A Multi-disciplinary Approach to Reclamation Research in the Oil Sands Region of Canada

C.J. Kelln, S.L. Barbour, B. Purdy, and C. Qualizza

Abstract A 7-year research project into the long-term performance of reclaimed landscapes on saline-sodic overburden from oil sands mining in north-central Canada has demonstrated the importance of a multi-disciplinary approach. The land capability assessment tool used by the industry evaluates three key areas: available soil moisture, salt impact, and biological response (including nutrients). Detailed field monitoring and sampling demonstrated the relative performance of three different layered covers (35, 50 and 100 cm) and one monolayer cover (100 cm) through the tracking of water content, suction, stored water volumes, interflow/runoff and water availability for plant growth. Salt ingress into the cover from the underlying waste and salt release through interflow flushing has also been monitored. This long-term monitoring has provided physically based measurements of cover performance that clearly highlight the inability of thin (35 cm) or monolayer covers for providing sufficient moisture to meet all demands throughout a growing season. Interpretation of this data has also provided key insights into the mechanisms governing cover performance. This physically based evaluation was supported by direct measurements of tree development and tree ecophysiology. Vegetation indicators included plant species composition and abundance, tree growth rates, foliar nutrient contents, and plant ecophysiology.

Keywords Mining • reclamation • covers • water balance • salts • vegetation

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1 Introduction

Land reclamation on saline-sodic shale overburden from oil sands mining in the boreal forests of north-central Canada will occur on an unprecedented scale. Approximately 70 km^2 of saline-sodic shale overburden will have to be reclaimed at the Syncrude Canada Ltd. mine alone, and there are currently three similar open-pit mining operations in the region. Government legislation (Alberta Environmental Protection 1994) requires oil sands operators to return the disturbed areas to an equivalent land capability (ELC). This capability is currently assessed using the Land Capability Classification System (Leskiw 1998, 2006), which is based on a comprehensive suite of soil and landscape parameters, with three of the most heavily weighted areas being Available Water Holding Capacity (AWHC), salt impacts, and nutrient availability.

The research efforts to date have reinforced the idea that an evaluation of the long-term performance of these reclaimed landscapes must: (1) adopt a multi-disciplinary approach that tracks the performance of the hydrological, geochemical, and biological functions of the cover; and, (2) be conducted on a ‘watershed’ scale in order to address the spatial variability in the cover-performance functions (Qualizza et al. 2004).

The objective of this paper is to demonstrate the value of a multi-disciplinary approach to reclamation cover research at a ‘watershed scale’. Various hydrometric and geochemical data are presented that, in isolation, provide limited insight into cover performance. Taken as a whole, the data helps elucidate the mechanisms and processes that govern the spatial controls on the bio-physical response of the cover. A brief synthesis of the cover vegetation research is provided to demonstrate the direct correlation between the ecological and physical responses of the cover.

2 Background

2.1 Study Site

The study was conducted at the SW30 Overburden Research Site (57°2′ N, 111°33′ W), located in north-central Canada at the Syncrude Canada Ltd. mine site. The climate of the region is classified as semi-arid to sub-humid with a mean annual air temperature of 1.5 °C and a mean annual precipitation is 442 mm (1945–1995). Monthly mean air temperatures range from 18 °C in July to −20.7 °C in January. Potential evapotranspiration (PET) as estimated by Penman (1948) typically exceeds 500 mm per year with daily maximums (~7 mm/day) occurring during July and August.

An instrumented watershed was commissioned in 1999 on a 2 km^2 saline-sodic shale overburden dump. The shale overburden is excavated during open-pit mining to gain access to the underlying oil-rich sand. It is then deposited in large waste dumps and re-contoured to create a natural landscape form. The shale is of marine origin (Cretaceous age) and is both saline and sodic. Reclamation is achieved by placing a two layer cover comprised of a thin, organic rich, peat/clay mixture over a thicker clay-rich layer (herein called ‘secondary’) which is salvaged from natural glacial deposits. This layering creates surrogate ‘A’ and ‘B’ horizons similar to that of a natural soil profile. It is expected that this cover will continue to evolve over several decades until capital and circulation rates for moisture and nutrients can be established that are similar to those for natural ecosystems (Qualizza et al. 2004).

