MODELING OF WATER MOVEMENT WITHIN RECLAMATION COVERS ON OILSANDS MINING OVERBURDEN PILES[1]

Robert E. Shurniak[2] and S. Lee Barbour

Abstract. The hydrologic performance of four different soil cover systems used to cover saline-sodic overburden has been studied at the Syncrude Canada Limited mine site since 1999. Part of this study requires the creation of computer models, using the program SoilCover 2000, that can accurately simulate the water movement within these soil covers. During the modeling process, due to the heterogeneity of the soils used in the cover systems, multi-modal soil-water characteristic curves and hydraulic conductivity functions were implemented for better reproduction of the field measurements and for increased ease of calibration. The vegetation on the covers also had a profound effect on the water movement within the covers. By understanding these three key parameters, the authors were able to greatly improve the models' results.

Additional Key Words: multi-modal soil-water characteristics, instantaneous profile method, *setaria viridis*, *bromus inermis*, saline-sodic shale, peat

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Introduction

A multi-year study began in 1999 at the Syncrude Canada Limited mine site, 40 kilometers north of Fort McMurray, Alberta. This study examined the hydrologic performance of four different soil cover systems used to conceal saline-sodic shale overburden. These covers were instrumented to measure soil water content, suction and temperature profiles, interflow, runoff, and climatic conditions on a continuous basis. A site location map and the details of the instrumentation program are provided in a companion paper to this conference by Meier and Barbour, 2002. Using these measurements, models of the four sites were created using the computer-modeling program SoilCover 2000 (Unsaturated Soils Group, 2000). These models simulate the soil-atmosphere fluxes and associated moisture movement in the cover systems. SoilCover is a one-dimensional finite element model that uses a physically based method for simulating the transient exchange of water and energy between the atmosphere and soil surface. The principles of Darcy's, Fick's, and Fourier's Laws are used to describe the flow of liquid water, water vapour and heat, respectively, in the soil profile below the soil / atmosphere interface. SoilCover predicts the evaporative flux from a saturated or an unsaturated soil surface based on atmospheric conditions, vegetation cover, and soil response. The objective of this modeling is to be able to accurately predict the performance of the cover systems.

During the model calibration process, it was found that the variables that have the most effect on moisture movement are the soil-water characteristic curve, hydraulic conductivity function and vegetation. Multi-modal soil-water characteristic curves and hydraulic conductivity functions were implemented in order to adequately simulate the moisture movement within the soil cover systems. A detailed study of characteristics of the main vegetative species on the covers was also necessary. This paper describes the authors' findings on these key variables, the effect they have on the model, and reports some of the results obtained from the field response modeling of the soil covers.

Background

Syncrude Canada Limited uses open-pit mining to extract the Athabasca oil sands. Glacial deposits and saline-sodic shale must be removed in order to reach the oilsand. Excavation of this over-consolidated shale requires the placement of large overburden piles at the surface. These piles are recontoured and then covered with reclamation soils. The objective is to return the disturbed land to a stable, biologically self-sustaining state.

The presence of saline-sodic overbuden beneath the cover systems poses a number of potential reclamation problems. Firstly, the shale is salt rich and sodic, which makes it dispersive, leading to potential problems with erosion. Salt leaching and weathering of the shale can cause problems with salinization. The shale is also placed frozen and without compaction. This may cause the overburden to undergo subsidence and compaction due to loading and wetting. Finally, the ingress of water into these large surface deposits may also lead to the development of saline groundwater discharge into surface water bodies (Barbour et al., 2001). Therefore, soil cover systems must be constructed to minimize the infiltration of moisture into the underlying shale, while providing sufficient moisture storage for vegetation.

Construction of three of the cover systems, referred to collectively as the prototype covers, took place during 1999 on the South Hills overburden piles. These covers were constructed with two soil layers of varying thickness in accordance with the soil classification system developed by Leskiw et al. (1999). The two soils were comprised of surface peat overlying ‘secondary’; a term referring to glacial lacustrine or glacial till deposits. Each of the prototype covers is approximately 1 hectare in size (200 m long and 50 m wide) and placed on a 5 to 1 slope. Figure 1 shows the three cover thickness designs, referred to as D1, D2 and D3, for the prototype covers. The fourth study site, referred to as Bill’s Lake, was constructed during 1996 in a wetland adjacent to the three prototype covers. The Bill’s Lake cover system consists of 100 cm of mixed peat / till secondary overlying the overburden (Figure 1).

