Alternatively, some physical processes (i.e. weathering) can “break down” cover material to a finer textured material, possibly reducing the saturated hydraulic conductivity of the cover material.

The SWCC, or moisture retention relationship, describes the effect of matric suction on the volumetric water content of the soil. Matric suction is a measure of the negative pore-water pressure within an unsaturated soil. It also indirectly describes the relationship between hydraulic conductivity and matric suction, because the hydraulic conductivity function depends on the SWCC and the saturated hydraulic conductivity. A soil that remains tension saturated at a higher value of matric suction, such as a fine textured material, will have a higher volumetric water content and therefore a higher relative hydraulic conductivity as compared to a coarse textured soil, which drains at low suction values. Figure A1.1 shows the SWCC and hydraulic conductivity functions for a fine textured and coarse textured material. The selected matric suction value is much greater than the air entry value (AEV) for the coarse textured material but only slightly greater than the AEV for the fine textured material. The AEV is the matric suction required to initiate drainage of an initially saturated soil. This leads to a large difference in the volumetric water content of the two different materials and a higher hydraulic conductivity in the fine textured material as compared to the coarse textured material.

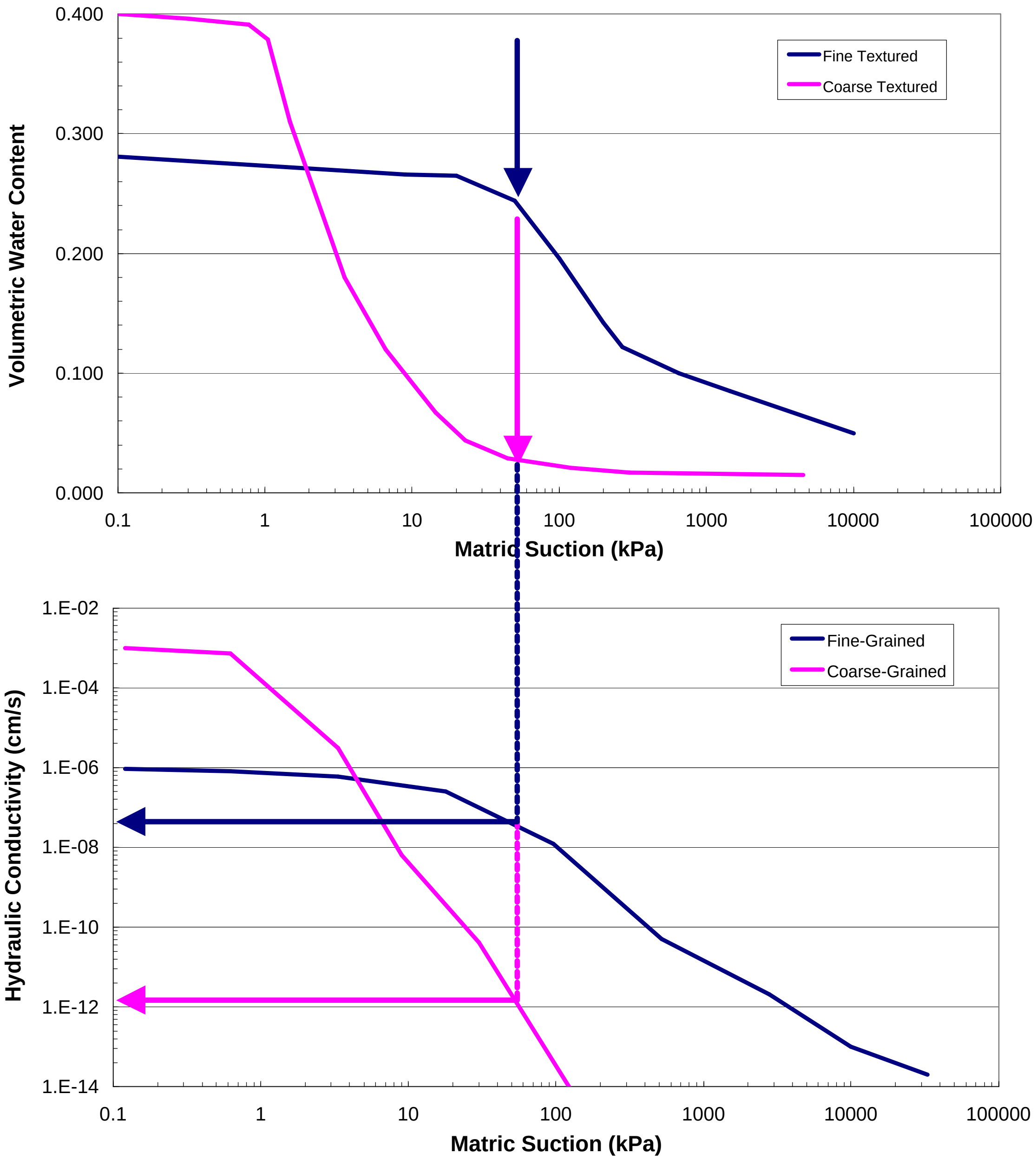

**Figure A1.1** Comparison of the hydraulic conductivity of fine and coarse textured soils.

The integrity of the cover system is a key property because predictions of the long-term performance are based on the physical dimensions of a specific cover design. If the natural environment changes the physical limits of the cover design, then the predictions based on the original physical dimensions cannot be considered valid. One of the best examples is erosion, which removes material from the cover surface, thus reducing the thickness of the cover layer(s).

The saturated hydraulic conductivity and SWCC are geotechnical properties of the cover material. Tests can be completed to assess the likely changes in the soil material (if any) over time. For example, a sample can be subjected to wet / dry cycles in the laboratory and the change in material saturated hydraulic conductivity can be evaluated. However, the physical integrity of the cover system is different; it is predicated by the interaction of the natural environment and the cover system. Prediction of the effects of this interaction is extremely difficult. The physical, chemical, and biological process most likely to affect the integrity of the cover will have to be identified and an estimation or sensitivity analysis of their effects completed. For example, it is more likely that erosion will adversely affect the performance of a steeply sloping cover system, as compared to the influence of burrowing animals.

The remainder of this section includes a brief discussion of the physical, chemical, and biological processes identified during Phase 1 and shown in Figure A1.2. Each process is discussed in terms of the potential impact they may have on the three key properties identified above. A detailed description of each process is provided in Appendix A2.

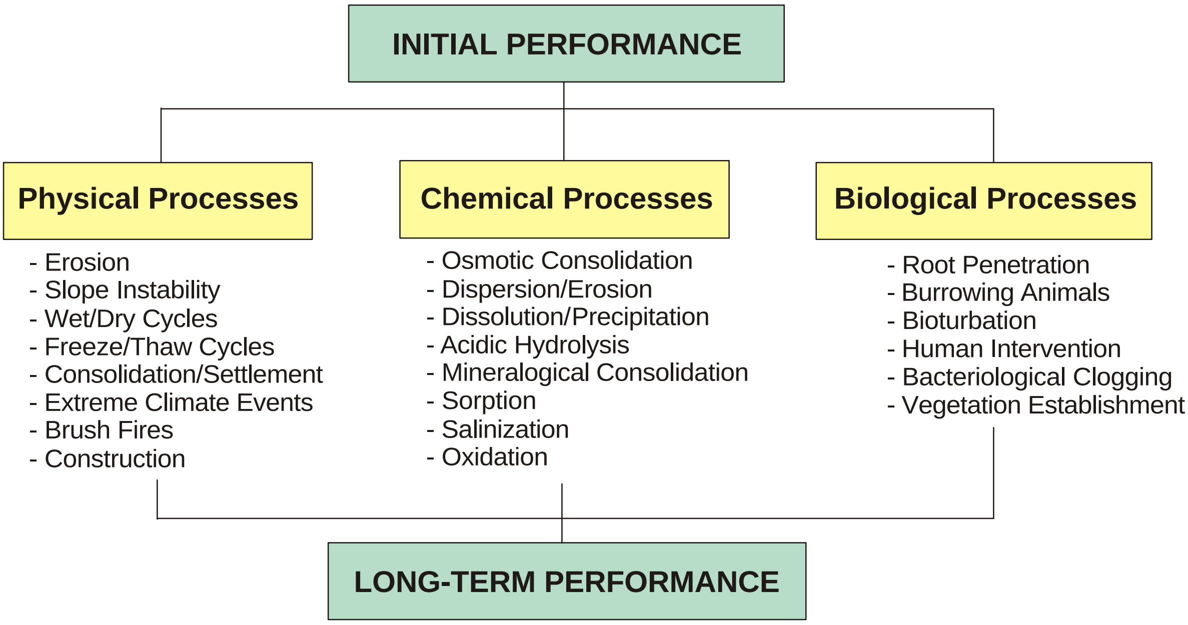

**Figure A1.2** Summary of the processes affecting long-term cover performance.

## 2.1 Physical Processes

The physical processes affecting the long-term performance of dry cover systems are listed in Figure A1.2. Each process involves the response of the cover materials to atmospheric forcing. For example, erosion is a possible response of a dry cover system to energy supplied by a large runoff event likely caused by high rainfall intensity.

### *2.1.1 Erosion*

Erosion is the most likely physical process to affect the integrity of a cover system. Generally, erosion is considered to reduce the cover thickness through rilling and gullying, but it can increase the cover thickness in flat, deposition areas. Rills and gullies reduce the length over which oxygen and water must percolate to reach the underlying waste materials. Erosion can also reduce the ability of the top cover layer, or growing medium, to sustain vegetation by washing away topsoil and fines, leaving coarser, rockier soil that is more difficult to establish vegetation. Erosion has a potentially large effect on the long-term performance of a dry cover system in many climates, but most significantly at sites that experience short duration, high intensity rainfall events.

Erosion can compromise the structural integrity of the cover system by reducing the thickness of the cover layer or removing it entirely. Erosion occurs when soil particles are detached from the soil matrix and then transported from the area. The erosion process is driven by the energy delivered from rainfall striking the soil or surface water or runoff flowing over the soil surface. It is generally agreed that the three main erosion processes are interrill, rill, and gully erosion.

Interrill erosion, also known as sheet erosion, consists of soil particle detachment from the soil matrix by raindrop impact and particle transport by splash and shallow overland sheet flow (Grosh and Jarrett, 1994). Rill erosion involves the concentration of runoff flow often caused on natural hillslopes by micro topography or vegetation (Bryan, 2000). The development of rills on a land area can greatly increase the soil erosion rate by concentrating runoff flow resulting in increased flow velocity and turbulence producing more energy to detach and transport material (Gatto, 2000). Gully erosion processes act on the sidewalls and head cut of gullies. Piest *et al.* (1975) defined gully erosion as a combination of processes including overland (shear) flow or rill flow, slope stability and mass wasting, and channel cleanout. As documented in interrill and rill erosion, the movement of soil from the gully is a function of the sediment transport capacity of runoff and the rate of soil detachment. Overland flow and mass wasting serve to detach material from the gully channel boundary while transport is achieved from energy supplied by gully flow.

Interrill, rill, and gully erosion are affected by the same set of factors. The factors listed below are believed to be the most important in terms of the erosion of dry cover system layers:

- Slope angle;
- Slope length;
- Material properties;
- Rainfall Intensity;
- Vegetation; and
- Antecedent moisture condition

### *2.1.2 Slope Instability*

Erosion and slope stability are often evaluated together when long-term performance of a dry cover system is considered. Slope instability is the mass movement of the entire slope surface destroying the integrity of the cover system or exposing the underlying waste material. Koerner and Daniel (1997) identified the three driving forces leading to slope instability as gravitational, seepage, and seismic forces.

Gravitational forces become an issue when the cover is placed on a slope. A component of the downward gravitational pull will act to push the cover material down the slope. Seepage forces ca potentially produce high pore-water pressures in the materials at the base of slopes. Both gravitational and seepage forces act to increase the shear stress being applied to the cover material. Seismic forces are created by earthquakes or large-scale movement of the earth's tectonic plates and must be considered in an area with the potential for earthquakes.

### *2.1.3 Wet / Dry Cycling*

Wet / dry cycling causes shrinkage and swelling of fine textured materials, which can be of considerable significance from the perspective of cover system integrity. Shrinkage cracks occur locally when the capillary pressures exceed the cohesion or the tensile strength of the soil. These cracks, part of the clay macrostructure, can significantly influence the overall performance of a cover material by altering the hydrogeologic and diffusion characteristics of the cover material.

The presence of cracks in the cover system can potentially have a significant influence on the hydrologic performance of the cover system. Desiccation of the cover material consolidates the matrix and increases the volume of macro-pores and cracks, which decreases the saturated hydraulic conductivity within the matrix and increases it within the total soil volume. Cracking of the cover material can then result in high potential infiltration rates and storage capacities. Capillary rise from the water table and evapotranspiration may then be hampered by low hydraulic conductivities. The overall potential result is that part of the precipitation flows through shrinkage cracks to the subsoil layers, thus bypassing the dry cover system material.

### *2.1.4 Freeze / Thaw Cycling*

Freeze / thaw cycling has an impact on the saturated hydraulic conductivity and moisture retention characteristics of soil covers. During freezing periods, water is drawn up from the soil to the freezing front leading to ice lenses within the cover material. The subsequent thaw of the material will decrease the material density as well as increase the water content and void ratio of the material ultimately leading to an increase in the saturated hydraulic conductivity. Wong and Haug (1991) observed that the hydraulic conductivity of clay and till liner materials increased as the number of closed system freeze / thaw cycles increased.

Casagrande (1931) identified silt as the material most susceptible to freeze / thaw cycling because silt pores are small enough to induce suction gradients during freezing but are large enough to allow an adequate supply of water to the freezing front. It is generally accepted that soils containing more than 10% of clay-sized particles are susceptible to freeze / thaw cycling.

### *2.1.5 Consolidation / Settlement*

Consolidation and settlement, as with most physical processes, will affect the integrity of the cover system by reducing the thickness of the cover layers. However, with consolidation also comes an increase in the density of the soil matrix, which can alter the saturated hydraulic conductivity and moisture retention characteristics of the material. Consolidation is the process of the cover material decreasing in volume from a decrease in the volume of voids within the material. Settlement is the term used to describe the reduction in volume of the cover material.

The process of settlement can change the geometry and drainage patterns of the cover system. Differential settlement can create local recharge and discharge areas on the cover system that were not accounted for in the cover design. Cover systems established on sloped surfaces utilise the slope to help shed water as runoff. This reduces the amount of water available to infiltrate the cover system and the underlying mine waste material. Figure A1.3 shows a conceptual schematic of the runoff flow on the altered slope surface.

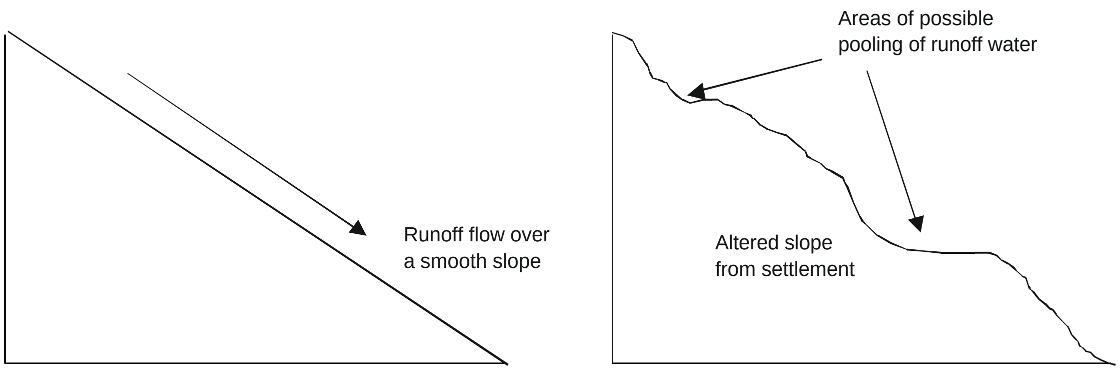

**Figure A1.3** A schematic representation of the effects of differential settlement on the surface hydrology of a slope.

### *2.1.6 Extreme Local Climate Events*

Extreme local climate events can potentially impact the integrity of a dry cover system. Extreme climate events usually refer to storm events causing high rates of precipitation and runoff, leading most often to erosion. However, extreme climate events can also include long periods of drought and desiccation or freezing conditions, which can lead to alterations in the hydraulic conductivity and moisture retention characteristics of the cover materials.

The local climate condition has a significant influence on the design of a dry cover system. A climate database is established based on the available weather data associated with the site during the cover system design stage. This climate information is often regionally based and not specific to the mine site as many mine sites only possess recent climate information.

Precipitation quantities greater than the historical average, both rainfall and snowfall, can lead to increased percolation through a cover system. Extreme precipitation events have the potential to exceed the storage capabilities of the cover material, saturate the cover system, and produce large net percolation to the underlying waste.

Drought conditions can impact the performance of an oxygen ingress barrier. A cover system designed to limit the transport of oxygen most often depends on the maintenance of a fine textured cover layer in a tension-saturated condition. A period of dry conditions can lead to a reduction in the degree of saturation of this layer, allowing more oxygen to reach the underlying waste. Drought conditions can also lead to desiccation and the cracking of cover layers, particularly those with a relatively high fines content. Any established vegetative stands will also be threatened by drought conditions, possibly leading to increased percolation when precipitation does occur, as well as runoff and associated erosion.

### *2.1.7 Brushfires*

The potential impact of brushfires on the integrity of a dry cover system should not be discounted. A brushfire will reduce vegetation, increasing runoff and likely increasing the rate of erosion on the cover system. If evapotranspiration through vegetation is an important component of the cover system design, a brushfire can severely decrease performance. Re-establishment of the vegetation at mine sites in semi-arid and arid climates following a brushfire can be a difficult and lengthy process.

## 2.2 Chemical Processes

The effect of chemical processes on the long-term performance of a cover system is not as obvious as a physical process such as erosion. Chemical processes have the potential to change the fabric of a cover material. Osmotic consolidation, dispersion, dissolution, acidic hydrolysis, mineralogical consolidation, and sorption are discussed in this section.

### *2.2.1 Osmotic Consolidation*

The process of osmotic consolidation can lead to shrinkage of clayey soil materials, causing cracks and fissures to develop in some cover systems. These openings provide a path for fluids to flow thereby increasing the material's hydraulic conductivity. Barbour (1987) identified two types of osmotic consolidation; namely osmotically induced consolidation and osmotic consolidation. Osmotically induced consolidation results from the release of water due to chemical gradients. Osmotic consolidation results from alterations in clay particle interactions due to changes in pore fluid chemistry.

Osmosis refers to the flow through a semi-permeable membrane that separates high and low concentration solutions. In the case of a soil cover system, the pore fluid surrounding the soil particles primarily consists of water and dissolved solids. Water is referred to as the 'solvent' while the dissolved solids are known as 'solute'. The clay material acts as a semi-permeable membrane letting the solvent move through at a much faster rate than the solute. There is extensive evidence in laboratory and field studies that clay soils have a semi-permeable nature (Barbour, 1987). Figure A1.4 illustrates the osmotic process.

Actions that assist in equalizing the solute concentrations occur because chemical equilibrium is desired by the system. Solvent from the lower concentration solution moves to the higher concentration fluid in attempt to balance the chemical gradient. The solute also has a tendency to migrate but the semi-permeable clay layer impedes solute flow. A decrease in pore fluid pressure in the clay develops as the water is removed, resulting in an increase in effective stress that leads to consolidation.

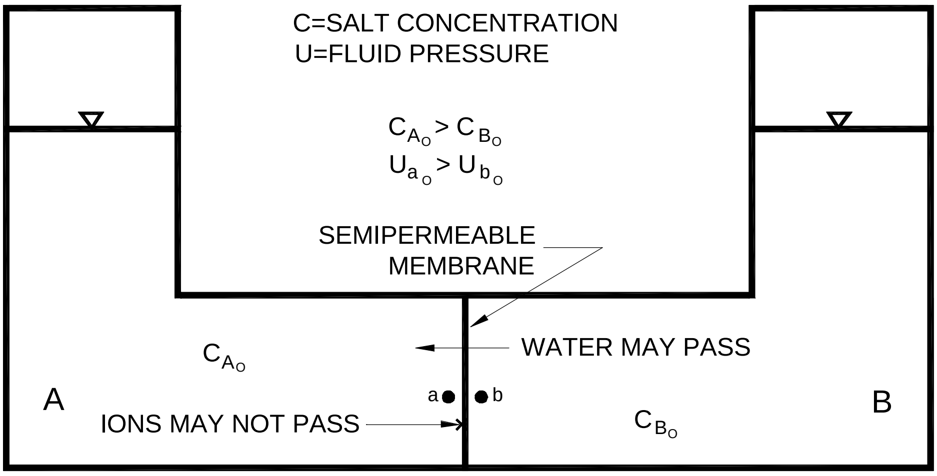

**Figure A1.4** A schematic representation of osmotic flow (from Barbour, 1987).

Osmotic consolidation results from alterations in clay particle interactions due to changes in pore fluid chemistry. Barbour (1987) suggests that particle-to-particle interaction is largely controlled by long-range repulsive forces. A change in pore fluid concentration can result in changes in these long-range electrostatic forces. The change in pore fluid concentration can cause a reduced thickness of the diffuse double layer. The diffuse double layer refers to the layer of cations established around the clay particle, with increasing cation concentration towards the surface of the clay particle. If cations enter into the clay with a higher valence than the exchangeable ions currently in place (e.g. $Ca^{++}$ for $Na^{+}$), stronger bonds between the clay particles may develop subsequently reducing the space between the clay particles (reducing the diffuse double layer thickness).

The desire to use clay materials in cover systems results from their lower hydraulic conductivity. The problem is that these low permeable clays are also strongly affected by electrolyte solutions (high salts), which can result in osmotic consolidation. When osmotic or osmotically induced consolidation occurs, cracks and fissures develop, which increase the hydraulic conductivity of the clay and inhibits the clay layer from preventing seepage into other areas.

Several methods have been formulated to limit the extent of osmotic consolidation including: minimising the clay content of the cover material, applying a sufficient confinement to the clay so that fractures and cracks are not able to develop, and reducing the potential for volume change (i.e. chemically pre-treat the cover material) (Haug *et al*., 1988).

### 2.2.2 Dispersion / Erosion

The dispersion of clay minerals and subsequent susceptibility to erosion should be considered in evaluating the long-term performance of a cover system possessing a clayey soil. Chemical processes can influence the arrangement of clay particles and may lead to the development of dispersed clay. Dispersed clays are prone to increased rates of erosion. Figure A1.5 shows the physical arrangement of dispersed and flocculated clays.

The stability of clays is dependent upon the arrangement of the soil particles. Important factors in determining clay stability include pore-water ion concentration, the type of clay minerals present, and the exchangeable cations present.

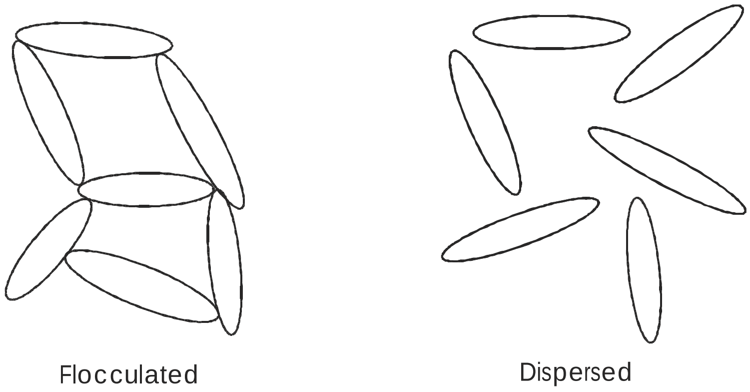

**Figure A1.5** Flocculated and dispersed arrangement of clay particles.

### *2.2.3 Dissolution / Precipitation*

The long-term performance of cover systems may be affected by the chemical processes of dissolution and precipitation. Dissolution occurs when a state of under saturation exists in the pore fluid solution. Dissolution involves the dissolving of a solid into separate components. Fluid carries the dissolved material away and voids are left in the material’s place. In the case of a soil cover system, the chemicals in fluid entering the cover system may dissolve the cover material. This can result in piping and void spaces within the cover material. Precipitation occurs as a result of over saturation of solute within a solution. Precipitation reactions involve the formation of an insoluble product, or precipitate from solution.

### *2.2.4 Acidic Hydrolysis*

Hydrolysis is a reaction that involves a component of water; acidic hydrolysis involves reactions with acids in aqueous solution. In a cover system, minerals in the cover materials may react with acids in the pore fluid forming new minerals.

Water molecules separate into $H^+$ and $OH^-$ ions. In acidic hydrolysis, an acid such as sulphuric acid ($H_2SO_4$) or water ($H_2O$) gives up a proton ($H^+$) (depending on the acid, maybe more than one proton) and picks up a cation from surrounding mineral grains. Minerals in the soil cover that contain ions with a strong attraction to hydrogen ions are susceptible to reacting with an acid. These minerals attract protons and can exchange cations with the acids in solution. The new minerals formed may or may not compromise the integrity of the soil cover in terms of slope stability, moisture retention, hydraulic conductivity, etc.

### *2.2.5 Mineralogical Consolidation*

Mineralogical consolidation may occur as a result of changes in the mineralogy of soil particles. This could involve a change in crystal structure or chemical composition of minerals. Long-term cover performance may be affected by the characteristics of the new mineral(s). If the newly formed mineral(s) causes consolidation to occur, crack or fissures may develop, thus reducing the effectiveness of the cover system.

### *2.2.6 Sorption*

Dissolved minerals within groundwater can be sorbed onto the surfaces of mineral grains in the soil cover. Sorption removes solute from the solution or causes retardation of solute movement. Sorption is assumed to be a reversible reaction. The sorption of minerals changes the chemistry of the cover material and may affect its long-term performance. Sorbed minerals may assist in the development of osmotic consolidation or dispersion / erosion processes.

Sorption isotherms, as shown in Figure A1.6, are used to estimate the amount of sorption for certain concentrations. All isotherms level off eventually because the capacity of the soil to store minerals is limited. Mineral surfaces have a limited amount of space for ions to bond to.

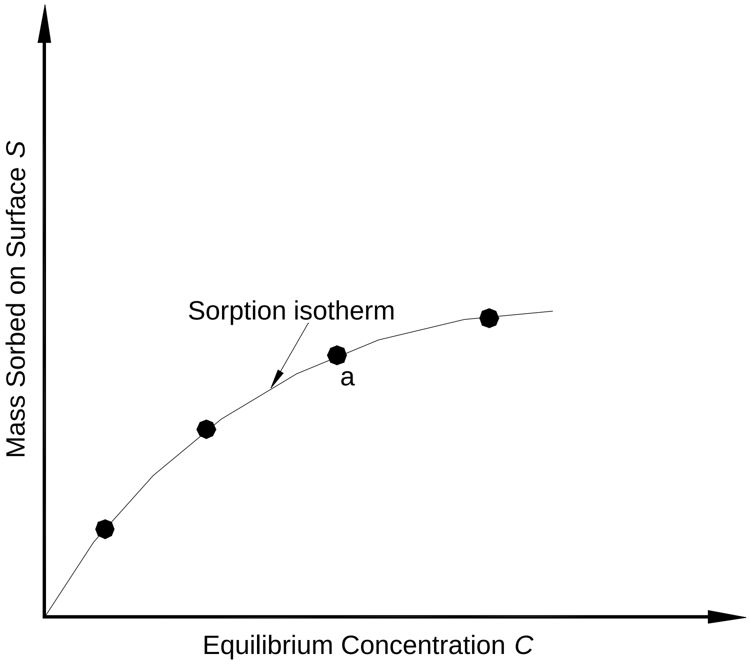

**Figure A1.6** Sample isotherm (from Domenico & Schwartz, 1998).

## 2.3 Biological Processes

The biological processes identified and researched in this project include the effect of root penetration, burrowing animals, bioturbation, human intervention, bacteriological clogging, and vegetation establishment.

### *2.3.1 Root Penetration*

Root penetration is generally thought to affect the integrity of the cover system and decrease the long-term performance of a dry cover system. Roots and plant biomass create macro-pores within the soil structure, allowing water to more easily infiltrate into the cover material and down to the underlying waste material. Koerner and Daniel (1997) summarise the damage that plant roots can have as follows:

- roots may penetrate the barrier layer of a cover system;
- decomposing roots leave channels for movement of water and vapours;
- roots may dry clayey layers, causing shrinking and cracking; and
- roots may enter the waste material and intake salts and undesired metals upward into the cover system and the soil surface.

For these reasons, grass and shrubs are often used to vegetate the surface of a dry cover system. The shrubs and grass have shallow rooting systems that do not reach into the barrier layers of the cover system. However, it is difficult to envision that deeper rooting species, if they were native to the site, would not eventually invade the cover system.

Research on the rooting depths and biomass distribution of tree species has showed that 80% of tree roots and up to 99% of the tree biomass stay within 0.6 m of the soil surface, indicating that many trees have shallow, lateral rooting systems. Active plant roots can potentially plug the macro-pores of the soil structure and consolidate the ground around them, leading to a decrease in the soil hydraulic conductivity in the vicinity of vegetation.

### *2.3.2 Burrowing Animals*

Burrowing animals also influence the integrity of the cover system. Koerner and Daniel (1997) summarised the effects that burrowing animals can have on the long-term performance of a cover system:

- the animals may burrow through the cover, resulting in direct channels for movement of water, vapour, roots, and other animals;
- they may carry waste material directly to the surface during excavation;
- animals construct their burrows for natural ventilation which may dry the soil and decrease water intrusion; and
- by working the soil and transporting seeds, they may hasten establishment of deep-rooted plants on the cover system.

# 3.0 COVER PERFORMANCE NUMERICAL MODELS

Water movement, or percolation, through soil materials is influenced by three components, consisting of the soil-atmosphere interface, the unsaturated zone, and the saturated zone (MEND, 1996). In the past, groundwater modelling was often limited to the saturated zone, but advances in the application of unsaturated soil technology have led to an abundance of saturated / unsaturated numerical modelling techniques. The next step in the evolution of groundwater flow models involved linking the boundary condition imposed by the atmosphere to the subsurface saturated / unsaturated flow system. A literature search was conducted to identify and evaluate the available numerical models with this capability. Table A1.1 is a list of the commercially available and freeware numerical models evaluated in this study. A short description of each model, adapted from the accompanying literature, is presented in Appendix A3.

**Table A1.1**

Cover performance numerical models identified in the literature search.

| Freeware | Commercially Available |
|---|---|
| VS – 2D | HYDRUS-2D |
| HELP | VADOSE/W |
| UNSAT-H | SWIM |
| SoilCover | |

Predicting the flow of water between the soil surface and the atmosphere is a critical issue in the design of cover systems for mine waste. The flow of moisture between the soil and the atmosphere is a complex process dominated by three coupled processes (Wilson, 1990). The first factor is the supply of and demand for water imposed at the soil surface by the atmosphere, including conditions such as precipitation, air temperature, and net radiation. The second factor is the ability of the soil to transmit water controlled by the soils hydraulic conductivity and moisture retention characteristics. Vegetation is the final factor that must be considered. Transpiration is influenced by the type and density of vegetation as water is consumed through plant water uptake.

## 3.1 Comparison of the Key Functions of the Numerical Models

The seven numerical models evaluated included two text-based input and output models, one DOS-based program, and four Windows interface models. Considerable time was spent working with each model to examine the numerical solutions and learn the input requirements and output capabilities of the programs. It was not possible, however, to learn all the nuances and capabilities of each of the numerical models.

Each of the models function extremely well for the purpose for which they were developed. Each is well programmed and rigorously tested to ensure accuracy. This exercise was not an analysis of the models and was not meant to critically review the work of others. The models were not scored or rated; rather they were examined to identify which model is best suited to predict the long-term performance of cover systems. Eight key functions, relating to the models ability to predict long-term performance, were identified and then each was evaluated. The identified key functions are:

- Formulation of numerical model;
- Heat transport capabilities;
- Solute transport capabilities;
- Specified boundary conditions;
- Surface boundary conditions;
- Evapotranspiration;
- Graphical interface and ease of use; and
- Observation nodes

The evaluation of each of the eight key functions is included in Appendix A3.

## 3.2 Selection of the Numerical Model for Phase 2

Table A1.2 is a summary of the key functions presented in Section 3.1 and discussed in detail in Appendix A1.3. An “A” signifies that the model performs adequately, whereas an “N” indicates the model is unsuitable for the application. A scoring of “L” shows that the model performs reasonably well, but not to the standard of the other models.

Interpretation of Table A1.2 shows that none of the seven numerical models is perfectly suited to predict the long-term performance of cover systems. Some of the models are better than the others; however, additions would be required for all models. The two-dimensional coupled heat and water flow numerical model VADOSE/W was selected as the most suitable model for predicting long-term performance because it includes more of the processes and characteristics that are important to cover system performance. Therefore, a user could better understand the impact of the processes and characteristics on long-term performance. Some of the attributes of the VADOSE/W model include:

- excellent Windows-based pre- and post-processor;
- two-dimensional capabilities to simulate the effects of slope and the diversion of water within subsurface flow;
- calculation of actual evapotranspiration rates with the Penman-Wilson formulation; and
- the capability to observe the results of each node at each time step.

## Table A1.2

Summary of the key functions required for a long-term performance numerical model.

| Model Name | Numerical Flow Solution | Coupled Heat Transport | Solute / Mass Transport | Specified Boundary Conditions | Defined Daily Climate Data | Vegetation | Evapo-transpiration | Graphics and Ease of Use | Observation Nodes |
|---|---|---|---|---|---|---|---|---|---|
| UNSAT-H | A | A | N | A | A | L | L | N | L |
| SWIM | A | A | A | A | N | L | L | N | L |
| HELP | N | N | N | N | A | L | L | N | L |
| SoilCover | A | A | L | A | A | L | A | A | A |
| VS-2D | A | A | A | A | N | L | L | A | A |
| HYDRUS-2D | A | A | A | A | L | L | L | A | A |
| VADOSE/W | A | A | L | A | A | L | A | A | A |

A = Adequate; N = Not Adequate; L = Limited

### 3.2.1 Proposed Outline of the Phase 2 Modelling Program

The planned review of the field data has changed somewhat from the proposed approach described in OKC (2001). Initially, the thought was to review the data with respect to net percolation, oxygen ingress, moisture storage changes, etc. However, at the current time the modelling plan is to "mine" the data for evidence of changes in the three key material properties that control performance. Once the evidence is found, then a basis will be developed as to which, or a combination of which, processes have resulted in the change in the material property. The rationale is that if the process, or processes, that caused the change in the key material property are not included in the numerical model, then it should potentially be included if in fact the change in the material property results in an impact on long-term performance.

It is proposed that the following sites be utilised during Phase 2 of the project.

1) Syncrude Canada Ltd., Mildred Lake Mine (tailings; semi-arid climate)
2) Placer Dome Canada Ltd., Equity Silver Division (waste rock; humid climate)
3) Teck Cominco Ltd., Kimberley Operations (tailings; semi-arid / semi-humid climate)
4) BHP Billiton Iron Ore Pty Ltd, Mt. Whaleback Operations (waste rock; arid tropical climate)
5) Historic reclamation site in southwestern United States (Note: In order to gain access to the site and the associated performance monitoring data, OKC cannot disclose the specific site).

In addition to the availability of detailed historical field data, the sites were proposed based on the type of waste material and the general annual climate conditions at the site.

A response from Freeport, Barrick, and Homestake to a request for potential sites was not received. Phelps Dodge did respond to an initial request for potential sites to be included, but subsequent communication did not yield a suitable site for inclusion in the project. The remaining INAP member companies have responded to the request for information or contact details. There are a number of Rio Tinto sites that are promising (e.g. Ridgeway, Greens Creek, Kestrel Coal, and Peak Gold), although the limited length of available detailed monitoring data does hinder the effective use of the field data for the purposes of this project.

An ideal sixth site to include in the project would be the Rum Jungle site. A request was made to ANSTO to include the Rum Jungle field data in the project. ANSTO indicated that the Rum Jungle site was already being reviewed as part of another INAP project, and thus preferred not to include it within the project reported herein.

# 4.0 DESIRED ADDITIONS TO THE VADOSE/W MODEL

VADOSE/W has been identified as the most suitable numerical model for long-term cover performance simulations. The current configuration of the model is only a starting point for additional modules that potentially could be added to the program. Ideally, the model should be able to adapt and change as climate and materials change and the physical limits of the cover are altered. The following sections discuss some suggested additions to the VADOSE/W model. They are presented in the manner in which they could theoretically be added to the VADOSE/W model only, although it is recognised that some of the additions may not be technically feasible with the present structure of the VADOSE/W program.

## 4.1 Erosion and Stability Module

The VADOSE/W model measures runoff and therefore it should be possible to model interrill and rill erosion. Interrill and rill erosion have been well researched and tested for agricultural and mining soils. Rill erodibility is the larger concern for dry cover systems; it produces concentrated channels that can significantly diminish the physical integrity of the cover system. Gully erosion is also a concern; it can cause large displacements of materials over a short time frame and can also compromise the integrity of the cover system. Gully erosion is an extremely complicated process, dependent on the material properties, antecedent moisture condition, storm characteristics, as well as runoff, vegetation, and rock cover as a minimum. A theoretical approach to modelling gully erosion, including a physically based equation, is required. A literature search by Christensen (2002) did not identify a suitable gully erosion equation. The additions made to VADOSE/W would likely require an adaptive model. The two-dimensional mesh may have to be reformed after each time step or after a threshold loss of material occurs. This will shorten the thickness of cover material for oxygen and water transport and greatly change the predicted performance of the cover system.

## 4.2 Expanded Vegetation Module

Each of the seven numerical models scored an “L” (limited) for the vegetation parameter in Table A1.2. This is due to the empirical nature of the transpiration calculation used by each model. A module using plant biomass as the driving force behind actual transpiration could be added to the VADOSE/W model. Plant growth models do exist and should be researched. The additional module will require a relationship to partition potential evaporation and potential transpiration at the ground surface, and then a definition of actual transpiration based on the potential transpiration.