Four alternative prototype test covers of varying thickness (35, 50, and 100 cm) were constructed on north-facing slopes and were comprised of: 15 cm of peat-mineral (PM) mix overlying 20 cm of secondary; 20 cm of PM overlying 30 cm of secondary; 20 cm of PM over 80 cm of secondary; and a 100 cm monolayer secondary cover. The three layered covers are each 50 by 200 m in area and were constructed on a 5:1 slope. Each cover drains into a single swale ditch located at the toe of the slope, which connects into the overall drainage system for the hill. The monolayer cover was constructed on a 4:1 slope and was placed 3 years earlier than the other covers (1996).

2.2 Instrumentation and Testing

Details of the soil instrumentation, laboratory testing, and field programs can be found in Barbour et al. (2004). A soil station was installed in the centre of each cover to measure matric suction, ground temperature, and soil moisture throughout the cover profile and into the shale. Two meteorological stations were installed on the site to measure air temperature, net radiation, wind speed and direction, relative humidity, and precipitation. Soil moisture conditions were also measured in neutron and capacitance access tubes at various locations traversing the entire watershed. Surface run-off was monitored at the down-slope edge of each cover using v-notch weirs equipped with automated water level monitoring and data acquisition systems. Subsurface saturated flow (i.e. interflow) was collected over the entire width of each cover using a sub-surface drainage system installed at the cover-shale interface near the toe of the slope. Shallow monitoring wells were installed at approximately 80 locations to monitor the development of a perched water table on the cover-shale interface and provide sampling points for water chemistry.

The in-situ hydraulic conductivity (K_s) of the cover and underlying shale was measured every year using a Guelph permeameter. Material characterization included particle size distribution (PSD), bulk density, and porosity along with a laboratory-based soil water characteristic curve. Major ion chemistry and stable isotope analyses (δD and $\delta^{18}O$) were performed on waters collected from the interflow system and shallow monitoring wells. One-dimensional profiles of *in-situ* pore water chemistry and $\delta^{18}O$ were determined at over 20 locations. Finally, vegetation surveys were conducted to evaluate cover performance including plant species composition and abundance, tree growth rates, and foliar nutrient contents.

3 Presentation and Discussion of Results

3.1 Soil Moisture

Multiple lines of evidence demonstrated that the performance of thin (i.e. 35 cm) multiple layer covers and thicker monolayer covers did not provide sufficient moisture storage to supply all of the evapotranspirative demands from vegetation. This evidence included measured and modelled moisture dynamics and evapotranspiration rates, frequency of wilting point conditions, the frequency and magnitude of water use from the saline shale overburden, the frequency of preferential flow during high intensity infiltration events, and the volumes of stored water (Barbour et al. 2006b). Due to space limitations, only a few examples of this evidence are summarized.

Soil moisture monitoring between 1999 and 2005 (Fig. 1) demonstrated that the volume of water stored in the layered covers approaches field capacity (FC) during the spring, when surface run-off rates are high due to snow melt, and net infiltration is greater due to spring rain and low evapotranspiration rates. These covers also reach FC occasionally throughout the summer and often in the autumn months due to heavy rainfalls. The monolayer cover appears unable to reach FC on an annual basis. This may be due to infiltrating water bypassing the clay matrix, passing directly through the cover along fractures and macropores. The presence of the peat/mineral layer appears to provide sufficient storage for infiltrating water so that it can be absorbed over a longer time period by the underlying clay matrix.

Soil water storage in the 35 cm cover did not reach wilting point (WP) conditions during the driest summer months (Fig. 1); however, the cover approaches the WP during most years due its lower available water holding capacity (AWHC). In contrast, soil water storage in the thicker layered covers remains significantly above WP conditions, even in the driest years, due to the higher AWHC of these covers. The 100 cm mono-layer cover appears to perform no better, and possibly poorer, than the 50 cm layered cover in limiting the onset of WP conditions.