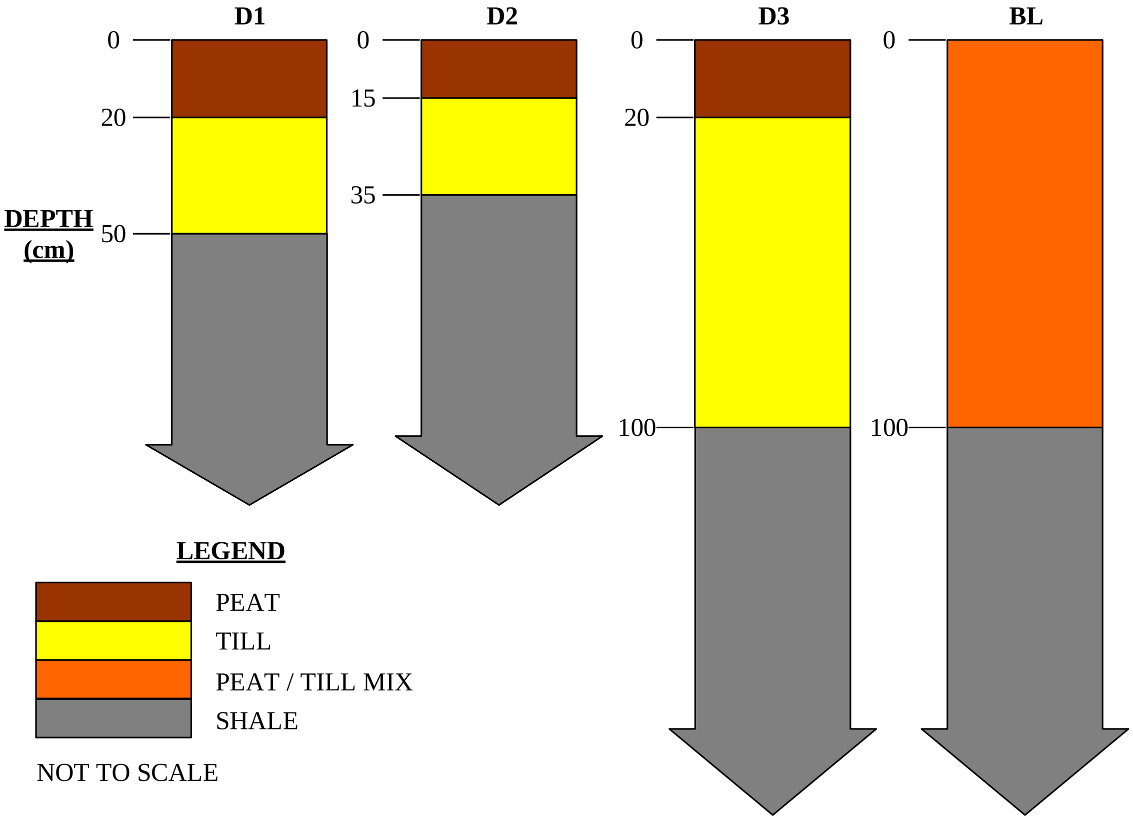

Figure 1. Design of the four soil cover systems used on the South Hills research area.

Instrumentation to monitor the hydrology and water balance of the three prototype covers, and the Bill's lake site were installed during the summers of 1999 and 2000. An instrumentation station was installed on each site to monitor soil suction, water content, and temperature profiles within the covers and shallow overburden. Figure 2 shows the locations of these instruments within each of the soil profiles. Note that water contents and soil suctions are measured at similar depths allowing for the creation of in situ soil-water characteristic curves. Runoff from the prototype covers is measured at the base of each plot using v-notch weirs. An interflow system allows for the measurement of water flowing down-slope along the soil cover / overburden interface. A weather station, located at the middle of the prototype covers, collects the necessary climate data (temperature, relative humidity, wind-speed, precipitation). A Bowen Ratio Energy Balance (BREB) apparatus was used over the summer period to measure evapotranspiration from the study sites. A field program was initiated during the summer of 2000 to measure in situ density profiles, obtain samples for soil chemistry and to perform Guelph permeameter testing in order to measure the saturated hydraulic conductivity of the cover soils and underlying shale. All monitoring is still on going. A companion paper by Meier and Barbour (2002) provides a more detailed description of the research site and the field-monitoring program.

