THE USE OF *IN SITU* MEASUREMENT OF HYDRAULIC CONDUCTIVITY TO PROVIDE AN UNDERSTANDING OF COVER SYSTEM PERFORMANCE OVER TIME[1]

Greg P. Meiers, Lee S. Barbour, and Clara V. Qualizza[2]

Abstract. Three prototype covers were constructed on a saline-sodic shale overburden fill at the Syncrude oil sands mine in Fort McMurray, Alberta, Canada in 1999. The covers are comprised of a surface layer of peat/mineral mix over glacial mineral soil placed over a sloping saline-sodic shale surface. The covers are designed to provide moisture storage for vegetation over the arid summer season while minimizing the impact of salt release from shale.

The evolution of the hydraulic performance of the covers was evaluated through repeated testing of *in situ* hydraulic conductivity (K) over time. These changes are related to changes in monitored interflow collection rates. The mean K of the cover material increased approximately two orders of magnitude during the first three years following placement and then remained relatively constant. The interflow collection volumes have increased each year with the magnitude of interflow offset from the measured K values by two to three years. It appears that the interflow volumes which are critical for flushing salt from the covers are dependent on both the K of the cover and yearly climatic variability.

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Introduction

The mining of oil sands at the Mildred Lake Mine, operated by Syncrude Canada Ltd. (SCL), in northern Alberta, Canada, requires the removal of a marine saline-sodic shale, in order to extract the underlying oil sands. The shale overburden is placed in large surface dumps that are reclaimed with a reclamation soil cover. The SCL mine produces over 200,000 barrels of oil per day. Up to 14 tonnes of overburden is excavated for each cubic meter of oil produced. These overburden deposits are salt rich (saline) and sodic and must be covered with nonsaline / nonsodic soils in order to provide for revegetation. These reclamation soil covers must provide adequate moisture storage for vegetation over the dryer summer period while at the same time minimizing the impact of salt release from the overburden.

Two key properties that influence cover system performance are the hydraulic conductivity and the moisture storage characteristic of the cover soil (MEND 2001). The design of reclamation covers is generally based on a laboratory characterization of these properties. This may be supplemented with a short term program (1-2 years) of field monitoring of small test covers. Yet these properties may change with time following cover placement as a result of site-specific biological, chemical, and physical processes (INAP 2003). Subsequently, changes in the hydrological properties can potentially alter the performance of a cover system over time.

It is important to understand the mechanisms and magnitude of changes in the hydraulic properties of reclamation covers over time and relate these changes to field performance. The objective of this paper is to relate changes in saturated hydraulic conductivity to the hydraulic performance of long-term (6 years) cover system field trials. The results suggest that an increase in hydraulic conductivity has led to changes in hydraulic performance in general and to interflow volumes in particular.

Background

Syncrude Canada Mine Site

The SCL mine is located 30 km north of Fort McMurray, Alberta, Canada. The regional climate is continental, in that seventy percent of total precipitation occurs during the summer. The mean annual precipitation is approximately 440 mm of which 310 mm is rain. July is generally the wettest month, reflecting the mid-Alberta storm track. The mean annual potential evaporation (Penman) is in the range of 600 to 700 mm/year with peak daily potential evaporation rates exceeding 5 mm/day. Actual evaporation rates (AET) over the summer growing season are often in excess of 300 mm and this leads to frequent net summer moisture deficits of as much as 70 to 80 mm. (Boese 2003, Barbour et al 2001, Elshorbagy et al 2005)

Cover System Field Trials

Three, 1 ha, prototype cover watersheds were constructed at a large overburden shale dump, referred to as SW30, during the winter and spring of 1999. These covers have nominal thicknesses of approximately 35, 50, and 100 cm and were placed adjacent to each other running lengthwise (50 m x 200 m) along a 5:1 north-facing slope. The covers were constructed with a surface layer of peat/mineral mix (1:1 to 3:1 ratio), obtained by overstripping of natural peat deposits on glacial soils, overlying a layer of glacial till or glaciolacustrine clay. The nominal thicknesses of the two layers are as follows:

- 35 cm cover; 15 cm of peat/mineral mix overlying 20 cm of glacial soil
- 50 cm cover; 20 cm of peat/mineral mix overlying 30 cm of glacial soil
- 100 cm cover; 20 cm of peat/mineral mix overlying 80 cm of glacial soil.

The grain size distribution of samples of the glacial soil and shale were measured using the method in ASTM D422-63. The glacial soil consists of approximately 2% gravel, 38% sand, and 60% silt and clay sized particles while the shale consists of approximately 0.5% gravel, 14.5% sand, and 85% silt and clay sized particles based on the USDA classification system. In general, the grain size of the peat/mineral mix is similar to that of the glacial soil with the addition of an increased organic content.