Long-term soil-vegetation-atmosphere (SVA) modelling (Shurniak 2003) suggested that: (1) the peat-mineral layer plays a critical role in maintaining sufficient moisture in the glacial soil of all covers; and, (2) the optimal cover thickness is greater than 60 cm to accommodate extreme dry conditions. In summary, the soil moisture data and SVA modelling indicated that moisture would likely be a limiting factor for vegetation growth in the thinnest layered cover, and even in thicker monolayer covers, during dry climatic years.

3.2 In-Situ Hydraulic Conductivity

The average *in situ* values of saturated hydraulic conductivity (K_s) are shown in Fig. 2. The K_s increased several orders of magnitude in all materials within 3 to 4 years after cover placement in 1999. The increase in K_s over time is consistent with

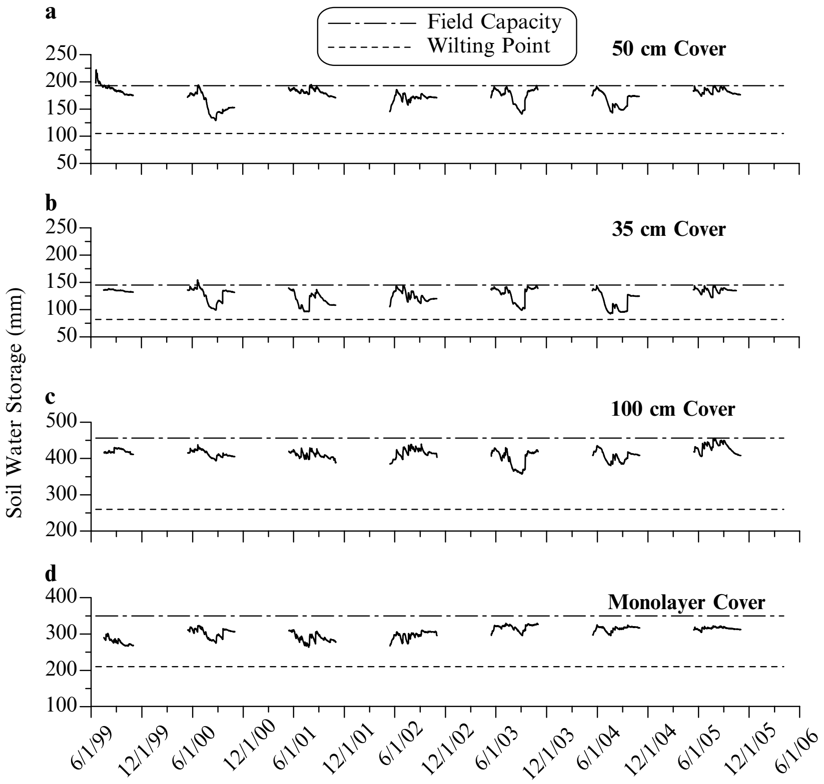

Fig. 3.1 Soil water storage in the 35, 50, 100 cm and monolayer covers

other cover performance studies in which K_s increases are either inferred by increasing drainage rates (e.g., Khire et al. 1997) or measured directly in the field and laboratory (e.g., Albright et al. 2006). In this case, the increase in K_s was attributed to the development of macrostructure caused by freeze-thaw and wet-dry cycling (Meiers et al. 2003). This data demonstrates the importance of tracking K_s over time as bio-physical processes can alter hydraulic properties and possibly the hydrologic response of the cover from the intended design (MEND 2004).