The constructed cover systems' thickness and layering were measured during installation of the instrumentation stations. Prototype covers D1 and D2 differed only slightly from the design. The thickness of the peat on D3 was 10 cm thinner than the design parameters. The D3 till layer, however, was found to be 25 cm thicker than the design. The peat / till mix layer at Bill's Lake was 25 cm thinner than the design had specified at the location of the instrumentation station. More measurements taken at Bill's Lake since 1999 have found that the cover varies from 50 cm to 150 cm in thickness. This variation is most likely due to initial construction.

Further layering was discovered during the analysis of the soil-water characteristic curves created using the measured data. These curves showed that the top half of the peat layer, referred to as shallow peat, had a different soil-water characteristic curve than the peat below, referred to as deep peat. The in situ soil-water characteristic curve for the peat surrounding the D3 instrumentation station differed from those of the peat used on D1 and D2. A layer of peat / till mix was also found to be located between two layers of till within the D3 cover. Finally, the curves showed that BL had three distinct layers. Figure 3 shows the soil-water characteristic curves generated using the in situ data. Table 1 summarizes the properties of the soils used for the cover systems.

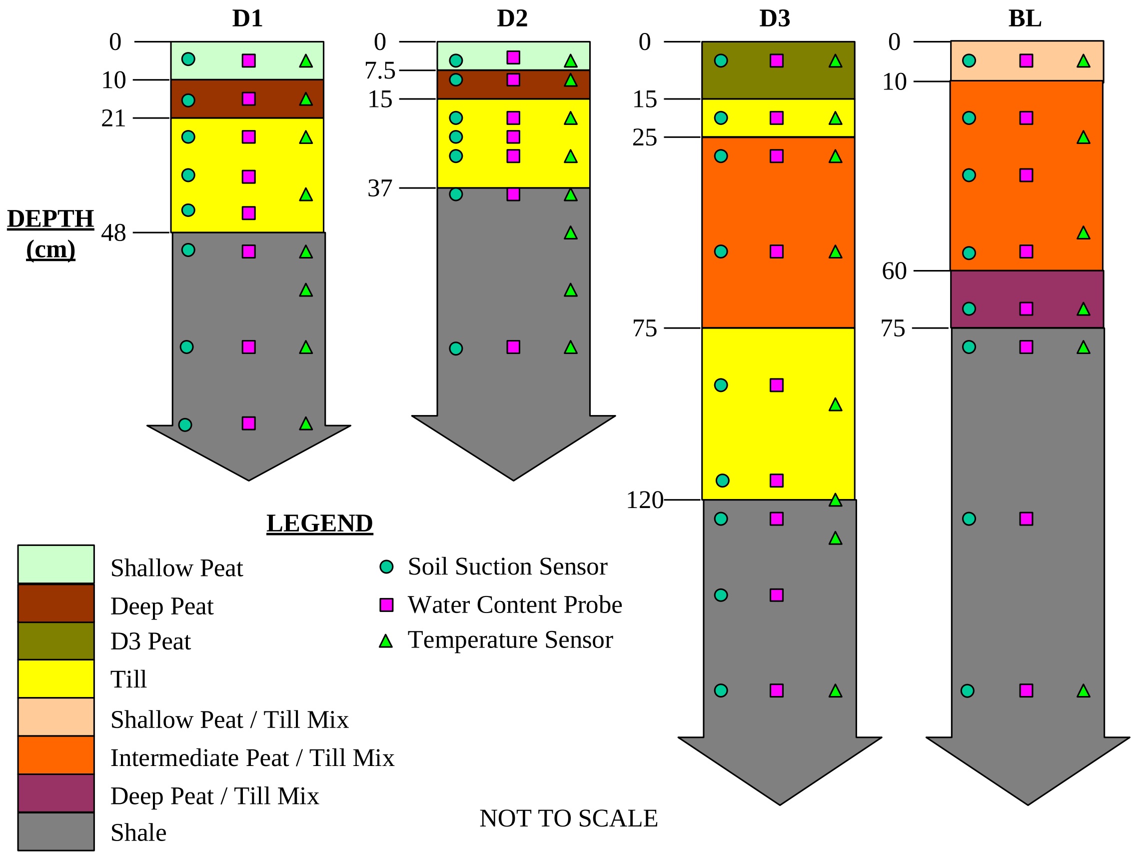

Figure 2. The actual dimensions of the soil cover systems and the locations of the instruments placed within the covers.