A key issue with the current approach to modelling vegetation is that the user defines the root depth of the vegetation modelled. Clearly, this will have a significant influence on predicted performance, and results in the need to conduct and extensive sensitivity analysis, which may or may not represent long-term performance. A more appropriate approach to modelling vegetation is to allow for root development in response to the availability of moisture, nutrients, and oxygen.

## 4.3 Saturated Hydraulic Conductivity and SWCC Evolution Module

The change in the saturated hydraulic conductivity and the moisture retention or soil water characteristic curve (SWCC) were identified along with the integrity of the cover profile as the three main concerns for the long-term performance of cover systems. Increases in the saturated hydraulic conductivity of barrier layers will decrease the performance of the cover system, while changes to the SWCC can cause changes in the flow patterns within the cover and will have a large effect on any capillary break cover systems. A possible addition to the VADOSE/W model would be the capability to alter the hydraulic conductivity and SWCC of the materials of the cover material. The alteration might be implemented after a set period of time, or after a set of key indicators has been achieved. For example, if five wet / dry cycles have occurred at a prescribed depth, the SWCC would be changed to represent the altered material. The input (i.e. number of cycles and degree of alteration) could be based on laboratory data and /or the discretion of the model user.

## 4.4 Modelling Changes Required Outside the Scope of VADOSE/W

To increase the accuracy of long-term cover performance modelling, additional work outside of the VADOSE/W model is likely required. Two examples are a climate change model, and a database of wildlife within the mine site area. A climate database compiled from the recent history of the site is not necessarily adequate for long-term future modelling. Some estimation of the likelihood of wildlife damaging the physical integrity of the cover system could also be undertaken.

# 5.0 LABORATORY CHARACTERISATION PROGRAM

The waste and cover system materials must be properly characterised to improve the accuracy of the long-term prediction model. Geotechnical properties of the materials such as saturated hydraulic conductivity, moisture retention characteristics, and particle size distribution must be defined with laboratory tests. This section of the report details the sample collection procedures and laboratory testing procedures used in the geotechnical characterisation of the waste and cover system materials.

## 5.1 Collection of Samples for Laboratory Characterisation

Material samples are collected in the field for both geotechnical and geochemical testing purposes. The samples are generally either small or large grab samples, depending on the characterisation test to be performed on the sample. For example, samples for particle size distribution and detailed geotechnical testing are typically placed in 20 litre pails, while smaller re-sealable bags are used to collect moisture content and geochemical samples.

The following is a brief summary of OKC's sample collection methodology for waste rock and cover materials with large particles sizes. The size of the sample collected should be indicative of the texture of the material being collected. In general, larger samples are required for run-of-mine waste materials and cover materials with large particles sizes. In all cases, however, duplicate samples must be collected to avoid the need to conduct future sampling in the event that additional material is required.

Each large sample collected from an excavated test pit is collected in up to seven 20 litre plastic containers. Four of the pails are filled with a representative material sample for testing of the particle size distribution (PSD) if there is significant coarse textured material within the sample. In general, particles greater than 100 mm are not included in the samples collected for laboratory characterisation. If the sample material is fairly fine textured (i.e. fine sands and clays) only two 20-litre plastic sample containers are required. Two 20-litre plastic container samples are collected for potential detailed physical and hydraulic characteristic testing (i.e. moisture retention and hydraulic conductivity). The seventh pail is considered an extra or spare sub-sample that can be used for further geotechnical or geochemical testing, such as metals and nutrient analysis to determine the material's suitability as a growth medium.

## 5.2 Laboratory Testing Methodology

The geotechnical laboratory test program is generally carried out on both the potential cover material and mine waste material samples. The program is designed to determine physical and hydraulic parameters of the materials for input to soil-atmosphere cover design and seepage numerical models.

A comprehensive geotechnical characterisation program would consist of laboratory tests to determine the following parameters:

- Particle size distribution (PSD);
- Atterberg limits;
- X-ray diffraction;
- Specific gravity;
- Compaction curve (i.e. Proctor curve);
- Saturated hydraulic conductivity;
- Consolidation-saturated hydraulic conductivity relationship; and
- Soil water characteristic or moisture retention curve.

Some of the tests, such as PSD and Atterberg limits, are well known and completed by almost all geotechnical engineering testing firms. Other tests, such as the hydraulic conductivity and moisture retention tests are specialised and performed by only a small number of laboratories. A brief description of the various geotechnical laboratory tests is provided below with a detailed description of the testing procedures for each included in Appendix A4.

### *5.2.1 Particle Size Distribution Test*

The particle size analysis testing procedure is detailed in ASTM D422-63 (ASTM, 1990). The PSD test is universally used in the engineering classification of soils (Bowles, 1992). The results of the PSD tests, in combination with the field characterisation and logging, allows classification of the potential cover materials under the broad categories of topsoil, well-graded, clay, and coarse materials.

### *5.2.2 Atterberg Limits*

The Atterberg limits tests, documented in ASTM D4318-95a (ASTM, 1995), measures the liquid and plastic limit of the soil sample. The limits are primarily used for soil identification and classification. Correlations between the Atterberg limits and soil strength and volume change have also been extensively investigated.

### *5.2.3 X-ray Diffraction Test*

X-Ray diffraction (XRD) is used to identify the types of clay minerals within a sample of run-of-mine waste or cover materials. Geotechnical and hydrological properties of a cover material are governed to a large extent by the mineral components of the soils, and predominantly the clay fraction. Therefore, an understanding of the nature and properties of different clay mineral components of the potential cover material is essential to a study of its geotechnical and hydrological properties.

### *5.2.4 Specific Gravity Test*

The procedure for conducting a specific gravity test on a soil sample is specified in ASTM D854-92 (ASTM, 1992). The specific gravity of a soil is used in calculating the phase relationships in soils, meaning the specific gravity is required to examine properties such as the soil void ratio, bulk density, and porosity.

### *5.2.5 Compaction (Proctor) Test*

The compaction test, also known as a Proctor test, is detailed in ASTM D698-91 (ASTM, 1991). The compaction test defines the moisture content – unit weight (density) relationship of a soil sample. This is widely used in construction to produce soils with their maximum unit weight for greatest soil strength.

### *5.2.6 Saturated Hydraulic Conductivity Test*

The saturated hydraulic conductivity of the potential cover and mine waste materials was identified as one of the key properties influencing the long-term performance of dry cover systems. Saturated hydraulic conductivity tests are most often completed using a triaxial permeameter, or in the case of a coarser textured material a falling head permeameter.

### *5.2.7 Consolidation-Saturated Hydraulic Conductivity Test*

Consolidation-saturated hydraulic conductivity testing is carried out in order to determine the relationship between effective stress, void ratio and saturated hydraulic conductivity for fine textured potential cover or waste materials samples.

### *5.2.8 Soil Water Characteristic Curve Test*

A key component of the laboratory program is the measurement of the moisture retention or soil water characteristic curve (SWCC). The moisture retention curve is a continuous function relating energy and the state of water, and hence describes the water content of a material as a function of soil suction, or negative pore-water pressure. The moisture retention curve is central to the design of an unsaturated soil system, which describes a cover system, and the most fundamental characterisation required for design.

# 6.0 COVER PERFORMANCE MONITORING

The data collected during cover performance monitoring can be used to calibrate numerical models used for predicting the long-term performance of dry cover systems. The information provided in this section was adapted from MEND (2001).

## 6.1 General

Direct measurement of field performance is the state-of-the-art methodology for measuring performance of a dry cover system. Field performance monitoring can be implemented during the design stage with test cover plots (e.g. Woyshner and Swarbrick, 1997; Aubertin *et al.*, 1997; O'Kane *et al.*, 1998a, 1998b, 1999), or following construction of the full-scale cover (i.e. O'Kane *et al.*, 1998c). Direct measurement of field performance of a dry cover system is the best method for demonstrating to regulatory agencies and the public that the cover system will perform as designed. The main objectives of field performance monitoring are to:

- obtain a water balance for the site;
- obtain an accurate set of field data to calibrate a numerical model;
- develop confidence with all stakeholders with respect to cover system performance; and
- develop an understanding for key characteristics and processes that control performance.

The desired field performance monitoring system should include monitoring of the various components that influence the performance of a dry cover system. These components are shown schematically in Figure A1.7.

MEND (2000) provides a detailed overview of field performance monitoring for dry cover systems. Some key points related to meteorological monitoring, measurement of moisture storage changes and lysimeters are provided below.

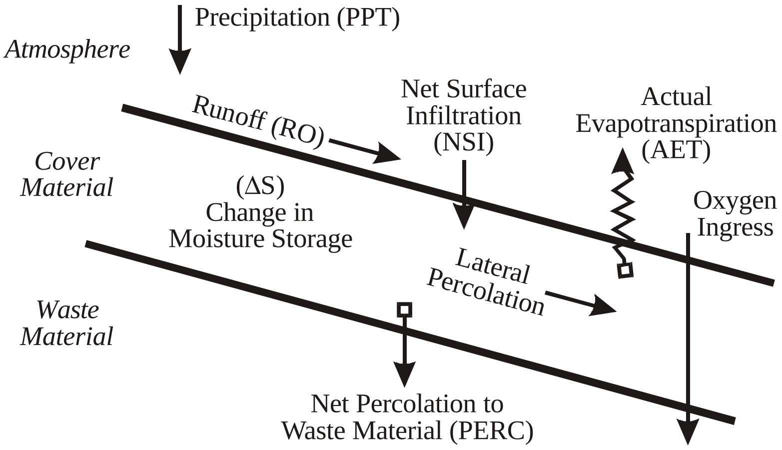

**Figure A1.7** Schematic of field performance monitoring system for dry covers systems.

## 6.2 Meteorological Monitoring

Measurement of site precipitation is the most crucial of all the site meteorological measurements. Rainfall during the summer should be measured by several inexpensive tipping bucket rain gauges for large sites to quantify spatial differences. Rain gauges should also be located at all test plot sites. Snowfall should be measured with an all-season precipitation gauge and in addition, regular depth / density measurements of the snow pack should be collected with increasing frequency as spring freshet approaches.

Other meteorological parameters that should be monitored include air temperature, relative humidity, wind speed and direction, and net solar radiation. This data is required as input to most soil-atmosphere cover numerical models and can be used to evaluate the potential evaporation for the site. It should be noted that measurements of pan evaporation are measurements of neither the potential nor actual evaporation, caution is required when using an evaporation pan because a great deal of experience is required to properly correlate pan evaporation to potential evaporation for all periods of the year.

## 6.3 Monitoring of Moisture Storage Changes

In general, water content sensors alone are needed to measure changes in moisture storage within a cover system; however, it is recommended that soil suction sensors be installed at the same location and depths of the water content sensors in each of the cover system layers. This enables a field soil water characteristic curve (SWCC) to be developed for each material in the cover system. A soil suction sensor can be thought of as the “piezometer of the unsaturated zone”. Measurement of soil suction is a fundamental component of the monitoring program because soil suction describes the stress state of the cover system. In other words, a change in the degree of saturation or water content of the cover system is caused by a change in soil suction within the cover material. Soil suction determines the volume of water present within the soil pores and subsequently the hydraulic conductivity of the porous material, as related by the hydraulic conductivity function. In addition, moisture flow gradients in a cover system can only be determined using suction sensors.

## 6.4 Monitoring of Net Percolation

Measurement of the net water percolation from the base of the cover layers into the underlying waste material is likely the most important component of a cover system monitoring program. In general, the design and installation of lysimeters to monitor evaporative fluxes as well as net infiltration is well understood and implemented in the soil science discipline. However, the design of lysimeters for dry cover system monitoring programs in the mining industry has typically not included fundamental lysimeter design aspects established in the soil science discipline. As a result, most lysimeter measurements used to monitor dry cover system performance should be used with caution unless a thorough review of the design and installation of the lysimeter is undertaken.

A lysimeter installed to monitor net percolation from the base of a cover system is part of an unsaturated system. Flow into the lysimeter may occur during saturated conditions; however, flow will primarily occur during unsaturated conditions. The percolation through the cover material is a function of the properties of not only the cover material, but also the material underlying the cover, which in turn controls the suction at the base of the cover. In addition, the lysimeter establishes an artificial water table boundary condition below the cover material that is different than outside the lysimeter. The design of field lysimeters requires that the geometry of the lysimeter (cross-sectional area and depth), hydraulic properties of the backfill (SWCC and saturated hydraulic conductivity), and the cover response (percolation) be integrated so that the suction at the cover layer-waste material interface is the same both inside and outside of the confines of the field lysimeter.

Bews *et al.* (1997, 1999) and O'Kane and Barbour (2003) provide further insight into the design and performance of field lysimeters for monitoring net percolation through dry cover systems.

## 6.5 Runoff and Erosion

Runoff is a complex process and therefore, accurate measurement of local surface runoff from a natural soil system is difficult. The quality of data obtained from surface runoff collection devices is questionable because installation of such devices typically requires disturbance of the natural ground surface. As a result, it is often desirable to install a surface runoff collection and monitoring system immediately upon completion of a cover trial or full-scale cover to avoid disturbance of vegetation and the macro-pore structure that will eventually exist on the surface. In addition, the quantity of surface erosion should also be assessed as part of the same collection and monitoring system because of the connection between surface runoff and erosion.

Other techniques have been used in the field to specifically assess the quantity of surface erosion. Quine et al. (1997) described a method for measuring the change in slope morphology on a small agricultural watershed. At two metre intervals down the slope a measuring tape was extended across the slope to record the location, depth, and width of the existing rill network. The measurement process can be repeated after specified intervals or after large erosion events to define the change in rill geometry and estimate the amount of soil lost to erosion.

A similar measurement method involves the installation of erosion pins to form a grid across the area being monitored. Measurement of the depth of scour or deposition at the pin allows the generation of erosion contours for the area. This technique was utilised to measure erosion at the Kidston gold mine in Australia (Horn *et al.*, 1998).

## 7.0 SUMMARY

O'Kane Consultants Inc. (OKC) have prepared this Phase 1 final report on the long-term performance of dry cover systems for the International Network for Acid Prevention (INAP). The objective of this report is to summarize the work completed during Phase 1 of this project. 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.

Identification of Cover Performance Properties

- Discussion with mine site personnel and the completion of an informal questionnaire identified the processes affecting the long-term performance of a dry cover system.
- Examination of the defined processes showed that each could be related to the change in three key cover performance properties; namely, the saturated hydraulic conductivity and moisture retention characteristics of the cover materials 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 A1.3.

**Table A1.3**

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 | |

## Cover Performance Numerical Models

- A literature study was completed to identify numerical models capable of simulating the long-term performance of a dry cover system.
- 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 use of the pre- and post-processor interfaces.
- VADOSE/W was determined to be the best-suited numerical model for predicting long-term performance of cover systems.

## 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.

## Laboratory Characterisation Program

- A suggested protocol for the collection of representative material samples for characterisation in the laboratory is provided.
- A comprehensive geotechnical characterisation program 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), 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, and erosion.
- The typical methods of measurement for each component of a field performance monitoring system was summarised in Table 6.1.

The Phase 2 work tasks, as outlined in OKC (2001), are currently being completed. Soil-atmosphere modelling has been initiated for the Syncrude Canada Ltd. site at Ft. McMurray, Canada, while performance monitoring data is being reduced in preparation for soil-atmosphere modelling at Equity Silver in northern British Columbia, Canada. A field characterisation study has been completed at Equity Silver.

OKC changed the scope of work for the project to include *in situ* field measurements at three of the five locations in light of the desire to evaluate cover system evolution. The *in situ* hydraulic conductivity of the cover material at Equity Silver has been measured at several different locations representing different ages of cover materials. This permits an assessment of the change in hydraulic conductivity with time (a range of 3 – 15 years). The same *in situ* hydraulic conductivity testing of cover system materials was completed in August 2002 at the Teck Cominco Ltd., Kimberly Operations site in the interior of British Columbia, Canada, and the site in Montana, USA. The field performance data collected over the past five years at the BHP-Billiton Iron Ore Pty Ltd., Mt. Whaleback site is also being reduced and analysed.

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# APPENDIX A2

## Evaluation of the Long-Term Performance of Dry Cover Systems

## (Appendix A of the Phase 1 Final Report)

# 1.0 DEFINITION OF THE IDENTIFIED PROCESSES

Discussion with mine site personnel and the completion of an informal questionnaire identified the processes affecting the long-term performance of a dry cover system. The processes were grouped into physical, chemical, and biological processes. A short definition and literature study was completed for each process and documented below.

## *1.1 Physical Processes*

The physical processes affecting the long-term performance of dry cover systems are detailed in this section. Each process involves the response of the cover materials to atmospheric forcing. For example, erosion is a possible response of a dry cover system to energy supplied by a large runoff event likely caused by high rainfall intensity.

### *Erosion*

Erosion is the most likely physical process to affect the integrity of a cover system. Generally, erosion is considered to reduce the cover thickness through rilling and gullying, but it can increase the cover thickness in flat, deposition areas. Rills and gullies reduce the length over which oxygen and water must percolate to reach the underlying waste materials. Erosion can also reduce the ability of the top cover layer or growing medium to sustain vegetation by washing away topsoil and fines, leaving only coarser, rockier soil for establishing vegetation.

Cover systems are designed with the assumption that they will remain intact and the basic physical dimensions and structure of the cover layer will not change. However, when long-term performance is considered, it becomes likely that the surrounding environment in some way will alter the cover system. Erosion has a potentially large effect on the long-term performance of a dry cover system in many climates, but most significantly at sites that experience short duration, high intensity rainfall events.

Erosion can compromise the structural integrity of the cover system by reducing the thickness of the cover layer or removing it entirely. Erosion occurs when soil particles are detached from the soil matrix and then transported from the area. The erosion process is driven by the energy delivered from rainfall striking the soil or surface water or runoff flowing over the soil surface. It is generally agreed that the three main erosion processes are interrill, rill, and gully erosion.

Interrill erosion, also known as sheet erosion, consists of soil particle detachment from the soil matrix by raindrop impact and particle transport by splash and shallow overland sheet flow (Grosh and Jarrett, 1994). Interrill erosion acts evenly over the soil surface, so changes in layer thickness are often not obvious. Smaller soil particles such as silts and clays are most often removed by interrill erosion because the impact of the raindrop hitting the soil surface is adequate to dislodge these smaller particles, but not sufficient to disturb larger sand and gravel sized particles. The removal of fine particles changes the structure of the cover layer at the surface, producing a blocky, open-faced material. This altered material is more likely to allow water to infiltrate across the cover surface.

Rill erosion involves the concentration of runoff flow often caused on natural hillslopes by micro topography or vegetation (Bryan, 2000). The development of rills on a land area can greatly increase the soil erosion rate by concentrating runoff flow resulting in increased flow velocity and turbulence producing more energy to detach and transport material (Gatto, 2000). The runoff flow produces shear forces that act on the soil surface attempting to detach material from the soil matrix. If there is sufficient energy in the rill flow, the soil particles will be entrained or caught up in the flow and transported away. The resistance of the material, defined by its strength and cohesiveness, to these shearing forces will determine the amount of erosion caused by rill flow.

While similar in shape to rills, gullies are much larger erosion features often created by extreme erosion events involving large mass movements of soil. Gullies frequently occur in unconsolidated materials such as desert sands (Archibold *et al.*, 1996) and range in size from shallow channel (approximately 0.3 metres deep), to deep and wide channels.

Gully erosion processes act on the sidewalls and the head cut of gullies. Piest *et al.* (1975) defined gully erosion as a combination of processes including overland (shear) flow or rill flow, slope stability and mass wasting, and channel cleanout. As documented in interrill and rill erosion, the movement of soil from the gully is a function of the sediment transport capacity of runoff and the rate of soil detachment. Overland flow and mass wasting serve to detach material from the gully channel boundary while transport is achieved from energy supplied by gully flow.

Interrill, rill, and gully erosion are affected by the same set of factors. The factors listed in Table A2.1 are believed to be the most important in terms of the erosion of layer of a dry cover system.

**Table A2.1**

Factors affecting the erosion of cover systems.

| Factor | Comments |
|---|---|
| Slope Angle | Erosion rate increases with increased slope angle |
| Slope Length | Erosion rate increases with increased slope length |
| Material Properties | Materials with low cohesion, and small particle size (lower mass) are more easily detached and entrained into water flow |
| Rainfall Intensity | Storm intensity defines the amount of runoff flow available for erosion; increased storm size will bring more erosion. It is not a linear relationship; a single large storm event has the ability to produce the majority of erosion experienced at a site over a long period of time. |
| Vegetation | Vegetation increases the strength of the soil and reduces the energy of runoff flow by creating barriers to flow |
| Base Flow (Antecedent Moisture Condition) | Increased erosion occurs at seepage faces due to the lower strength of the saturated material as compared to the unsaturated material |

Each of the factors listed in Table A2.1 must be considered when evaluating the risk of interrill, rill, and gully erosion on the cover system. The factors or combination of factors might have a varying influence on the amount of erosion experienced at a given site. For instance, there might be two areas on the mine site that have similar slope angles and slope lengths, but one slope generally experiences less erosion. Possibly one slope has more vegetation, or does not have seepage flow emanating from its base, or does not have accumulated flow over-topping the crest, thus reducing the erosion rate.

The following questions should be considered when determining the potential impact of erosion on the long-term performance of the cover system.

- Are there long, unbroken slopes on the cover system?
- What is the angle of these slopes?
- Is the vegetation established on the slope surface? What is the percentage of surface coverage?
- Are there any visible signs of erosion such as rill and gullies on the slope or debris deltas at the base of the slope?
- Do the debris deltas consist of well-graded erosion material or poorly-graded material? What is the size of the poorly-graded material (Fine materials indicate interrill or rill erosion, while well-graded materials suggest gully erosion)?
- Are there visible signs of seepage at the base of any slopes?
- Are high intensity rain events common at the site? Have they occurred in recent memory and what was their effect on erosion of the cover system? Has an extreme storm event such as the 100-year return period storm occurred in recent memory? What was its effect?
- Are erosion control structures in place on the site? Are they functioning properly?
- Is there any accumulated runoff flow overtopping the crest of the slope?

### *Slope Instability*

Erosion and slope stability are often evaluated concurrently when long-term performance of a dry cover system is considered. Slope instability is the mass movement of the entire slope surface; destroying the integrity of the cover system or exposing the underlying waste material. Koerner and Daniel (1997) identified the three driving forces leading to slope instability as gravitational, seepage, and seismic forces.

Gravitational forces become an issue when the cover material is placed on a slope. A component of the downward gravitational pull will act to “push” the cover material down the slope. Seepage forces produce high pore water pressures in the materials at the base of slopes. Both gravitational and seepage forces act to increase the shear stress being applied to the cover material. The shear strength of the material counteracts these forces. The shear strength equation presented by Fredlund and Rahardjo, (1993), known as the Mohr-Coloumb equation, is:

$$t = (s - u) \cdot \tan f^{/} + c \qquad \text{[A2.1]},$$

where: τ = shear strength;
σ = total stress;
u = pore water pressure;
ϕ' = effective soil friction angle; and
c = cohesion strength.

Seismic forces are created by earthquakes or large-scale movement of the earth's tectonic plates and must be considered in an area with the potential for earthquakes.

Often the driving forces leading to slope instability are evaluated using a commercially available limit equilibrium analysis model.

The following questions should be considered when determining the potential impact of slope instability on the long-term performance of a dry cover system.

- Is the cover system installed on a slope? If so, what is the slope angle or inclination of the cover material?
- Has slope stability modelling been completed on the waste and cover material layers?
- Are there visible signs of seepage at the base of any slopes?
- What are the pore-water pressures within and underlying the cover material?
- Are earthquakes a potential hazard at the mine site? If so, what is the hazard classification for the mine site area? (Low, Moderate, High)

### *Wet / Dry Cycling*

Wet / dry cycling causes shrinkage and swelling of fine textured materials, which can be of considerable significance from the perspective of cover system integrity. Shrinkage cracks occur locally when the capillary pressures exceed the cohesion or the tensile strength of the soil. These cracks, part of the clay macrostructure, can significantly influence the overall performance of a soil cover by altering the hydrogeologic and diffusion characteristics of the cover material.

Shrinkage and swelling involve particle rearrangement. Shrinkage is rapid, and is complete when the decrease in water content is complete. Swelling, however, is a slow process, occurring in the field over several months or years. The process of shrinkage and swelling is not completely reversible; the soil will always possess a "memory" of its stress history and will show the effects of previous wet / dry cycles.

Shrinkage and drying cracks in dry climates are caused by evaporation from the surface and lowering of the ground water table. Desiccation of soil by vegetation during temporary dry spells in otherwise humid climates can also lead to cracking. The soil tends to increase in volume, or swell, once the climate changes and the soils have access to water again.

The presence of cracks in the cover system can potentially have a significant influence on the hydrologic performance of the cover system. Desiccation of the cover material consolidates the matrix and increases the volume of macro-pores and cracks, which decreases the saturated hydraulic conductivity within the matrix and increases it within the total soil volume. Cracking of the cover material can then result in high potential infiltration rates and storage capacities. Capillary rise from the water table and evapotranspiration may then be hampered by low hydraulic conductivities. The overall potential result is that part of the precipitation flows through shrinkage cracks to the subsoil layers, thus bypassing the matrix of the dry cover system material.

### *Freeze / Thaw Cycling*

Freeze / thaw cycling has an impact on the saturated hydraulic conductivity and moisture retention characteristics of soil covers. During freezing periods, water is drawn up from the soil to the freezing front leading to ice lenses within the cover material. The subsequent thaw of the material will decrease the material density as well as increase the water content and void ratio of the material, ultimately leading to an increase in the saturated hydraulic conductivity. Wong and Haug (1991) observed that the hydraulic conductivity of clay and till liner materials increased as the number of closed system freeze / thaw cycles increased.

Wong and Haug (1991) discussed the effects of freeze / thaw cycling under two types of freezing conditions, an open system and closed system. An open system possesses a constant source of water that can be drawn to the freezing front. If freezing conditions persist, a large ice lens will be produced reducing the density of the soil material subsequent to the material thawing. A closed system does not have a constant source of water; the ice lens is produced from *in situ* water drawn from the soil material itself. This limits the size of the ice lens but causes a redistribution of moisture within the material profile, which can potentially lead to desiccation cracking. Upon thawing, the upper part of the material profile will have an increased void ratio and decreased density due to the ice lens, while the lower part of the profile will have a lower moisture content and increased soil density. Wong and Haug (1991) reported cracking within the soil profile below the freezing front. The cracks within the soil profile can lead to increased hydraulic conductivity as described in the wet / dry cycling section.

Casagrande (1931) identified silt as the material most susceptible to freeze / thaw cycling because silt pores are small enough to induce suction gradients during freezing but are large enough to allow an adequate supply of water to the freezing front. It is generally accepted that soils containing more than 10% of clay-sized particles are susceptible to freeze / thaw cycling.

### *Consolidation / Settlement*

Consolidation and settlement, as with most physical processes, will affect the integrity of the cover system by reducing the thickness of the cover layers. However, with consolidation also comes an increase in the density of the soil matrix, which can alter the saturated hydraulic conductivity and moisture retention characteristics of the material. Consolidation is the physical process of the cover material decreasing in volume from a decrease in the volume of voids within the material. Settlement is the term used to describe the reduction in volume of the cover material.

The process of settlement can change the geometry and drainage patterns of the cover system. Differential settlement can create local recharge and discharge areas on the cover system that were not accounted for in the cover design. Cover systems established on sloped surfaces utilise the slope to help shed water as runoff. This reduces the amount of water available to infiltrate the cover system and the underlying mine waste material. Figure A2.1 shows a conceptual schematic of the runoff flow on the altered sloping surface.

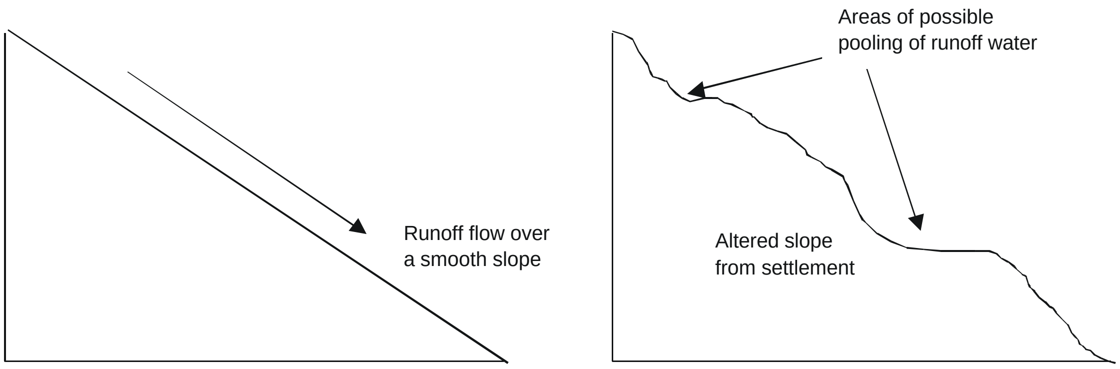

**Figure A2.1** A schematic representation of the effects of differential settlement on the surface hydrology of a slope.

Holtz and Kovacs (1981) reported that a soil compresses because of:

- deformation of soil grains;
- compression of air and water in the voids; and
- the squeezing out of water and air from the voids.

Under the low loading condition associated with a dry cover system, the deformation of soil particles can be considered negligible. An unsaturated soil will have both water and air within the soil matrix, so consolidation will occur as the pore fluids are squeezed out of the soil matrix and the soil particles rearrange into a more compact structure. Due to small variations in the properties of the cover material and the underlying mine waste, some areas will experience settlement while others will not, causing the micro-peaks and valleys conceptually shown in Figure A2.1.

*Extreme Local Climate Events*

Extreme local climate events can potentially impact the integrity of a dry cover system. Extreme Climate events usually refer to storm events causing high rates of precipitation and runoff, leading most often to erosion. However, extreme climate events can also include long periods of drought and desiccation or freezing conditions, which can lead to alterations in the hydraulic conductivity and moisture retention characteristics of the cover materials.

The local climate condition has a large influence on the design of a dry cover system. A climate database is established based on the available weather data associated with the site during the cover design stage. This climate information is often regionally based and not specific to the mine site as many mine sites only possess recent climate information.

Precipitation quantities greater than the historical average, both rainfall and snowfall, can lead to increased percolation through a cover system. Extreme precipitation events have the potential to exceed the storage capabilities of the cover material, saturate the cover system, and produce large net percolation to the underlying waste.

Drought conditions can impact the performance of an oxygen ingress barrier. A cover system designed to limit the transport of oxygen most often depends on the maintenance of a fine textured cover layer in a saturated condition. A period of dry conditions can lead to a reduction in the saturation of this layer, allowing more oxygen to reach the underlying waste. Drought conditions can also lead to desiccation and the cracking of cover layers, particularly those with relatively high fines content. Any established vegetative stands will also be threatened by drought conditions, possibly leading to increased percolation when precipitation does occur.

Extreme climate events have the ability to damage the structure of a dry cover system. For example, erosion events are caused by the delivery of a large amount of erosive energy in a short time period (i.e. an intense precipitation event causing large volumes of runoff).

The following questions should be considered when determining the effect of extreme climate events on the long-term performance of the cover system.

- Is local climate data being collected on the site? What parameters are being recorded?
- How long has the information been collected?
- What climate information was used for the design of the cover system?
- What is the nature of precipitation events at the site? Are intense precipitation events common?
- Is the cover system designed to limit the ingress of oxygen? Is drying and cracking a concern?
- Have climate patterns changed in the last 5-10 years; changes that could be attributed to events such as global warming?
- Has a hydrological study of the site been completed and the large return period storm events estimated?
- What is the largest precipitation event measured at the site? How does it compare to the extreme storm events predicted for the site?

*Brushfires*

The potential impact of brushfires on the integrity of a dry cover system should not be discounted. A brushfire will reduce vegetation, increasing runoff and likely increasing the rate of erosion of the cover system. If evapotranspiration through vegetation is an important component of the cover system design, a brushfire can severely decrease the performance of the cover system. Re-establishment of the vegetation at mine sites in semi-arid and arid climates following a brushfire can be a difficult and lengthy process.

## *1.2 Chemical Processes*

The effect of chemical processes on the long-term performance of a cover system is not as obvious as a physical process such as erosion. Chemical processes have the potential to change the fabric of a cover material. Osmotic consolidation, dispersion, dissolution, acidic hydrolysis, mineralogical consolidation, and sorption are discussed in this section.

### *Osmotic Consolidation*

The process of osmotic consolidation can lead to shrinkage of clayey soil materials, causing cracks and fissures to develop in some cover systems. These openings provide a path for fluids to flow thereby increasing the cover hydraulic conductivity. Barbour (1987) identified two types of osmotic consolidation; namely osmotically induced consolidation and osmotic consolidation. Osmotically induced consolidation results from the release of water due to chemical gradients. Osmotic consolidation results from alterations in clay particle interactions due to changes in pore fluid chemistry.

Osmosis refers to the flow through a semi-permeable membrane that separates high and low concentration solutions. In the case of a soil cover system, the pore fluid surrounding soil material primarily consists of water and dissolved solids. Water is referred to as the ‘solvent’ while the dissolved solids are known as ‘solute’. The clay material acts as a semi-permeable membrane letting the solvent move through at a much faster rate than the solute. There is extensive evidence in laboratory and field studies that clay soils have a semi-permeable nature (Barbour, 1987).

Osmotically induced consolidation arises from chemical differences between the waste material and cover material pore water, creating a chemical gradient. Figure A2.2 illustrates the osmotic process.

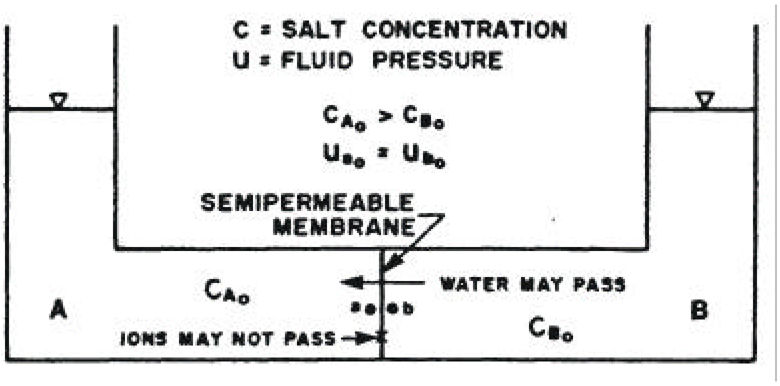

**Figure A2.2** A schematic representation of osmotic flow (from Barbour, 1987).

As chemical equilibrium is desired by the system, actions that assist in equalizing the solute concentrations occur. Solvent from the lower concentration solution moves to the higher concentration fluid in an attempt to balance the chemical gradient. The solute also has a tendency to migrate but the semi-permeable clay layer impedes solute flow. A decrease in pore fluid pressure in the clay develops as the water is removed, resulting in an increase in effective stress and leading to consolidation.

Osmotic consolidation results from alterations in clay particle interactions due to changes in pore fluid chemistry. Barbour (1987) suggests that long-range repulsive forces largely control particle-to-particle interaction. A change in pore fluid concentration can result in changes in these long-range electrostatic forces. The change in pore fluid concentration can cause a reduced thickness of the diffuse double layer. The diffuse double layer refers to the layer of cations established around the clay particle, with increasing cation concentration towards the surface of the clay particle. If cations enter into the clay with a higher valence than the exchangeable ions currently in place (i.e. $Ca^{++}$ for $Na^{+}$), stronger bonds between the clay particles may develop subsequently reducing the space between the clay particles (reducing the diffuse double layer thickness).

The long range electrostatic forces within the soil can be positive or negative. The inter-particle stress due to these physio-chemico interactions is represented by R-A (repulsive stresses – attractive stresses) (Barbour, 1987). These stresses are incorporated into the equation:

$$\sigma^* = \sigma' - (R\text{-}A) \qquad \text{[A2.2]},$$

where: $\sigma^*$ = true effective stress
$\sigma'$ = effective stress
(R-A) = net long-range repulsive stress

The R-A decreases and the true effective stress increases with an increased attraction between clay particles. This increase in effective stress can cause consolidation.

The desire to use clays in cover systems results from their comparatively lower hydraulic conductivity and higher moisture retention. The issue is that these low permeable clay materials are also strongly affected by electrolyte solutions (high salts), which can result in osmotic consolidation. When osmotic or osmotically induced consolidation occurs, cracks and fissures develop, which increases the hydraulic conductivity of the clay material and inhibits the clay layer from controlling percolation into other areas (i.e. to underlying reactive waste material).

Several methods have been formulated to limit the extent of osmotic consolidation including:

- Minimising the clay content of the layers of the cover material;
- Using a high level of effective stress – apply sufficient confinement of the clay so that fractures and cracks are not able to develop (Haug *et al*., 1988); and
- Chemically alter the soil prior to use – reduce the potential for volume change (i.e. pre-treat cover material) (Haug *et al*., 1988).

The following questions should be considered when determining the potential impact of osmotic consolidation on the long-term performance of a dry cover system.

- Does the cover system design include clayey soils?
- What is the chemistry of the pore fluid in the waste material and cover materials?
- Will a chemical gradient develop thereby inducing osmotic consolidation?
- What is the potential for a change in the pore fluid chemistry in the clay material, thus leasing to osmotic consolidation?
- In the future, could the pore fluid chemistry change?
- What can be done to reduce the effects of osmotic flow and subsequent consolidation?

*Dispersion / Erosion*

The dispersion of clay minerals and subsequent susceptibility to erosion should be considered in evaluating the long-term performance of a cover system possessing a clayey material. Chemical processes can influence the arrangement of clay particles and may lead to the development of dispersed clay. Dispersed clays are prone to increased rates of erosion. Figure A2.3 shows the physical arrangement of dispersed and flocculated clays.