3.3 Hydrometric Data

Figure 3 presents the cumulative volume of water collected in the interflow system for 2005 along with measured precipitation. Only specific hydrometric data are

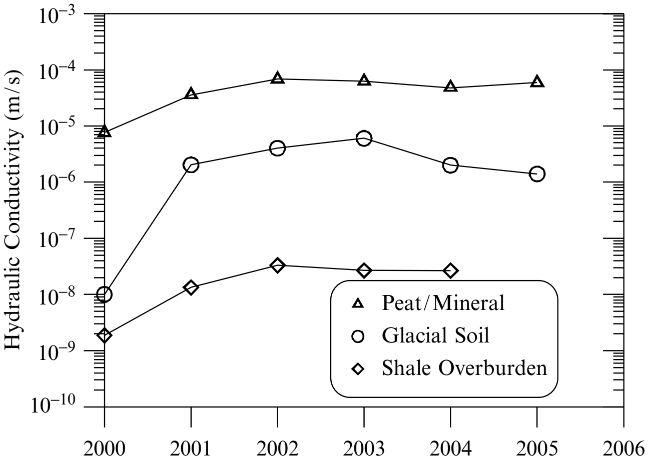

Fig. 3.2 Measured hydraulic conductivity over time (After Meiers et al. 2006)

presented for brevity. Annual interflow volumes ranged from about 1,000 L in 2001 to over 60,000 L in 2005. The shallow monitoring well data indicated that a perched water table, extending approximately 15 m upslope from the toe, develops annually on the cover-shale interface. A comparison between yearly ground temperature data and interflow response revealed the following annual pattern: (1) snow-melt (air temperatures above 0 °C) is complete approximately 1-month prior to the onset of interflow; (2) the majority of snow-melt water reports as surface-runoff; (3) a perched water table develops and interflow begins almost immediately when the ground thaws; and, (4) the cessation of interflow coincides with a recession of the perched water table and increased matric suction in the cover due to elevated evapotranspiration rates in the summer (Kelln et al. 2006).

The most interesting aspect of these observations is the time-lag between snow melt and the initiation of ground thaw. It is well known that surface run-off occurs in cold northern climates during spring due to frozen ground conditions. Infiltration into frozen unsaturated soil is restricted due to pore ice blockage (Newman and Wilson 1997). Consequently, snow melt infiltration must occur via preferential pathways (i.e. macrostructure) when the ground is frozen. Water stored in the macrostructure then migrates into the soil matrix as the ground thaws, creating a perched water table (interflow) on the cover-shale interface.

Finally, it is interesting to note that interflow monitoring is somewhat unconventional for engineers, but more commonplace for hydrologists. In this study, the SVA modelling suggested that saturated conditions would not develop at the base of the cover, particularly in the thickest covers, due to the large amount of AWHC and the semi-arid climate. In contrast, both preferential flow and interflow are reported as near ubiquitous phenomenon in hillslope hydrology studies (Grayson and Western 2001; McDonnell 2003) and form an integral component of watershed monitoring

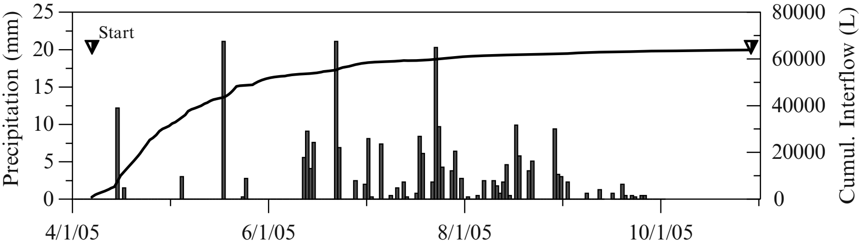

Fig. 3.3 Cumulative interflow and precipitation measured in 2005

programs in all climatic regions. Both interflow and preferential flow have implications for the moisture and salt balance of reclamation covers and should therefore be monitored on a watershed scale (MEND 2004).

3.4 Chemistry and Isotopes

Figure 4 presents the SO_4 concentration in the interflow water (Fig. 4a) and the $\delta^{18}O$ (Fig. 4b) of interflow water, snow, and monitoring wells during the 2005 snow melt. Solute concentrations in the interflow water increase each year from near 0 mg/L at the start of spring melt to a value equivalent to the pore water concentration near the interface. Similarly, the $\delta^{18}O$ interflow water evolves from a fresh snow melt water signature, to a $\delta^{18}O$ value that is consistent with measured *in-situ* $\delta^{18}O$ values of pore water. The *in-situ* $\delta^{18}O$ values were characteristic of summer and fall precipitation, indicating that connate pore water in the cover was derived from precipitation in the following year. An isotope hydrograph separation demonstrated that the interflow waters are eventually comprised of about 80% connate pore water.