Table 1. Summary of soil properties used for the soil cover systems.

	Porosity, n (%)		Hydraulic Conductivity, K (cm/s)		Specific Gravity, G_s
Soil	maximum	minimum	maximum	minimum	
Shallow Peat†	69.4	47.8	4.38×10^{-3}	3.27×10^{-4}	2.61
Deep Peat	69.4	47.8	4.38×10^{-3}	3.27×10^{-4}	2.61
D3 Peat	51.7	46.4	5.46×10^{-3}	1.92×10^{-3}	2.61
Till	64.4	43.7	3.77×10^{-3}	3.21×10^{-7}	2.62
Peat/Till Mix‡	45.8	34.7	7.33×10^{-4}	3.52×10^{-6}	2.66

† Unable to measure differences between the shallow and deep peat due to the thinness of the layers.

‡ No significant differences measured for those parameters in the table for the shallow, intermediate and deep peat/till mix soils.

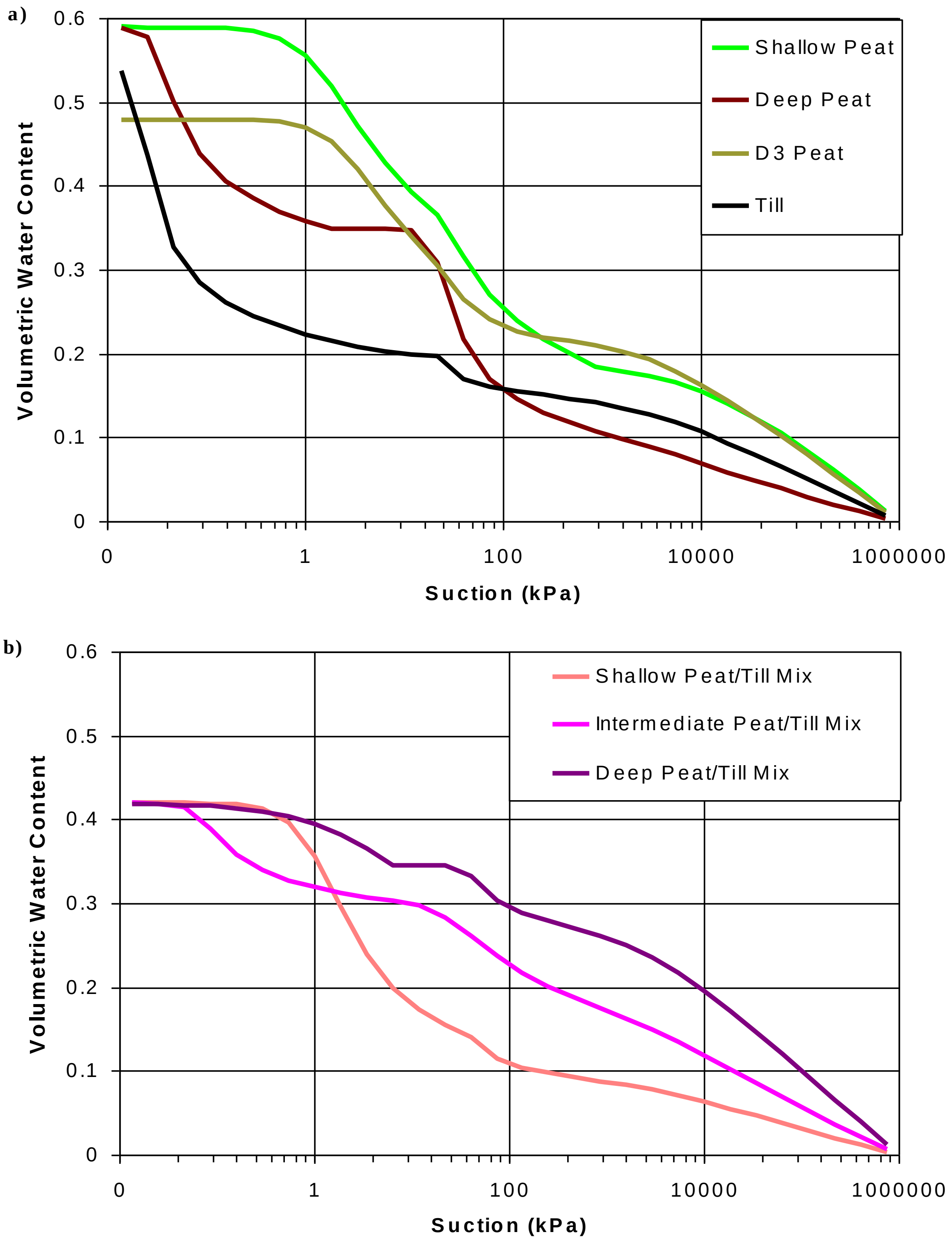

Figure 3. Soil-water characteristic curves of the soils used to construct the cover systems.

Description of Key Variables

Soil-Water Characteristic Curve

The data used to create the soil-water characteristic curves was obtained from in situ measurements of volumetric water content and soil suction at various depths within each prototype cover. These measurements were compared to the soil-water characteristic curves obtained from laboratory procedures using a pressure plate apparatus for suctions up to 500 kPa and an osmotic desiccator for suctions greater than 500 kPa.