The stability of clay materials is dependent upon the arrangement of the soil particles. Important factors in determining clay stability include pore-water ion concentration, the type of clay minerals present, and the exchangeable cations present.

Electrical imbalances in the molecular configuration of clays provide them with an “inherent” negative charge. The negatively charged outer surface of clay attracts cations from the pore fluid solution in an attempt to gain electrical neutrality. A diffuse layer of cations is established around the clay particle, with increasing cation concentration towards the surface of the clay particle. This is termed as the ‘diffuse double layer’ around the clay particle. The cations are “held” to the clay particles due to electrostatic forces but can be removed from the clay particle in response the attractive forces of stronger cations. Consequently, these cations are called exchangeable cations.

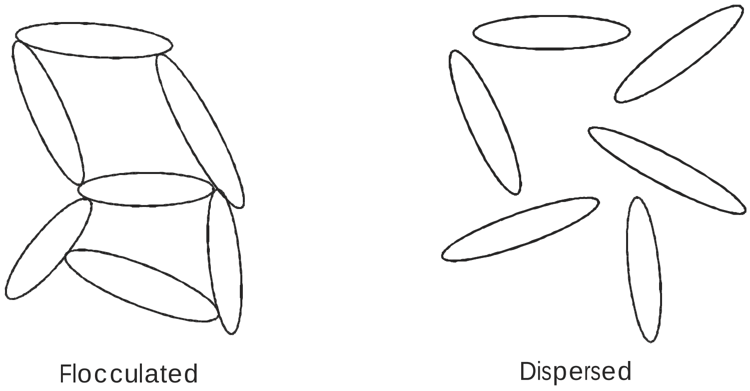

**Figure A2.3** Flocculated and dispersed arrangement of clay particles.

The strength and size of the ‘diffuse double layer’ depends partly upon the type of exchangeable cations held onto the clay minerals. Generally, the higher the charge of the exchangeable cation, the more tightly the clay particles are held together and hence, the higher the clay stability. With an increased charge of the exchangeable cation, less swelling / shrinkage occurs because the clay particles are bound more closely together and pore fluid / exchangeable ions are less capable of entering. Morin (1993) gives the following cation stability order.

$$Al^{+++} > Fe^{+++} > Cu^{++} > Ca^{++} > Mg^{++} > K^{+} > Na^{+}.$$

As seen from the sequence of cations shown above, divalent cations seem to reduce the thickness of the double layer more than monovalent cations. Calcium (Ca) cations have a $^{+}2$ charge while sodium (Na) cations have a $^{+}1$ charge. Calcium cations would hold the clay particles more tightly together than the sodium cations resulting in a smaller double layer. A reduction in the diffuse double layer thickness produces a more flocculated, or “less dispersed” material, whereas an increase in the diffuse double layer thickness results in a more dispersed clay. A higher concentration of salts in solution (more electrostatic forces holding clay particles together) also causes a smaller diffuse double layer.

In particular, potential for dispersion of clay particles is sensitive to sodium ion adsorption by the clay particles and the ion concentration of the permeating fluid. The sodium adsorption ratio (SAR) is used to estimate the susceptibility of a soil to dispersion, and is determined from the following relationship:

$$SAR = \frac{Na^{+}}{\left[\dfrac{(Ca^{++} + Mg^{++})^{1/2}}{1.41}\right]} \tag{A2.3}$$

Work completed by Toride *et al.* (2001) demonstrates that the hydraulic conductivity of a clay-sand mixture strongly depends on the concentration of soil solution and the exchangeable ions it contains. Figure A2.4 shows how an increased SAR results in a lower hydraulic conductivity and hence, a more highly dispersed soil. Figure A2.4 also shows that increased pore fluid concentration results in a higher soil hydraulic conductivity and therefore, more flocculation.

The dispersion of clay particles results in the clogging up of the pore spaces and swelling of the clay leading to a decrease in hydraulic conductivity. Increases in ion concentration reduce the double layer thickness, produce less dispersion, and generate a higher hydraulic conductivity.

The result of dispersion is an increased susceptibility of the clay to erosion. Dispersed clays have weaker bonds between the clay particles, meaning it takes less energy to break apart bonds between the clay particles. The decreased hydraulic conductivity of dispersive clays leads to increased amounts of runoff during intense rainfall events contributing to increased erosion of the soil layer.

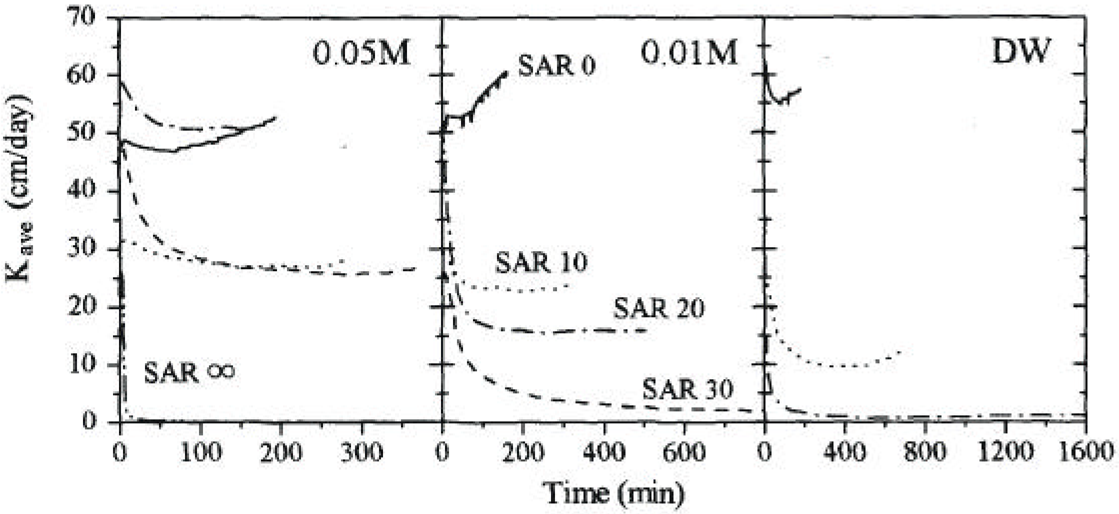

**Figure A2.4** Hydraulic conductivity vs. time for varying solution concentration and SAR for a clay-sand mixture (from Toride *et al.*, 2001).

Smectite clays (montmorillonite) are often used in cover systems because of their low hydraulic conductivity. The significant swelling that occurs in smectitic clays results from weak bonding of the clay plates. The weak bonds allow abundant water and exchangeable cations to enter in between the clay plates and may lead to dispersion. Illitic soils are also quite susceptible to dispersion of clay particles (Morin, 1993).

The following questions should be considered when determining the potential impact of dispersion / erosion on the long-term performance of a dry cover system.

- Are clayey soils present in the cover system?
- If clayey soils are present, are they dispersive clays?
- Will leachate provide cations into the clay cover layer that may cause dispersion of clays?

*Dissolution / Precipitation*

The chemical processes of dissolution and precipitation may affect the long-term performance of cover systems. Dissolution removes solid material from the soil while precipitation adds solid material to the soil.

Sparks (1999) suggests there are two steps which precipitation and dissolution reactions must undergo. Firstly, ions must be transported to or from the mineral surface via the aqueous phase. Secondly, reactions must occur on the surface of the mineral grains. These reactions will incorporate or remove the constituent ions from the crystal lattice.

Dissolution occurs when a state of under saturation exists in the pore fluid solution. Dissolution involves the dissolving of a solid into separate components. Fluid carries the dissolved material away and voids are left in the material's place. In the case of a soil cover system, the chemicals in fluid entering the cover system may dissolve the cover material. This can result in piping and void spaces within the cover. Carbonic acid is a common acid involved in dissolution reactions:

rain + carbon dioxide (from air) → carbonic acid (reacts with rocks)

$$H_2O + CO_2 \rightarrow H_2CO_3. \qquad [A2.4]$$

Carbonic acid dissolves certain rocks and minerals such as limestone and marble. Most precipitation is slightly acidic with an average pH slightly less than 7. Highly acidic substances have a pH of 1 while neutral substances have a pH of 7. Mine waste with acidic pore-fluid have a strong dissolution effect on carbonate phases such as calcite, whereas quartz and amorphous silica are soluble in strong alkaline solutions.

Precipitation occurs as a result of over saturation of solute within a solution. Precipitation reactions involve the formation of an insoluble product, or precipitate, from solution.

Whether precipitation or dissolution reactions will occur depends upon the solubility of the solute. Using solubility rules and solubility products, predictions can be made as to whether precipitates will form when solutions are mixed or when soluble compounds are added to a solution (Chang, 1998).

Leeder (1999) describes an example of how to determine if an aqueous solution will dissolve certain minerals or precipitate minerals. Laboratory experiments have been performed which provide the maximum concentrations (saturated concentration) of solute that a solution can hold. Concentrations above this value result in over saturation and subsequent precipitation of solute. Concentrations below this value result in under saturation and if soluble minerals are present, dissolution can occur.

The following questions should be considered when determining the potential impact of dissolution / precipitation on the long-term performance of a dry cover system

- What minerals are present in the cover material?
- Are these minerals soluble?
- If they are soluble, is the aqueous solution under saturated or oversaturated?
- Will dissolution result in void spaces and result in the failure of the cover system?
- Will precipitated minerals compromise the effectiveness of the cover system?

*Acidic Hydrolysis*

Hydrolysis is a reaction that involves a component of water; acidic hydrolysis involves reactions with acids in aqueous solution. In a cover system, minerals in the cover materials may react with acids in the pore fluid from the underlying waste, thus forming new minerals.

Water molecules separate into $H^+$ and $OH^-$ ions. In acidic hydrolysis, an acid such as sulphuric acid ($H_2SO_4$) or water ($H_2O$) gives up a proton ($H^+$) (depending on the acid, maybe more than one proton) and picks up a cation from surrounding mineral grains. Minerals in the soil cover that contain ions with a strong attraction to hydrogen ions are susceptible to reacting with an acid.

These minerals attract protons and can exchange cations with the acids in solution. The new minerals formed may or may not compromise the integrity of the soil cover.

A common example is the hydrolysis of feldspar. Feldspar is one of the most abundant minerals on the earth's surface. It can react with water to form a secondary mineral such as kaolinite clay. The integrity of the cover system may be compromised because clay is more easily weathered than the feldspar, which existed previous to the hydrolysis reaction.

feldspar + hydrogen ions (acid) + water ? clay + dissolved ions

$$4KAlSi_3O_8 + 4H^+ + 2H_2O \ ? \ Al_4Si_4O_{10}(OH)_8 + 4K^+ + 8SiO_2 \qquad [A2.5]$$

Strong acids increase the solubility of carbonates, silicates, phosphates and sulphides because of the affinity of these minerals for hydrogen ions, which are more abundant in strong acids (Faure, 1998).

The following questions should be considered when determining the potential impact of acidic hydrolysis on the long-term performance of a cover system.

- What type of fluids will potentially be interacting with the cover materials? What is the solution chemical composition? Is the fluid acidic or will it be in the future?
- What is the chemical composition of the materials within the cover material?
- What are the potential new minerals that could form? How will they affect the integrity of the cover system?

### *Mineralogical Consolidation*

Mineralogical consolidation may occur as a result of changes in the mineralogy of soil particles. This could involve a change in crystal structure or chemical composition of minerals. Long-term cover performance may be affected by the characteristics of the new mineral(s). If the newly formed mineral(s) causes consolidation, cracks or fissures may develop, thus reducing the effectiveness of the cover system.

A common example of mineralogical transformation is the change of sodium montmorillonite to calcium montmorillonite or potassium illite. This can happen via the interaction of solutions with montmorillonite. This change results in volume decrease and decreased swelling potential.

### *Sorption*

Dissolved minerals within groundwater can be sorbed onto the surfaces of mineral grains in the soil cover. Sorption removes solute from the solution or causes retardation of solute movement. Sorption is assumed to be a reversible reaction. The sorption of minerals changes the chemistry of the cover material and may affect its long-term performance. Sorbed minerals may assist in the development of osmotic consolidation or dispersion/erosion processes.

The sorption process includes adsorption, ion exchange, chemisorption, and absorption (Fetter, 1999). Adsorption refers to the physical adherence or bonding of ions and molecules onto surfaces of another molecule. Ion exchange is a reversible process involving the exchange of ions between a solid and a liquid. Electrostatic forces are the controlling factor in the exchange of ions. Generally, cation affinity for exchange sites increases with increased ionic charge. Ion exchange is strongly related to surface area and does not result in a substantial change in the structure of the solid. Chemisorption involves chemical bonding of adsorbed molecules to a surface. Absorption refers to the incorporation of solute into the crystal structure of minerals grains.

Sorption isotherms (Figure A2.5) are used to estimate the amount of sorption for certain concentrations. All isotherms eventually level off because the capacity of the soil to store minerals is limited. Mineral surfaces have a limited amount of space for ion bonding.

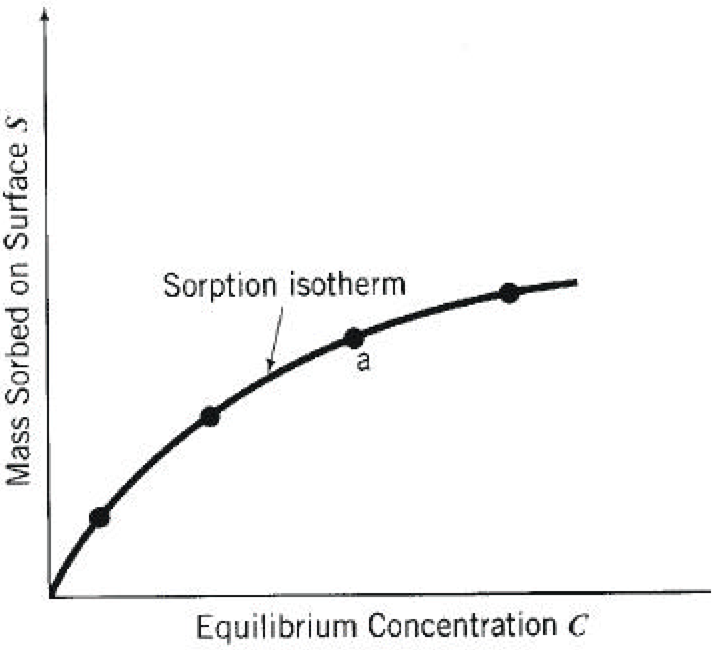

**Figure A2.5** Sample isotherm (from Domenico & Schwartz, 1998).

## 1.3 Biological Processes

The biological processes identified and researched in this report include the effect of root penetration and burrowing animals.

*Root Penetration*

Root penetration is generally thought to affect the integrity of the cover system and decrease the long-term performance of a dry cover system. Roots and plant biomass create macropores within the soil structure, allowing water to more easily infiltrate into the cover material and down to the underlying waste material. Koerner and Daniel (1997) summarise the damage that plant roots can have as follows:

- roots may penetrate the barrier layer of a cover system;
- decomposing roots leave channels for movement of water and vapour;
- roots may dry clayey layers, causing shrinking and cracking; and
- roots may enter the waste material and intake salts and undesired metals upward into the cover system and the soil surface.

For these reasons, grass and shrubs are often used to vegetate the surface of a dry cover system. The shrubs and grass have shallow rooting systems that do not reach into the barrier layers of the cover system.

Research on the rooting depths and biomass distribution of tree species has showed that 80% of tree roots and up to 99% of the tree biomass stay within 0.6 m of the soil surface, indicating that many trees have shallow, lateral rooting systems. Active plant roots will plug the macropores of the soil structure and consolidate the ground around them, leading to a decrease in the soil hydraulic conductivity in the vicinity of vegetation.

The following questions should be considered when determining the potential impact of root penetration on the long-term performance of a dry cover system.

- Is transpiration through vegetation an important design characteristic of the cover system?
- What are the native vegetation species adjacent to the cover system?
- What is the rooting pattern of the native vegetation?

*Burrowing Animals*

Burrowing animals also influence the integrity of the cover system. Koerner and Daniel (1997) summarised the effects that burrowing animals can have on the long-term performance of a cover system:

- the animals may burrow through the cover, resulting in direct channels for movement of water, vapour, roots, and other animals;
- they may carry waste material directly to the surface during excavation;
- animals construct their burrows for natural ventilation which may dry the soil and decrease water intrusion; and
- by working the soil and transporting seeds, they may hasten establishment of deep-rooted plants on the cover.

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# APPENDIX A3

## Evaluation of the Long-Term Performance of Dry Cover Systems

## (Appendix B of the Phase 1 Final Report)

# 1.0 COVER PERFORMANCE NUMERICAL MODELS

This appendix presents detailed information concerning the numerical models investigated in the INAP Phase 1 project.

## *1.1 Description of the Numerical Models*

A user manual and/or an evaluation or full working copy of the software was collected for each of the seven numerical models listed above. The solution method and the capabilities of each model were examined. A description of each, adapted from the accompanying literature, is presented below.

*Hydrologic Evaluation of Landfill Performance* (from Schroeder *et al*., 1994)

Hydrologic Evaluation of Landfill Performance (HELP) is a layered, water budget model for hydrologic evaluation of landfill performance developed at the U.S. Army Engineer Waterways Experiment Station under a cooperative agreement with the U.S. Environmental Protection Agency (EPA). The primary purpose of the model is to assist in the comparison of design alternatives as judged by their water balances. The model is sufficiently sophisticated to consider all of the principal design parameters including vegetation, soil types, geosynthetic materials, initial moisture conditions, thicknesses, slopes, and drain spacing as well as climate effects. Landfill systems including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low hydraulic conductivity barrier soils, and synthetic geomembrane liners may be modelled.

In the model, precipitation is partitioned into surface storage, runoff, percolation, soil moisture storage, evapotranspiration, and lateral drainage using a quasi-two-dimensional approach. The runoff is computed using the runoff curve number method and percolation by Darcy's law applied to unsaturated conditions. Lateral drainage is computed from a modified non-linearised Boussinesq equation. Evapotranspiration is calculated using a modified Penman method. Furthermore, the HELP model requires as design specifications the number of layers and their description, including type, thickness, slope, and maximum lateral distance to a drain. The HELP model maintains a climatologic database and default soil characteristics for 21 soils. Landfill systems modelled by HELP include various combinations of vegetation, cover soils, waste cells, special drainage layers, and impermeable barrier soils, as well as synthetic membrane liners and drainage nets. The model includes features to simulate frozen soil effects, leachate recirculation and subsurface inflow, leakage through liners, and snowmelt.

*UNSAT-H (from Fayer, 2000)*

UNSAT-H, developed at the Pacific Northwest Laboratory, is a model for calculating water and heat flow in unsaturated media. The code is primarily used to predict deep drainage as a function of such environmental conditions as climate, soil type, and vegetation. UNSAT-H is a one-dimensional model that simulates the dynamic processes of infiltration, drainage, redistribution, surface evaporation, and uptake of water from soil by plants.

UNSAT-H uses a finite-difference approximation to solve the one-dimensional vertical form of Richard's equation, which governs unsaturated moisture movement. UNSAT-H was designed for use in water balance studies and has capabilities to estimate evaporation resulting from meteorological surface conditions and transpiration from plants. Parameters required for each material type are saturated hydraulic conductivity, volumetric moisture content at saturation, irreducible moisture content, air entry head, and inverse pore size distribution index.

*SWIM (from Verburg et al., 1999)*

SWIM is a software package developed within the CSIRO Division of Soils (Australia) for simulating water infiltration and movement in soils. The SWIM model is based on a numerical solution of the Richards' equation and the advection-dispersion equation. The SWIM model is a one-dimensional model that is capable of analysing multi-layered soil profiles assuming each soil layer is homogenous. It can be used to simulate runoff, infiltration, redistribution, solute transport and redistribution of solutes, plant uptake and transpiration, soil evaporation, deep drainage, and leaching. Soil water and solute transport properties, initial conditions, and time dependent boundary conditions (i.e. precipitation, evaporative demand, solute input) need to be supplied by the user in order to run the model.

*SoilCover (from MEND, 1996)*

SoilCover is a one-dimensional finite element package, developed by the Geotechnical Engineering Group at the University of Saskatchewan, Canada, which models transient water and heat transport in a soil profile. The model uses a physically based method for predicting the exchange of water and energy between the atmosphere and a soil surface. The theory is based on the well-known principles of Darcy's and Fick's Laws that describe the flow of liquid water and water vapour, and Fourier's Law to describe conductive heat flow in the soil profile below the soil/atmosphere boundary. SoilCover predicts the evaporative flux from a saturated or an unsaturated soil surface on the basis of atmospheric conditions, vegetation cover, and soil properties and conditions. A modified Penman formulation (Wilson, 1990) is used to compute the actual rate of evaporation from the soil/atmosphere boundary.

*VS-2D (from Hsieh et al., 2000)*

VS-2D is a two-dimensional finite difference simulator for cross-sectional or cylindrical variably saturated flow in porous media. VS-2DT is a solute transport module to be used with VS-2D. It is based on a finite difference approximation of the advection-dispersion equation for a single species. Program options include first-order decay, equilibrium adsorption described by Freundlich or Langmuir isotherms, and ion-exchange.

Nonlinear boundary conditions treated by the code include infiltration, evaporation, and seepage faces. Extraction by plant roots is included as a nonlinear sink term. Initial conditions may be input as moisture content or pressure head by blocks defined by row and column, or in a formatted file by cell. An equilibrium profile may be specified above a user-defined free water surface. Infiltration may be simulated by specified flux nodes, specified pressure nodes, or a ponding function where the user specifies rainfall rate and ponding height. Evaporation is simulated by a user-defined potential evapotranspiration, pressure potential of the atmosphere, and surface resistance. Evapotranspiration is simulated through the use of user-defined potential evapotranspiration, minimum root pressure, depth of rooting, and root activity at the bottom of the root zone and land surface.

*HYDRUS-2D (from HYDRUS-2D v2.05 Online Help, 1996)*

HYDRUS-2D, developed by the U.S. Salinity Laboratory at the U.S. Department of Agriculture, may be used to simulate two-dimensional water flow, heat transport, and the movement of solutes involved in consecutive first-order decay reactions in variably-saturated soils. An interactive graphics-based user interface HYDRUS-2D was developed in support of the HYDRUS2 computer model. HYDRUS-2D uses a finite element solution of the Richards' equation for simulating variably-saturated flow and Fickian-based convection-dispersion equations for heat and solute transport. The water flow equation incorporates a sink term to account for water uptake by plant roots. The heat transport equations consider transport due to conduction and convection with flowing water. The solute transport equations consider convective-dispersive transport in the liquid phase, as well as diffusion in the gaseous phase. The transport equations also include provisions for non-linear, non-equilibrium reactions between the solid and liquid phases, linear equilibrium reactions between the liquid and gaseous phases, and zero-order production. The transport equations also include provisions for two-first-order degradation reactions, one, which is independent of other solutes, and a second that provides coupling between solutes involved in the sequential first-order decay reactions.

*VADOSE/W (from VADOSE/W Online Help v1.01, 2002)*

VADOSE/W, developed by Geo-Slope International, uses the state of the art formulation first presented in the 1D SoilCover model and modified for 2D analysis. The model uses numerical solutions of Darcy's Law and Fick's Law to simulate water, heat, and solute transport through variably-saturated media. VADOSE/W uses the Penman-Wilson method (Wilson, 1990 and Wilson *et al.,* 1994) for computing actual evaporation (AE) at the soil surface such that AE is computed as a varying function of potential evaporation dependent on soil pore-water pressure and temperature conditions, and independent of soil type and drying history. The coupled heat and mass equations with vapor flow in VADOSE/W permit the necessary parameters at the soil surface to be available for use in the Penman-Wilson method.

VADOSE/W accounts for precipitation, evaporation, snow accumulation / melt / runoff, ground water seepage, ground freezing and thawing, ground vapor flow, and actual transpiration from plants. All parameters can be applied in unique ways dependent on site requirements. The program comes with a built in soil property database as well as full year detailed climate data for over 40 sites worldwide. Climate data can be scaled to suite specific conditions or site-specific climate data can be entered.

## 1.2 Comparison of the Key Functions of the Numerical Models

The seven numerical models evaluated included two text-based input and output models, one DOS-based program, and four Windows interface models. Considerable time was spent working with each model to examine the numerical solutions and learn the input requirements and output capabilities of the programs. It was not possible, however, to learn all the nuances and capabilities of each of the numerical models.

Each of the models function extremely well for the purpose in which they were developed. Each is well programmed and rigorously tested to ensure accuracy. This exercise was not an analysis of the models and was not meant to critically review the work of others. The models were not scored or rated, rather they were examined to identify which model is best suited to predict the long-term performance of cover systems. Eight key functions, relating to the models ability to predict long-term performance, were identified and then each was evaluated. The identified key functions are:

- Formulation of numerical model;
- Heat transport capabilities;
- Solute transport capabilities;
- Specified boundary conditions;
- Surface boundary conditions;
- Evapotranspiration;
- Graphical interface and ease of use; and
- Observation nodes

The remainder of this section contains a review of each model in terms of the identified key functions.

*Formulation of Numerical Model*

All of the numerical models, with the exception of the HELP model, use a numerical solution of the Richard's equation to model the water and vapour flow. The HELP model does not incorporate a mesh like the two-dimensional models (VADOSE/W, HYDRUS-2D, VS-2D) or specify nodes within the profile like the one-dimensional models (SoilCover, UNSAT-H, SWIM). Rather, the HELP model specifies each material as a layer. HELP is pseudo two-dimensional; it assumes that all vertical drainage is by gravity. Percolation through soil liners is modelled by Darcy's law, assuming free drainage from the bottom of the liner. The liners are assumed to be saturated at all times, but leakage occurs only when the soil moisture of the layer above the liner is greater than the field capacity. The program assumes that an average hydraulic head can be computed from the soil moisture and that this head is applied over the entire surface of the liner. As such, when the liner is leaking, the entire liner is leaking at the same rate. The liners are assumed to be homogeneous and temporally uniform (Schroeder *et al.*, 1994).

*Heat Transport Capabilities*

Heat transport must be considered in a coupled soil-atmosphere model. Heat energy supplied by the sun is used first in evaporation and transpiration at the cover surface. However, not all of the potential energy for evapotranspiration is used if the soil surface is in an unsaturated condition. The remaining heat energy will increase the temperature of the ground surface in order to ensure a proper balance of the heat energy. The temperature within the soil profile will have an effect on the percolation of water through the profile, most notably on the flow of water vapour. All of the numerical models, except the HELP model, have the ability to model the flow of heat energy.

*Solute Transport Capabilities*

Solute transport should be considered in an analysis of cover system performance. Dry cover systems are generally implemented over sulphide-bearing waste materials to reduce the amount of oxygen and water available for the acid generation process. However, no cover is impermeable and therefore, some degree of acidic drainage will develop in the potentially acid-generating waste. A model predicting the long-term performance of a cover system will have to consider the movement of oxygen and the products of chemical reactions within the cover and waste materials. This also includes the upward migration of salts that can have an adverse impact on vegetation growth.

The SWIM, VS-2D, and HYDRUS-2D models each have the capability to predict the movement of solutes. The HELP, UNSAT-H, SoilCover, and VADOSE/W models are not formulated to predict the movement of solutes. However, SoilCover incorporates a module that calculates the diffusive transport of oxygen through the cover profile. VADOSE/W does not include solute transport, but apparently it is to be added in subsequent releases of the program. Currently, the output from the

VADOSE/W program can be directly input to CTRAN/W, a rigorous contaminant transport model distributed by GeoSlope International Ltd.

*Specified Boundary Conditions*

The ability to specify boundary conditions is critical to produce an accurate representative model of the field condition of the cover system. When modelling a finite area of space, the four sides of a two-dimensional model or the top and bottom of a one-dimensional model must incorporate the same condition that exists within the area being examined. The hydraulic head or flux condition of the boundary must be specified and for best accuracy should be variable and reviewable. Each of the models, with the exception of HELP, allow the user to implement hydraulic head or flux boundaries.

In a one-dimensional model, boundary conditions are required only at the top and bottom nodes. It is important that the top node is variable to simulate the changing weather conditions at the site, and the bottom node has a constant head or constant flux condition. The top node or boundary surface condition is discussed in the following section. UNSAT-H, SWIM, and SoilCover each allow for a constant head or constant flux bottom boundary condition.

Boundary conditions are required for all the boundary nodes in a two-dimensional analysis. Similar to the one-dimensional models, the surface boundary condition is extremely important while the sides and bottom surfaces can often be constant head or constant flux. Simulating flow in a two-dimensional analysis also requires the use of reviewable boundary nodes that can oscillate between a head and flux condition. An example of this might be a boundary node set to a zero flux (no flow) boundary condition. If the model calculates a buildup of head behind the boundary node then a flux calculated from the surrounding nodal head values exits the model during that time period. Both HYDRUS-2D and VADOSE/W include the reviewable boundary conditions while the VS-2D model does not.

*Surface Boundary Condition*

Perhaps the most important component of the model is the manner in which the surface boundary condition is represented. As discussed, there are three components within the cover system to consider, the unsaturated and saturated zones and the soil-atmosphere interface. Each of these models calculates flow through saturated and unsaturated media and the soil boundary condition will simulate the soil-atmosphere interface. This condition is driven by the interaction of the climate with the soil profile and is heavily influenced by the growth of vegetation. The flow of heat and water in and out of the model can be calculated using climate data such as temperature, precipitation and net radiation. Additional evapotranspiration affecting the percolation of water within the cover system is driven by the type, coverage, and activity of vegetation. Both the site climate conditions and vegetation conditions must be represented to produce an accurate surface condition. Climate data and vegetation are discussed separately in the subsections below.

### User-Defined Climate Data

User-defined data allows for the input of daily climate values for precipitation, net radiation, temperature, wind speed, and relative humidity. These are the most important climate parameters used to calculate the evaporative and precipitation flux.

The HELP model allows for input of daily weather data including precipitation, solar radiation, and temperature. The program contains an extensive US database and a module to generate daily weather data. Two options are available for UNSAT-H simulations. Daily potential evapotranspiration values or a full set of climate data including temperature, dew point, solar radiation, wind speed, cloud cover, and precipitation can be inputted. The SWIM model only considers daily precipitation and potential evapotranspiration values. The SoilCover model also has two climate data input options. The detailed climate option includes temperature, relative humidity, net radiation, wind speed, and precipitation, while the limited climate option requires temperature, relative humidity, potential evaporation, and precipitation.

Both the VS-2D and HYDRUS-2D models allow only the input of precipitation and potential evaporation. While daily values can be defined in HYDRUS-2D, VS-2D uses recharge periods of constant precipitation and potential evaporation. To simulate a daily climate cycle, a separate recharge period must be specified for each day of the cycle. Air temperature, relative humidity, wind speed, and precipitation are the minimum inputs for the VADOSE/W model. The program can estimate potential evaporation with this data or daily net radiation or pan evaporation values can be entered.

### Vegetation

The influence of vegetation on the performance of a cover system is calculated in a similar manner by each of the models. Modelling of vegetation is based on an empirical formula using the leaf area index (LAI). The LAI is used to partition the total energy from the sun into the amount of net radiation intercepted by the surface vegetation for plant transpiration and the soil surface for direct evaporation.

Vegetation is represented within the HELP, UNSAT-H, SoilCover, and VADOSE/W models in the same manner. A user-defined, variable LAI is inputted to partition the potential evaporation energy striking the ground surface. Additionally, moisture limiting and plant wilting values, which define the effect of matric suction on transpiration, are required. At matric suction values below the moisture limiting point, the actual transpiration rate will be equal to the potential transpiration rate, with the latter defined by the LAI. Actual transpiration decreases as the matric suction increases until it becomes zero at the plant wilting point. Lack of available plant water causes most plants to biologically react by closing stoma, reducing transpiration, and reducing metabolic reactions. Under continued and increasing stress the plant will reach its wilting point resulting in leaf drop and tissue death (Saxton, 1982). Root distribution and depth define the amount of actual transpiration for each node within the model. Each of the models requires the input of a root depth or evaporative zone depth.

Vegetation within the SWIM model is similar to the models discussed above except SWIM allows the consideration of four different vegetation types for each simulation. Actual transpiration is dependent on root density and size as well as the soil resistance. The vegetation parameters required for the VS-2D model are much simpler, requiring only the input of a root activity. Plant transpiration in the HYDRUS-2D model is also simulated in relatively simple manner. A maximum and minimum transpiration rate is inputted as well as moisture limiting and plant wilting matric suction values. The actual transpiration rate is at the maximum value when matric suction is below the moisture limiting value and is zero when the matric suction is greater than the plant wilting value.

*Evapotranspiration*

Discussion of the numerical formulation of each of the seven models would be a complicated and lengthy process. Within this report, the required inputs rather than the model theory have been described. However, evapotranspiration is the most important component of the soil water interface. It defines the surface flux or infiltrative flux that drives the water percolation, heat flow, and solute transport within the cover profile.

The evapotranspiration theory of the SoilCover and VADOSE/W models is discussed below. The calculation of the actual evaporation and actual transpiration rates from a cover system is based on the inputted climate data and the soil stress state. The discussion is adapted almost entirely from the VADOSE/W online help module (VADOSE/W Online Help v1.01, 2002). The remaining models calculate evapotranspiration in a similar way; the largest difference being the way the model derives actual evaporation from the potential evaporation.

Evaporative flux modelling has been limited to methods that predict the unit flux evaporation rate based on a potential evaporation (PE) value. This PE value is computed based on some form of a Dalton type equation such that PE is a function of a turbulence mixing parameter multiplied by the difference between the saturation vapor pressure at the ground surface and that in the air above the ground. This approach forms the basis for the widely used Penman (1948) method, which assumes the ground surface is always saturated.

The rate of actual evaporation (AE) is only equal to the PE rate when the soil is saturated; the AE rate starts to decrease as the soil de-saturates at the surface. Wilson (1990) plotted AE/PE versus time, water content and soil water pressure for three very different soil types (silt, sand and plastic clay) under the same atmospheric climate conditions. Wilson (1990) showed that if the ratio AE/PE is plotted versus matric suction, the AE/PE curves for all soil types plot directly on top of each other. Figure A3.1 shows the AE/PE ratio plotted against the matric suction for each of the three materials. When AE/PE is plotted versus time or soil water content, there is no correlation between the AE/PE rate for any of the soil types.

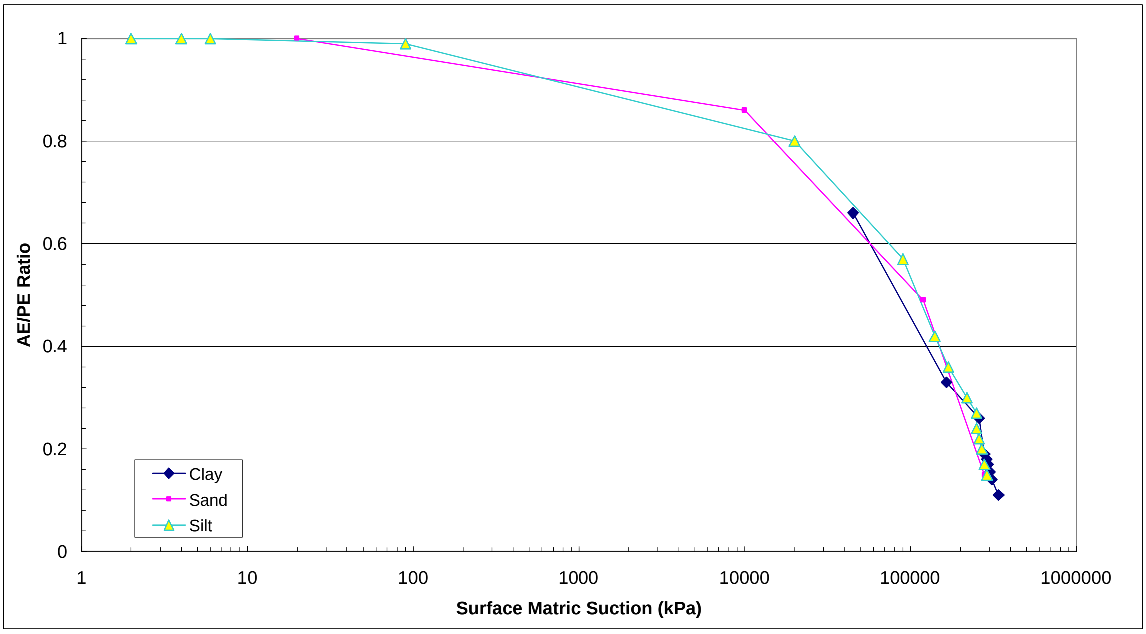

**Figure A3.1** AE/PE versus matric suction for clay, sand, and silt materials (adapted from Wilson, 1990).

Wilson (1990) showed that the rate of actual evaporation is not dependent on a measured soil parameter (i.e. water content or temperature or time of exposure to drying), but on the soil stress state (i.e. matric suction). Thus, in order to accurately determine AE, it is necessary to know the matric suction within the soil. SoilCover and VADOSE/W use the Penman-Wilson method for computing AE at the soil surface such that AE is computed as a function of PE for all soil moisture conditions, independent of soil type and drying history.

Atmospheric coupling is achieved by calculating the soil evaporative flux based on the Penman-Wilson formulation as follows:

$$E = \frac{\Gamma \cdot Q + u \cdot E_a}{u \cdot A + \Gamma} \qquad [A3.1]$$

where: E = vertical evaporative flux (mm/day);

$\Gamma$ = slope of the saturation vapour pressure versus temperature curve at the mean temperature of the air (kPa/°C);

Q = net radiant energy available at the surface (mm/day);

$\nu$ = psychrometric constant;

$E_a$ = $f(u) \cdot P_a \cdot (B-A)$

f(u) = function of wind speed, surface roughness, and eddy diffusion = $0.35 \cdot (1 + 0.15 \cdot U_a)$;

$U_a$ = wind speed (km/hr);

$P_a$ = vapour pressure in the air above the evaporating surface (kPa);

B = inverse of the relative humidity of the air = $1/h_A$; and

A = inverse of the relative humidity at the soil surface = $1/h_R$.