The 'evolution' of interflow SO_4 and $\delta^{18}O$ concentrations suggests that the interflow evolves from preferential waters to flow through the soil matrix. The fresh water in the preferential flow paths nearest the interflow pipe drain into the interflow collection system almost immediately, followed by connate water that is transported down slope as the ground thaws and a perched water table develops upslope of the interflow collection system. The time to transition from preferential to predominantly connate water would depend on the upslope continuity and connectivity of preferential flow paths and the volume of water stored in the macrostructure.

These observations are consistent with hillslope hydrology studies, which report that, on average, 75% of 'stormflow' reporting to streams is attributed to connate water stored in the catchment before the episode (Buttle 1994). The geochemistry is also in keeping with the hydrometric data, which indicated that macrostructure is the dominant pathway available for infiltration during snow melt. More importantly, the interflow is responsible for the down-slope translocation of soil moisture and the flushing of salts from the cover in lower-slope positions.

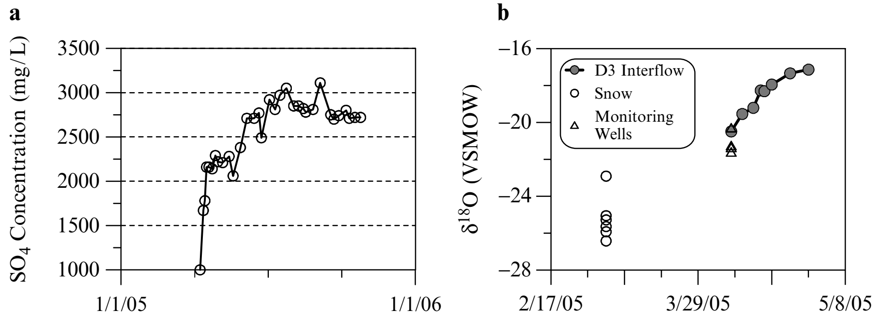

Fig. 3.4 Sulphate concentration and $\delta^{18}O$ signature of interflow waters

3.5 *Salt Ingress*

In-situ profiles of pore water solute revealed the following (Barbour et al. 2006c): (1) salt ingress is ubiquitous across the watershed; (2) the extent of salt ingress varies from cover to cover and is also a function of location within each cover (i.e. spatial variability); and, (3) interflow and deep percolation are key processes acting to attenuate salt ingress. On average, salt ingress has occurred 15–30 cm above the cover-shale interface in the 35 and 50 cm thick covers, and about 40 cm above the interface in the 100 cm cover. The increased salt ingress in the 100 cm cover is attributed to excess moisture conditions at the base of the cover, which increases the coefficient of diffusion (Lim et al. 1998). Although salt ingress has occurred to a greater extent in the thickest cover, the thinner covers have the greatest potential for 'failure' over time due to the encroachment of salt-rich pore water on the rooting zone.

A comparison of measured and modelled one-dimensional pore water Na^+ profiles demonstrated that salt ingress is greater in lower-slope positions than upper-slope positions due to spatial variability in the soil moisture regime and groundwater flux conditions. The upper-slope regions are drier due to down-slope moisture translocation and a lack of up-slope contributing area for surface run-off during the spring melt. As a result, upward salt transport in upper-slope regions is attenuated by the reduced coefficient of diffusion. The profiles also suggested that at least some deep percolation and/or interflow is occurring in upper-slope regions and is acting to minimize salt ingress, which is consistent with the preferential flow mechanism discussed above.