The van Genuchten equation (1980), and more recently, the Fredlund and Xing equation (1994), have been commonly used to describe the shape of a soil-water characteristic curve. These equations create an excellent fit for unimodal soil-water characteristic curves, however, the soils on the South Hills study site have heterogeneous pore systems. A pore system is heterogeneous if the pore-size distribution of a representative elementary volume (Bear and Bachmat, 1991) cannot be correctly described with a unimodal soil-water characteristic curve (Durner, 1994).

In order to describe these multi-modal soil-water characteristic curves using the traditional equations, Durner (1992) introduced the concept of superimposing multiple van Genuchten equations (1980), known as the multi-van Genuchten model. Kastanek (2001) noted that it is possible to superimpose other unimodal soil-water characteristic equations in the same manner as Durner (1992) suggested for the van Genuchten equation (1980). For modeling the covers on the study area, the Fredlund and Xing equation (1994) was used because it is the one programmed into the SoilCover 2000 model.

Figure 4 illustrates the unimodal van Genuchten and Fredlund and Xing equations plotted along with the measured in situ data and porosity range. The measured data is for the peat of the D1 prototype cover at 16 cm depth during 2000 and 2001. Both equations create a superb fit when just fitted to the in situ data. However, when fitted to both the average porosity (59%) and the in situ data the fit is far from adequate. By superimposing multiple Fredlund and Xing equations (1994), referred to as the multi-Fredlund and Xing model, a much better fit is realized (Figure 5).