The Penman-Wilson formulation accounts for net radiation, wind speed, and the relative humidity of both the air and soil surface while calculating the evaporation from an unsaturated soil surface.

The Penman-Wilson formulation reduces to the conventional Penman (1948) method when the surface is saturated as the soil will have a relative humidity equal to 100% and "A" in the above equation will equal unity. The relative humidity of the soil surface is evaluated by simultaneously solving the rigorously coupled moisture and heat flow equations. The addition of the vapor flow component ensures that all moisture flow is not shut down when the hydraulic conductivity decreases due to drying. Thus, vapor flow can supply the soil surface and the Penman-Wilson formulation can account for its removal to the atmosphere.

Equation [A3.2] calculates the actual evaporation from a bare surface using the soil stress state and the inputted climate data. If vegetation is present on the ground surface, the AE value must be reduced to represent a vegetated surface with the equation:

$$E^* = E \cdot e^{(-0.21+0.7\cdot\sqrt{LAI})} \qquad \text{[A3.2]}$$

where: $E^*$ = actual evaporation from the vegetated surface (mm/day);
E = actual evaporation from a bare surface (mm/day); and
LAI = leaf area index.

The actual transpiration from the cover profile is obtained by first calculating the potential transpiration:

$$PT = PE \cdot (-0.21 + 0.7\sqrt{LAI}) \qquad \text{[A3.3]}$$

where: PT = potential transpiration from a vegetated surface (mm/day);
PE = potential evaporation (mm/day); and
LAI = leaf area index.

The PT value is the energy that is now available to the plant. If the soil is saturated, the full amount of this energy will be applied to the roots according to the root depth and root shape functions. If the soil is partially saturated, then the actual transpiration (AT) value is further reduced according to the plant moisture limiting function entered by the user that requires definition of the moisture limiting and plant wilting matric suction values. The amount of AT from each node is a function of the root depth and its nodal contributing area.

The Penman-Wilson method of calculating actual evaporation is based on a stress state variable that is unchanged with material type. This is the advantage of the method over other site-specific, empirical methods. For example, the SWIM model uses a constant relative humidity of air variable in its calculation of the actual evaporation.

*Graphical Interface & Ease of Use*

This category is easily influenced by the model users' tastes and background. While some researchers may still prefer DOS based or text input programs, Windows based programs are often the easiest to work with. VADOSE/W, SoilCover, HYDRUS-2D, VS-2D all have windows-based pre- and post-processors. UNSAT-H and SWIM are text-based programs, while HELP is a DOS program, although there is a Windows based pre and post processor program, which uses the HELP model for the simulation. Each requires the knowledge gained by experience with the program. SoilCover and VADOSE/W allow the input of user-defined functions directly from spreadsheet programs. Each of the programs has an on-line help manual and have example programs to demonstrate the model capabilities. VADOSE/W has an on-line tutorial that demonstrates how to set up a simulation with a step-by-step procedure.

*Observation Nodes*

Observation nodes are important because they allow the user to "see what is happening" at the waste material/cover profile interface. Some programs have the capability within their meshing scheme to designate observation nodes. The information from these nodes can then be displayed during post-processing to allow assessment of the flow of heat, water and solutes through the cover system to the underlying waste material.

The HELP, UNSAT-H, and SWIM models do not designate observation points within their program output. However, because UNSAT-H and SWIM are text-based outputs, the results for specific nodes are easily compiled. The VS-2D model records the total head, pressure head, moisture content, saturation, and temperature of an unlimited number of specified nodes for each time step. SoilCover allows the designation of one observation node for which the total water flux and oxygen flux are calculated each time step. An unlimited number of observation nodes showing pressure head, water content, and solute concentration can be identified with the HYDRUS-2D model. Finally, the VADOSE/W model automatically allows the user to monitor any of the nodes within the models two-dimensional mesh. Stress states, heat and flow gradients, and heat and flow conductivities can be viewed at any node within the mesh. Cover liquid and vapour fluxes can also be viewed for each material layer within the cover system.

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# APPENDIX A4

## Evaluation of the Long-Term Performance of Dry Cover Systems

## (Appendix C of the Phase 1 Final Report)

# 1.0 LABORATORY TESTING METHODOLOGY

The geotechnical laboratory test programme is generally carried on both the potential cover material and mine waste material samples. The programme is designed to determine physical and hydraulic parameters of the materials for input to soil-atmosphere cover design and seepage numerical models. A comprehensive geotechnical characterisation programme would consist of laboratory tests to determine the following parameters:

- Particle size distribution (PSD);
- Atterberg limits;
- X-ray diffractions;
- Specific gravity;
- Compaction curve (i.e. Proctor curve);
- Saturated hydraulic conductivity;
- Consolidation-saturated hydraulic conductivity relationship; and
- Soil-water characteristic or moisture retention curve.

Some of the tests, such as PSD and Atterberg limits, are well known and completed by almost all geotechnical engineering testing firms. Other tests, such as the hydraulic conductivity and moisture retention tests, are specialised and performed by only a small number of laboratories. A brief description of the various geotechnical laboratory tests is provided below.

## *1.1 Particle Size Distribution Test*

The particle size analysis testing procedure is detailed in ASTM D422-63 (ASTM, 1990). The PSD test is universally used in the engineering classification of soils (Bowles, 1992). The results of the PSD tests, in combination with the field characterisation and logging records, allows for classification of the potential cover materials under the broad categories of topsoil, well-graded, clay, and coarse materials.

The distribution of grain sizes larger than 75 mm (retained on the No. 200 sieve) is determined by sieving, while the distribution of grain sizes smaller than 75 mm is determined by a sedimentation process using a hydrometer. The standard sieve test involves passing approximately 500 g of oven-dried (110°C) soil through a series of sieves and then recording the mass retained on each sieve.

The standard hydrometer test involves the use of a specially designed hydrometer to measure the density of a soil in suspension in water at various time intervals. A known mass (approximately 50 g) of oven-dried (110°C) soil passing the No. 10 (2.0 mm) sieve is placed in a 250 mL beaker. Approximately 125 mL of a dispersing agent solution is then mixed in with the soil sample in order to eliminate particle coagulation. After the specimen soaks for at least 16 hours, the sample is dispersed further using a mechanically operated stirring device (i.e. a blender). Immediately after dispersion, the soil-water slurry is transferred to a glass sedimentation cylinder and distilled water is added until the total volume is 1000 mL. After manually agitating the contents of the sedimentation cylinder for approximately one minute, hydrometer readings and the temperature of the suspension are taken at various time intervals over a 24-hour period. ASTM (1990) provides the relationship for computing the grain size and corresponding percentage of soil remaining in suspension, based on the above measurements. After taking the final hydrometer reading, the suspension is transferred to a No. 200 sieve and washed with tap water until the wash water becomes clear. The material retained on the No. 200 sieve is subsequently oven-dried (110°C) and then analysed by a sieve test.

### *1.2 Atterberg Limits*

The Atterberg limits tests, documented in ASTM D4318-95a (ASTM, 1995), measures the liquid and plastic limit of the soil sample. The limits are primarily used for soil identification and classification. Correlations between the Atterberg limits and soil strength and volume change have also been extensively investigated. The liquid limit has been arbitrarily defined as the water content at which a soil sample placed in a cup with a 12.7 mm groove through its center will close at with 25 – 10 mm drops in the measurement device. The plastic limit is arbitrarily defined as the water content at which a soil thread crumbles when it is rolled down to a diameter of 3 mm.

### *1.3 X-ray Diffraction Test*

X-ray diffraction tests or XRD analysis measures the nodal spacing of the clay minerals within the test sample. The nodal spacing for each clay mineral is distinct and consistent allowing identification of the clay mineralogy. Each sample should be separated into four sub-samples of which each was exposed to individual treatments, being Mg-saturation air dried, Mg-saturation glycerol-solvated, K-saturated air dried, and K-saturated heated to 550°C. The samples are prepared using these procedures to remove ambiguity with respect to what minerals are represented in each gradation, and to ensure that the highest degree of certainty is obtained for interpretation of the clay component. These procedures are considered the standard in the field of XRD analysis, and should only vary slightly depending on the objectives of the testing programme.

### *1.4 Specific Gravity Test*

The procedure for conducting a specific gravity test on a soil sample is specified in ASTM D854-92 (ASTM, 1992). A known mass of oven-dried (110°C) soil, approximately 50 g, is placed into a calibrated pycnometer (volumetric flask). The pycnometer is then filled with distilled water to a level slightly above that required to cover the soil. After soaking the specimen for 12 hours, the entrapped air is removed by boiling the contents of the pycnometer for at least 10 minutes. The contents are then subjected to a vacuum for at least 30 minutes by connecting the pycnometer directly to a vacuum pump. After filling the pycnometer to the calibration mark with distilled water, the mass and temperature of the contents of the pycnometer are measured. ASTM (1992) provides an equation for computing specific gravity based on the above measurements.

### *1.5 Compaction (Proctor) Test*

The compaction test, also known as a Proctor test, is detailed in ASTM D698-91 (ASTM, 1991). The compaction test defines the moisture content – unit weight (density) relationship of a soil sample. This is widely used in construction to produce soils with their maximum unit weight for greatest soil strength. A soil sample is poured into a standard compaction mold in three lifts. At each lift, the material is compacted into the mold using a 24.5 N rammer being dropped 25 times from the height of 0.305 m. The density of the material within the 944 $cm^3$ mold is calculated from the measurement of the sample mass. A measurement of the gravimetric water content of the sample is completed to compute the dry density of the material sample. This procedure is carried out at a minimum of three water contents to define the relationship between density and water content.

### *1.6 Saturated Hydraulic Conductivity Test*

The saturated hydraulic conductivity of the potential cover and mine waste materials is generally measured using a constant head triaxial permeameter apparatus (Figure A4.1). The triaxial permeameter shown in Figure A4.1 was specially designed for low-gradient hydraulic conductivity testing applications (Yanful *et al.*, 1990; Wong and Haug, 1991). The system consists of a triaxial cell, control panel, and data-acquisition system. The lines and fittings for flow in and out of the sample are constructed from high-grade stainless steel, in order to resist the effects of various reactive permeant.

Pressures required for hydraulic conductivity testing are obtained from a central (dried and filtered) air pressure source. The pressure is directed to three fluid reservoirs through a system of regulators on the control panel. The regulators control the inflow, outflow, and confining pressures applied to the sample. The reservoirs are constructed of Lucite to prevent corrosion and to allow visual observation of the effluent test fluid. Gauges on the control panel measure the coarse pressure readings, while the fine adjustments are recorded electronically on the data acquisition system. Twin, double-tube volume-change burettes located between the reservoir and the sample measure flow in and out of the sample to the nearest 0.01 mL.

Permeant is supplied under pressure to the bottom of the sample and exits the top under a back pressure. A confining pressure applied to the sides of the sample minimises sidewall leakage along the outside surface of the sample. The hydraulic gradient during testing is controlled by adjusting the difference between the inflow and outflow pressures; however, the hydraulic gradient is also a function of the sample height. Low gradient and confining pressure testing produces only slight changes in stress across the sample, minimising consolidation and artificially low hydraulic conductivity readings (Wong and Haug, 1991). The main disadvantage of low hydraulic gradients is that the total flow through the sample is small, and thus the precision of the hydraulic conductivity measurements is decreased under these conditions.

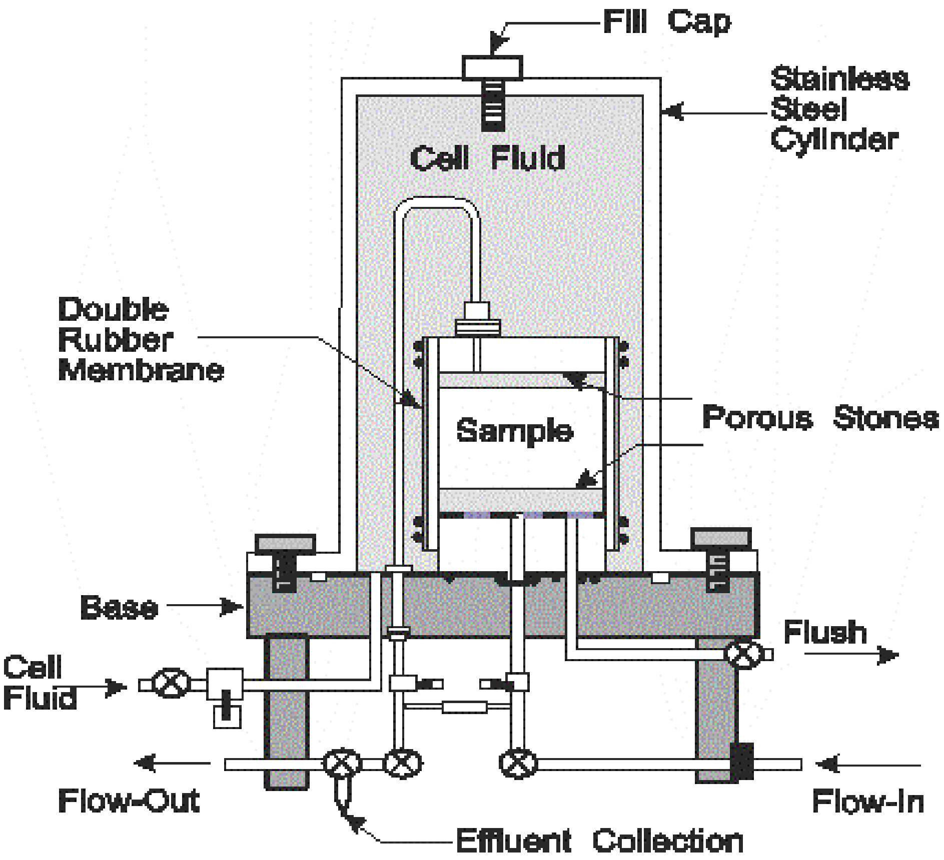

**Figure A4.1** Schematic of a constant head permeameter apparatus.

A number of techniques are available to offset the precision losses associated with low gradient hydraulic conductivity testing. These involve calibration tests where a solid aluminum cylinder is substituted for a soil sample, and apparent flow rates are recorded on the burettes for different pressure configurations. These leakage values can then be applied as a correction to the measured flow rates during the actual hydraulic conductivity tests. The results of this analysis and adjustments indicate that the accuracy of these permeameters is approximately 25%, for a hydraulic conductivity of 1 x $10^{-10}$ m/s. In addition to leakage corrections, it may also be possible to increase the diameter of the test specimen, effectively increasing the area over which flow is taking place. It may also be possible to increase the precision of the burettes used to measure flow in and out of the sample.

The density conditions (i.e. void ratio) for the test specimens will depend on the estimated or measured field conditions. The objective is to evaluate the change in saturated hydraulic conductivity between each sample, as well as for differing initial density conditions, to ensure that the soil-atmosphere cover design modelling accounts for these effects during sensitivity analyses. The initial moisture conditions for the test specimens are based on field measurements obtained during the site visit for sample collection.

### 1.7 Consolidation-Saturated Hydraulic Conductivity Test

Consolidation-saturated hydraulic conductivity testing is carried out in order to determine the relationship between effective stress, void ratio and saturated hydraulic conductivity for fine textured potential cover or waste materials samples. The test specimens are slurried with distilled water to an over-saturation condition and placed into a stainless steel oedometer ring, which has an inside diameter of 64 mm and a height of 32 mm. A steel mesh and filter paper is placed above and below the sample in the oedometer ring to prevent the loss of material during the test. The oedometer ring is then placed on the base plate of a modified oedometer apparatus.

The modified oedometer apparatus, illustrated in Figure A4.2, was developed for the measurement of both volume change and saturated hydraulic conductivity. Vertical loading of the sample is provided through a standard consolidation loading frame. The oedometer ring and base plate are sealed using a rubber O-ring. The base is connected to calibrated burettes using a system of valves that are connected either to a falling head hydraulic conductivity test system or to permeant reservoirs.

The consolidation portion of this test is performed in accordance with ASTM D2435-96 (ASTM, 1996). Vertical consolidation pressures are generally applied to the sample using a load-increment ratio of one, with a minimum load duration of 24 hours. After each loading and unloading, a falling head hydraulic conductivity test is performed.

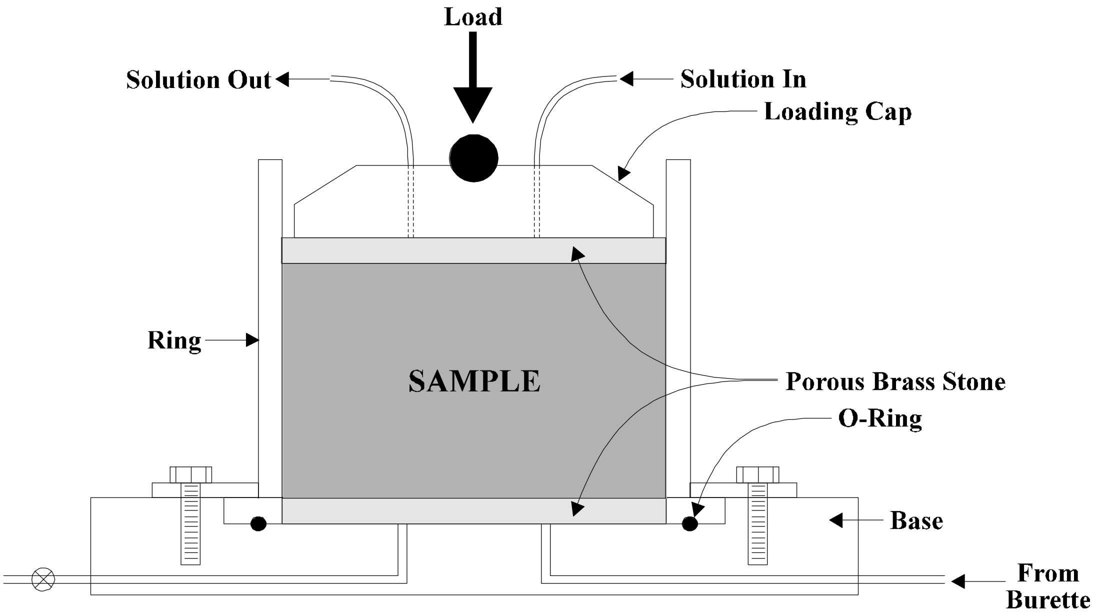

**Figure A4.2** Schematic of a modified oedometer apparatus (after O'Kane, 1996).

### *1.8 Soil Water Characteristic Curve Test*

A key component of the laboratory programme is the measurement of the moisture retention or soil water characteristic curve (SWCC). The moisture retention curve is a continuous function relating energy and the state of water, and hence describes the water content of a material as a function of soil suction, or negative pore-water pressure. The saturated hydraulic conductivity and the relationship between the effective diffusion coefficient for oxygen and the degree of saturation are also key parameters for soil cover design. The moisture retention curve is central to the design of an unsaturated soil system, which describes a cover system, and the most fundamental characterisation required for design.

The moisture retention curves are obtained by the axis-translation technique using a pressure plate apparatus, as well as vapour extraction techniques. A schematic of the soil water characteristic curve test apparatus is shown in Figure A4.3. The high air-entry ceramic disks of the pressure plate cells are saturated at the start of each test, before the specimens are mounted onto the base of the pressure plate cell. A saturated high air-entry ceramic remains saturated for applied suctions lower than the air-entry value of the ceramic disk. A saturated ceramic disk is impervious to air. However, air can diffuse slowly through the water in the ceramic and air bubbles will eventually appear below the ceramic disk. Air that diffuses into the water compartment below the ceramic disk is accounted to correctly monitor the amount of water that is driven out of the soil under each applied matric suction condition. The diffused air is flushed from the system on a regular basis.

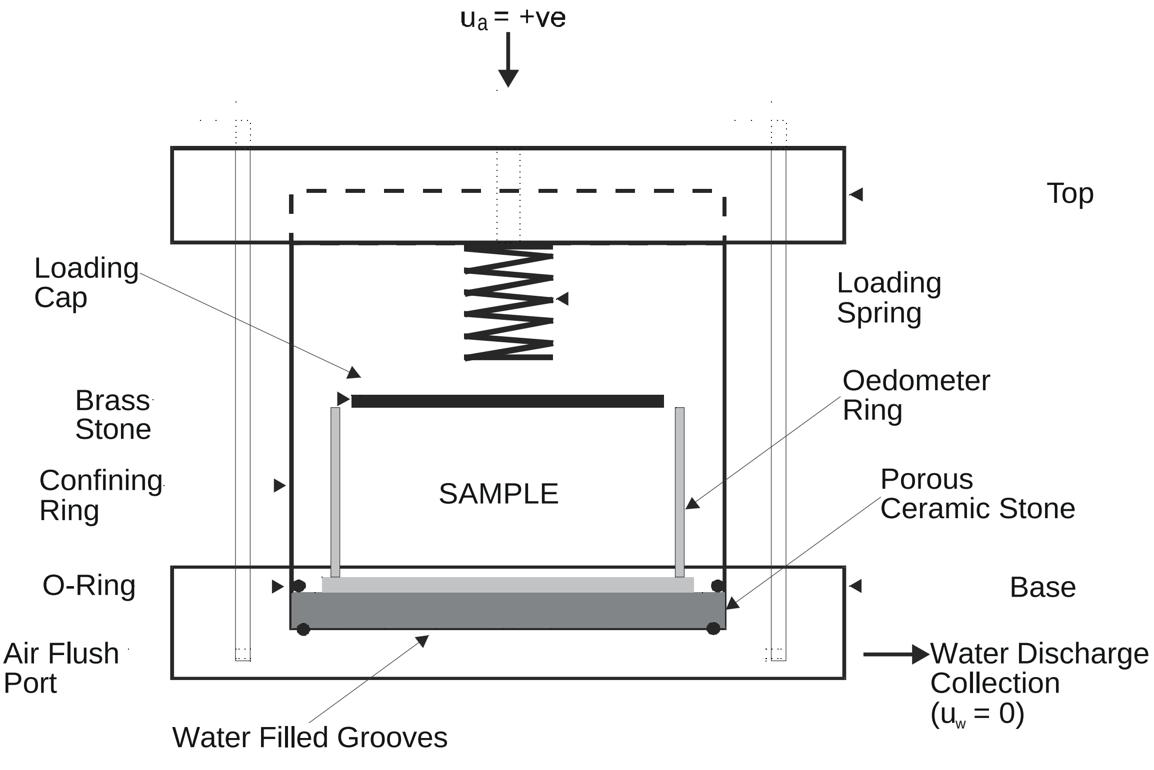

**Figure A4.3** Schematic of a soil water characteristic curve testing apparatus.

Matric suction is applied to the soil either by directly pulling on the water phase (i.e. using a method employed in the Buchner-Funnel method by creating a hanging water column and maintaining atmospheric conditions within the apparatus above the high air-entry disk), or by elevating the air pressure in the cell and using the axis translation technique. In either case the difference between the pore-air pressure and pore-water pressure is used to calculate the matric suction applied.

Matric suction is applied by directly pulling on the water phase for matric suction values below 10 kPa. A water column is used for extracting water directly from the soil. A water column provides good accuracy for small suction values. Long flexible tubing is attached to the outlet located at the base of the pressure plate cell. The flexible tubing is filled with water to form a continuous water phase to the ceramic plate and the soil. A negative water head (i.e. matric suction) is applied to the soil specimen by maintaining the water level in the flexible tubing at the required distance below the specimen. The inlet at the top of the pressure plate cell is vented to the atmosphere to ensure that the air pressure inside the cell is atmospheric. Water draining from the soil specimen is collected in a vented glass vial. Matric suction equilibrium equal to the applied negative water head is established in the soil specimen when water ceased to drain from the soil and the mass of the apparatus is constant. A negative head equal to the next matric suction increment is then applied by further lowering the level of the water column. The process is repeated using the hanging water column for each matric suction increment up to a matric suction value 10 kPa.

The test is continued using an air pressure supply. An air pressure regulator with accuracy in the range of 0.5 kPa is used to regulate the pressure to the pressure plate cell. The air is supplied to the pressure plate cell through the air pressure inlet located at the top of the pressure plate cell. The water drainage outlet located at the base of the pressure plate cell is maintained at atmospheric pressure conditions. Water draining from the soil specimen as a result of the applied air pressure is collected in a vented glass vial. Matric suction equal to the applied air pressure is established in the soil specimen when water ceases to drain from the soil and the mass of the apparatus is constant. The next matric suction increment is then applied by raising the air pressure. The process is repeated for each required matric suction value.

The volume-mass properties of the soil specimen are determined at the completion of the pressure plate test. The volumetric and gravimetric water content of the soil specimen corresponding to each matric suction increment are computed from the volume-mass data obtained at the end of the test, by accounting for the amount of water that was lost from the soil at each applied matric suction value.

Large-scale moisture retention tests (30 cm diameter cells) are conducted on the potential cover materials to ensure that a representative particle size range is measured and density conditions encountered in the field could be replicated in the laboratory. The samples are prepared in the same manner as described for the saturated hydraulic conductivity tests.

Water is removed from the specimens by vapour extraction using vapour equilibrium chambers for tests involving suctions higher than 1,500 kPa. Small samples are obtained from each of the soil specimens in the soil water characteristic curve tests after reaching equilibrium at the final matric suction increment inside a pressure plate apparatus. A saturated salt solution is placed in the base of the equilibrium chamber. The small soil samples are placed in the vapour equilibrium chambers above the saturated salt solutions. The chamber is sealed to allow the sample to come into equilibrium with the atmosphere created by the saturated salt solution. The mass of the sample is recorded periodically until the sample mass was constant. The total suction is calculated using the Edlefsen and Anderson (1943) formulation after the water content of the soil sample comes to equilibrium in the chamber. Temperature has a significant effect on the humidity of saturated salt solutions. A temperature of 20°C is typically used for the vapour equilibrium test. Table A4.1 summarizes the equivalent total suctions measured on selected samples.

**Table A4.1**

Summary of saturated salt solution humidity and equivalent total suction.

| Salt | Temperature (°C) | Relative Humidity (%) | Equivalent Total Suction (kPa) |
|---|---|---|---|
| Lithium Chloride<br>($LiCl_2 \cdot H_20 + LiCl_2 \cdot 2H_20$) | 20 | 11.5 | $2.93 \times 10^5$ |
| Magnesium Chloride<br>($MgCl_2 \cdot 6H_20$) | 20 | 33.0 | $1.50 \times 10^5$ |
| Magnesium Nitrate<br>($Mg(NO_3)_2 \cdot 6H_20$) | 20 | 54.3 | $8.26 \times 10^4$ |
| Sodium Chloride<br>(NaCl) | 20 | 75.5 | $3.80 \times 10^4$ |
| Potassium Sulphate<br>($K_2SO_4$) | 20 | 97.0 | $4.12 \times 10^3$ |

## 2.0 REFERENCES

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# APPENDIX B1

## Evaluation of the Long-Term Performance of Dry Cover Systems

## Evaluation of the BHP Billiton, Mt. Whaleback Mine Cover System Field Trials using State-of-the-Art Soil-Atmosphere Numerical Models

## EXECUTIVE SUMMARY

The cover system field trials at BHP Billiton Iron Ore, Mt. Whaleback, located in Western Australia, were evaluated using state-of-the-art soil-atmosphere numerical models. The site was simulated using the one-dimensional modelling program SoilCover 2000 (GeoAnalysis 2000 Ltd., 2000), and the two-dimensional program VADOSE/W (Geo-Slope, 2003).

The performance monitoring data collected at Mt. Whaleback allowed for the development of field *in situ* soil-water characteristic curves for the cover materials and waste rock. These field soil-water characteristic curves were found to differ substantially from the original curves obtained from laboratory measurements. Field responses were simulated to verify the accuracy of the updated model inputs. These new inputs were then used to re-evaluate the preliminary predictive numerical model. Although the updated model calculated some large differences for the water balance compared to the original model, it still predicted that the cover would perform adequately during the extreme year estimated for the preliminary modelling. However, a larger rainfall year than the one used in preliminary modelling has occurred since the construction of the cover system field trials. The numerical model predicted that a non-vegetated cover would allow significantly higher net percolation to occur during this larger rainfall year, than was predicted during the preliminary modelling. However, if the cover system were vegetated, it would perform as designed. The cover system performed well when the larger rainfall year was applied repeatedly (i.e. consecutive extreme wet seasons). VADOSE/W was used to understand the effect of an undulating surface topography and segregated cover material on performance. The model predicted that water during an extreme rainfall event flowed down along the segregated sloping layer to the underlying waste rock. Further monitoring is required to understand this phenomenon and its implications on the performance of the cover.

# TABLE OF CONTENTS

# 1.0 INTRODUCTION

Numerical models are valuable tools to help understand the processes controlling the performance of mine waste cover systems. In this report, the BHP Billiton Iron Ore, Mt. Whaleback Operations cover system field trials, which had been previously modelled at the time of construction, were evaluated using the most recent version of the SoilCover and VADOSE/W numerical models, as well as the collected field data. The objectives of this work are to:

- Assess the accuracy of the original model inputs and predictions;
- Evaluate the performance of the cover systems since installation;
- Illustrate the capabilities of the latest model programs; and
- Develop an understanding for the key processes and characteristics that control the cover system at the site.

## 1.1 Background

Preliminary modelling was completed in 1996 to aid in the design of a dry cover system for the net acid generating overburden material produced at Mt. Whaleback. The modelling was conducted using the computer program SoilCover Version 3.0 (MEND, 1996). The modelling concluded that 2.0 m of run-of-mine (ROM) inert cover material was sufficient to minimise the infiltration of net percolation to the underlying waste rock.

During 1997, 1 ha field test plots, referred to as Test Plot No. 1 (TP1) and Test Plot No. 2 (TP2), was constructed by block dumping the ROM cover material on the waste rock surface to create an undulating surface with a minimum cover thickness of 2 m and 4 m, respectively. Instrumentation to measure *in situ* suction, volumetric water content, and temperature throughout the cover material profile and within the underlying overburden material were installed after cover placement. A fully automated meteorological station was placed on the cover surface to monitor air temperature, relative humidity, net radiation, wind speed, wind direction, and rainfall. In addition, large-scale lysimeters to measure net percolation were installed.

For this report, performance of the TP1 field trial was re-evaluated using the data collected since 1997 and using the computer programs SoilCover 2000 Version 5.2 (GeoAnalysis 2000 Ltd., 2000), and VADOSE/W Version 1.11 (Geo-slope, 2003). The following sections describe this work.

# 2.0 FIELD RESPONSE MODELLING

Field response modelling was undertaken to establish an updated set of material properties. These properties were then used to re-evaluate the preliminary model simulations and to further evaluate the performance of the cover. The following sections describe the field response model inputs and results.

## 2.1 Model Inputs

The simulation period for the field response modelling runs from January 1, 1998 until February 18, 2000 and from October 26, 2000 until February 1, 2002. The break in the simulation between February 18 and October 26, 2000 is due to the tipping bucket rain gauge at the TP1 location being offline. Bare surface conditions were modelled. The main reason for modelling field response is to establish the properties of the cover material and underlying overburden material, as well as ensure that key processes controlling performance are understood.

The soil-water characteristic curves (SWCCs) used for the preliminary model were developed from laboratory testing. However, the field data collected over the past 5 years has allowed for the creation of field *in situ* SWCCs that better describe the performance of the cover materials. Figure B1.1 shows a comparison of the preliminary and field *in situ* SWCCs. Note that the *in situ* SWCC data indicated a definite change between the “surface” cover material (representing the top 10 cm of the cover) and the “general” cover material below the surface material (representing the cover from 10 cm to 200 cm depth). The *in situ* SWCCs were used for the updated simulations presented in this report.

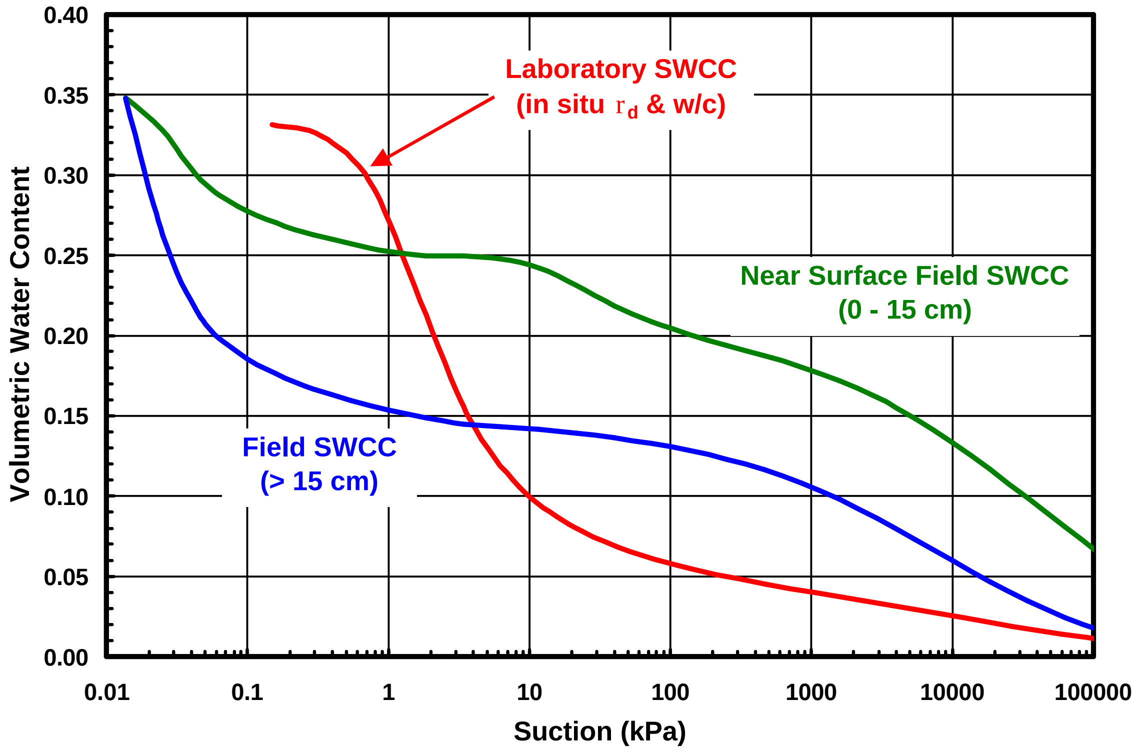

**Figure B1.1** SWCCs used to model the response of the TP1 cover system.

Figure B1.2 shows the hydraulic conductivity functions developed for the preliminary and updated models. The hydraulic conductivity functions used for the updated model were estimated from the *in situ* SWCCs using the Fredlund *et al.* (1994) equation. It is interesting to note how close the original and updated hydraulic conductivity curves plot, considering the large differences shown for their respective SWCCs. This indicates the importance of the hydraulic conductivity function when simulating water movement within soil covers. Other than vegetation, the hydraulic conductivity function is the controlling factor for water movement within the cover material and must be calibrated for the simulation to be accurate.

The specific gravity and porosity of the cover materials and waste rock were taken from laboratory and field measurements, respectively. The specific gravity for all the materials was be 2.9 while the porosity of the cover and overburden materials were input as 0.35 and 0.30, respectively.

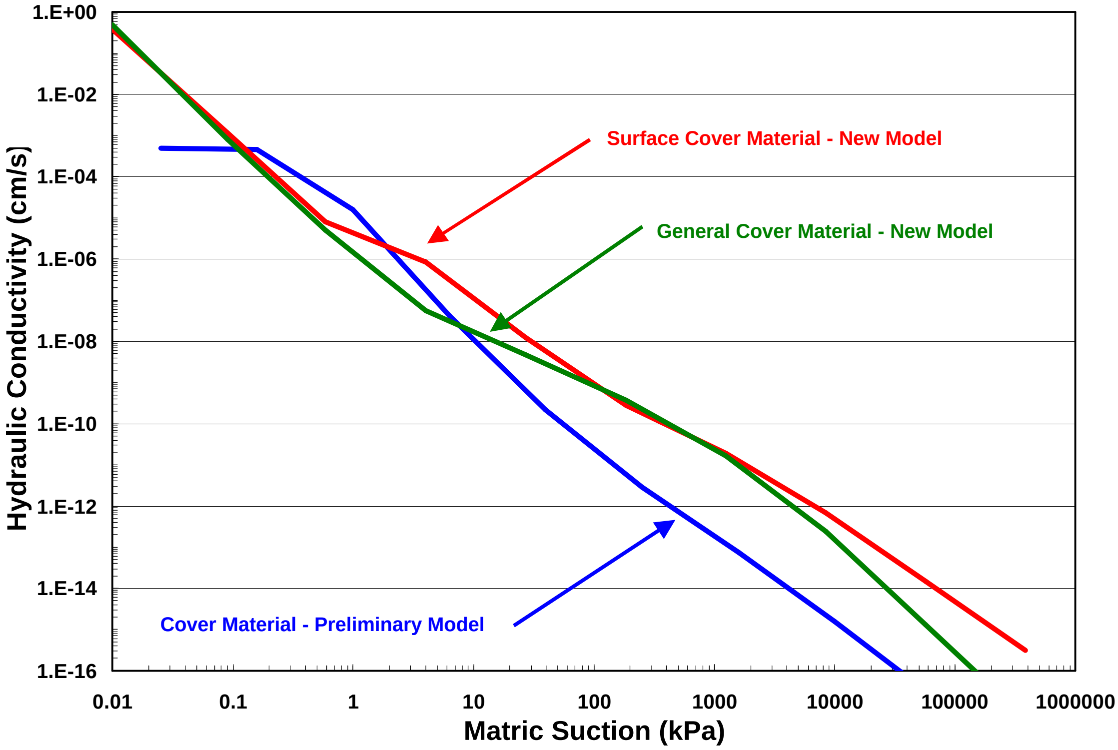

**Figure B1.2** Hydraulic conductivity functions used to model the TP1 cover system.

## 2.2 Model Results

Figure B1.3 shows the daily rainfall and modelled cumulative water balance for TP1 during the two simulation periods. The total rainfall during these two periods was 2,172 mm. The largest amount of rainfall recorded for a one-year period (starting in October and ending in September) prior to the construction of the cover system was 500 mm. For the period of October 1, 1998 to September 30, 1999, the cover was exposed to approximately 727 mm of rainfall, almost 50% more than the highest recorded prior to construction of the field trials. Therefore, the cover system experienced rainfall conditions that were not modelled prior to construction, which has led to results not anticipated, but also has provided the opportunity to evaluate field performance of the cover system in response to extreme climate conditions.