Cover System Field Trial Monitoring System

Instrumentation was installed as part of an ongoing research program to establish a water balance for the covers and to identify and characterize key processes controlling moisture dynamics within the covers. Runoff was monitored through a series of weirs constructed along a drainage channel at the toe of the covers. A weather station and Bowen Ratio system were installed at the centre of the field trial area to monitor climate (precipitation, air temperature, relative humidity, wind speed and direction, and net solar radiation) and AET.

Continuous monitoring of *in situ* suction, temperature and water content across the cover profile and into the shale was obtained through an instrumented soil station located midslope on each cover. Thermal conductivity and frequency domain reflectometry sensors were used to monitor suction and water content, respectively. Deeper water content profiles were monitored using a neutron probe at access tubes located at the crest, midslope, and toe.

The above field monitoring was installed during the 1999 field season. An interflow collection system was installed in the 2000 field season. This consisted of a HDPE geombrane placed along the shale/glacial soil interface which was backfilled with a seepage collection pipe and filter sand which drained to 200 L sump tanks. PVC access tubes were also installed at various locations along the slope profile to facilitate spatial monitoring of the *in situ* moisture conditions using a portable soil moisture probe (Sentek Diviner). Figure 1 is a schematic of the cover system performance monitoring system. Full details of all instrumentation/monitoring are provided in Boese (2001).

Measurements of *In Situ* Hydraulic Conductivity

Field measurements of hydraulic conductivity (K) were obtained using a constant head well permeameter - the Guelph permeameter (GP) technique. Field measurements of K have an advantage over laboratory measurements in that a relatively larger volume of soil can be tested and the network of pores and soil structure representative of field conditions remains relatively undisturbed. GP measurements of hydraulic conductivity involve the measurement of the steady-state infiltration rate for a constant depth of water in an uncased, cylindrical auger hole (diameter 5 cm). Once steady state conditions are reached a small inner saturated zone adjacent to the well develops which is enveloped by a larger wetted, but unsaturated volume of soil.

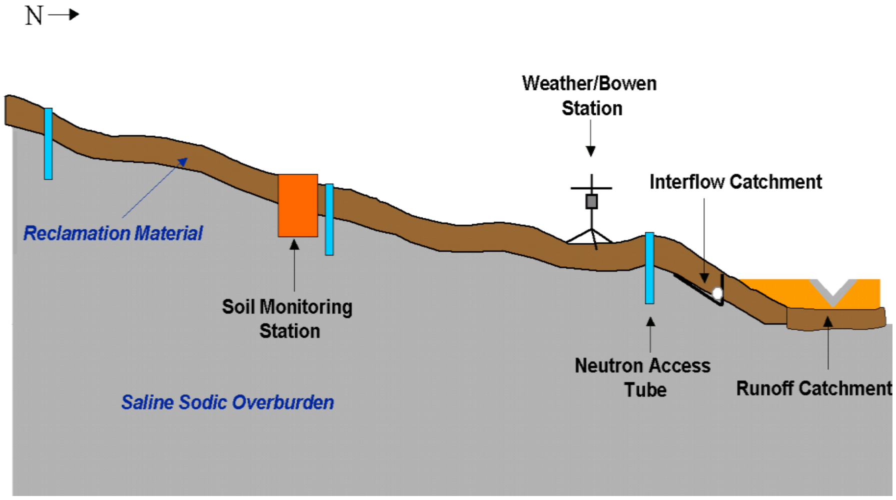

Figure 1. Schematic of the instrumented test section (from Boese, 2003).

The range of K values that can be accurately measured with the GP is approximately 10^{-6} cm/s to 10^{-2} cm/s (Reynolds 1993). Beyond these limits there is a reduction in accuracy and precision. Values encountered beyond these limits during the field testing were recorded at face value acknowledging that a reduction in the precision and accuracy exists. Testing during hot, clear, summer days required the use of a radiation shield in order to minimize thermally induced volume changes associated with heating of the gas in the reservoir headspace. This helped to increase the accuracy and therefore the lower limit of the GP measurement (Elrick and Reynolds 1992).

Two methods are widely accepted for determining K from a constant head well permeameter; a single height analysis (Elrick et al., 1989) and a dual height analysis (Simultaneous Equation) (Reynolds et al., 1985). The GP procedure in this study used two ponded water heights of 5 cm and 10 cm. The K was calculated from the steady state flow rate from each of the ponded heights. In this respect there were two K values measured at each auger hole.