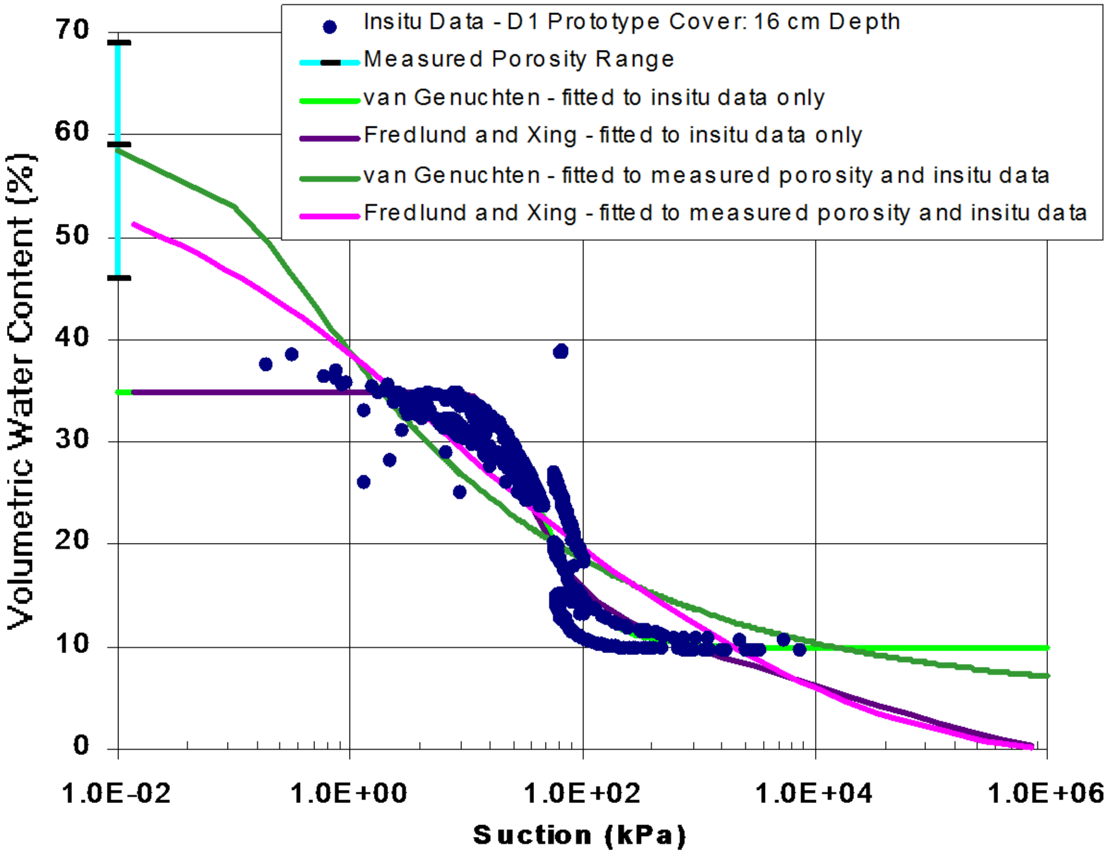

Figure 4. In situ water content versus suction data fitted by unimodal equations for the soil-water characteristic curve.

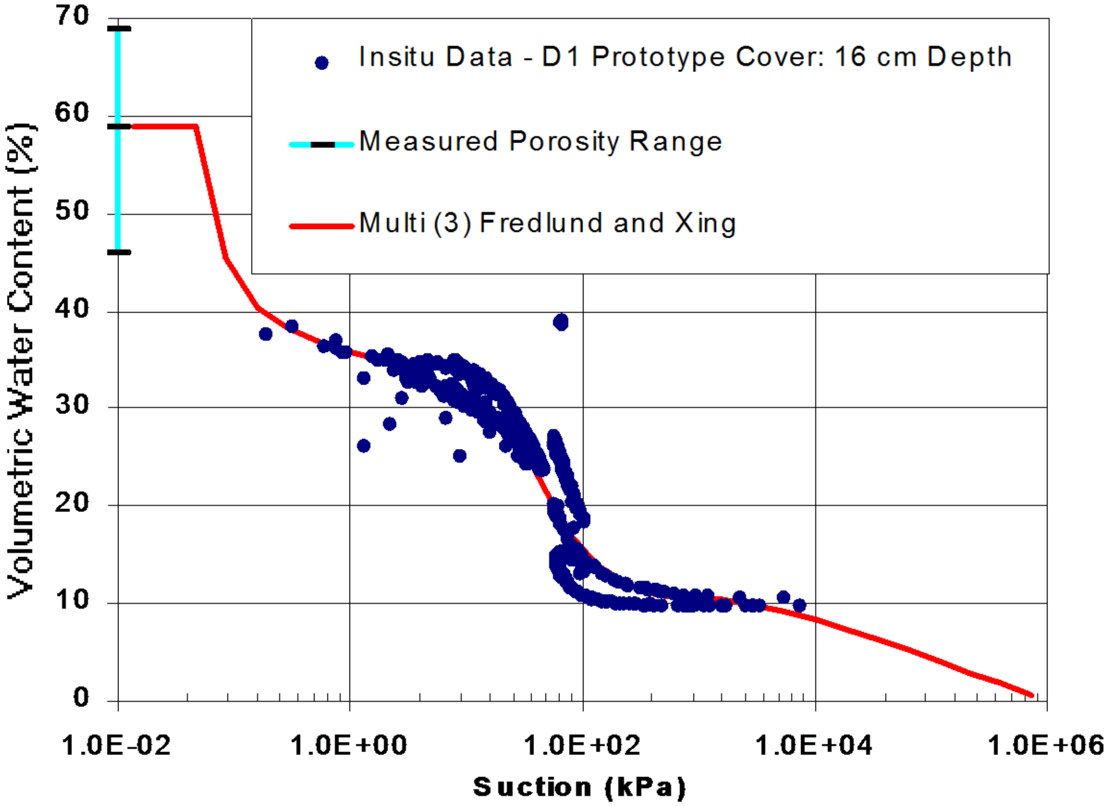

Figure 5. In situ water content versus suction data fitted by the multi-Fredlund and Xing model.