In lower-slope positions, interflow and deep percolation both appear to counteract the increased diffusive transport rate caused by increased soil moisture. The pore water chemistry demonstrated that current reclamation landscapes are (1) effective in reducing salt ingress, which will ultimately bode well for the development of a healthy eco-system, and (2) the thickest cover is the optimal design for mitigating the effects of salt ingress over the short and long-term. The latter observation is again consistent with the soil moisture monitoring and demonstrates that pore water chemistry is a valuable tool for evaluating long-term cover performance.

3.6 Vegetation Growth

A tree-growth survey was conducted in 2005 to determine if there is spatial variability in vegetation response on the three layered covers. In general, the overall health of vegetation depends on the edaphic factors (moisture and nutrients) and the potential for toxicity caused by salt ingress into the covers. The average measured height and diameter of planted trembling aspen trees on the 50 and 100 cm covers together was about 220 and 28.5 cm, respectively. In contrast, the average height and diameter of trembling aspens on the 35 cm cover was 195 and 26.4 cm, respectively. The datasets for both the 50 and 100 cm covers proved to be statistically different from the 35 cm cover tree data.

The trembling aspen tree data demonstrate that tree growth rates have been greater on the thicker covers (50 and 100 cm). This observation is in keeping with other vegetation studies at the site that have shown a greater number of species have established themselves on the thicker covers, and that the thicker covers have remained more amenable for germination and establishment than the thin cover over time (Purdy, unpublished data). The discrepancy between the two thickest cover prescriptions and the 35 cm cover is likely attributable to the measured differences in soil moisture. Previous studies have shown that the foliar nutrient levels in all three covers were generally within ranges considered acceptable and non-limiting in aspen and white spruce based on comparisons of measured and literature values (Purdy, unpublished data). Finally, the lower AWHC of the thinner cover is consistent with lower transpiration rates that were measured in both white spruce and trembling aspen saplings (Elshorbagy and Barbour 2007).

4 Summary and Conclusions

A multi-disciplinary approach to monitoring and evaluating the long-term performance of a reclamation cover provided important insight into the various mechanisms and processes that will control the hydrological and biological function of the reclaimed landscape. Conventional monitoring of soil moisture in the alternative prototype covers indicated that thin (35 cm) layered covers cannot meet all the moisture demands placed on them and plant communities characteristic of drier sites would likely develop. The saturated hydraulic conductivity of the clay-rich cover material increased by two orders of magnitude within 4 years of cover placement due to freeze-thaw effects. These preferential flow paths play a pivotal role in the formation of interflow as a result of infiltration of fresh snow melt water to the base of the cover during the spring melt. Interflow and deep percolation are important mechanisms for salt flushing, which protect the cover from ongoing salt ingress from the underlying shale. Finally, there is a correlation between the physical and ecological response of the covers. Tree growth and physiologic indicators showed that aspen growth on the shallower covers was lower than that observed on thicker covers. This is attributed to the measured lower volumes of water in the shallower covers.

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References

Alberta Environmental Protection 1994. A Guide for Oil Production Sites, Pursuant to the Environmental Protection and Enhancement Act and Regulations. Queen's Printer.

Albright, W.H., Benson, C., Gee, G.W., Abichou, T., McDonald, E.V., Tyler, S.W., and Rock, S.A. 2006. Field performance of a compacted clay landfill final cover at a humid site. Journal of Geotechnical and Environmental Engineering, **132**(11): 1393–1403.

Barbour, S.L., Chapman, D., Qualizza, C., Kessler, S., Boese, C.D., Shurniak, R., Meiers, G.P., O'Kane, M., Hendry, J., and Wall, S.N. 2004. Tracking the evolution of reclaimed landscapes through the use of instrumented watersheds – a brief history of the Syncrude Southwest 30 overburden reclamation research program. *In* International Instrumented Watershed Symposium, Edmonton, Canada, pp. 622–644.

Barbour, S.L., Chanasyk, D., Hendry, J., Macyk, T., Mendoza, C., Nichol, C., Naeth, A., Leskiw, L.A., Purdy, B., Qualizza, C., Quideau, S., and Welhelm, C. 2006a. Phase 4 Technology Transfer Integration Document (Draft), Syncrude Canada Ltd.