The test locations were adjacent to the location of neutron probe access tubes located at the crest, midslope, and toe of each field trial slope profile. In general, a total of approximately twelve to thirty single height measurements of hydraulic conductivity were made for each of the cover materials and the underlying shale for a given cover system during a given year. Repeated measurements of hydraulic conductivity were made at the midway point of each cover material profile and 30 cm below the secondary / shale material interface. An arbitrary K value of 9 x 10^{-8} cm/s was assigned for any test in which measurable infiltration was not observed.

Literature Review of Wet/Dry Freeze/Thaw Cycles

Wet/dry and freeze/thaw cycles can have a significant impact on the hydraulic properties of fine-grained cover materials. Watson and Luxmoore (1986), Wilson and Luxmoore (1988) and Dunn and Phillips (1991) reported that a high percentage of water is transported through an extremely small portion of the pore-space in structured fine-grained soils. These findings indicate that the development of a secondary soil structure will strongly influence the hydrological properties of fine-grained cover materials. Field measurements of hydraulic conductivity provide a direct method of determining if a secondary structure has developed in fine-grained soils.

Changes in hydraulic conductivity in fine-grained soils due to wet/dry cycles are caused by the volume change (shrinkage and swelling) associated with moisture content changes. This volume change leads to the development of a secondary structure of aggregated clay "clods" as well as cracks or fissures. Several studies have shown that wet/dry cycles can increase the hydraulic conductivity of compacted clays. Albrecht and Benson (2001) performed hydraulic conductivity tests on compacted clay samples exposed to wet/dry cycles and showed that K values increased by up to three orders of magnitude. Daniel and Wu (1993), Boynton and Daniel (1985), and Sim et al. (1996) all reported similar results.

Changes in hydraulic conductivity as a result of freeze/thaw cycles are due to the formation of voids, desiccation cracks, and the development of ice lenses (Konrad and Morgenstern 1980). Recent laboratory studies have shown that the hydraulic conductivity of a compacted clay can increase significantly when exposed to freeze/thaw cycles. Benson et al. (1995), Othman and Benson (1993), Wong and Haug (1990) and Kim and Daniel (1992) have shown that increases in hydraulic conductivity of one order of magnitude or more can result from one freeze/thaw cycle and that an increase of one to three orders of magnitude can occur as a result of three to five cycles. After approximately three to five freeze/thaw cycles the hydraulic conductivity remains relatively unchanged. Laboratory testing has shown that increases in hydraulic conductivity as a result of freeze/thaw cycles are the highest for clays with the lowest initial hydraulic conductivity (high density and or structureless material). The effect of freeze/thaw cycles on clays with a high initial hydraulic conductivity is minimal (Othman and Benson 1993).

Results and Discussion

In Situ Hydraulic Conductivity Testing

Table 1 summarizes the geometric mean and standard deviation of the hydraulic conductivity data. The standard deviation is calculated on log transformed K data. These changes are shown graphically in Fig. 2. The percentage of "no measurable infiltration events" (NMIEs) are summarized in Table 2.

The mean K for all tests in the peat/mineral layer increased from 8 x 10^{-4} cm/s to 7 x 10^{-3} cm/s from 2000 to 2002. This value then remained relatively constant for each of the remaining field seasons. The K of the glacial soil cover layer increased by approximately two orders of magnitude during the first year of monitoring, from 2 x 10^{-6} cm/s to 2 x 10^{-4} cm/s and then remained unchanged at approximately 4 x 10^{-4} cm/s for each of the remaining field seasons.

The mean hydraulic conductivity of the peat/mineral cover soil was similar for each of the three covers for a particular year. This was also true for the glacial soil layer. As a result the hydraulic conductivity of these soils as presented in Figure 2 is representative of all three covers. The percent of NMIEs recorded in the 2000 field season for the 35, 50, and 100 cm covers were 32%, 29%, and 43%, respectively. This decreased to zero for each of the remaining field seasons.

Table 1. Geometric mean (M) and standard deviation (σ) for measured K data.

Material	2000		2001		2002		2003		2004	
	M (10^{-5} cm/s)	σ	M (10^{-5} cm/s)	σ	M (10^{-5} cm/s)	σ	M (10^{-5} cm/s)	σ	M (10^{-5} cm/s)	σ
35 cm Cover System										
Peat/Mineral	40	0.05	400	0.11	700	0.3	400	0.2	800	0.3
Glacial Soil	0.2	1.2	30	0.7	30	0.7	70	0.8	8	0.7
Shale	0.03	0.6	0.5	0.3	0.7	0.6	0.4	0.6	0.4	0.5
50 cm Cover System										
Peat/Mineral	90	0.5	300	0.2	500	0.3	600	0.3	500	0.7
Glacial Soil	0.4	1.1	20	0.4	60	0.7	*	*	30	0.8
Shale	0.02	0.4	0.3	0.9	0.4	0.8	0.4	0.7	*	*
100 cm Cover System										
Peat/Mineral	100	0.4	400	0.3	900	0.7	900	0.7	300	0.3
Glacial Soil	0.1	1.3	20	0.9	40	0.6	60	0.7	20	0.8
Shale	0.01	0.4	0.02	0.6	0.1	0.7	0.1	0.8	0.3	0.5

* Data not presented

Table 2. Percent of no measurable infiltration events recorded during field testing.