Hydraulic Conductivity Function

Evaluation of the hydraulic conductivity of the unsaturated soils on the South Hills study site was based on the instantaneous profile method (Richards and Weeks, 1953; Weeks and Richards, 1967; Daniel, 1983; Eching et al., 1994). The instantaneous profile method uses the measured daily changes in water content and suction to calculate the hydraulic conductivity using Darcy's equation. The saturated hydraulic conductivity and the hydraulic conductivity at suctions 0.5 of 1.0 kPa were measured during the summers of 2000 and 2001 using a Guelph permeameter (Meiers, 2002). This data was compared to the function created using the Fredlund et al. (1994) equation. The created function was estimated from the multi-Fredlund and Xing soil-water characteristic curve and the average saturated hydraulic conductivity. Figure 6 shows the hydraulic conductivity function created for the shallow peat.

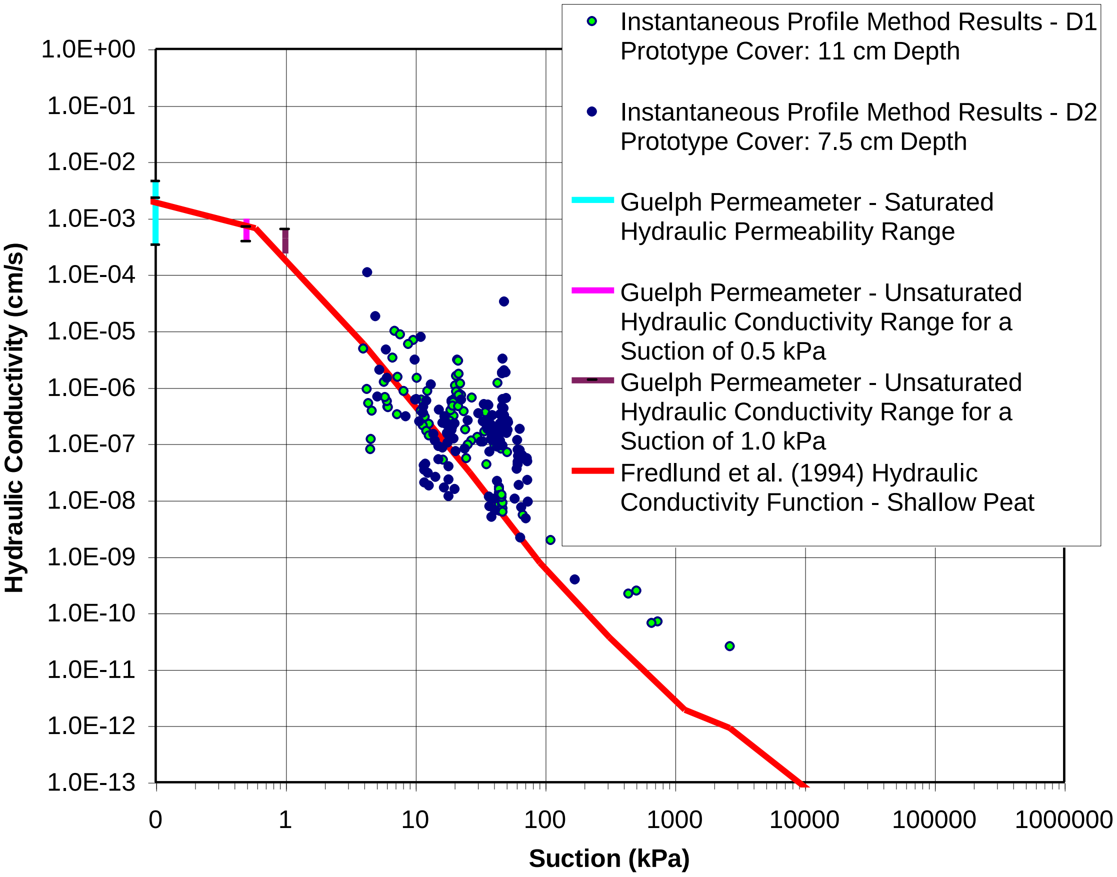

Figure 6. In situ unsaturated hydraulic conductivity versus suction data fitted by a hydraulic conductivity function estimated from the multi-Fredlund and Xing soil-water characteristic curve.