The primary result not anticipated was the increased amount of net percolation into the underlying overburden material. The model simulated that 139 mm of water would percolate into the waste rock during the first simulation period (January 1, 1998 to February 18, 2000). This represents approximately 9% of the total rainfall occurring during the same time period. However, during the second simulation period (October 26, 2000 to February 1, 2002) the model simulated a net upward flux, indicating that the cover was performing as designed. It also must be reiterated that a bare surface (without vegetation) cover system was modelled, which is representative of field conditions. The addition of vegetation has the potential of substantially reducing the amount of percolation into the waste rock. Note that all model results reported in this section were obtained using the 1-D SoilCover model.

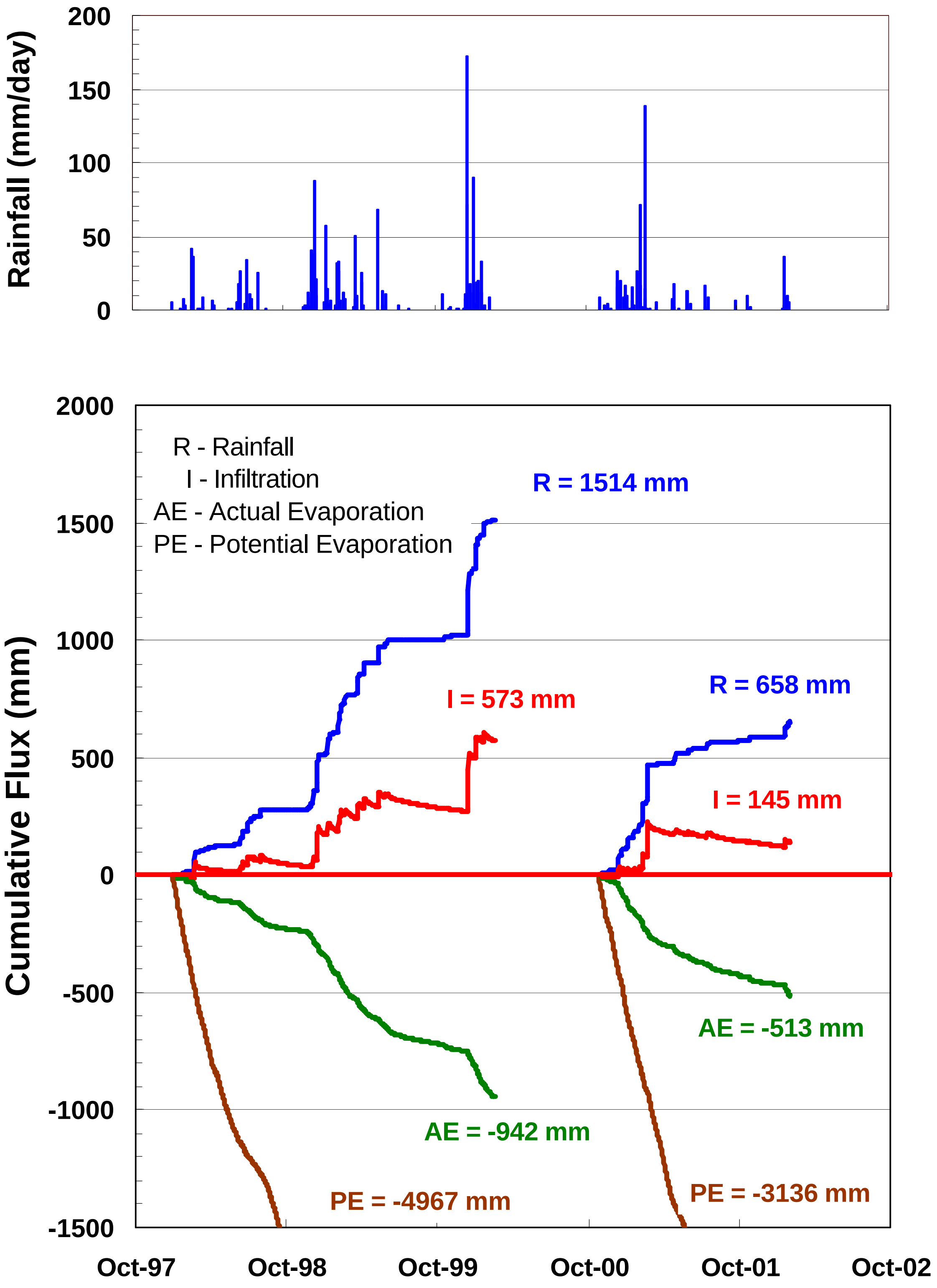

**Figure B1.3** Daily rainfall and modelled cumulative water balance for the field response modelling of the TP1 cover system (positive values indicate water entering the cover system; negative values indicate water leaving the cover system).

Comparisons between the modelled and measured matric suction response at depths of 10 cm, 100 cm and 230 cm within the cover system are shown in Figure B1.4. The updated model produces results that compare reasonably well to the field measurements. However, the comparison does degrade with depth. This is not surprising since factors such as soil structure, preferential flow paths, and three-dimensional effects cannot be taken into account. If these factors could be added, the model would be better able to simulate the water movement, particularly the deep infiltration observed shortly after rainfall events.

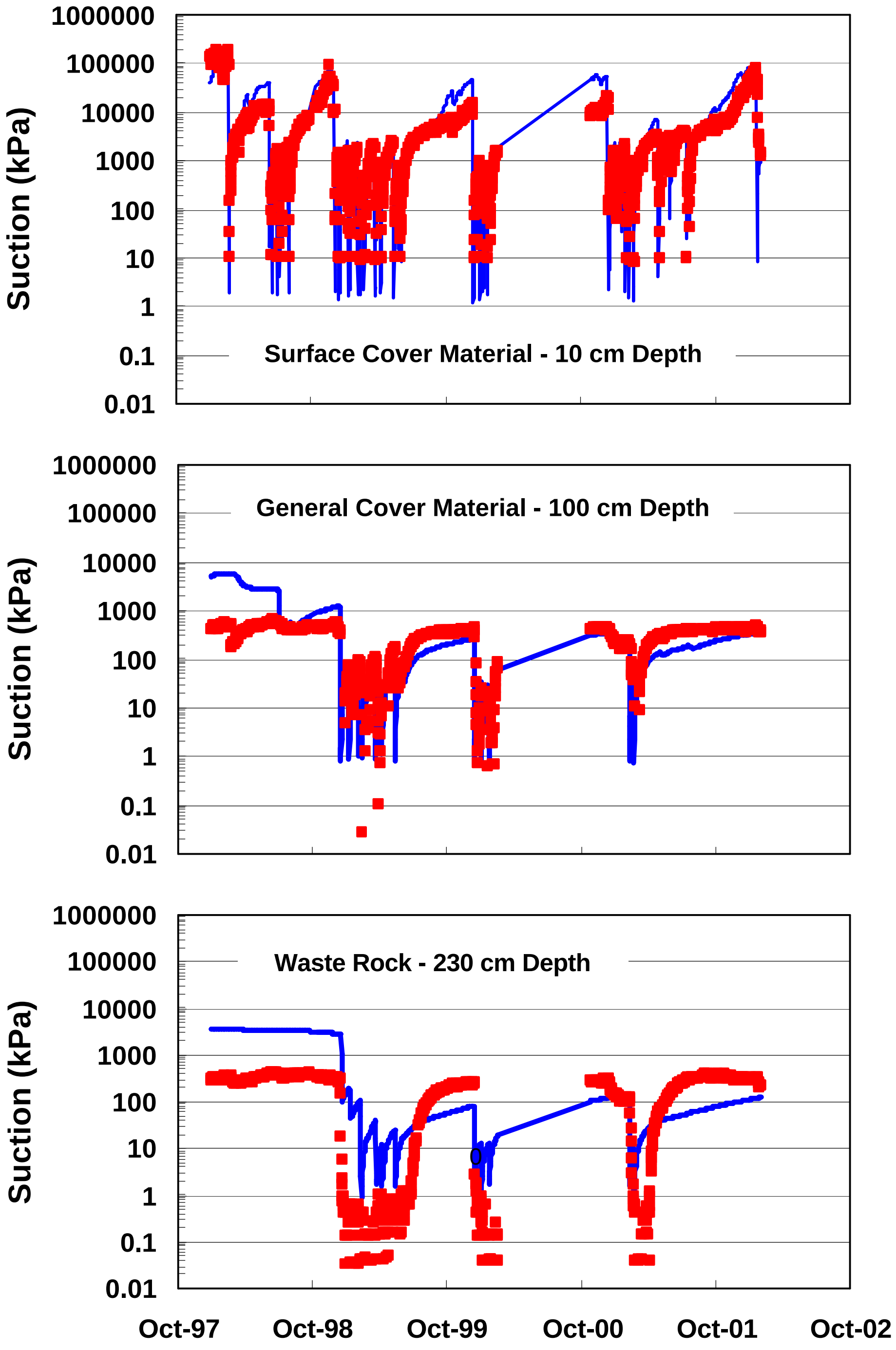

**Figure B1.4** Comparison of measured and modeled matric suction responses within the cover and overburden material at TP1.

Figure B1.5 shows the comparison between the computed and measured water volumes for the entire cover material. The updated model produces results that compare reasonably well to the field measurements ($r^2$ = 0.81). The reasonable comparison between the field data and model output is notable considering that little time and effort was made to "fine-tune" the model. The soil properties were determined from the field data and no systematic adjustments were made to improve the simulation. Without the comprehensive monitoring program being conducted at Mt. Whaleback, the model would be significantly less accurate. This point reinforces the need for consistent monitoring of soil and climate parameters, with data being collected at a regular and frequent rate. Most important for the accuracy of the model is automated measurement of matric suction and water content, at the same time and depth, throughout the cover profile. These measurements allow for the creation of the *in situ* SWCC and hydraulic conductivity functions that are vital for developing representative models.

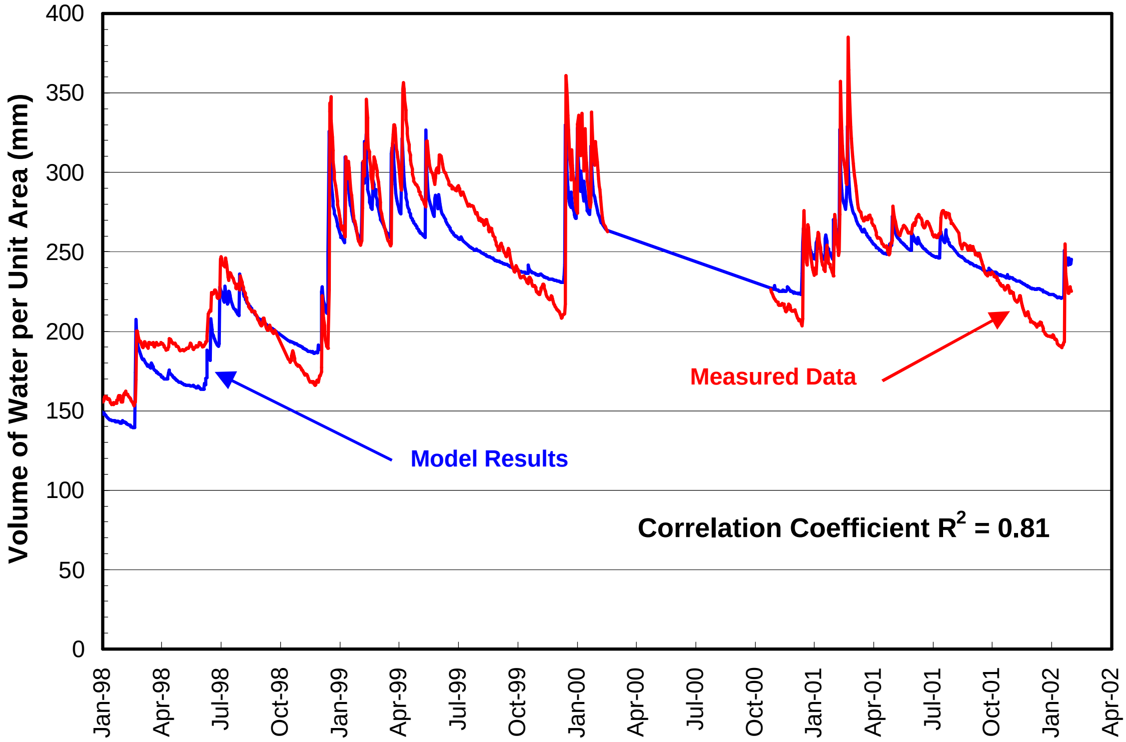

**Figure B1.5** Comparison of the calibrated numerical model results to actual measured field data covering the period from January 1998 to February 2002.

## 2.3 Comparison of Preliminary and Updated Simulations

The performance of the cover system was evaluated during the preliminary modelling by subjecting it to the highest yearly rainfall on record at that time. The thirty-year (1966-1996) historical rainfall database for Newman, Western Australia, was evaluated to determine the maximum rainfall for a 365-day period from October 1 to September 30. This period was chosen because, on average, the lowest monthly rainfall was recorded during the months of September and October, allowing the use of an initially dry soil profile for the model and for the model to "straddle" the wet season. The database showed that the maximum rainfall on record for the one-year period was approximately 500 mm and occurred from October 1, 1994 to September 30, 1995. Note that this maximum yearly rainfall has been surpassed at the mine site since the preliminary modelling was completed.

Using the updated model inputs developed during the field response modelling process reported herein, the performance of the cover system was re-evaluated for the October 1, 1994 to September 31, 1995 climate year using the SoilCover 2000 program. The physical model was the same as that used for the preliminary model; 2 m of cover material over 3 m of overburden cover material. However, the cover material for the updated model was separated into two layers, with the "surface" cover material representing the top 10 cm of the cover and the "general" cover material representing the remainder of the cover layer. It was assumed that the cover system was poorly vegetated (i.e. leaf area index to a maximum of 1.0).

The predicted cumulative fluxes obtained using the updated SoilCover model are shown in Figure B1.6. The numbers in parentheses are the cumulative fluxes predicted by the preliminary model. The major difference between the two models is the predicted amount of runoff. The preliminary model predicted that almost 300 mm of runoff (approximately 60% of the rainfall) would occur during the year. However, the updated model predicted that no runoff occurred during the year. This discrepancy caused the updated model to predict much more actual evapotranspiration (455 mm) and infiltration (42 mm) than the preliminary model. Finally, the preliminary model predicted that less than 1% of the rainfall would percolate into the waste rock. However, the updated model found that there would be no percolation into the waste rock and that there would actually be a net upward flux.

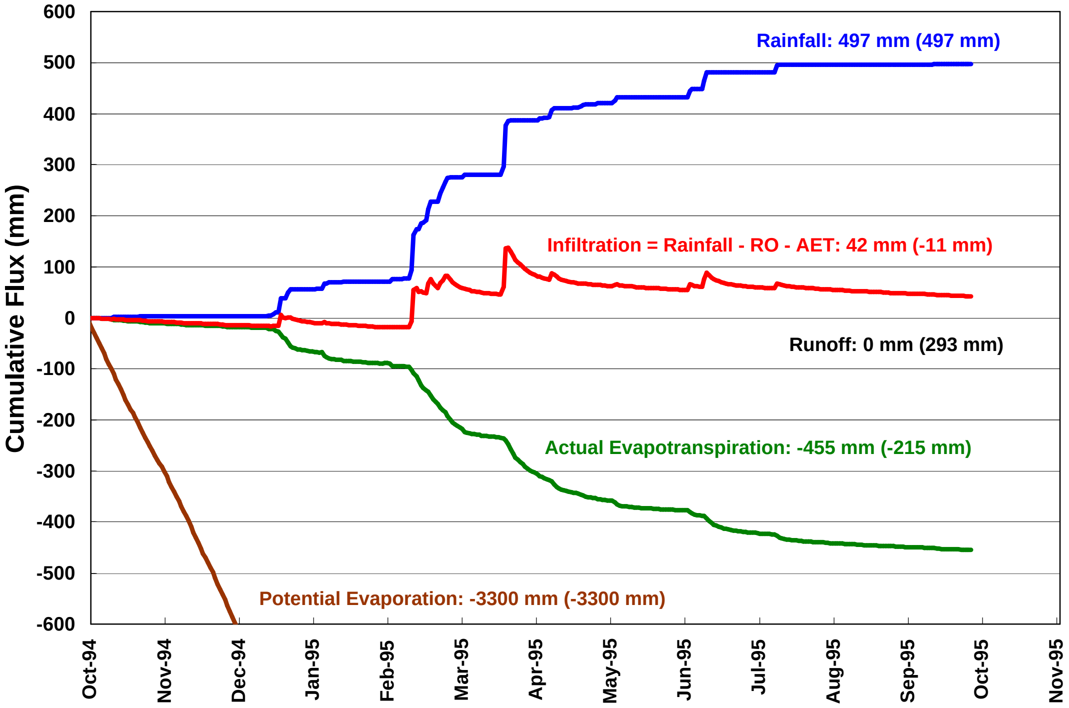

**Figure B1.6** Predicted cumulative fluxes using the updated SoilCover model (numbers in parentheses were obtained from the preliminary modelling).

## 2.4 Updated Predictive Modelling

One factor that was not simulated during the preliminary modelling was the occurrence of multiple extreme rainfall years, and the effect that would have on the performance of the cover system. For this report, evaluation of these conditions was conducted using the updated model and by repeatedly applying the climate data measured at the TP1 site from October 1, 1998 to September 30, 1999. The amount of rainfall recorded during this period was larger than that used for the preliminary model and is the largest amount of rainfall recorded by the TP1 weather station for the October through September period. The field conditions simulated to occur on September 30, 1998, during the field response modelling were used as the initial conditions for this model.

Figures B1.7 and B1.8 show the results obtained by simulating multiple extreme rainfall years occurring on the TP1 cover system. The model was run twice; once with no vegetation (simulating the current state of the TP1 test plot); and once with a “poor” growth of vegetation. Figures B1.7 and B1.8 clearly show that vegetation substantially reduces the rate and amount of percolation while keeping the amount of water stored from year-to-year relatively unchanged. In comparison, the model with a bare surface predicted significant net percolation and a substantial increase in the volume of stored water during the first year (see Figure B1.8). During the two subsequent applications of the extreme rainfall year the predicted performance of the non-vegetated improved, with almost no change in the year-to-year amount of water stored and a net upward flux of water from the waste rock. However, during these years there is a constant movement of moisture back-and-forth across the cover/overburden interface (see Figure B1.7). Vegetation dampens this dynamic water movement across the interface substantially.

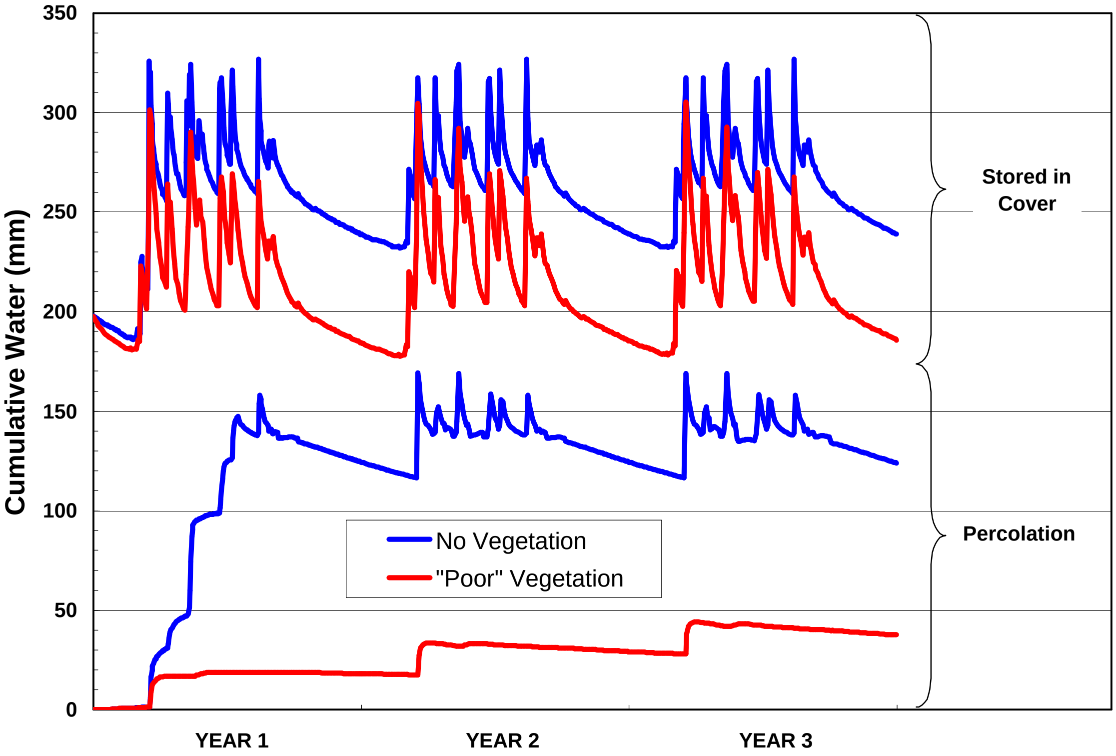

**Figure B1.7** Cumulative volume of water predicted to be stored in the cover and percolating into the waste rock if the extreme rainfall year is repeatedly applied to the TP1 cover system.

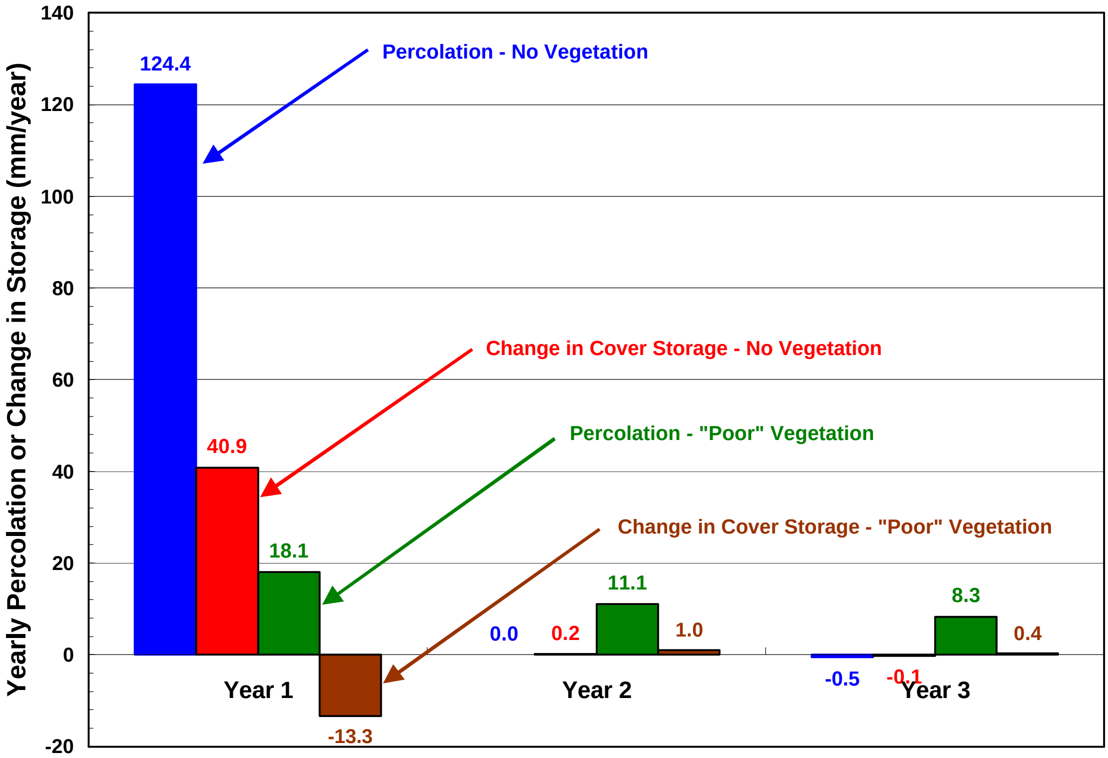

**Figure B1.8** Annual percolation and change in cover storage predicted by the updated model when the extreme rainfall year is repeatedly applied to the TP1 cover system.

This simulation indicates that the TP1 cover would function as the preliminary design indicated if vegetation was established on the cover.

## 3.0 ILLUSTRATION OF TWO-DIMENSIONAL MODEL

The cover system at Mt. Whaleback was constructed by block-dumping the well-graded ROM material 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 can lead to preferential flow paths within the cover system and possibly increased net percolation to the underlying waste material.

VADOSE/W, a 2-D soil-atmosphere numerical model, was used to predict the effects of segregation on cover system performance. The model is an extension of the 1-D SoilCover model and therefore the same material properties were input to the VADOSE/W model.

The numerical simulation program included an analysis of the net percolation of a 2.0 m BIF cover system with a hummocky surface and with the addition of a segregated layer within the cover system. Figure B1.9 shows the two meshes used in the numerical analysis. The model was completed using the climate data collected at the TP1 site from October 1, 1998 to September 30, 1999, which is the same time period used for the updated predictive modelling

The results of the simulations are summarised in Figure B1.10. Minimal net percolation was predicted for the hummocky cover system with no segregation layers (i.e. a homogeneous layer of ROM cover material). Net percolation, although not significant, was highest (approximately 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 approximately 2.5 mm, which corresponds to less than 1% of the rainfall modelled. The predicted net percolation for the cover system with segregation layers was significantly higher in the two areas where the segregated layer connected with the surface of the underlying overburden material. Net percolation was approximately 180 mm in these areas bringing the average net percolation for the surface area modelled up to between 2% and 3% of the rainfall modelled.

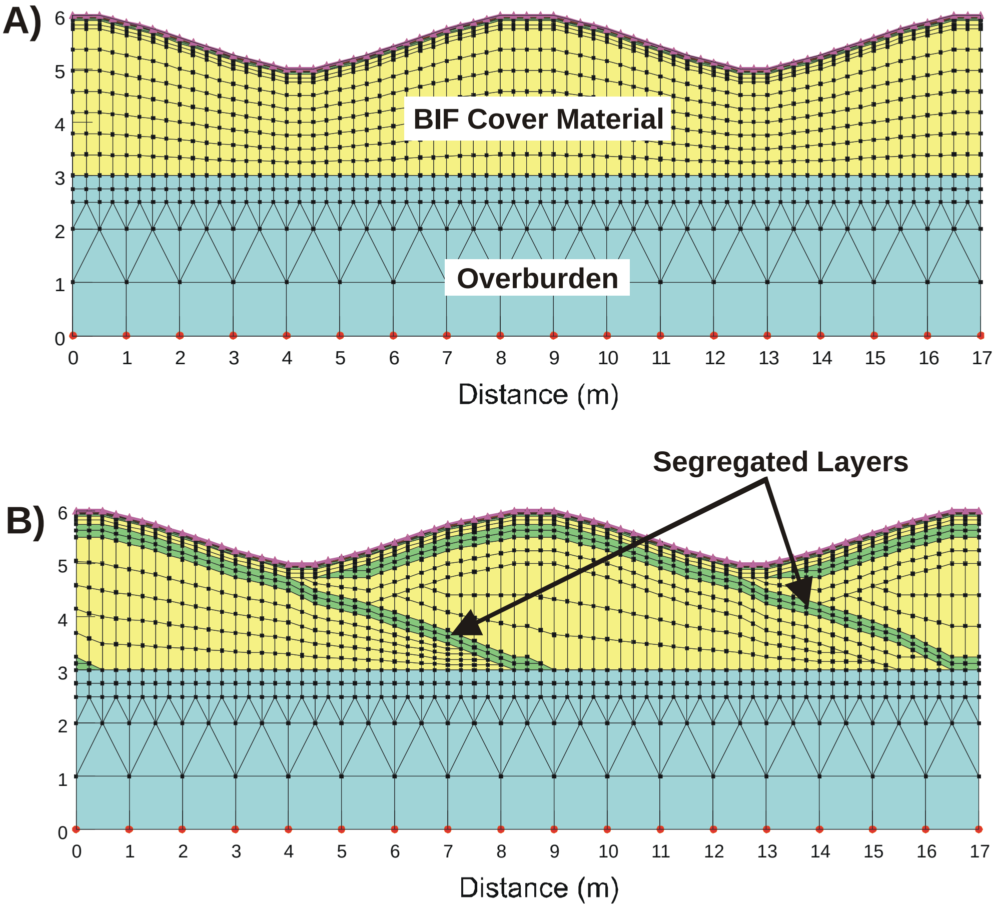

**Figure B1.9** a) Mesh used in the 2-D analysis of the Mt. Whaleback hummocky cover system.
b) Coarse-textured segregation layers added to the 2-D mesh.

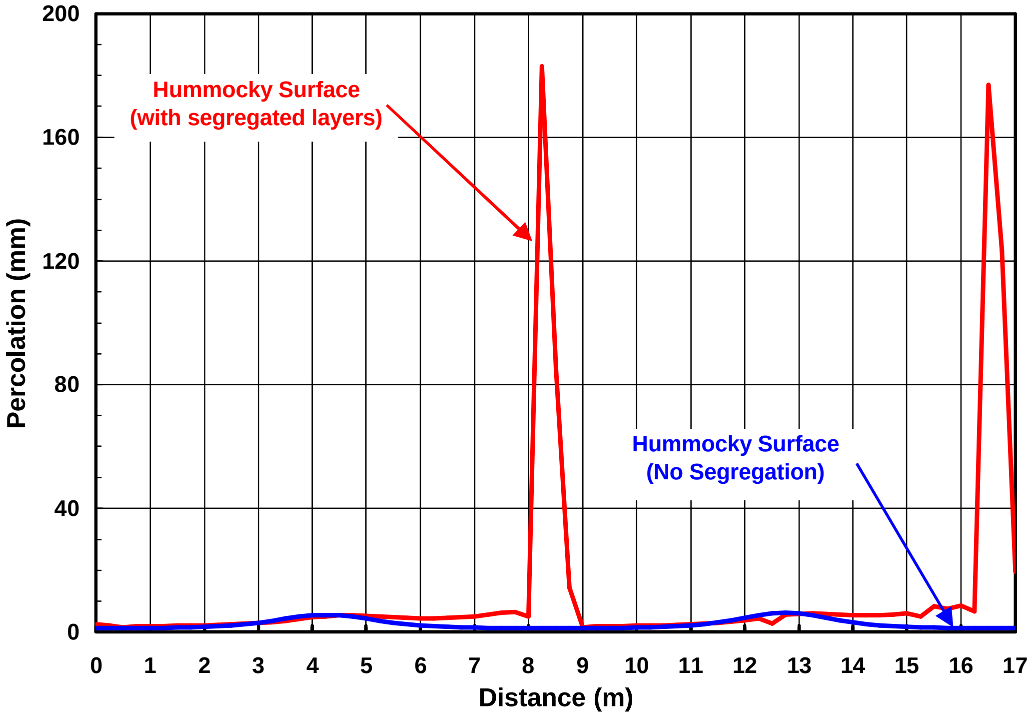

**Figure B1.10** Net percolation results predicted for the Mt. Whaleback BIF cover systems.

The segregation layer produces a preferential flow path for meteoric waters to infiltrate to the underlying overburden material. Macropore flow occurs in these areas resulting in high hydraulic conductivity rates causing rapid percolation to the underlying overburden material. The effects of segregation have been observed at both horizontal surface test plots at the Mt. Whaleback site. Volumetric water content sensors will show quick responses to extreme rainfall events at depths up to two to three metres, which suggest high hydraulic conductivity flow paths exist within the test plot. Once the meteoric waters percolate to these depths, it is an extremely slow process to "pull" the moisture back to the surface because the moisture must exfiltrate within the finer-textured matrix material. Segregation has an adverse effect on store and release cover systems because the preferential 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 or rainfall event.

## 4.0 SUMMARY AND CONCLUSIONS

For this report, the 2 m Test Plot No. 1 Mt. Whaleback cover system trial was evaluated using models and collected field data. The objectives were to:

- Assess the accuracy of the original model inputs and predictions;
- Evaluate the performance of the cover systems since installation;
- Illustrate the capabilities of the latest model programs; and
- Develop an understanding for the key processes and characteristics that control the cover system at the site.

The following is a non-technical summary of the work completed as part of the INAP study. General conclusions and recommended future work to improve the ability to model the cover system are also provided.

- The SWCCs developed from the field measurements were found to differ substantially from the original curves obtained from laboratory measurements. However, the hydraulic conductivity functions were found to be similar, indicating the importance of the hydraulic conductivity function when simulating water movement within soil covers.
- Field response modelling indicated that the updated material properties could accurately predict moisture storage and flow in the TP1 cover system.
- The preliminary predictive modelling scenario was re-run using the updated model. Although the updated model calculated some large differences for the water balance compared to the original model, it still predicted that the cover system would function during the extreme climate year estimated for the preliminary modelling.
- Higher annual rainfall conditions than were input during the preliminary modelling have been recorded since construction of the TP1 site was completed. The model calculated that a non-vegetated cover system would allow a significant amount of percolation to occur during this larger rainfall year. However, if the cover were vegetated, the cover system would perform as designed. Predicted performance of the cover system was good when the larger rainfall year was applied repeatedly.

- VADOSE/W was used to simulate the effect of an undulating cover surface with underlying segregated cover material on performance. The model computed that water flowed down along the coarse textured layers and to the underlying waste rock during extreme rainfall events. Additional field performance monitoring is required to fully understand this phenomenon and its implications on the long-term performance of the cover system.

General Conclusions and Recommended Future Work

- The measurement of suction and water content profiles in the field, in the same location and at the same time, substantially improves the ability to simulate performance of cover systems.
- Vegetation is a major factor that needs to be considered when designing or simulating a cover system. However, it is difficult to develop a defensible prediction of the performance of a vegetated cover system because a knowledge gap exists with respect to transpiration rates and rooting characteristics of native species. Research on transpiration rates and rooting characteristics of native species on reclaimed landform is required to better simulate their impact on the soil-water regime.

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# APPENDIX C1

## Evaluation of the Long-Term Performance of Dry Cover Systems

## Summary of the Field *In Situ* Hydraulic Conductivity Testing Program
at
Equity Silver

# 1.0 INTRODUCTION

An *in situ* saturated hydraulic conductivity testing program was completed in 2002 at Equity Silver, which is located 35 km southeast of Houston and approximately 575 km north northwest of Vancouver, British Columbia. The objective of the study program was to evaluate of any changes in the saturated hydraulic conductivity of cover materials had occurred since placement because, in general, physical, chemical, and biological processes will affect the long-term performance of a dry cover system. These processes will act to change the key properties of the cover materials, such as the saturated hydraulic conductivity and moisture retention characteristics. In cover systems with soil structure (development of cracks, worm holes, root channels, etc.) provide the dominant flow path in the cover materials. The evolution of soil structure with time will significantly alter the saturated hydraulic conductivity of the cover materials.

The field hydraulic conductivity test program investigated:

- The difference in the saturated hydraulic between the oldest and most recently constructed cover systems at the site (i.e. does the cover material evolve due to environment factors); and
- The effectiveness of the non-compacted till overlying growth medium layer in "protecting" the compacted till layer from environmental factors.

# 2.0 THEORY OF *IN SITU* SATURATED HYDRAULIC CONDUCTIVITY TESTING

Measurements of saturated hydraulic conductivity in the unsaturated zone are referred to as the "field-saturated" hydraulic conductivity ($K_{fs}$) (Reynolds *et al.*, 1983). This is in recognition of the fact that air bubbles are usually entrapped in the porous media when it is "saturated" by downward infiltrating water, particularly under ponded conditions. The water content of a porous medium at "field saturation" is consequently lower than at complete or true saturation and depending on the amount of entrapped air, $K_{fs}$ can be lower then that at true saturation conditions. Various methods exist for measuring the $K_{fs}$ of soil, ranging from *in situ* to laboratory procedures. In this study *in situ* measurements of hydraulic conductivity were obtained with the constant head well permeameter and the constant pressure (single-ring) infiltrometer.

Constant head well permeameter methods provide an *in situ* determination of the value of $K_{fs}$ in the unsaturated zone. It involves the measurement of the steady-state infiltration rate required to maintain a steady depth of water in an uncased, cylindrical auger hole that terminates above the water table (Reynolds, 1993). There are several constant head well permeameter methods that differ to varying degrees in theory, procedure, and apparatus. The constant well permeameter technique used in this study is known as the Guelph permeameter method.

The values of $K_{fs}$ that can be measured accurately with the Guelph permeameter range from $1 \times 10^{-2}$ cm/s to $1 \times 10^{-6}$ cm/s. Beyond these limits there is a reduction in accuracy and precision. Values of $K_{fs}$ measured with the Guelph permeameter in this study did not exceed these measurement limits.

Constant pressure infiltrometers involve the measurement of the steady-state infiltration rate required to maintain a steady depth of water (or constant water pressure) within a single ring inserted a small distance into a porous medium. The largest difference between the pressure infiltrometer method and traditional single-ring infiltrometer method is the theoretical treatment of water flow out of the ring and into the unsaturated soil. In the single-ring infiltrometer approach, $K_{fs}$ is determined assuming 1-D vertical flow through and below the ring. However, it is well established that the flow beneath the ring is not 1-D, rather, it diverges laterally due to the capillarity of the unsaturated soil and the hydrostatic pressure of the ponded water in the ring. This divergence that is not accounted for results in an overestimation of $K_{fs}$, particularly in fine-textured soils. Attempts to prevent the flow divergence by adding a concentric outer guard ring have shown to be unsuccessful (Bouwer, 1986). The pressure infiltrometer takes flow divergence into account by using a three-dimensional flow analysis.