Materials	No Measurable Infiltration Events (%)				
	2000	2001	2002	2003	2004
35 cm Cover System					
Peat/Mineral	0	0	0	0	0
Glacial Soil	32	0	0	0	0
Shale	55	0	0	0	0
50 cm Cover System					
Peat/Mineral	0	0	0	0	0
Glacial Soil	29	0	0	*	0
Shale	50	25	13	0	*
100 cm Cover System					
Peat/Mineral	0	0	0	0	0
Glacial Soil	43	0	0	0	0
Shale	83	80	21	25	0

* Data not presented

The mean K of the shale underlying all three covers was approximately 2 x 10^{-7} cm/s in 2000. This value increased to approximately 4 x 10^{-6} cm/s by 2004; however the rate of change of K within the shale underlying the 100 cm cover appeared to initially "lag behind" that of the 35 and 50 cm covers.

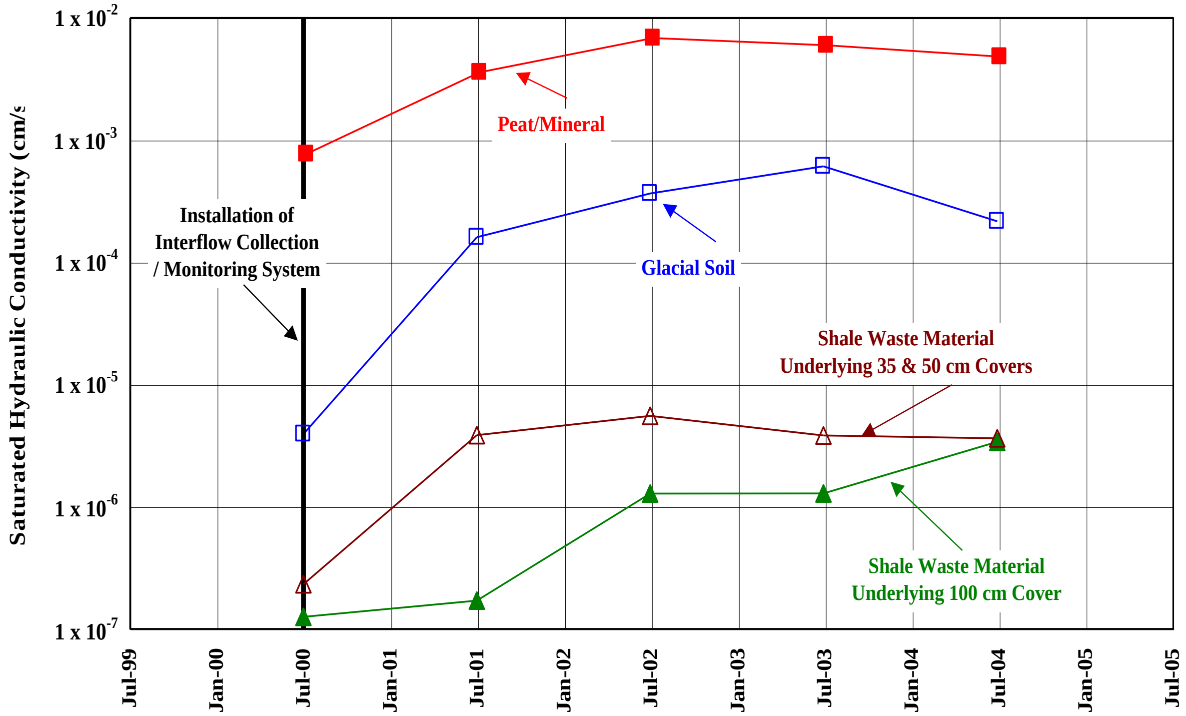

Figure 2. Mean saturated hydraulic conductivity of the cover materials and shale.

The *in situ* temperature measurements suggest that temperatures less than 0^{o}C were not reached at all of the GP test locations below the 100 cm cover during the winter of 2000. The frost depth did appear to encompass all GP test locations during the following winter. This demonstrates the influence of freeze/thaw cycles, and subsequently cover thickness, on changes in hydraulic conductivity. Meiers et al., (2003) demonstrated that freeze/thaw cycling was the dominant process leading to changes in hydraulic conductivity within the glacial soil and shale and that surcharge depths of less than 60 cm do not appear to limit changes in hydraulic conductivity.