Barbour, S.L., Chanasyk, D., Hendry, J., Macyk, T., Mendoza, C., Nichol, C., Naeth, A., Leskiw, L.A., Purdy, B., Qualizza, C., Quideau, S., and Welhelm, C. 2006b. Phase 1 Technology Transfer: Soil Structure and Moisture Regimes, Syncrude Canada Ltd.

Barbour, S.L., Chanasyk, D., Hendry, J., Macyk, T., Mendoza, C., Nichol, C., Naeth, A., Leskiw, L.A., Purdy, B., Qualizza, C., Quideau, S., and Welhelm, C. 2006c. Phase 2 Technology Transfer: Salt Impacts on Soil Covers in Saline Sodic Overburden Landscapes, Syncrude Canada Ltd.

Buttle, J.M. 1994. Isotope hydrograph separations and rapid delivery of pre-event water from drainage basins. Progress in Physical Geography, **18**(1): 16–41.

Elshorbagy, A. and Barbour, S.L. 2007. A probabilistic approach for design and hydrologic performance assessment of reconstructed watersheds. Journal of Geotechnical and Environmental Engineering.

Grayson, R. and Western, A. 2001. Terrain and the distribution of soil moisture. Hydrological Processes, **15**: 2689–2690.

Kelln, C.J., Barbour, S.L., Elshorbagy, A., and Qualizza, C.V. 2006. Long-term performance of a reclamation cover: The evolution of hydraulic properties and hydrologic response. *In* The Fourth International Conference on Unsaturated Soils. *Edited by* ASCE. Carefree, Arizona. April 2–6.

Khire, M.V., Benson, G.H., and Bosscher, P.J. 1997. Water balance modelling of earthen final covers. Journal of Geotechnical and Environmental Engineering, **123**(8): 744–754.

Leskiw, L.A. 1998. Land Capability Classification for Forest Ecosystems in the Oil Sands Region, Alberta Environment C&R IL.

Leskiw, L.A. 2006. Land Capability Classification System for Forest Ecosystems in the Oilsands Region, Alberta Environment C&R IL.

Lim, P.C., Barbour, S.L., and Fredlund, D.G. 1998. The influence of the degree of saturation on the coefficient of aqueous diffusion. Canadian Geotechnical Journal, **35**: 811–827.

McDonnell, J. 2003. Where does water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response. Hydrological Processes, **17**: 1869–1875.

Meiers, G.P., Barbour, S.L., and Meiers, M.K. 2003. The use of field measurements of hydraulic conductivity to characterize the performance of reclamation soil covers with time. *In* 6th International Conference on Acid Rock Drainage. Cairns, Australia.

Meiers, G.P., Barbour, S.L., and Qualizza, C.V. 2006. The use of *in situ* measurements of hydraulic conductivity to provide an understanding of cover system performance over time. *In* 7th International Conference on Acid Rock Drainage. St. Louis, MO, March 26–30.

MEND 2004. Report 2.21.4: Design, Construction, and Performance Monitoring of Cover Systems for Waste Rock and Tailings, p. 93.

Newman, G.P. and Wilson, G.W. 1997. Heat and mass transfer in unsaturated soils during freezing. Canadian Geotechnical Journal, **34**: 63–70.

Penman, H.C. 1948. Natural evapotranspiration from open water, bare soil and grass. Proceedings of the Royal Society of London, **A193**: 120–145.

Qualizza, C., Chapman, D., Barbour, S.L., and Purdy, B. 2004. Reclamation research at Syncrude Canada's mining operation in Alberta's Athabasca oil sands region. *In* 16th International Conference, Society for Ecological Restoration. Victoria, Canada, August 24–26.

Shurniak, R. 2003. Predictive Modeling of Moisture Movement Within Soil Cover Systems for Saline/Sodic Overburden Piles. M.Sc., University of Saskatchewan, Saskatoon, SK.