The values of $K_{fs}$ that can be measured accurately with the constant pressure infiltrometer range from $1 \times 10^{-7}$ cm/s to $9 \times 10^{-2}$ cm/s. Beyond these limits there is a reduction in accuracy and precision. Values of $K_{fs}$ less than $1 \times 10^{-7}$ cm/s in this study were recorded as a “failed” test.

During the field testing program, the Guelph permeameter was used to measure the saturated hydraulic conductivity of material near the cover surface while the pressure infiltrometer was used to measure hydraulic conductivity at depth. Tests were completed at three different depths within the cover system to allow the analysis of change in saturated hydraulic conductivity with both time (cover systems constructed at different times) and depth.

## 3.0 RESULTS OF THE *IN SITU* SATURATED HYDRAULIC CONDUCTIVITY TESTING

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 metres to greater than 20 metres. 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 metres 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.

Twelve measurements of $K_{fs}$ were made at a depth of 18 cm with the Guelph permeameter for each of the four cover systems at Equity Silver. In addition, three measurements of $K_{fs}$ were taken at each depth of 2 cm, 30 cm, and 70 cm with the pressure infiltrometer. Four measurements of $K_{fs}$ attempted with the pressure infiltrometer at a depth of 70 cm “failed” indicating that the hydraulic conductivity of the material at a depth of 70 cm at these locations was less than the measurement limits of the instrument. Additional pits were excavated to a depth of 70 cm for hydraulic conductivity testing until three successful infiltration tests were completed. Finally, one measurement of dry density was obtained with a sand cone at depths of 2 cm, 30 cm, and 70 cm. These measurements were obtained in pits similar to the ones excavated for hydraulic conductivity testing. Table C2.1 summarises the results of the pressure infiltrometer and Guelph permeameter hydraulic conductivity tests. The number of “failed” hydraulic conductivity tests is included in Table C2.1, it should be noted that if the tests had not failed (i.e. if the measurement range of the pressure infiltrometer has not been exceeded) the average hydraulic conductivity would be slightly lower than the recorded value at these depths.

**Table C2.1**

Summary of Guelph permeameter and pressure infiltrometer tests at Equity Silver (Geometric mean (M), standard deviation (σ), dry density ($\rho_d$)).

| **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 |

Figures C2.1 and C2.2 show $K_{fs}$ and density as a function of depth for the sloped cover systems at the Main and Southern Tail Dump and the relatively horizontal cover systems at the top of the Main Dump and the Bessemer Dump, respectively. Measurements of $K_{fs}$ taken at a depth of 30 cm and 70 cm were completed within the compacted "barrier" layer, with the former depth being the top of the compacted layer. In general, $K_{fs}$ decreased one order of magnitude from the 2 cm depth within the growth medium to the 30 cm depth at the top of the compacted layer, and decreased two additional orders of magnitude from 30 cm to 70 cm. On the sloped cover systems, the dry density was lowest at a depth of 2 cm and increased sharply at 30 cm.

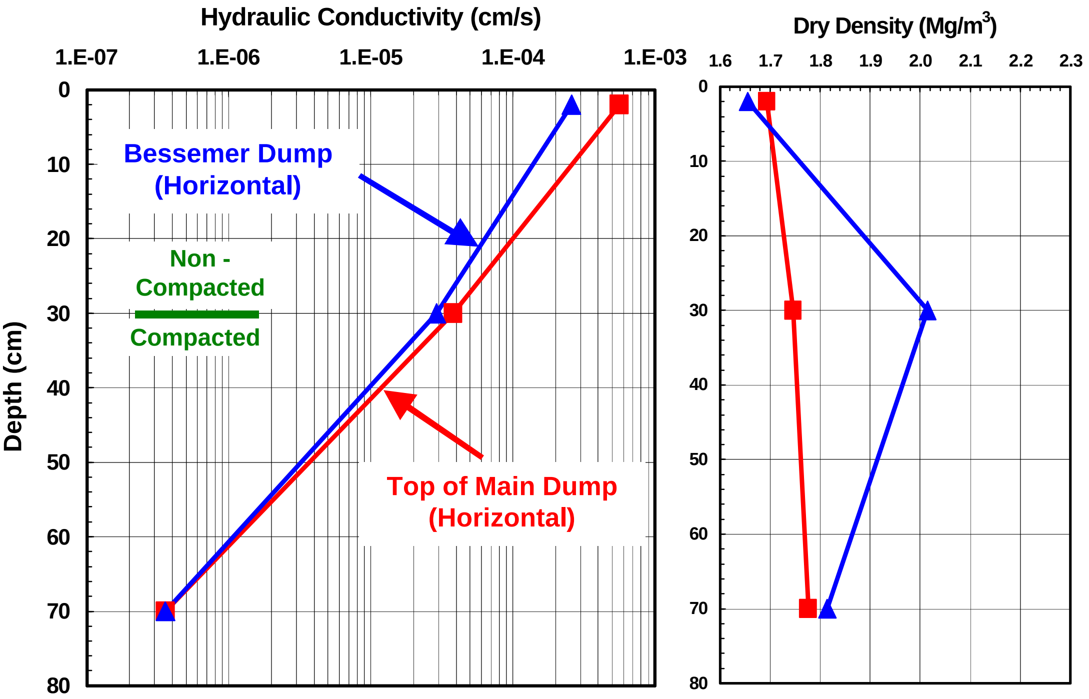

**Figure C2.1** Results of the field saturated hydraulic conductivity tests at the sloping cover systems.

The *in situ* density test results were anticipated as the 30 cm density measurements were made within the compacted layer. Dry density decreased in the Southern Tail Dump cover system as the depth increased to 70 cm.

The density was relatively constant from 30 cm to 70 cm on the Main Dump cover system. The dry density values measured on the relatively horizontal cover systems were similar to the sloping cover systems being lowest at 2 cm, increasing at the top of the compacted layer (30 cm) and staying constant (top of Main Dump) or decreasing (Bessemer Dump) as depth increased to 70 cm.

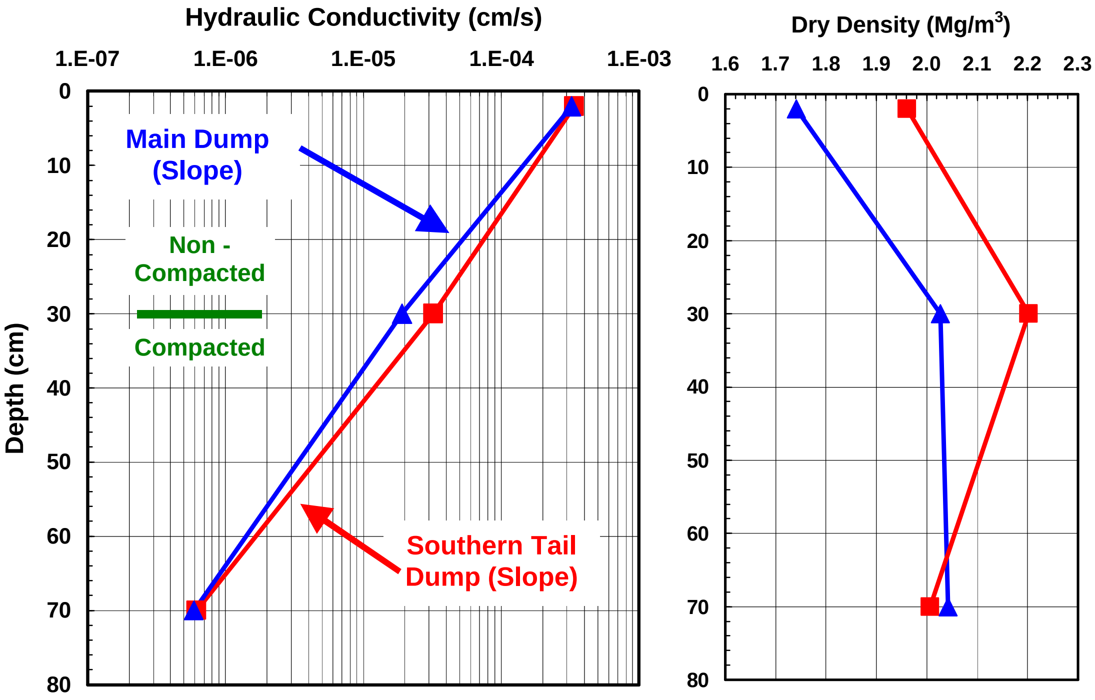

**Figure C2.2** Results of the saturated hydraulic conductivity tests at the relatively horizontal cover systems.

Based on the relationship between density and hydraulic conductivity it was anticipated that values of $K_{fs}$ measured at a depth of 30 cm (i.e. at the top of the compacted layer) 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 are two orders of magnitude greater than at 70 cm. It is reasonable to hypothesis that the increase in hydraulic conductivity would be 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, more than likely due to the presence of the overlying growth medium as well as snow cover. However, matric suction sensors and neutron moisture probe measurements indicate that wet / dry cycles started occurring in the upper 10 cm of the compacted layer approximately three years ago and have continued in each subsequent summer. Matric suction values measured during the summer in the compacted layer have fluctuated between 400 kPa and 1,000 kPa, significantly higher than the air entry value of the compacted cover material. 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 hydraulic conductivity measured at the top of the layer, as compared to the lower values measured at a depth of 70 cm. Periodic *in situ* water content measurements obtained using the neutron moisture probe support the automated matric suction measurements.

Figure C2.3 is a cumulative histogram of $K_{fs}$ values measured at 18 cm with the Guelph permeameter for the four cover systems. The sloping cover systems at the Main and Southern Tail Dump were both completed in the same year. Figure C2.3 shows that the distribution of $K_{fs}$ for the cover systems is similar. Each cover system was exposed to environmental conditions for the same period of time. If the hydraulic conductivity of these cover systems are evolving the $K_{fs}$ measured should be similar due to exposure to the same conditions over a the same time frame. The cover system on the top of the Main dump was also completed 12 years ago while the Bessemer Dump cover system was constructed nine years ago. The distribution of $K_{fs}$ values for the top of the Main Dump is located in the range of increased hydraulic conductivity as compared to the Bessemer Dump. For example, 50% of $K_{fs}$ values for the top of the Main Dump cover system are higher than 5 x $10^{-4}$ cm/s while only 16% of the $K_{fs}$ values for the Bessemer Dump cover system are greater than 5 x $10^{-4}$ cm/s. These results seem to suggest that the hydraulic conductivity has evolved to a greater degree for the top of the Main Dump as compared to the Bessemer Dump, possibly due to the former cover system responding to the site's environmental conditions over a longer time frame. The distribution of $K_{fs}$ for cover systems placed on the sloping surface should not be compared to the horizontal surface cover systems. This is due to the inability to determine if factors driving the evolution of $K_{fs}$ are present at both locations.

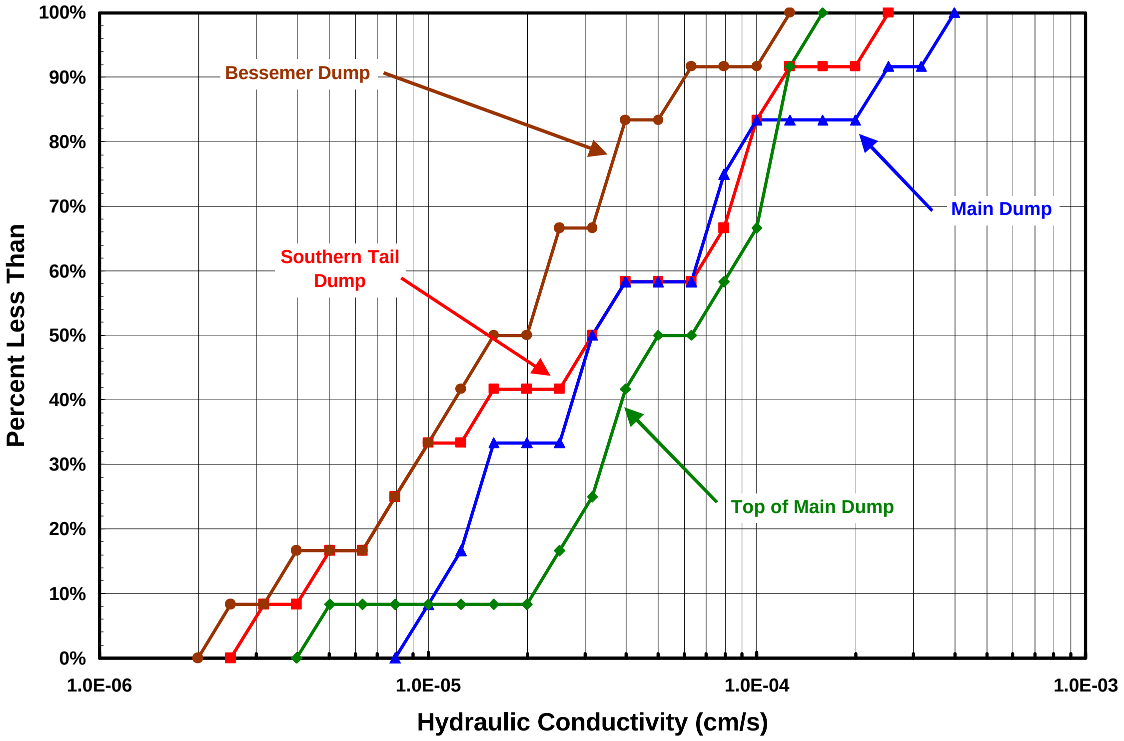

**Figure C2.3** Cumulative histogram summarising the saturated hydraulic conductivity measurements at Equity Silver.

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# APPENDIX C2

## Evaluation of the Long-Term Performance of Dry Cover Systems

## Evaluation of the Equity Silver Full-Scale Cover Systems using a State-of-the-Art Soil-Atmosphere Numerical Model

## EXECUTIVE SUMMARY

The performance of the full-scale dry cover system at the Equity Silver Division of Placer Dome Canada Ltd., located in British Columbia, Canada was evaluated using the most recent version of the SoilCover soil-atmosphere numerical model.

Swanson (1995) performed the preliminary modelling of Equity Silver's soil cover system using the one-dimensional computer program SoilCover Version 1.0 (MEND, 1993). The original model results were found to be repeatable using the most recent version of the SoilCover modelling program. However, updating the model inputs using more recent field data was difficult due to the limited amount of field data available. The performance of the cover system during recent years was simulated using the Swanson (1995) model inputs. The SoilCover model predicted low net percolation rates that achieve the cover system design requirements. However, adding vegetation influences or updating the saturated hydraulic conductivity of the cover materials with recent field *in situ* measurements significantly reduced the performance of the cover with respect to oxygen ingress. The net percolation predicted with the most recent version of the 1-D SoilCover model was similar to that predicted by Swanson (1995).

# 1.0 INTRODUCTION

Numerical models are valuable tools to help understand the processes controlling the performance of soil cover systems. In this appendix, Equity Silver's full-scale cover system, which had been previously modelled shortly after construction, was evaluated using the most recent version of the 1-D SoilCover numerical model and collected field data. The objectives of this work are to:

- Assess the accuracy of the original model inputs and predictions;
- Evaluate the performance of the cover systems since installation;
- Illustrate the capabilities of the latest model programs; and
- Develop further understanding for the key processes and characteristics controlling cover system performance at the site.

## *1.1 Background*

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 metres 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.

Instrumentation to monitor performance of the cover system was installed in late 1992 with data collection beginning in the spring of 1993. Figure C2.1 shows the location of the instrumentation, which included an automated meteorological station, 14 neutron probe access tube locations, and three automated instrumentation stations monitoring matric suction and temperature profiles within the cover material and underlying waste rock (O'Kane, 1995). The location of the three automated instrumentation stations are referred to as the top of the Main dump (TMD), the southwest face of the Main dump (SWF), and the Southern Tail dump (STD). The instrumentation has been monitored continuously since 1993; however, numerous sensors have stopped functioning in the past four to five years, which when coupled with infrequent manual neutron probe measurements, resulted in significant difficulty modelling the current cover system conditions. This issue will be discussed in the following sections, but in short, the lack of consistent automated field data (suction and water content) made it difficult to develop field SWCCs and k-functions, which resulted in difficulty calibrating the newest version of the 1-D SoilCover model. It is important to note however, that the sensors installed in 1992 were state-of-the-art, and were functional for a reasonable length of time. This problem highlights the importance of conducting routine data management to ensure data capture rates are maintained.

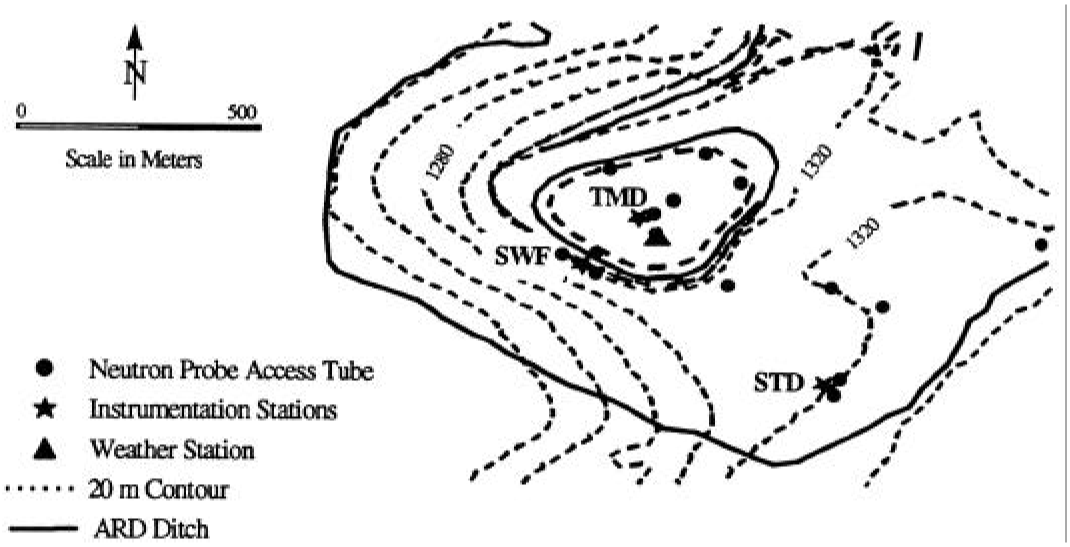

**Figure C2.1** Location of the instrumentation at Equity Silver (after O'Kane, 1995).

Swanson (1995) completed the preliminary modelling of the soil cover system using the 1-D SoilCover Version 1.0 program (MEND, 1993). The following sections will revisit and continue this modelling using the newest version of the program, SoilCover 2000 Version 5.2 (GeoAnalysis2000, 2000).

# 2.0 EVALUATION OF ORIGINAL MODEL

Swanson (1995) simulated the field responses measured at the TMD instrumentation station from June 4 to November 4, 1993 to develop a set of model inputs. This modelling was repeated as part of the INAP study reported herein to evaluate the preliminary model inputs and to test the SoilCover 2000 program. The model was then used to simulate field responses measured since 1993. The following sections describe this work.

## *2.1 Material Properties*

The model results were made to reasonably correlate with the measured field responses during the preliminary modelling process by modifying the SWCCs and saturated hydraulic conductivity of the loose and compacted tills measured in the laboratory. The SWCCs were adjusted to correspond to moisture content and suction readings obtained in the field. Figure C2.2 shows the SWCCs developed for the preliminary model.

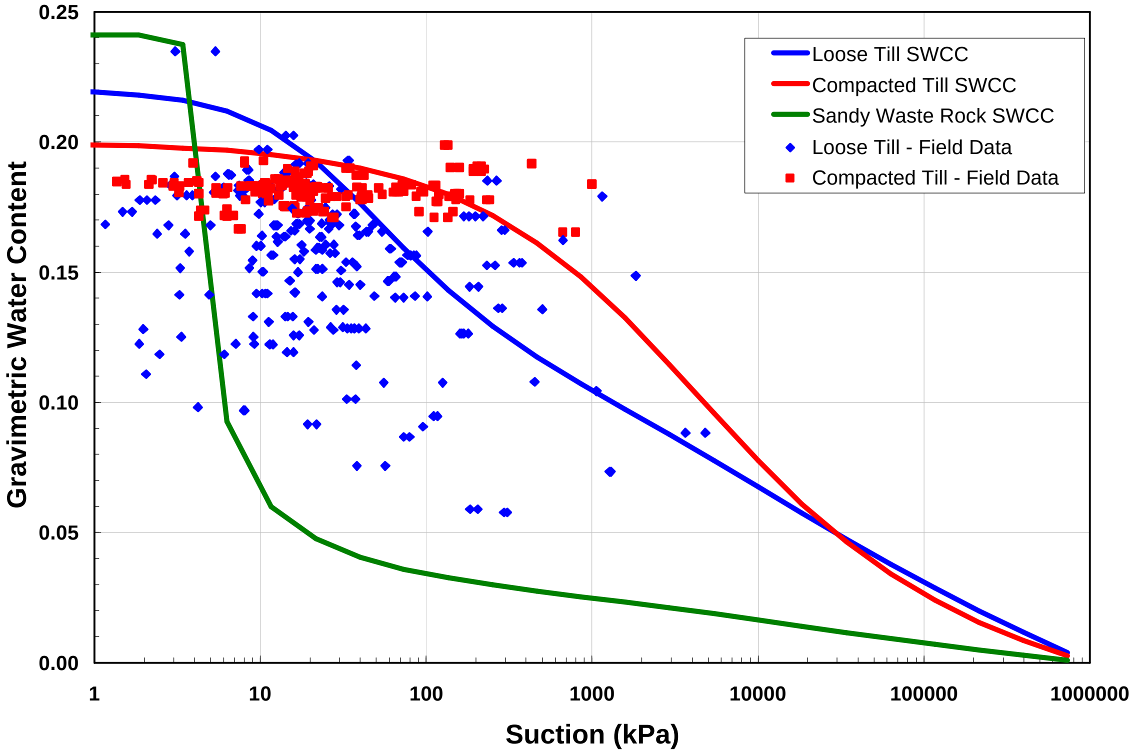

**Figure C2.2** Soil-water characteristic curves developed by Swanson (1995) compared to field data collected since 1993.

The field data points included in Figure C2.2 were generated by pairing the matric suction measurements, collected at the three instrumentation stations, with the *in situ* moisture content measured at an adjacent neutron probe access tube. Approximately 30 measurements have been obtained at each of these neutron probe access tubes since 1993. The infrequency of these measurements limits the amount of generated points, which reduces the ability to define the SWCCs of the materials. For example, the points that were generated for the loose till layer are too random to suggest a defensible update to the preliminary SWCC. The randomness of this data may be an indication that the properties of the loose cover material differ spatially, but there is not enough data available to offer a definitive conclusion to this hypothesis. The data recorded for the compacted till layer field data has a pattern, but does not differ significantly from the preliminary SWCC to warrant a change. There was no new data available for the waste rock material; hence the updated models used SWCC developed during the preliminary modelling.

Figure C2.3 shows the hydraulic conductivity functions developed by Swanson (1995) for the preliminary models. To generate these curves, the saturated hydraulic conductivity values for the loose till were adjusted so that computed peaks in matric suction corresponded to measured peaks throughout the simulation period used for the field response modelling. Note that there are three hydraulic conductivity functions for the loose till. Swanson (1995) found that the simulation was improved by sub-dividing the loose till layer into three secondary layers:

- “top” loose till – top 10 cm of the cover;
- “middle” loose till – layer between 10 and 20 cm depth; and
- “bottom” loose till – layer between 20 and 30 cm depth.

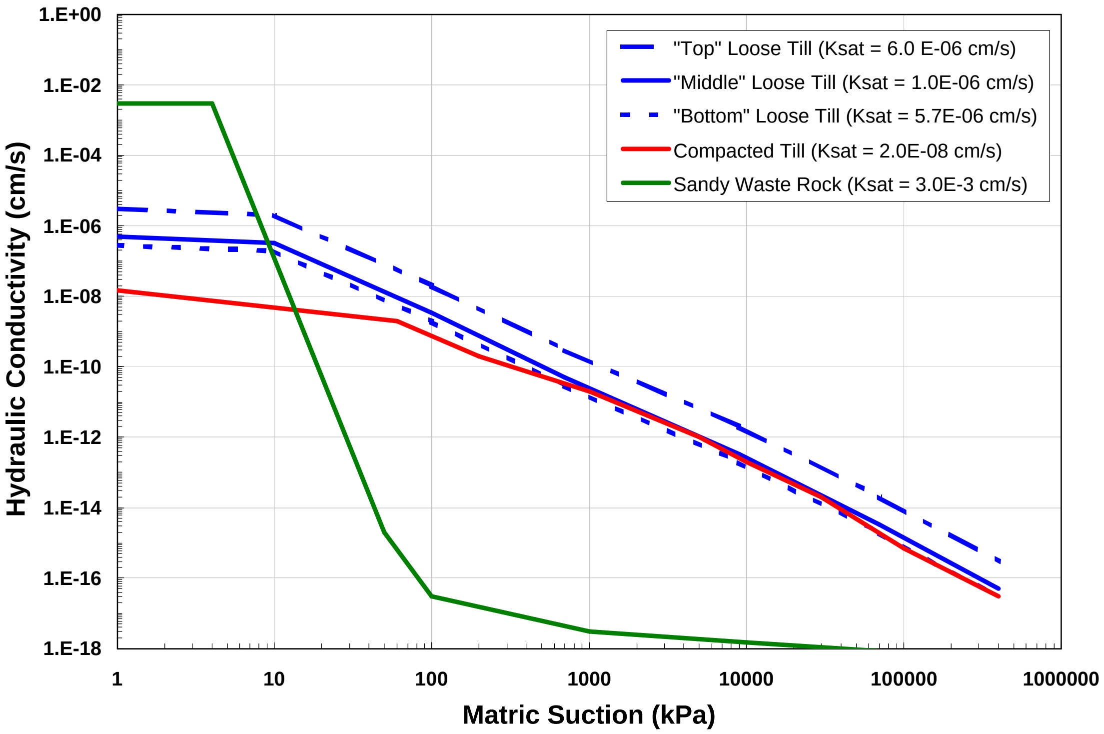

**Figure C2.3** Unsaturated hydraulic conductivity functions for the cover materials and waste rock (after Swanson, 1995).

Field saturated hydraulic conductivity ($K_{fs}$) measurements were obtained at the site for the compacted till layer as part of the INAP study reported herein (refer to Appendix C1). These measurements found that the $K_{fs}$ of the top 10 cm of the compacted till layer was, on average, $3 \times 10^{-5}$ cm/s, and for the bottom 40 cm of the layer was, on average, approximately $4 \times 10^{-7}$ cm/s. The effect of these changes on the simulations will be evaluated in a following section. Although it is important to note that the $K_{fs}$ measured for the lower 40 cm of the compacted layer does not account for "failed" $K_{fs}$ measurements, which occur when the field conditions exceed the measurement range of the pressure infiltrometer (i.e. values are less than approximately 1 x $10^{-7}$ cm/s).

The specific gravity and porosity of the cover materials and waste rock were estimated from field and laboratory measurements for the preliminary models. The specific gravity for all the materials was assumed to be 2.9 while the porosity of the cover materials and waste rock were set at 0.35 and 0.30, respectively. The values were not changed for the current models.

## *2.2 Field Response Modelling Results for Original Simulation Period (1993)*

Figure C2.4 shows the cumulative water balance for the 153-day simulation calculated using the SoilCover 2000 program. The numbers in parentheses are the original results from the preliminary modelling. Both models calculated similar results, indicating that any changes to the SoilCover program have not altered the preliminary modelling predictions.

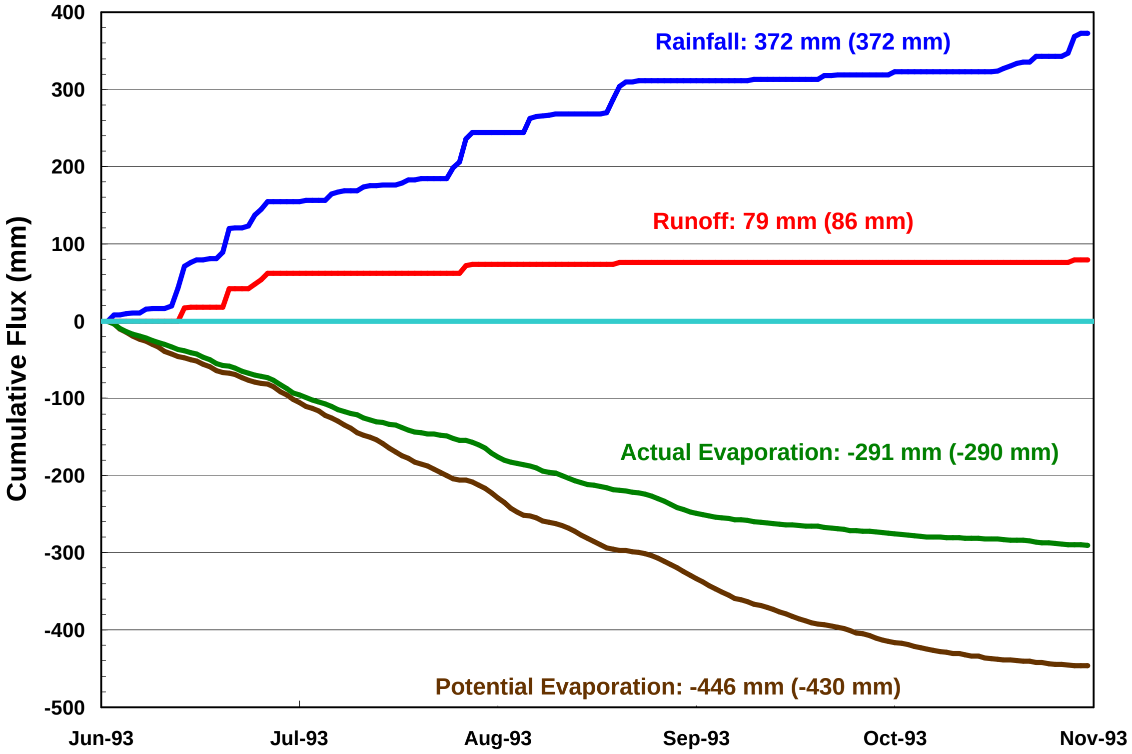

**Figure C2.4** Simulated cumulative fluxes for the original simulation period using SoilCover 2000. Positive values indicate water entering the cover system; negative values indicate water leaving the cover system (numbers in parentheses represent Swanson (1995) model results).

A comparison between the measured and modelled matric suction responses at two depths in the soil cover is shown in Figure C2.5. The model produces a reasonable match to the data measured at the TMD instrumentation station, and similar to that predicted by Swanson (1995). However, the model results do not compare well to the measurements obtained at the STD instrumentation station, indicating spatial variability between the two sites. The variability may be due to a number of factors such as; different soil properties; time of cover placement; development of preferential flow paths; and variations in climate between the two sites. Differing soil properties are likely the largest contributor to the variations. The soil properties at the STD site could be estimated by simulating the measured field response, in the same way as was done for the TMD site. However, this is a difficult task since water content profiles are only measured occasionally and not in the same location as the matric suction sensors. Therefore, a limited amount of SWCC points can be estimated directly from the field data.

The limited number of field measurements means that water content profiles can only be compared a few times during the simulation period, increasing uncertainty in the model. This is best illustrated in Figure C2.6. Field measurements of the gravimetric water content profile in the cover system were obtained on five separate occasions during the simulation period. These measurements were used to estimate the cumulative change in storage in the cover system. At first glance, the measured and modelled values seem to be quite similar. However, the daily computed results reveal a much more dynamic system than the five sampling dates indicate. When the daily computed responses are compared concurrently with the matric suction responses (Figure C2.5) some questions arise as to the accuracy of the model, particularly near the end of the simulation period. For example, the suction measurements seem to indicate that the cover was drier before the water content profile measured on September 30, 1993, and that it may have desiccated further after that date. The model, on the other hand, simulates a continuous drying of the cover material and does not show that the cover system was drier prior to the end of September. This may indicate that the model does not accurately simulate the cover system during dry conditions. Further evidence of this is provided in the next section.

In general, the Swanson (1995) model is a good simulation given the limited amount of available data. If both matric suction and water content profiles had been measured in unison throughout the cover profile, a more accurate model could be produced with a higher degree of certainty in the results. Without this data, the Swanson model inputs cannot be easily re-adjusted as the dynamics of the cover system change with time.

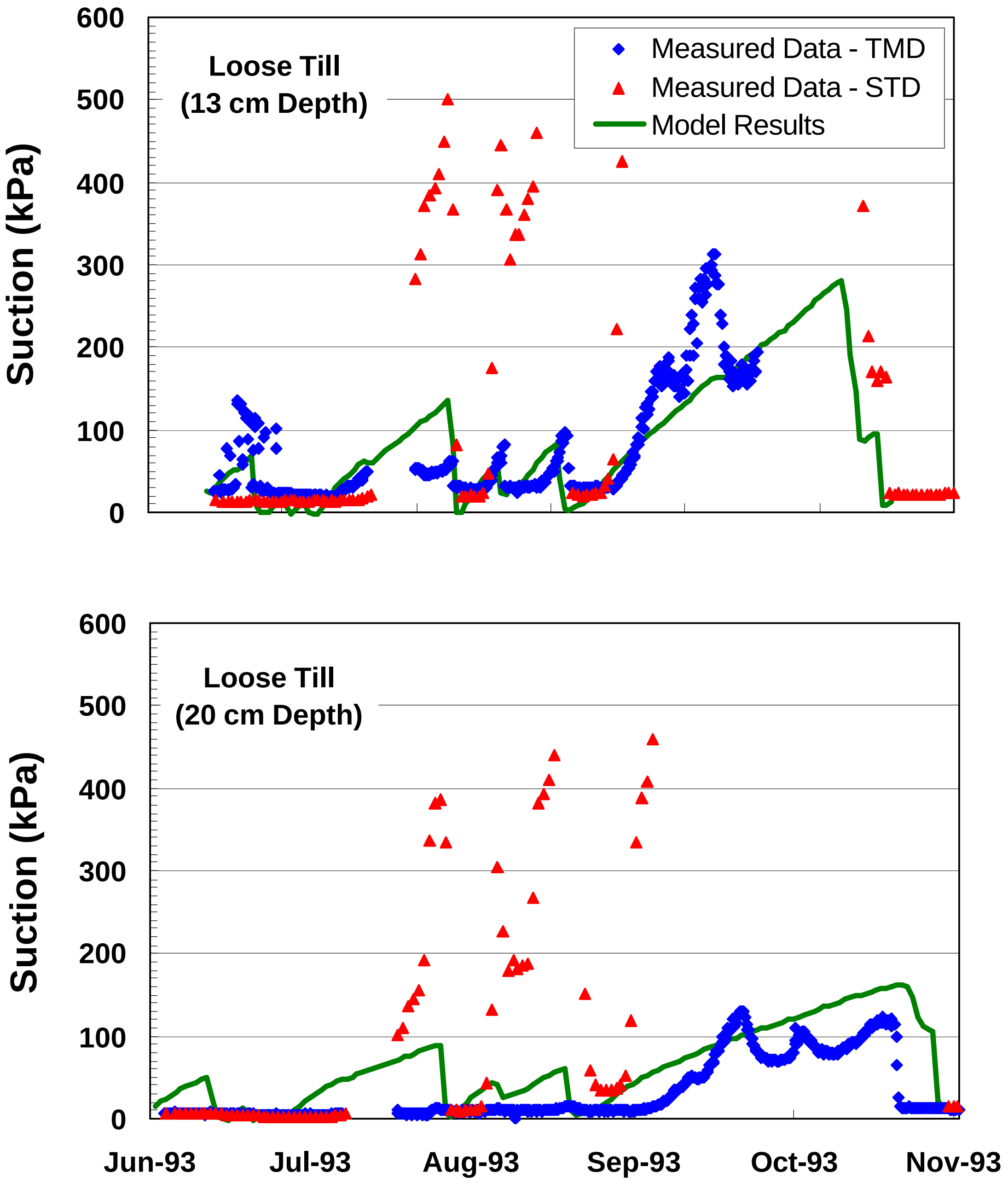

**Figure C2.5** Comparison of the modeled matric suction responses to the responses measured at the TMD and STD instrumentation stations at two depths in the soil cover for the original simulation period.

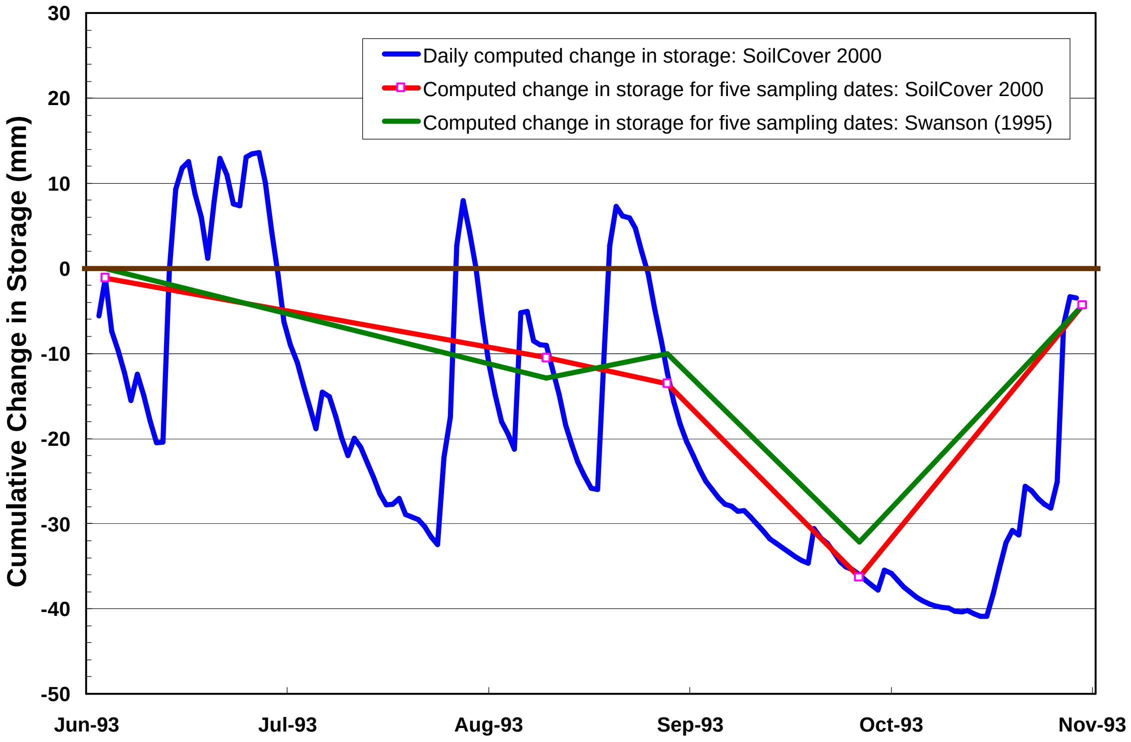

**Figure C2.6** Measured and computed change in storage per unit area for the cover system monitored at the TMD instrumentation station for the original simulation period.