A histogram (cumulative percentage), of the K measurements for the glacial cover layer is shown in Fig. 3 for the 2000 to 2004 field seasons. Approximately 60% of the hydraulic conductivity values were lower than 6 x 10^{-6} cm/s during the 2000 field season. This decreased to approximately 2% of the values during each of the following seasons. During the first year of monitoring, the majority of the measured K values were within a range of approximately four orders of magnitude. This decreased to approximately three orders of magnitude for each of the remaining field seasons.

The relatively high hydraulic conductivity of the peat/mineral layer - measured at 8 x 10^{-4} cm/s (28 mm/hour) during the 2000 field season - would be high enough to allow most significant precipitation events to infiltrate. The relatively high hydraulic conductivity and moisture storage of the peat/mineral layer promotes the infiltration of rainfall events and allows this water to be reabsorbed by the underlying glacial soil without causing preferential flow which might bypass the matrix of the glacial soil (Barbour et al 2004).

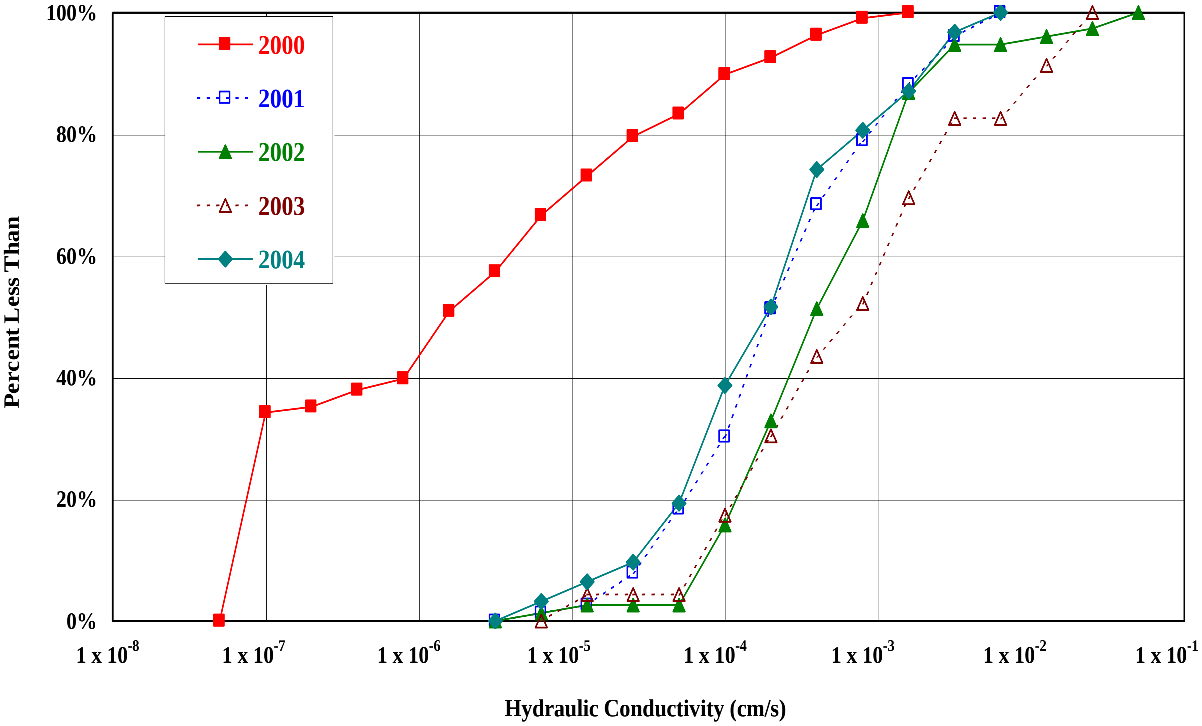

Figure 3. Cumulative histogram of the K values measured for the glacial cover soil.

Meteorological Parameters

Figure 4 shows the total rainfall and snowfall measured at the cover site. Rainfall decreased consistently over the first four years of monitoring, from 351 mm in 2000 to 231 mm in 2003, and then increased during the final year to 271 mm but was well below the annual average of 310 mm.

Measurements of total snowfall ranged from 15 to 70 mm, which is also significantly less than the mean annual average (130 mm). A tipping bucket rain gauge is used to record rainfall, while an antifreeze reservoir adaptor is added to the gauge for measurements of precipitation during the winter period. Rainfall was interpreted as precipitation that occurred while the day time temperature was above 0^oC, consequently there may be a small error in separating precipitation into snow and rain. Even so, Fig. 4 clearly shows a decline in precipitation during the first four years of monitoring, followed by a slight increase during the final year. Snowpack surveys were conducted at the cover system field trial area. However, the data set does not encompass the entire monitoring period and consequently was not presented in this paper.

In Situ Moisture Content

Figure 5 shows the volumetric water content measured within the 100 cm cover system at a depth of 30 cm, immediately below the peat/mineral – glacial soil interface, and at a depth of 115 cm, immediately above the glacial soil/shale interface. The cover thickness at this location is 120 cm.

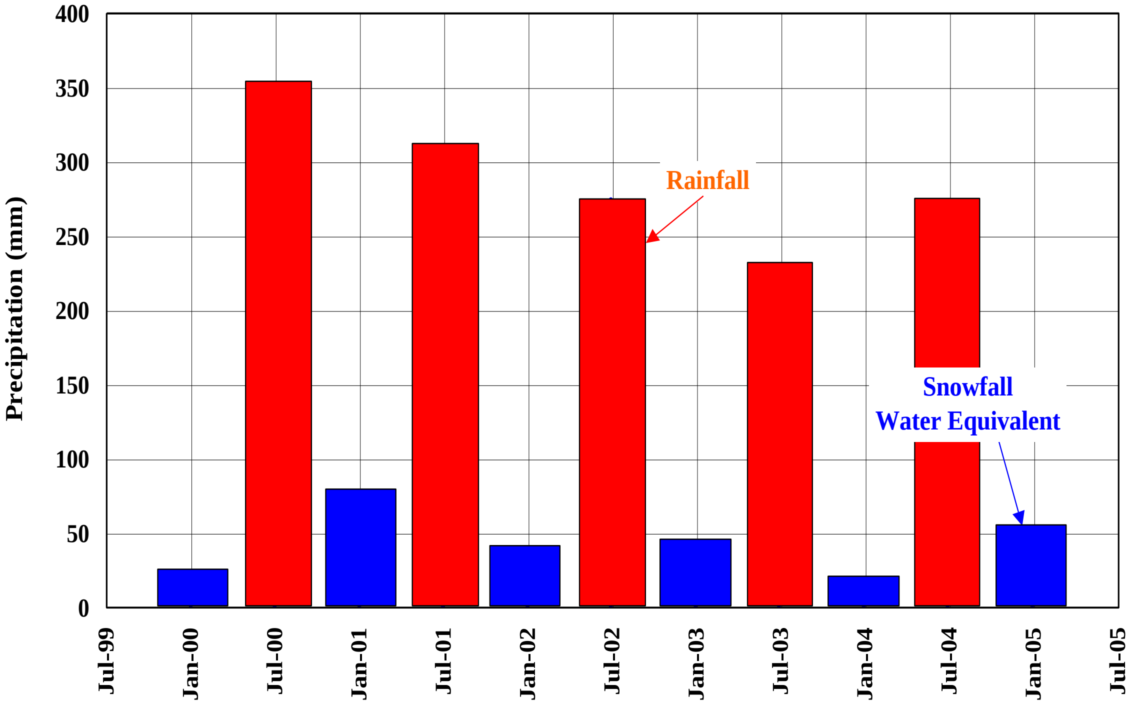

Figure 4. Annul rainfall and snowfall measured at the cover system field trial area.