## 3.0 SIMULATION OF RECENT FIELD PERFORMANCE (1998-2002)

The model inputs developed by Swanson (1995) were used to simulate the periods of April 2 to October 31, 1998, and April 15 to October 31 for the years of 1999 to 2002. The years 1994 to 1997 were not simulated because the automated meteorological station was not fully operational for key times during these years. It should also be noted that the maximum and minimum air temperatures used for the model after June 5, 2000, were assumed to be the daily averages measured at Smithers, British Columbia. This was done because the temperature measurements recorded by the weather station were inaccurate after this date.

The initial water content profile for the cover system was taken from field measurements collected on April 2, 1998. The initial conditions for subsequent years were assumed to be the same as the final conditions for the previously simulated year. The precipitation that fell between simulation periods was assumed to be stored on the surface of the cover as snow. This precipitation was applied to the cover system during the first 15 days of the model to simulate snowmelt.

Figure C2.7 shows the cumulative water balance for the five simulation periods. During the five periods, 1,550 mm of precipitation was applied to the cover system. The model simulated that the cover lost 1,570 mm to actual evaporation and that 21 mm of runoff occurred. The simulation predicted that there would be a net upward flux from the waste rock.

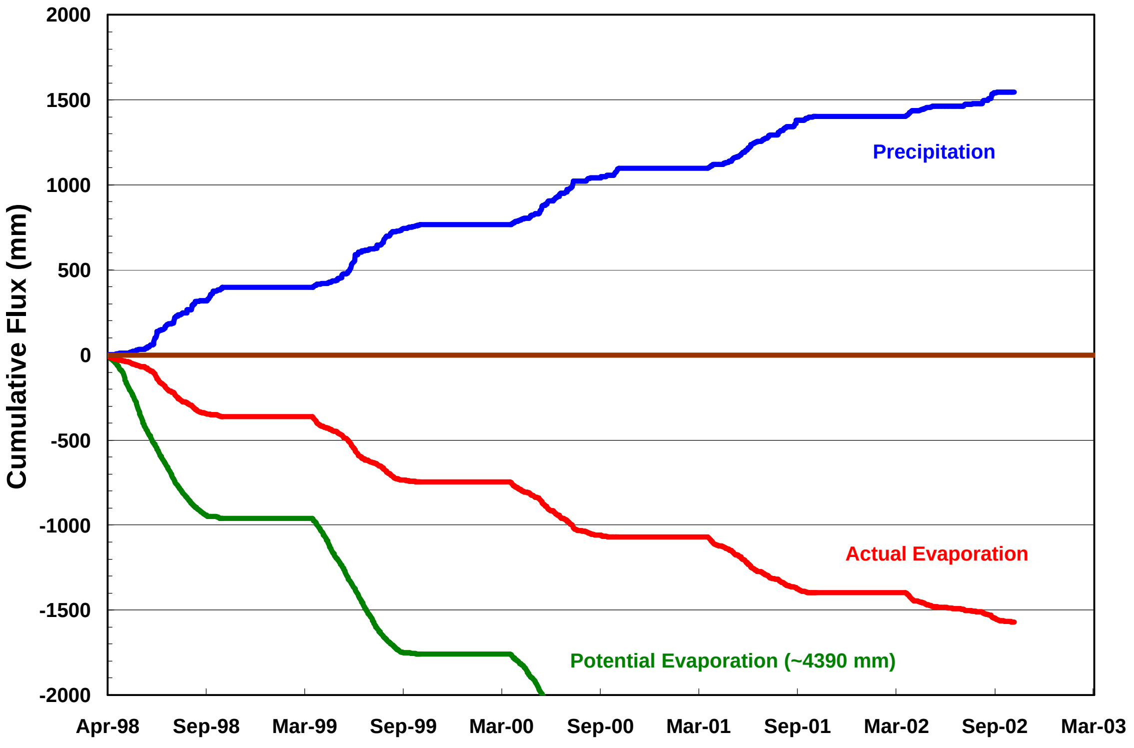

**Figure C2.7** Simulated cumulative fluxes for the recent simulation periods. Positive values indicate water entering the cover system; negative values indicate water leaving the cover system.

Figure C2.8 shows a comparison between the measured and modelled matric suction response at two depths in the soil cover system during the simulation periods. Note that there are no measurements available from the TMD site at 13 cm depth after May 15, 2000. The suction sensor at this depth stopped providing reliable data after this date. In fact, of the 24 suction sensors installed at the site, nine are still operational (1 at TMD, 7 at STD, and 1 at SWF). This creates difficulty from a modelling standpoint, as matric suction is the only continuously monitored soil response available for evaluating the performance of the cover system.

Figure C2.8 also shows that the model does not accurately simulate cover system performance at high suctions (i.e. when the cover is dry). This issue was discussed in the previous section and is further verified by the results given in Figure C2.9. Figure C2.9 shows that the model results always predict the volume of water contained within the cover to be at the "high end", or greater than the volume of water measured at the three instrumentation sites.

The models were completed two more times after the simulations were completed using the original model inputs, with two key inputs adjusted to see what effect these changes would have on the predicted cover system performance. The first simulation involved updating the saturated hydraulic conductivities of the cover materials to reflect the field measurements obtained at the site in 2002. Using these measurements the cover was modelled as three layers; a 40 cm base layer of compacted till with a saturated hydraulic conductivity of 4 x $10^{-7}$ cm/s; a 10 cm layer of compacted till overlying the base layer with a saturated hydraulic conductivity of 3 x $10^{-5}$ cm/s and; a 30 cm surface layer of loose till with a saturated hydraulic conductivity of 3 x $10^{-5}$ cm/s.

The effect of vegetation on the cover was simulated for the second scenario. The vegetation season was set to start on May 1 and continue until October 31. The vegetation was assumed to be rooted for the entire thickness of the non-compacted layer (30 cm) and have a maximum leaf area index of 1, representing a "poor" vegetative cover. As seen in Figure C2.9, both these simulations predicted the cover material to be drier than the field measurements. Both changes are likely influencing the measured field responses but are likely occurring at the same time as other changes to the cover system that have not been measured (e.g. changes in the soil water characteristics; development of soil structure and preferential flow systems). For the first simulation, the hydraulic conductivity of the cover materials were likely less in 1998 than what was measured in 2002, however, the measured changes were applied for all the simulation periods. The vegetation for the second scenario was set to grow for the same period, with the same canopy and rooting depth, for each year simulated. This is an over-simplification of a complex variable as the water-use of the plants on the cover depends on a multitude of factors such as species, climate, and soil conditions. The simulation of vegetation could be improved by researching the growth behavior of the dominant species on the cover during these years.

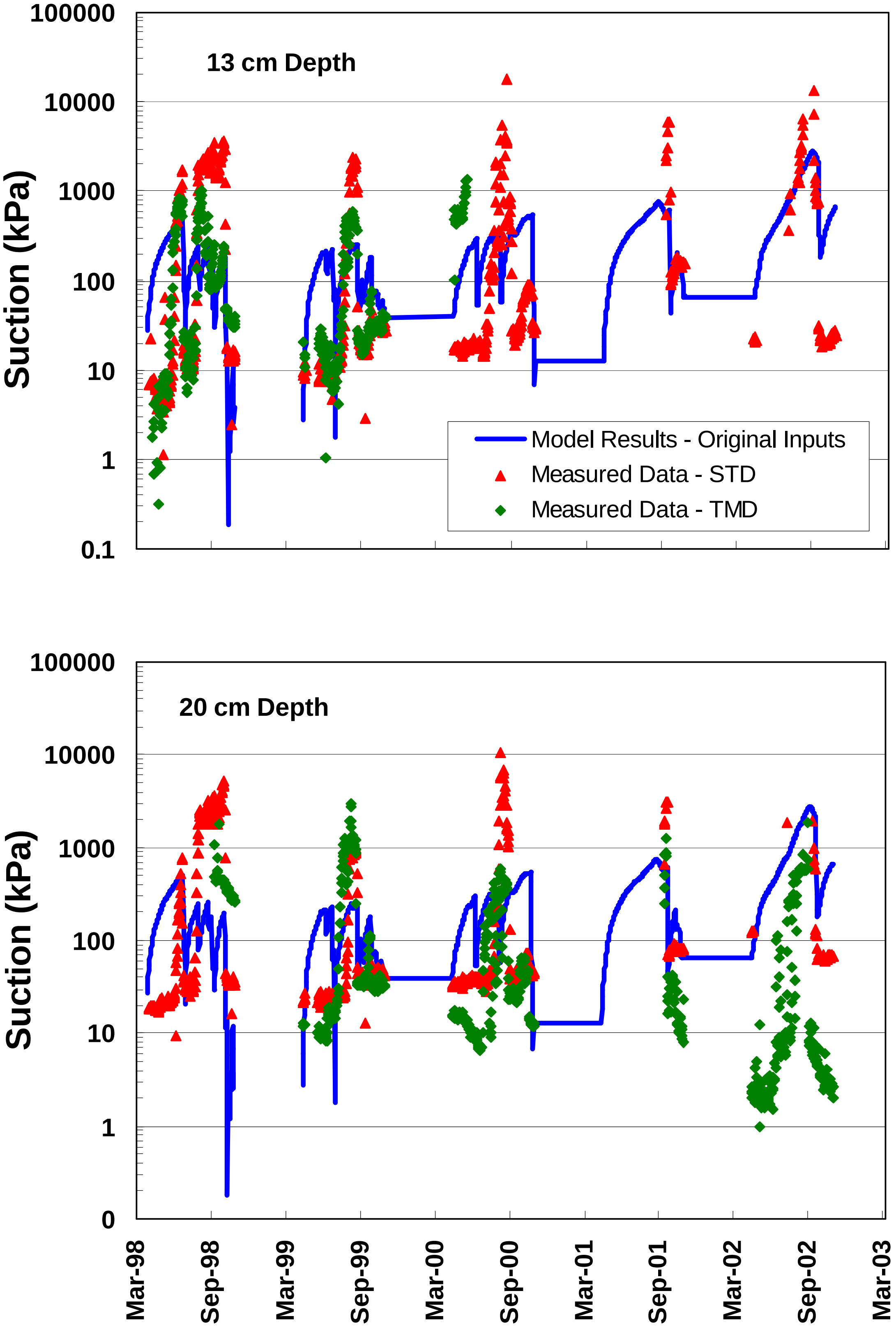

**Figure C2.8** Comparison of the computed matric suction responses to the responses measured at the TMD and STD instrumentation stations at two depths in the soil cover for the recent simulation periods.

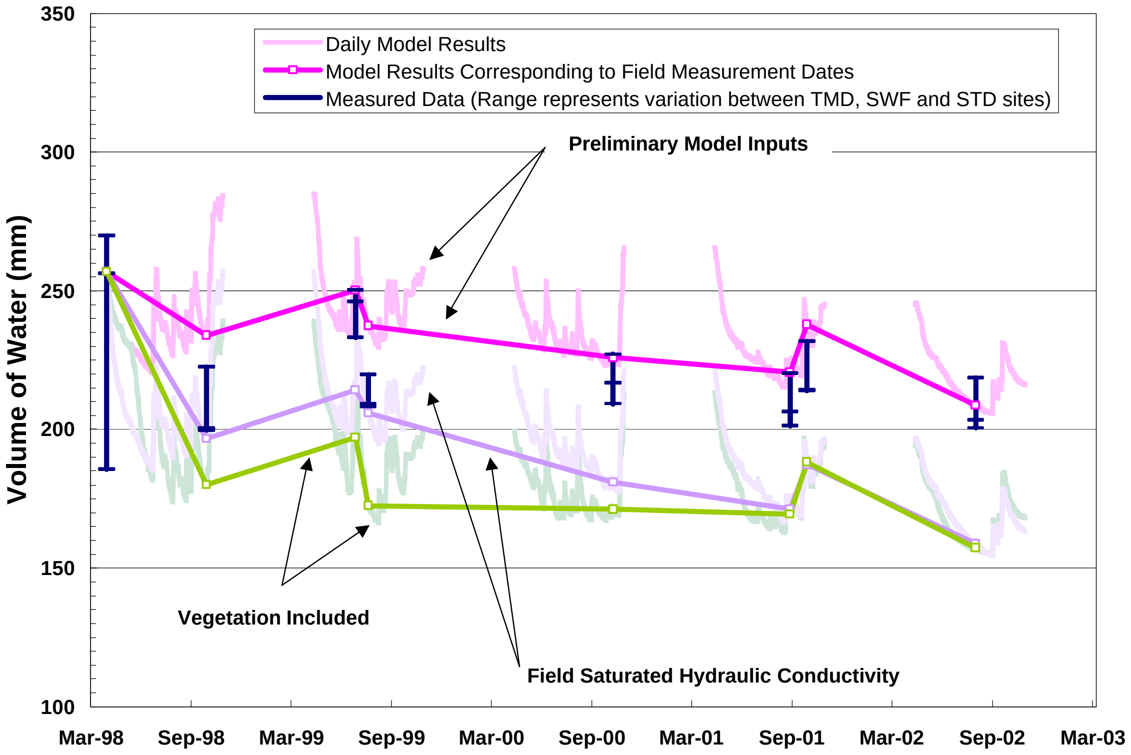

**Figure C2.9** Cumulative volume of water within Equity Silver's cover system for the recent simulation periods.

Figure C2.10 shows the predicted oxygen mass flux through the cover for each simulation year. The drier cover material conditions leads to an increase in the mass of oxygen predicted to ingress to the underlying waste material. Having said this, if the cover system is operating as predicted by the original model, as the measured data suggests, the amount of oxygen permeating the cover is minimal. Oxygen monitoring at the site indicates concentrations in the waste rock dump is spatially and temporally variable. Hence, it is difficult to quantify which model is more representative, but it would appear that conditions modelled by some combination of the two models is likely occurring at the site. Further field performance monitoring is required to continue to develop an understanding for the oxygen mass flux into the underlying waste rock.

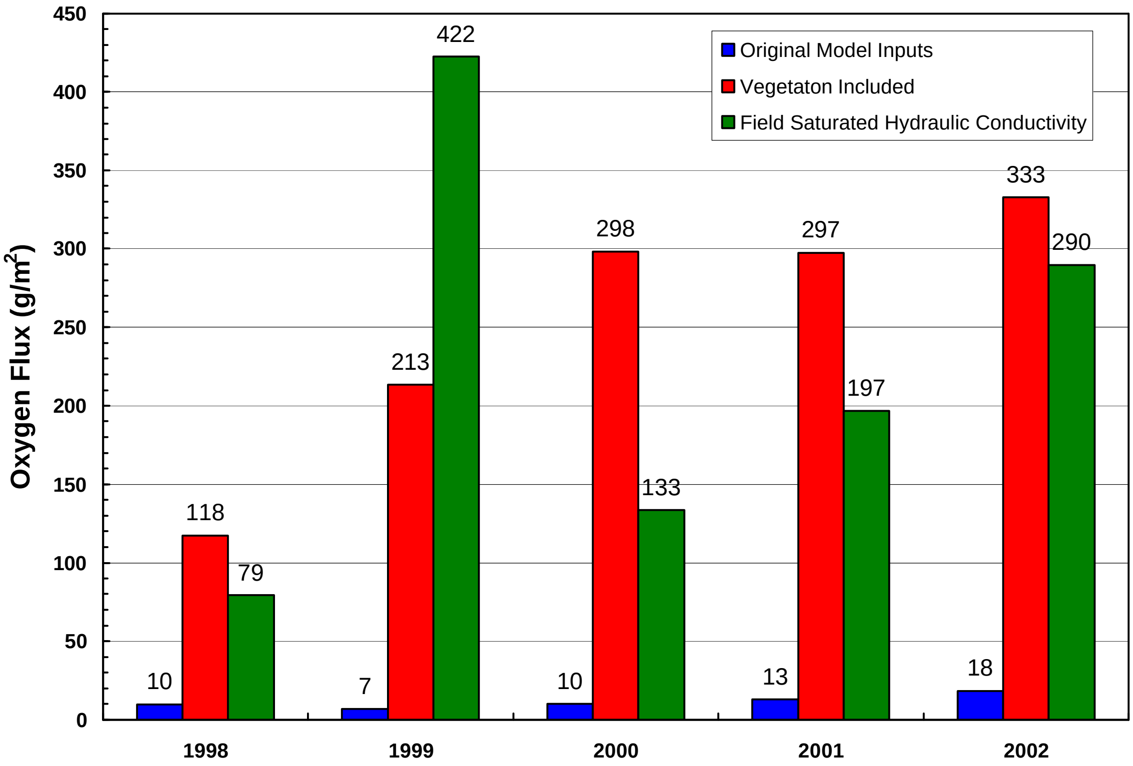

**Figure C2.10** Predicted annual oxygen mass flux through Equity Silver's cover system for each of the recent simulation years.

### 3.1 Comparison of Predicted Performance Using Uni-Model and Multi-Modal SWCCs

The SWCCs used to represent Equity Silver's cover materials and input to the models discussed above were all assumed to be "uni-modal". That is, the shape of the SWCCs was defined by a single air entry value, which corresponded, in general, to the suction condition that led to de-saturation of the cover materials (see Figures C2.2 and C2.3). However, Shurniak (2003) demonstrated that multi-model SWCCs and k-functions can develop in high clay content till cover material (refer to Appendix D1, summary of the Syncrude Canada Ltd. case study). The till cover material at Equity Silver is also a high clay content till. Hence, it can be hypothesised that due to the development of soil structure in response to wet / dry and freeze / thaw cycling at Equity Silver, the cover material at this site may also have evolved from one that possesses uni-modal SWCCs and k-functions, to one that possesses multi-modal SWCCs and k-functions.

It must be noted that there is no cover system field performance monitoring data for Equity Silver site to verify this hypothesis. Although, the $K_{fs}$ measured at Equity Silver, and the corresponding histograms developed using the $K_{fs}$ data, are similar to that measured at Syncrude Canada, which lends some credence to the hypothesis.

Multi-modal field SWCCs and k-functions, shown in Figures C2.11 and C2.12, respectively, were estimated based on the uni-model SWCCs and k-functions shown in Figures C2.2 and C2.3, respectively, and Shurniak's (2003) research.

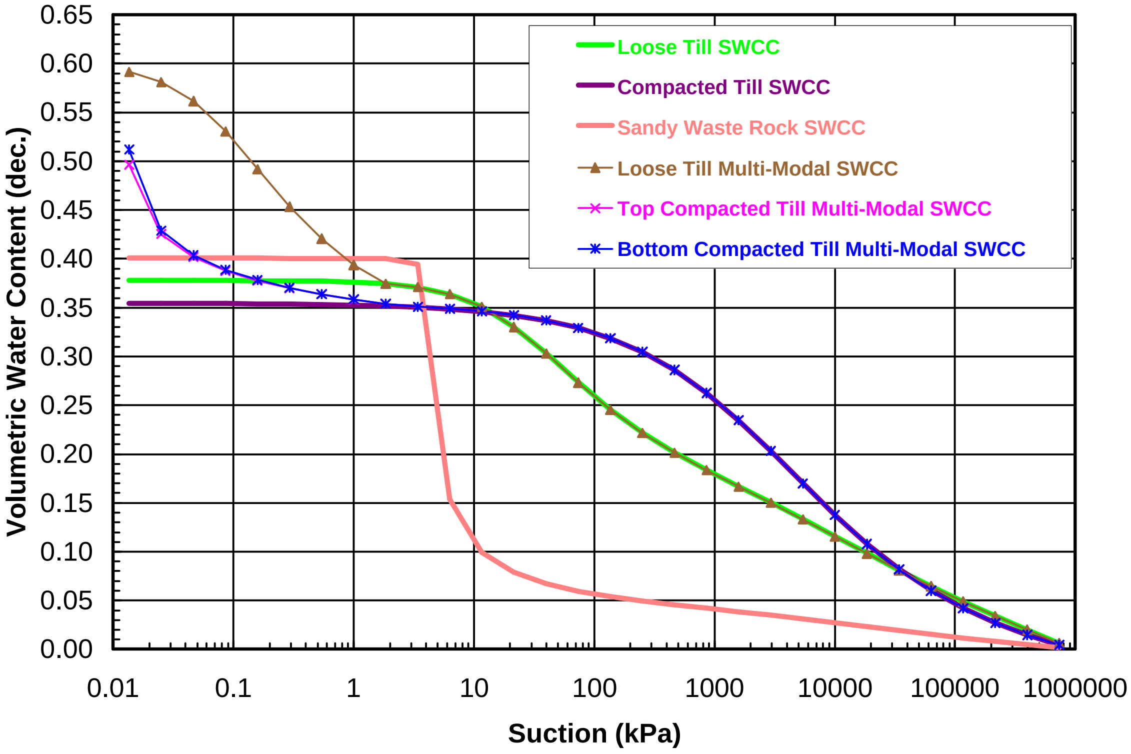

**Figure C2.11** Multi-modal soil water characteristic curves estimated for Equity Silver's cover material compared to uni-modal curves developed by Swanson (1995).

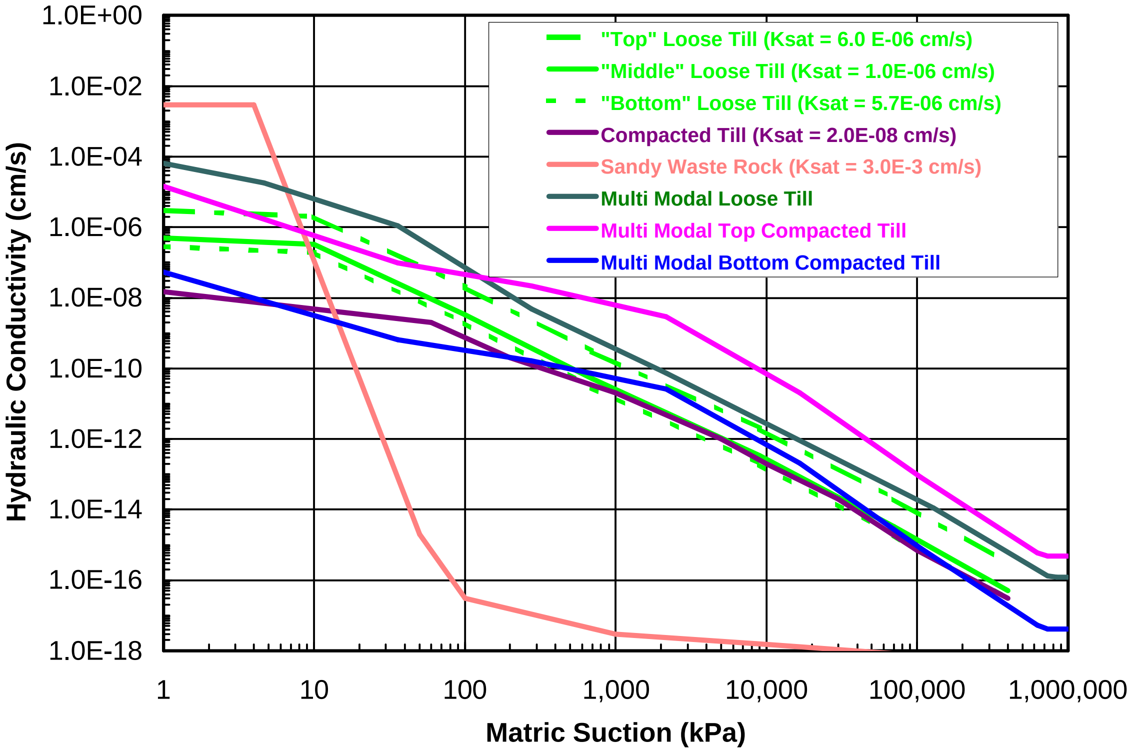

**Figure C2.12** Multi-modal k-functions estimated for Equity Silver's cover material compared to uni-modal k-functions developed by Swanson (1995).

The multi-modal SWCCs and k-functions, shown in Figures C2.11 and C2.12, respectively, were input to the SoilCover model and the compared to the uni-modal SoilCover model results. Figure C.2.13 shows the cumulative volume of water in the cover material predicted by the uni-modal and multi-modal numerical models in comparison to the neutron moisture probe *in situ* moisture content data. A significant number of modelling iterations were completed in an effort to improve the response of the model in comparison to the field data. The "fit" to the field data is not entirely defensible; particularly during the last simulation year (2002), but in the interest of completing the project the modelling effort was curtailed. However, it is clear that the model using the multi-modal SWCCs and k-functions does represent a significantly improved model response in comparison to the field data. Automated *in situ* suction and water content measurements would provide the necessary data to verify, and further enhance, the multi-modal SWCCs and k-functions used to generate the modelling results shown in Figure C2.13. This key field data would ensure that a thorough understanding of the key processes and characteristics controlling cover system performance at the site are understood.

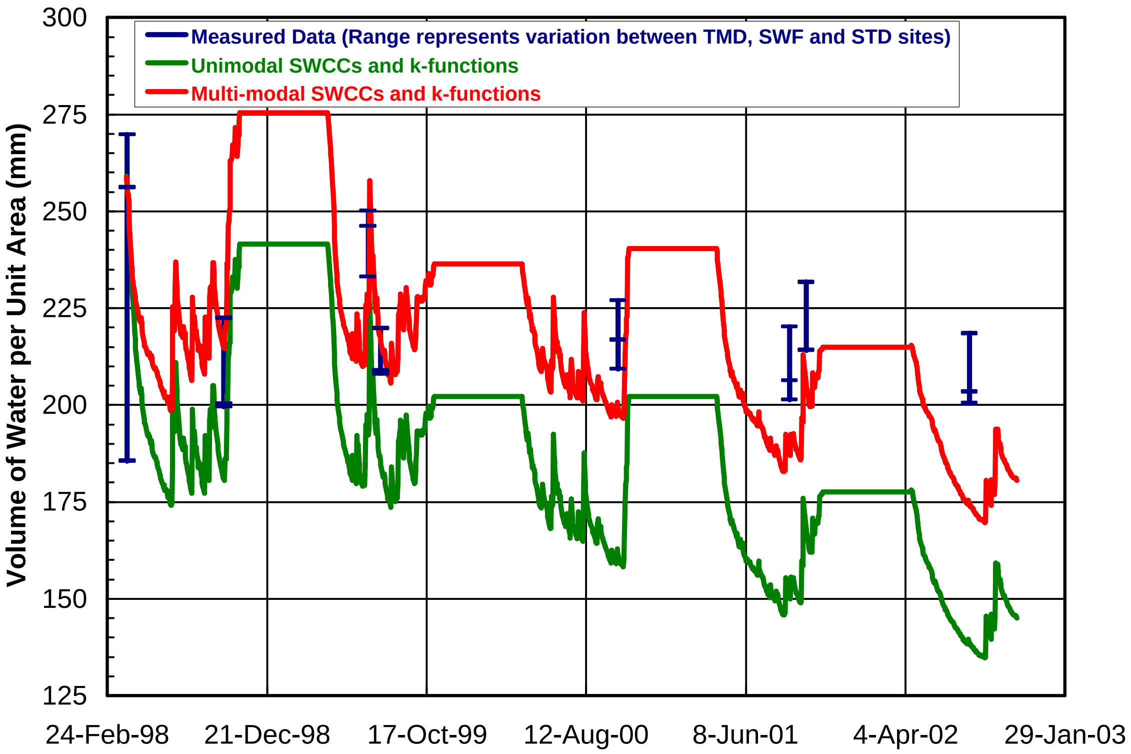

**Figure C2.13** Comparison of predicted cumulative moisture storage using multi-modal SWCCs and k-functions to that predicted using uni-modal SWCCs and k-functions.

The predicted oxygen and net percolation using the multi-model SWCCs and k-functions is compared to that predicted using the uni-modal functions in Figures C2.14 and C2.15. The results presented are not entirely defensible because there is no definitive field evidence for the multi-modal SWCCs and k-functions. There is no appreciable difference between predicted net percolation for the two models. However, predicted oxygen mass flux is approximately twice as high for the multi-modal SWCC and k-function model. Note however, that these results implicitly assume that the 1-D SoilCover model is representative of the full-scale cover system.

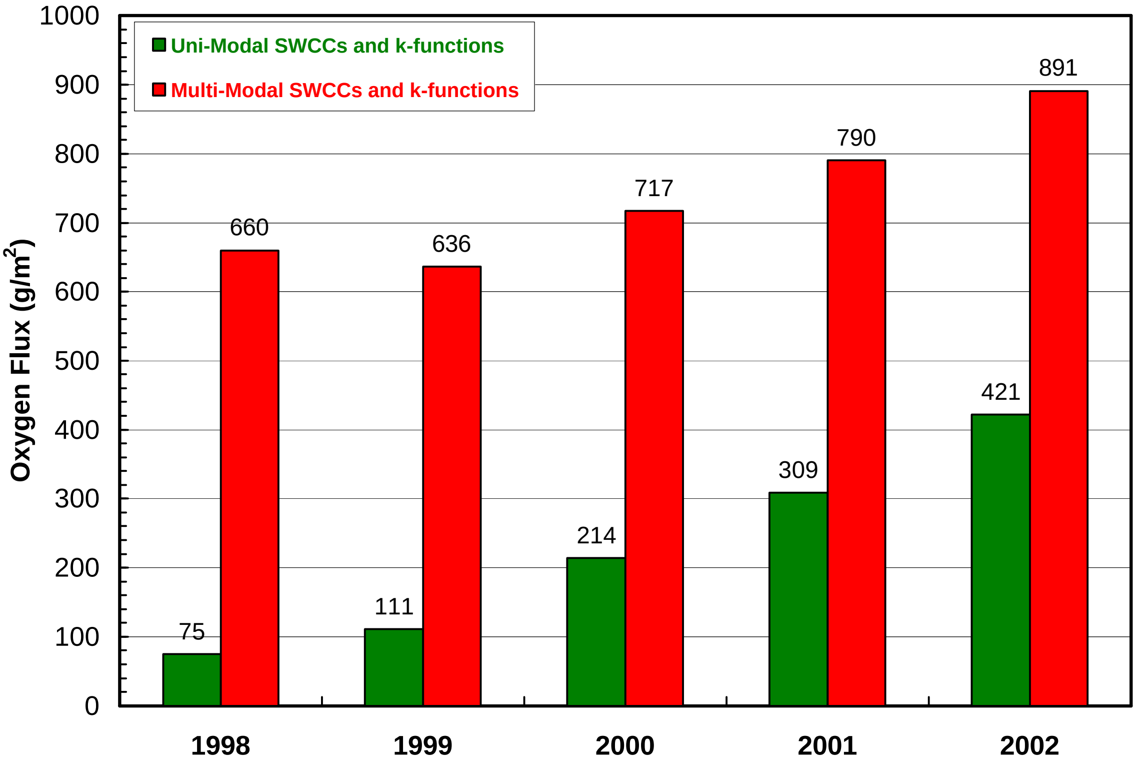

**Figure C2.14** Comparison of predicted annual oxygen mass flux using multi-modal SWCCs and k-functions to that predicted using uni-modal SWCCs and k-functions.

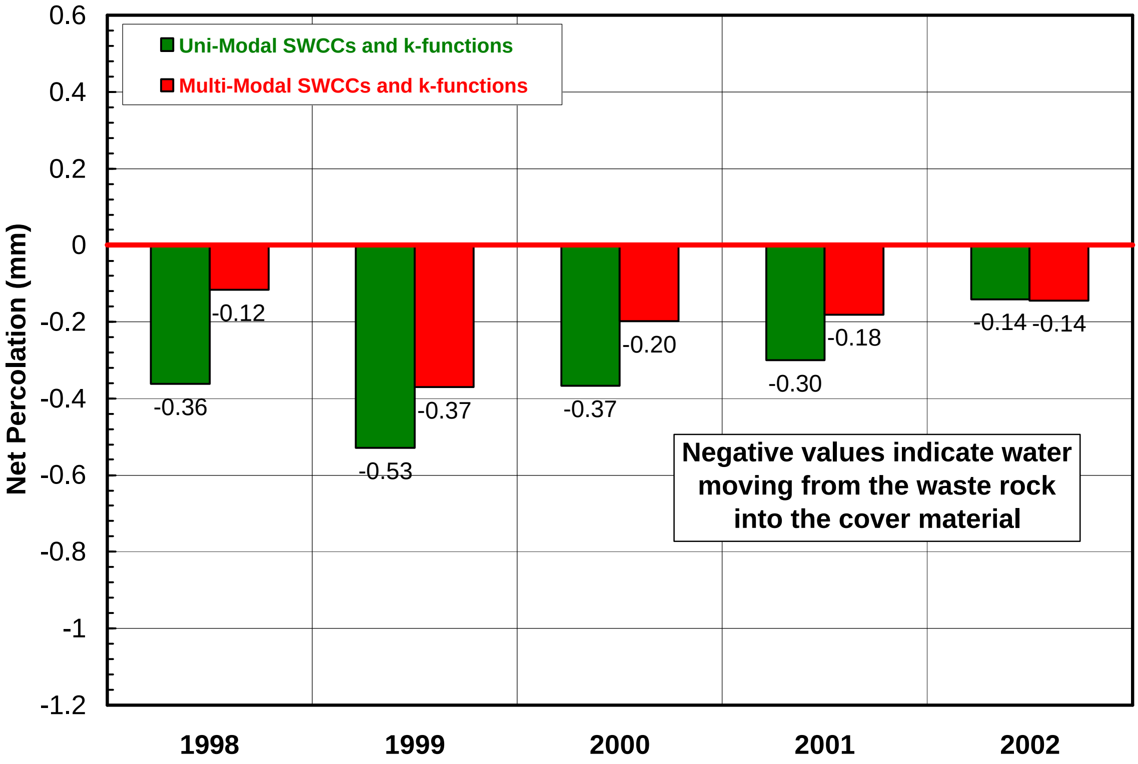

**Figure C2.15** Comparison of predicted annual net percolation using multi-modal SWCCs and k-functions to that predicted using uni-modal SWCCs and k-functions.

## 4.0 SUMMARY

In this appendix, the full-scale dry cover systems at Equity Silver were evaluated using the most recent SoilCover numerical model and collected field data. The objectives were to:

- Assess the accuracy of the original model inputs and predictions;
- Evaluate the performance of the cover systems since installation;
- Illustrate the capabilities of the latest model programs; and
- Develop further understanding for the key processes and characteristics controlling cover system performance at the site.

The following is a non-technical summary of the findings the site, some general conclusions, and recommended future work to improve numerical simulation of the cover systems.

- The Swanson (1995) model results were found to be repeatable using the latest version of the SoilCover modelling program.
- Updating the model inputs using more recent field data was difficult due to the limited amount of field data available. Therefore, the Swanson (1995) model inputs are still the best estimate of the soil properties and layering; although the field hydraulic conductivity measurements (see Appendix C1) would imply that this layering is not representative of current conditions.
- Comparison of the data measured at the TMD and STD instrumentation stations indicate spatial variability of the cover material.
- Using the Swanson (1995) model inputs, the simulations calculated that the cover has been performing as designed during recent years. However, adding vegetation influences or updating the saturated hydraulic conductivities of the cover soils with recent measurements reduced the performance of the cover reduced with respect to oxygen ingress. This result should be revisited as part of additional field and modelling work.
- Bi-modal moisture retention and hydraulic conductivity functions appear to provide significantly improved modelled results in comparison to field conditions, as opposed to uni-modal functions.

General Conclusions and Recommended Future Work

- Automated measurement of suction and water content profiles in the field, in the same location and at the same time, substantially improves the capability to simulate the performance of cover systems.
- Continued maintenance of a soil cover monitoring system after implementation enhances the ability to evaluate the change in performance of a cover system over time. As instrumentation at a site breaks-down, the ability to determine changes in the soil properties and other variables decreases.
- Vegetation is a major factor that needs to be considered when designing or simulating a cover system. The types and variability of vegetation growing on the sites must be researched to better simulate their impact on the soil-water regime. Fundamental and applied research in this area should be conducted.

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Wilson, G.W., Newman, L., Barbour, S.L., O'Kane, M., and Swanson, D.A., 1997. The cover research program at Equity Silver Mine Ltd. Forth International Conference on Acid Rock Drainage, May 31 – June 6, 1997, Vancouver, British Columbia, Canada.

# APPENDIX D1

## Evaluation of the Long-Term Performance of Dry Cover Systems

## One-Dimensional and Two-Dimensional Numerical Analysis at the Mildred Lake Operations

# 1.0 INTRODUCTION

The VADOSE/W and SoilCover numerical models were utilised to simulate water movement within two dry cover systems installed at the Syncrude Canada Ltd. (SCL), Mildred Lake Operations in northern Alberta. The objective of the modelling program was to match the one-dimensional (1-D) and two-dimensional (2-D) simulated results with measured field conditions at the site. Shurniak (2003) completed detailed numerical modelling with the SoilCover model at Mildred Lake. The inputs to the SoilCover model were utilised in the VADOSE/W program to complete 1-D and 2-D simulations. These simulations were compared to the measured field responses, and between each other, to ensure continuity between the SoilCover and VADOSE/W numerical models.