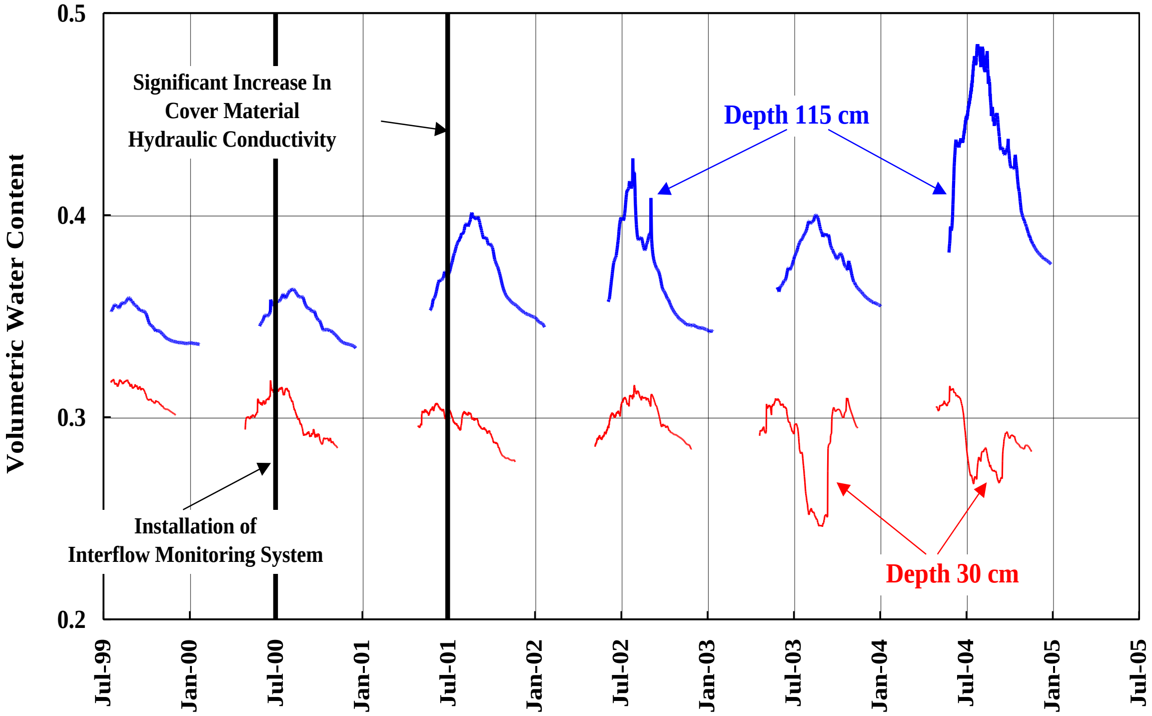

Figure 5. Monitored volumetric water contents within the 100 cm cover.

The sensors cannot measure total water content under freezing conditions due to the change in the dielectric constant between liquid water and ice. Breaks in the data in Fig. 5 correspond to periods where the measured *in situ* temperature is below 0°C.

The initial increase in water content in the spring is due, in part, to snowmelt and spring rain infiltration combined with low potential evaporation (PE). At a depth of 30 cm the increase in water content occurs until around July at which time the water content begins to decrease in response to transpiration. This decrease is more dramatic during the 2003 and 2004 field seasons as vegetation becomes more established.

The volumetric water content measured at a depth of 115 cm starts to increase as soon as the *in situ* temperature conditions rise above 0°C at the 115 cm measurement depth. A lag time of approximately two months exists between thawing at the surface and the base of the cover. The reverse is also true during winter freeze up. The increase in the water content at the base of the cover system is due to the downward percolation of meteoric waters. Three factors that may contribute to the decrease in water content at the base of the cover includes: (1) downward percolation into the underlying shale; (2) lateral movement of water down slope along the glacial soil/shale interface; and (3) evapotranspiration from the cover including upward movement of water into the shallower root zone.

The trends in the moisture content at a depth of 115 cm measured during 1999 and 2000 are similar. However, during the 2001 season the magnitude of the fluctuation in moisture content is greater than that recorded during the previous two field seasons. The moisture content at the start and end of the monitoring period is also greater than in the previous year. This is contrary to what might be expected from the decline in the annul precipitation. The increase in hydraulic conductivity, from 2 x 10^{-6} cm/s in 2000 to 2 x 10^{-4} cm/s in 2001, appears to have led to an increase in the dynamics of moisture movement to the base of the cover, even in the presence of lower precipitation.

These moisture dynamics continued throughout each field season with the exception of 2003. In this case the dramatic decrease in moisture storage within the shallow cover in response to increase rates of transpiration, and the lower summer precipitation, likely resulted in the upward movement of moisture within the cover.

<u>Change in Hydraulic Conductivity and Moisture Cycling</u>. As previously discussed, the increase in the moisture content at the base of the 100 cm cover from 2000 to 2001 is likely related to the significant increase in hydraulic conductivity that occurred within the glacial soil layer. However, the continuing increases in moisture content in subsequent field seasons may seem somewhat counterintuitive, given the decrease in annual precipitation and the stabilization of hydraulic conductivity values. The continued increase in moisture at the base of the cover may be due in part to the following: first, the measured K values were obtained at a depth of 60 cm, mid-depth within the glacial cover layer, and consequently may not reflect the rate of change of K near the base of the cover; second, the development of the secondary structure causing the increase in K from 2000 to 2001, may still be occurring, but acting primarily to expand the degree of interconnectedness at a larger scale than is detectable by the GP technique.

The increase in hydraulic conductivity measured within the shale at a depth of 30 cm below the cover/shale interface occured one year after the increases measured in the overlying glacial soil. As a result the hydraulic conductivity, between a depth of approximately 70 cm and the base of the cover system, may have evolved at a rate somewhere between these two measured rates.

Interflow Measurements

The total volume of water moving laterally down-slope through the covers along the glacial soil/shale interface can be estimated from the volumes of collected interflow. The data for the 35 cm and 100 cm covers is presented in Fig. 6. Installation of the interflow collection system occurred during the summer of 2000.

The annual cumulative volume of interflow increased consistently from 2001 to 2004 for all covers. The volume of interflow for the 100 cm cover was consistently greater than for the other covers in 2001, 2003, and 2004. The dramatic increase in interflow volumes even in the face of small decreases in rainfall and snowmelt suggest that the changes in hydraulic conductivity as measured by the GP are influencing the hydrologic performance of the covers.

It is evident that the increase in interflow volumes is off set from the increases in measured K by approximately two years. This offset may be due to the development of a more interconnected secondary structure, which is required to transport water laterally down-slope along the glacial soil/ shale interface, as discussed above. The installation of the interflow collection system itself may also have disturbed the secondary structure/flow paths. In general, a comparison of the duration and volume of interflow for any particular year and cover suggests that the interflow is controlled by cover thickness, precipitation, and changes in the hydraulic conductivity.

Summary

Three cover system field trials were constructed at the Syncrude Canada Limited mine in 1999. Instrumentation was installed for monitoring the hydraulic performances of the cover system field trials. A field testing program was implemented to monitor changes in hydraulic conductivity over time. Performance monitoring data have been collected for six years. This paper relates changes in hydraulic conductivity to the hydraulic performance of the 35 cm and 100 cm cover system field trials.

The collected field performance data shows that changes in hydraulic conductivity have resulted in an increase in the interflow volumes even in the presence of a slight decline in annual precipitation levels. It would appear that the interflow characteristics are a function of the cover thickness; precipitation; and the *in situ* hydraulic conductivity.

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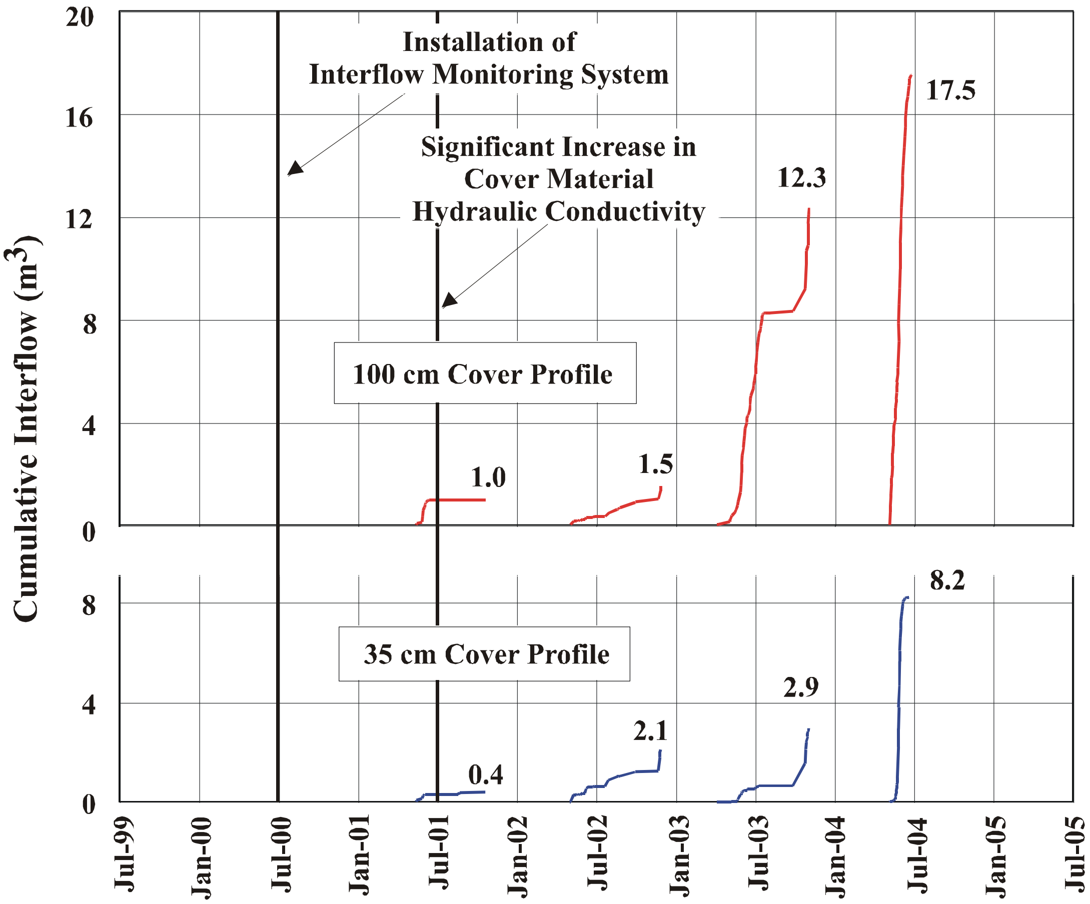

Figure 6. Measured interflow volumes for the 35 and 100 cm cover system field trials.

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