Shurniak (2003) completed all of the 1-D modelling as part of a graduate research project under the supervision of Dr. Lee Barbour, Department of Civil Engineering, University of Saskatchewan. The field data was a result of Boese's (2003) graduate research project, which was also supervised by Dr. Barbour. Hence, the 1-D modelling reported herein is summarised from Shurniak's (2003) and Boese's (2003) research. The 2-D soil-atmosphere modelling was completed as part of INAP's dry cover system longevity research project.

The geometry of the dry cover systems simulated within the modelling program is shown in Figure D1.1. Both cover systems consist of a layer of peat overlying a layer of glacial till (till), with the D1 cover consisting of 20 cm of peat on top of 30 cm of till, and the D2 cover having 15 cm of peat overlying 20 cm of till. During the analysis of the data it was found that the hydraulic properties of the peat layer differed substantially with depth. Therefore, the peat was further divided into two layers, referred to as the "shallow" and "deep" peat layers. The "shallow" peat was assumed to extend from the surface to a depth of 10 cm, with the "deep" peat used to define the remainder of the peat layer. For the VADOSE/W models, a third layer of peat (referred to as "surface" peat) was added at the surface; as recommended in the VADOSE/W User Manual. This layer has similar hydraulic properties to the "shallow" peat, however, its hydraulic conductivity function was set to drop only a few orders of magnitude over the entire suction range. This layer improves the model's ability to infiltrate water across the soil-atmosphere interface during dry surface conditions.

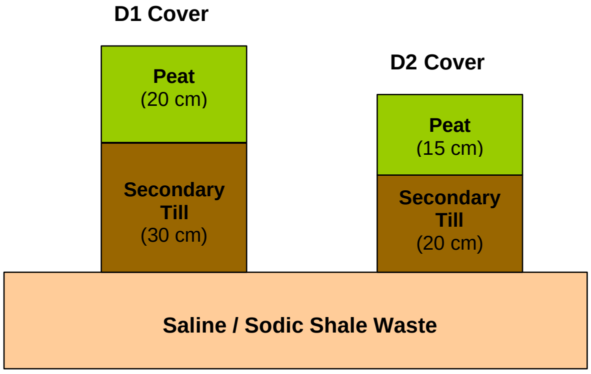

**Figure D1.1** The cover systems investigated in the Mildred Lake Operations case study modelling program.

## 2.0 RESULTS OF THE MODELLING PROGRAM

Figure D1.2 shows the results obtained from the D1 cover simulation. The simulations were completed for 157 days in order to simulate the frost-free conditions at the site. The SoilCover and VADOSE/W models produce reasonable simulations of field responses and have similar results. Discrepancies between the simulated results are likely due to:

- Differences in the geometry of the finite element meshes;
- Slight variations in the input parameters; and
- The inclusion of the "surface" peat layer for the VADOSE/W model.

Figure D1.3 summarises the results obtained from the simulations of the D2 cover. The results are similar to those obtained simulating the D1 cover, however, there is a significant divergence that occurs between the measured data and simulated results following a rainfall event on September 28th. On this day, 22 mm of rain was recorded, but the measured moisture storage increased 32 mm; 10 mm more than was recorded for the rainfall event. It is hypothesised that the additional water was due to horizontal fluxes that cannot be accurately simulated with the one-dimensional models.

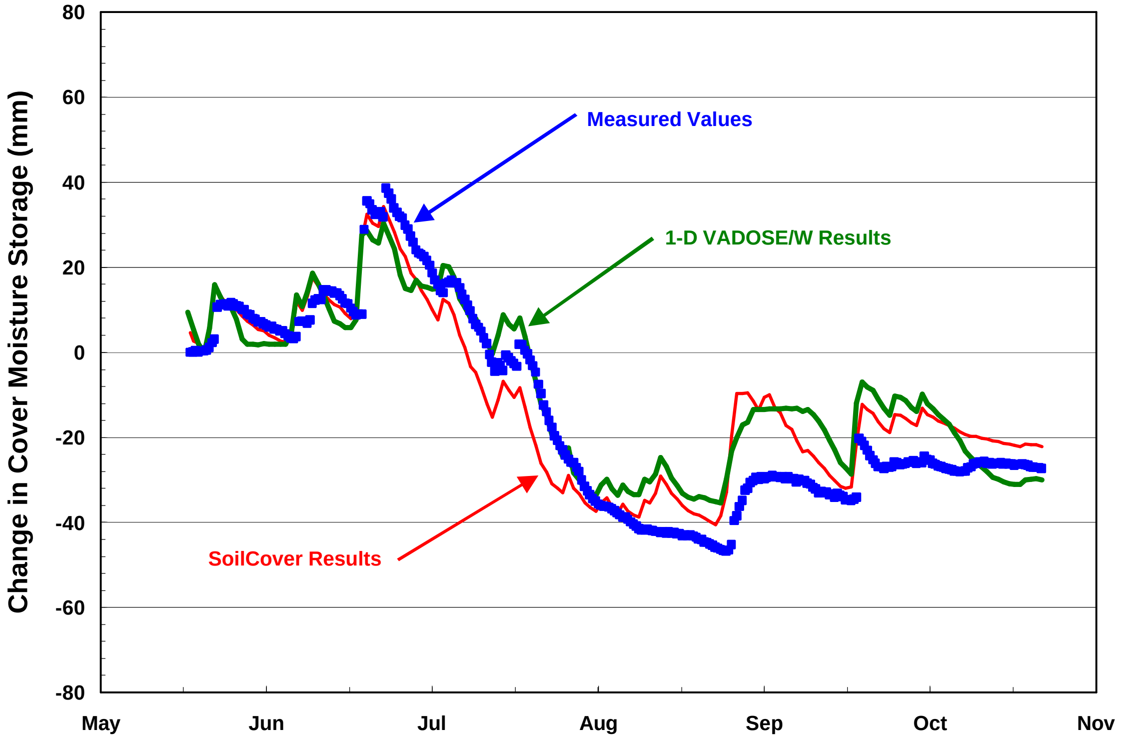

**Figure D1.2** Total cumulative change in moisture storage for the D1 cover system simulations.

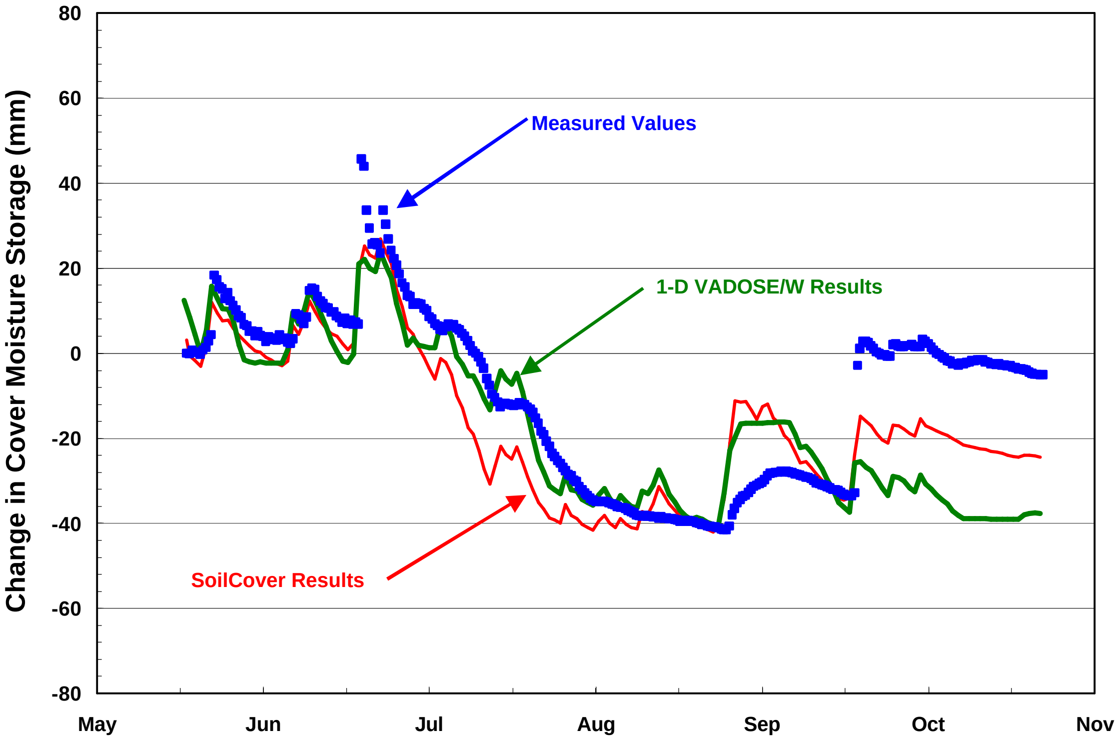

**Figure D1.3** Total cumulative change in moisture storage for the D2 cover system simulations.

A 2-D VADOSE/W model of the D2 cover system was created, which was based on a detailed survey of the local topography, to determine its effect on the simulated results (Figure D1.4). A zero-flux boundary was placed at the base of the cover for simplicity. Figure D1.5 shows that, due mainly to runoff, the infiltration and, therefore, moisture storage fluctuates along the slope. These fluctuations cause changes in the cumulative moisture storage along the slope, as shown in Figure D1.6. The average change in moisture storage for the slope is similar to the results obtained from the one-dimensional model. However, when the predicted change in moisture storage at a single location along the slope is observed (50 m up-slope in this case), a significantly different moisture storage pattern is observed. Hence, it is further hypothesised that the fluctuations along the slope are the likely reason for the divergence shown in Figure D1.3. That is, the topographic depressions and "flatter" areas along the slope result in higher moisture storage at certain points (i.e. in the depressions and flatter areas).

The 2-D modelling results predicted using the representative local topography are positive because it implies that "localised" 2-D flow can be utilised to control moisture storage and thus enhance a cover system's potential to reduce net percolation, for a given thickness of material. In the case of Mildred Lake Operations' D2 cover system, the local topographic depressions were a result of differential settlement of the cover and / or underlying waste material. However, the field data and modelling results imply that only a marginal effort would be required when preparing the final surface of a cover system to "engineer" improved moisture storage in the cover system (e.g. using a dozer to create small depressions at it travels down the slope).

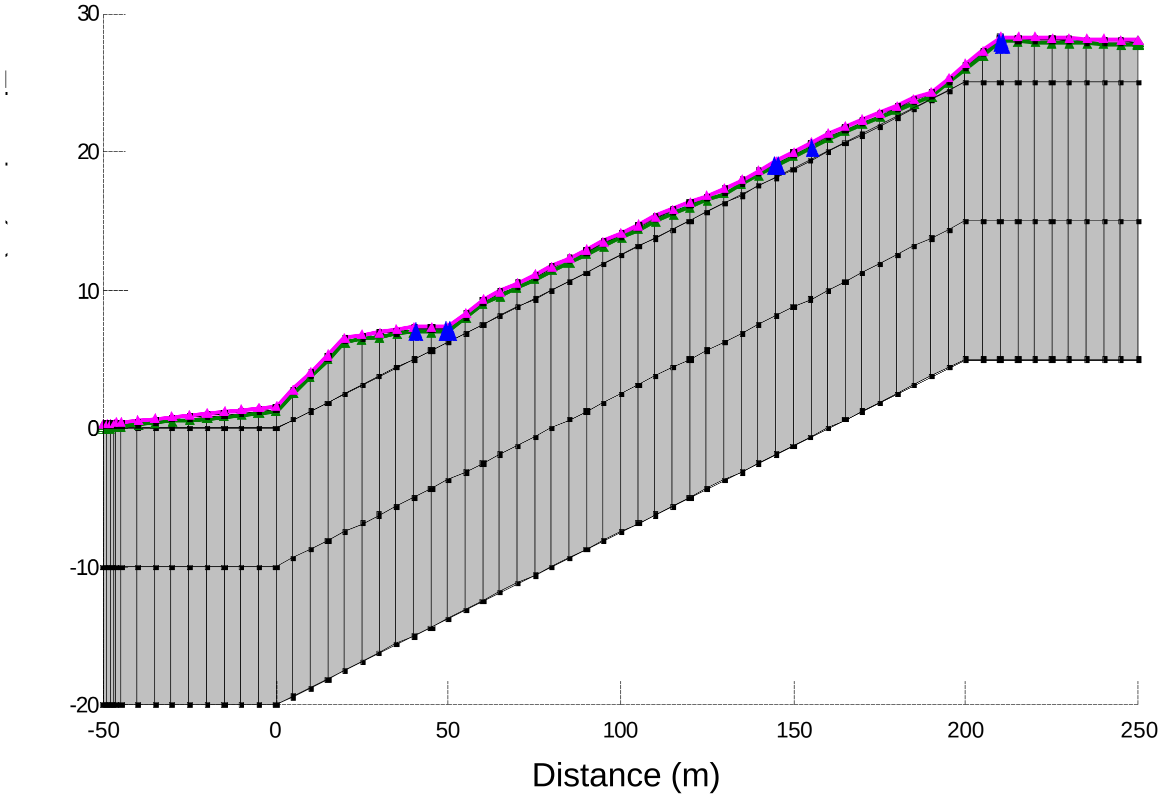

**Figure D1.4** Defined mesh for the two-dimensional VADOSE/W model of the D2 cover.

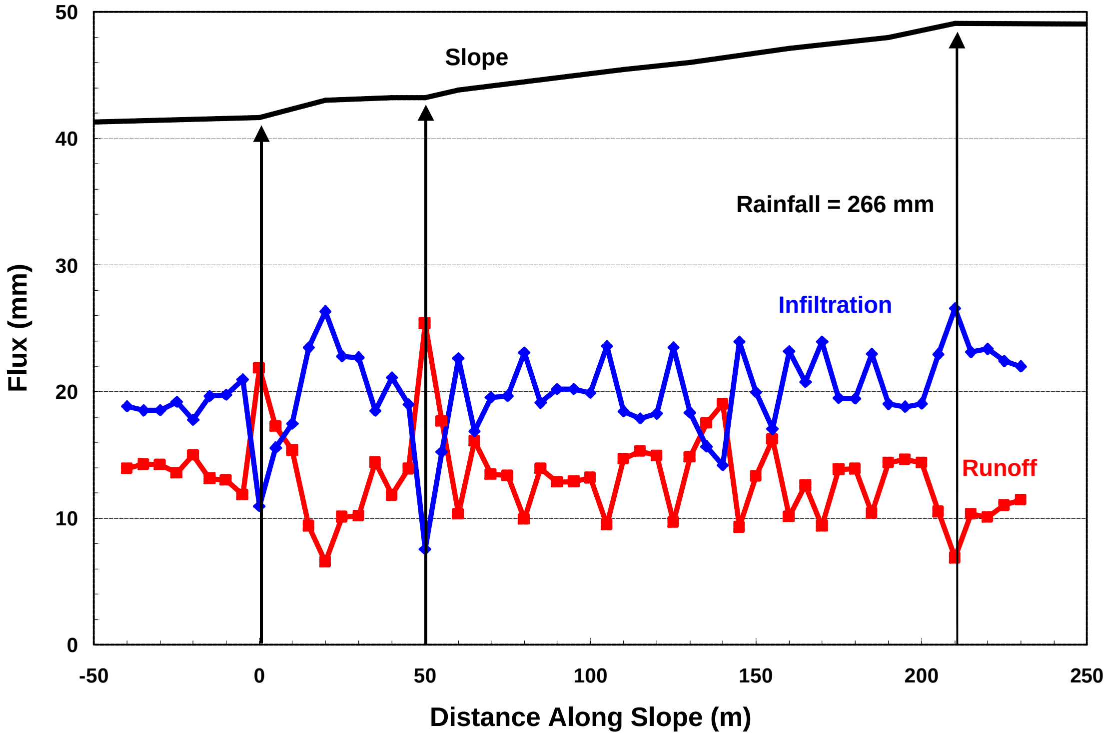

**Figure D1.5** Simulated fluxes as a function of distance at the D2 cover system.

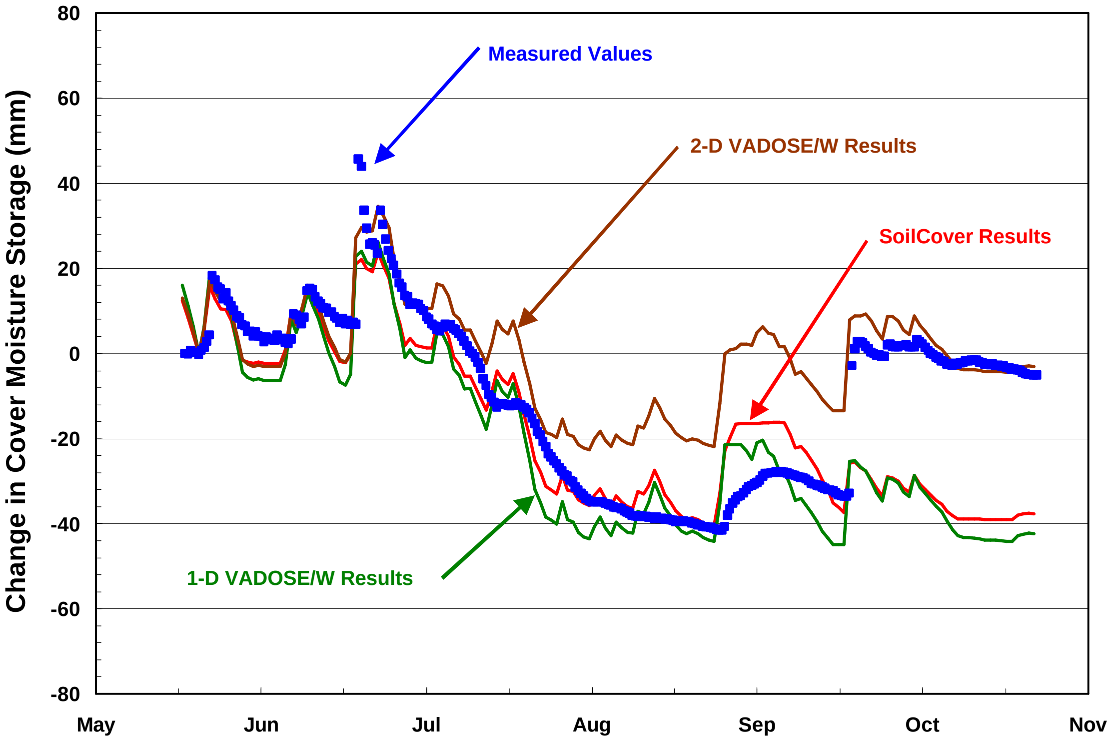

**Figure D1.6** Impact of two-dimensional effects on the total cumulative change in moisture storage for the D2 Cover.

## 3.0 SUMMARY

Significant watershed based research is being undertaken by Syncrude Canada Ltd., which has not been included in the case study reported in this appendix. The reader is referred to Dr. Lee Barbour, Department of Civil Engineering, University of Saskatchewan and / or Ms. Clara Qualizza, Syncrude Canada Ltd. for further details. Small components of the D1 and D2 large-scale field trials were the focus of this case study to demonstrate the importance of modelling two-dimensional effects when simulating water movement within dry cover systems. Although a one-dimensional model can adequately simulate performance of a cover system placed on a sloping surface on occasion, in order to properly account for two-dimensional effects (caused mainly by micro topography or the sloping surface itself, as well as the site-specific material properties and climate conditions), a 2-D soil-atmosphere model should be utilised. By using a 2-D model, such as the VADOSE/W model, potential problems and “fatal” design flaws can be avoided prior to installation of the full-scale dry cover system. In addition, any potential advantages to cover system performance resulting from the 2-D effects can be evaluated.

# APPENDIX E1

## Evaluation of the Long-Term Performance

## of Dry Cover Systems

### Summary of the *In Si*tu Hydraulic Conductivity Testing Program
### at the
### Teck Cominco Ltd., Kimberly Operations Mine Site

# 1.0 INTRODUCTION

An *in situ* saturated hydraulic conductivity ($K_{fs}$) testing program was completed at the Teck Cominco Ltd., Kimberly Operations in Kimberley, British Columbia, which is located within the Purcell range of the Rocky Mountains. The objective of the field study program was to evaluate changes in $K_{fs}$ of dry cover system materials with time. Physical, chemical, and biological processes affect the long-term performance of the dry cover system. These processes will act to change the key properties of the cover materials such as the $K_{fs}$ and moisture retention characteristics. In cover systems, soil structure (cracks, worm holes, root channels, etc.) can provide the dominant flow path in the cover materials under high infiltration conditions. The evolution of soil structure with time will significantly alter the $K_{fs}$ of the cover materials.

The field hydraulic conductivity test program investigated:

- The difference in the $K_{fs}$ between the oldest and youngest cover systems at the (i.e. does the cover material evolve due to environment factors); and
- The effectiveness of the non-compacted till overlying growth medium layer in protecting the compacted till layer from environmental factors.

## 2.0 THEORY OF *IN SITU* SATURATED HYDRAULIC CONDUCTIVITY TESTING

Measurements of saturated hydraulic conductivity in the unsaturated zone are referred to as the "field-saturated" hydraulic conductivity ($K_{fs}$) (Reynolds *et al.*, 1983). This is in recognition of the fact that air bubbles are usually entrapped in the porous media when it is "saturated" by downward infiltrating water, particularly under ponded conditions. The water content of a porous medium at "field saturation" is consequently lower than at complete or true saturation and depending on the amount of entrapped air, $K_{fs}$ can be lower than that at true saturation conditions. Various methods exist for measuring the $K_{fs}$ of soil, ranging from *in situ* to laboratory procedures. In this study *in situ* measurements of hydraulic conductivity were obtained with a constant head well permeameter and a constant pressure (single-ring) infiltrometer.

Constant pressure infiltrometers involve the measurement of the steady-state infiltration rate required to maintain a steady depth of water (or constant water pressure) within a single ring inserted a small distance into a porous medium. The largest difference between the pressure infiltrometer method and the traditional single-ring infiltrometer method is the theoretical treatment of water flow out of the ring and into the unsaturated soil. In the single-ring infiltrometer approach, $K_{fs}$ is determined assuming 1-D vertical flow through and below the ring. However, it is well established that the flow beneath the ring is not 1-D, but diverges laterally due to the capillarity of the unsaturated soil and the hydrostatic pressure of the ponded water in the ring. This divergence, when not accounted for, results in an overestimation of $K_{fs}$, particularly in fine-grained soils. Attempts to prevent the flow divergence by adding a concentric outer guard ring have shown to be unsuccessful (Bouwer, 1986). The pressure infiltrometer takes flow divergence into account by using a three-dimensional flow analysis.

The values of $K_{fs}$ that can be measured accurately with the constant pressure infiltrometer range from $1 \times 10^{-7}$ cm/s to $9 \times 10^{-2}$ cm/s. Beyond these limits there is a reduction in accuracy and precision. Values of $K_{fs}$ less than $1 \times 10^{-7}$ cm/s in this study were recorded as a "failed" test.

During the field testing program, the pressure infiltrometer was used to measure hydraulic conductivity at depth. Tests were completed at three different depths within the cover system to allow the analysis of change in $K_{fs}$ with both time and depth.

## 3.0 RESULTS OF THE *IN SITU* SATURATED HYDRAULIC CONDUCTIVITY TESTING

Teck Cominco Ltd., Kimberly Operations constructed cover system field trials in 1993 and 1994. The field trials constructed in 1994 were duplicates of the 1993 field trials. The Kimberley Operations *in situ* saturated hydraulic conductivity case study reported herein focuses on two of the cover system field trial designs. In addition, $K_{fs}$ of cover materials placed as part of full-scale cover systems constructed in 1997 and 2001 were evaluated. All four cover systems were constructed using a till material consisting of approximately 24% cobbles and gravel, 32% sand, 44% silt, and trace amounts of clay. The design for one of the 1993 cover systems (Test Plot #1) incorporated 45 cm of non-compacted till material while Test Plot #2 possesses 25 cm of non-compacted till material overlying a 30 cm compacted layer constructed in two lifts. The 1997 and 2001 cover systems (referred to as Test Plots #3 and #4, respectively in this appendix) each consists of 30 cm of non-compacted till material overlying 25 cm of compacted material.

The cover material properties at Kimberley Operations prevented using the Guelph permeameter for obtaining measurements of $K_{fs}$. Eight measurements of $K_{fs}$ using the pressure infiltrometer were obtained at each selected depth for the four cover systems. Three pits were excavated to the required depth for conducting hydraulic conductivity and density measurements. One measurement of density using the sand cone method was obtained at the same depth as the hydraulic conductivity tests. The values of $K_{fs}$ measured with the pressure infiltrometer were statistically analysed and are summarised in Table E1.1. The tests conducted at the surface (0 cm depth) were located in the non-compacted till material, while tests at 30 cm or deeper in the Test Plot #2, #3, and #4 cover systems were completed in compacted till material. There were no “failed” tests during the testing program at Kimberly Operations.

Figure E1.1 shows mean values of $K_{fs}$ and density as a function of depth for the Test Plot #1 and Test Plot #2 cover systems. The $K_{fs}$ measured at 2 cm, 25 cm, and 40 cm is similar for the Test Plot #1 cover system (the non-compacted cover system), which agrees with the similar densities measured at 2 cm and 30 cm. Values of $K_{fs}$ measured for the Test Plot #2 cover system at a depth of 30 cm and 50 cm are at the surface of each of the two compacted lifts of the cover system. The mean value of $K_{fs}$ measured at the surface of the second compacted lift (closest to the surface) is one order of magnitude greater than the underlying first lift of compacted till. It is anticipated that the $K_{fs}$ of these two lifts would have been similar following construction due to the compaction procedure outlined above. The difference in hydraulic conductivity between the two lifts could be explained by environmental factors altering the properties of the compacted layers. Excavation of the cover system indicated that significant amounts of roots had penetrated the second (upper) compacted lift, while only trace amounts of roots were found to have penetrated the first lift. Matric suction sensors installed into the cover system indicate that the entire cover system is undergoing significant wet / dry cycling during the dry summer months. The *in situ* moisture content in the summer of 2002 (by mass), based on measurements completed as part of the density testing, was approximately 3%.

**Table E1.1**

Summary of pressure infiltrometer tests at Kimberly Operations
(Geometric mean (M), standard deviation (σ), dry density ($\rho_d$)).

| Depth (cm) | *M* ($10^{-4}$ cm/s) | *s* ($10^{-4}$ cm/s) | $r_d$ (g/cm$^3$) | **Comp. Area** | *M* ($10^{-4}$ cm/s) | *s* ($10^{-4}$ cm/s) | $r_d$ (g/cm$^3$) | **Comp. Layer** |
|---|---|---|---|---|---|---|---|---|
| | **Test Plot #1** | | | | **Test Plot #2** | | | |
| 0 | 25.6 | 7.54 | 1.71 | No | 20.4 | 3.93 | 1.76 | No |
| 25 | 10.4 | 1.36 | 1.71 | No | 1.00 | 0.29 | 2.06 | Yes |
| 40 | 8.99 | 5.93 | N/A | No | 0.18 | 0.08 | 2.23 | Yes |
| | **Test Plot #3** | | | | **Test Plot #4** | | | |
| 0 | 9.55 | 4.73 | 1.82 | No | 2.66 | 2.04 | 1.84 | No |
| 30 | 0.75 | 0.48 | 2.01 | Yes | 1.27 | 0.42 | 1.93 | Yes |

Figure E1.1 shows mean values of $K_{fs}$ and density as a function of depth for the Test Plot #1. Measurements of hydraulic conductivity and density, as well as observations of root penetration, indicate that environmental factors have altered the second lift of the compacted layer. It is also likely that the presence of the second compacted lift mitigated these impacts on the underlying first compacted lift. This suggests that the thickness of the overlying non-compacted cover layer, or the "growth medium" directly affects the long-term performance of a compacted barrier layer, and in the case of Test Plot #2 at the Kimberley Operations, demand for atmospheric moisture was not satisfied by the growth medium. This implies that the growth medium was not thick enough to minimise the impact of wet / dry cycling on the $K_{fs}$ and moisture retention capability of the underlying compacted material.

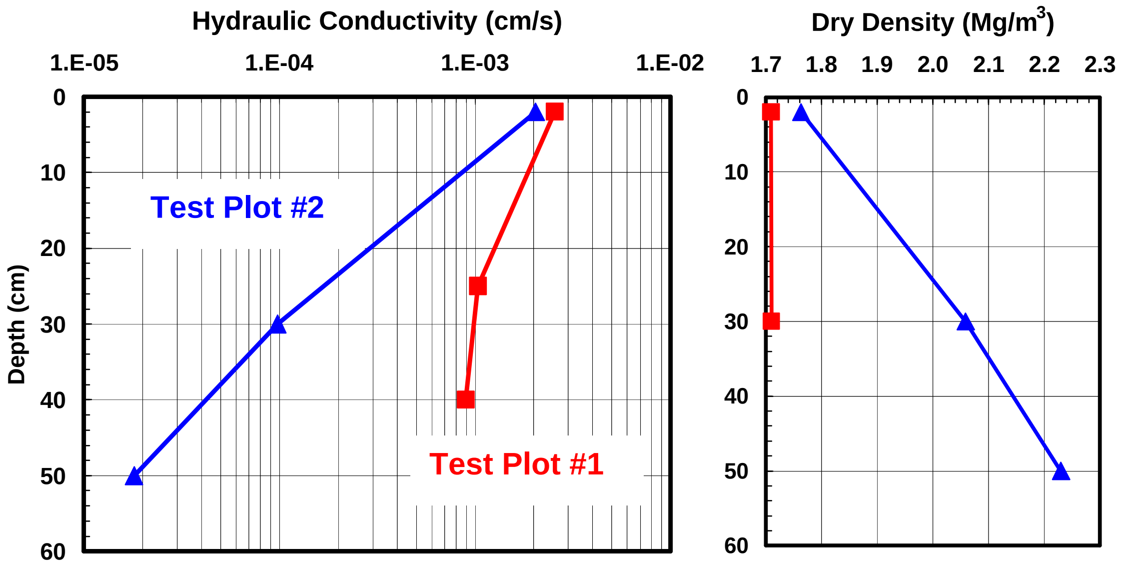

**Figure E1.1** Results of the saturated hydraulic conductivity tests at Test Plot #1 and Test Plot #2.

Figure E1.2 shows the mean $K_{fs}$ values and density as a function of depth for the Test Plot #3 and Test Plot #4 cover systems. The saturated hydraulic conductivity of the near surface non-compacted till cover material is approximately equal to that measured at 30 cm within the compacted barrier layer. These results indicate that the compaction energy applied to the compacted layer lift did not adequately penetrate the lift or ripping of the surface material may have altered the underlying material. If the compaction energy did penetrate and adequately compact the underlying material, ripping of the surface material may have disturbed the underlying material. However, it is clear that compaction of cover material at the site can reduce the hydraulic conductivity to at least 2 x $10^{-5}$ cm/s based on values of $K_{fs}$ measured within the Test Plot #2 compacted layer. The question though is whether the positive influence of compaction can be realised over the long-term.

Measurements of density summarised in Table 3 indicate that the density of the upper compacted layer is less than the lower compacted layer for the Test Plot #2 cover system. The density and hydraulic conductivity of the second (upper) lift of the Test Plot #2 cover system and the compacted lift of the Test Plot #4 cover system are similar. This seems to suggest that the compaction and hydraulic properties obtained by compacting with a D8 dozer after one year are similar to the second upper lift of the Test Plot #2 cover system, which has been affected by environmental factors (rooting and wet/dry cycling) for nine years. The Test Plot #3 cover system, compacted using wheel tractor-scrapers, obtained slightly higher density and lower hydraulic conductivity at a depth of 30 cm as compared to results measured for the Test Plot #4 cover system compacted layer, which was created using a D8 dozer.

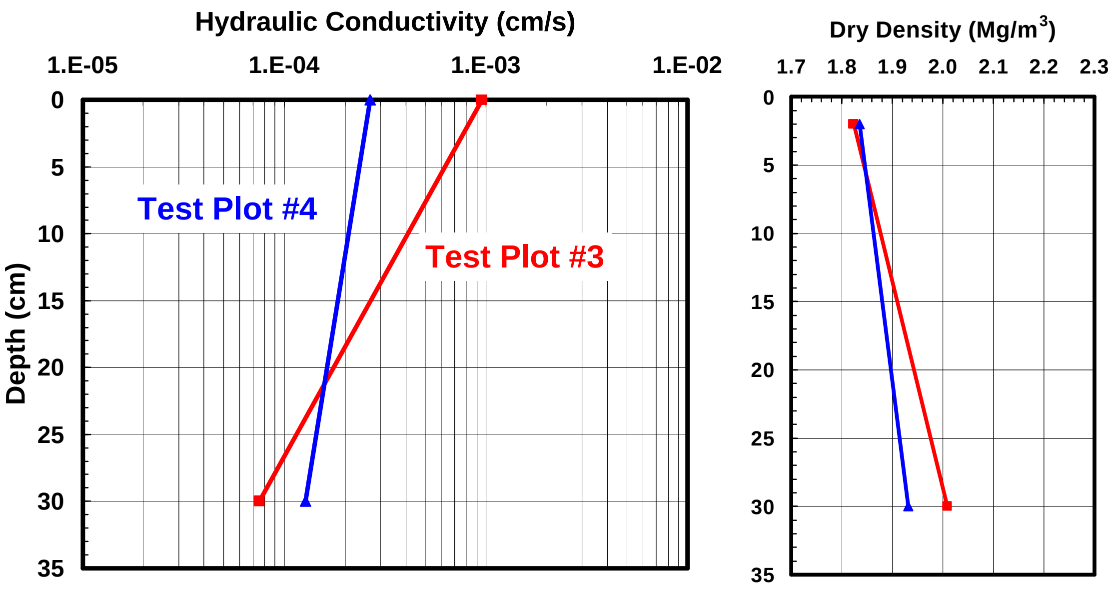

**Figure E1.2** Results of the saturated hydraulic conductivity tests at Test Plot #3 and Test Plot #4.

Figure E1.3 is a cumulative histogram of $K_{fs}$ values measured at the surface of the Kimberly Operations test plot cover systems using the pressure infiltrometer. This figure suggests the cover materials at the surface are evolving over time. The non-compacted till material at Test Plot #1 and Test Plot #2 possess similar saturated hydraulic conductivity values, which was expected as they were both constructed nine years ago. The Test Plot #3 cover system is approximately six years old and shows a slight but distinctly lower saturated hydraulic conductivity than the older cover systems. Test Plot #4 is only two years old and has a much lower saturated hydraulic conductivity (approximately 1 order of magnitude) as compared to the nine-year-old cover systems. This suggests that the greatest changes in hydraulic conductivity at the surface occurred shortly after the material was placed (< 4 years). Field performance monitoring data at Test Plots #1 and #2 suggest that wet / dry moisture cycling of the cover material is the most likely process that led to the evolution of the *in situ* hydraulic conductivity of the growth medium material.

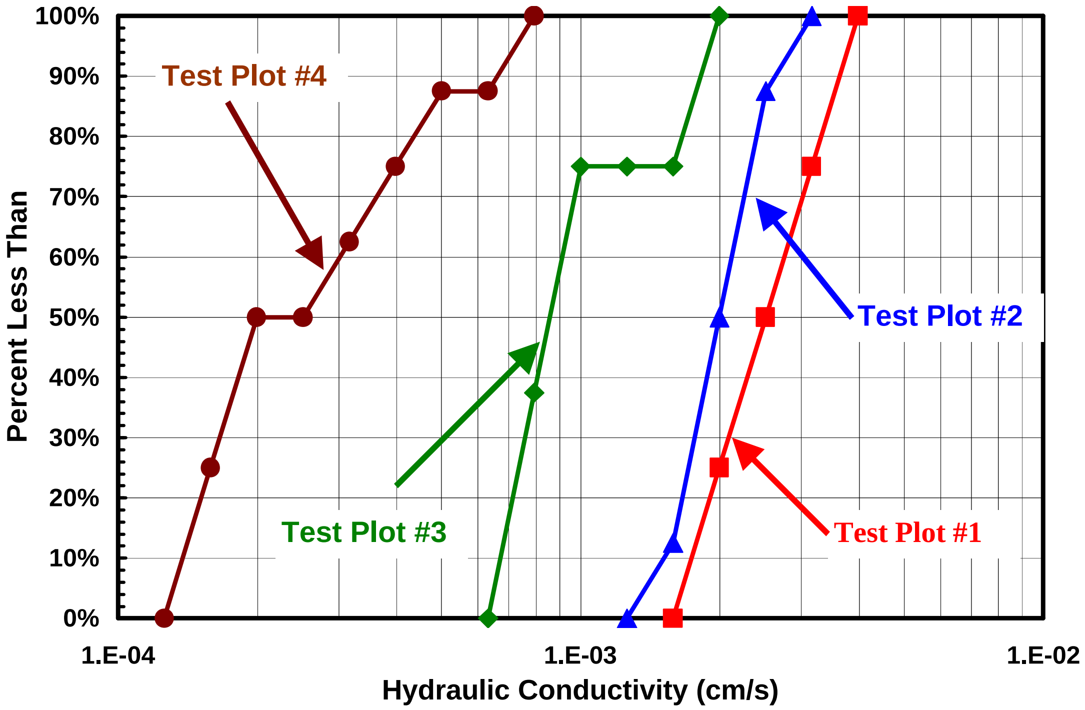

**Figure E1.3** Cumulative histogram summarising the *in situ* saturated hydraulic conductivity measurements at Kimberly Operations for material placed in 1993 (Test Plots #1 and #2), 1997 (Test Plot #3), and 2001 (Test Plot #4).

## 4.0 REFERENCES

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