Vegetation

There were two predominant types of vegetation found on the South Hills Study Site during 2000, *Setaria viridis* and *Bromus inermis*. *Setaria viridis*, commonly known as green foxtail, was the prevalent vegetation found on the three prototype covers; while *Bromus inermis*, or smooth brome, was the main vegetation on the Bill's Lake Site.

Green Foxtail

Green Foxtail. Green foxtail is an annual grass and one of the most prevalent weed seeds in the world (Holman, 2001), with each plant being able to produce over 34000 seeds (Province of British Columbia, 1998). It grows erect (but may sometimes be curved at the base) to a height of 30 to 100 cm. Green foxtail is able to germinate over a large range of temperatures. Anderson (1968) reported that Lauer (1953) obtained some germination at constant temperatures from 7 to

40^{o}C, with the optimum germination temperature between 20 to 30^{o}C. Yabuki and Miyagawa (1959) obtained the best germination with a diurnal alteration in temperature from 15 to 35^{o}C. Vanden Born (1971) noted that germination occurred readily at temperatures from 15 to 35^{o}C, but at 10^{o}C there was no sign of germination for a period of nearly four weeks. Fifty percent of seeds germinate after 7 days at a temperature 15^{o}C (Vanden Born, 1971). Seedlings emerge readily from shallow planting depths of between 0.5 and 8 cm (Vanden Born, 1971 and Holman, 2001), with the best emergence occurring from a depth of 4 cm (1.5 in) (Dawson and Bruns, 1962). There is little chance of emergence from seedlings planted below 10 cm (Dawson and Bruns, 1962). Fifty percent of germinated seeds emerge 17 days after germination at a temperature of 15^{o}C (Vanden Born, 1971). Green foxtail also exhibits peaks in emergence following rainfall (Banting et al 1973, Douglas et al 1985). The roots are fibrous and shallow, and Orwick and Schreiber (1975) found that the seminal root growth of green foxtail, exposed to 16 hours of light and 8 hours of dark per day, to be at a rate of approximately 0.9 mm per day.

For use in the models, it was assumed that the green foxtail seeds germinated after 7 days with an average air temperature of 15^{o}C, and emerged 17 days later. This emergence date was assumed to be the start of the growing season. The roots were started at a depth of 1 mm and extended by 1 mm per day from the germination date until they reached the shale. The growing season was ended on the date of freezing temperatures after the start of the season. The lushness of the vegetation was estimated from observations.

Smooth Brome. Smooth Brome is a strongly rhizomatous, sod-forming perennial grass, which can grow to a height of between 0.4 and 1.2 m tall (Duke, 1983; USGS, 2001). Each plant can produce over 10000 seeds. Sather (1987) reported that Dibbern (1947) found that the roots of Brome could reach a depth of 1.4 m (4.7 feet). Lamba et al. (1949) found 21% by weight of brome roots between depths of 40 and 100 cm (16 and 40 inches), 10% between 20 and 40 cm (8 and 16 inches) and 64% in the top 20 cm (8 inches). This heavy concentration of total root mass near the surface is the result of smooth brome’s creeping rhizomatous habit (Sather, 1987). Smooth brome grows between temperatures of 4.3 to 19.9^{o}C, becoming dormant during the warmer months and, depending on soil moisture, may regrow in September or October (Duke, 1983 and USGS, 2001). Smooth brome is reported to tolerate alkali, disease, drought, frost, fungi, grazing, heavy soil, high pH, mycobacteria, salt, viruses, and weeds (Duke, 1978). It can also tolerate flooding for up to 24 days (USGS, 2001).

To simulate the growth of smooth brome on the BL cover system it was assumed that the existing plants began to regrow when the air temperature stayed above 4.3°C. The rooting depth was assumed to be 20 cm at this time. The roots were extended at a rate of 1 mm per day until the air temperature increased above 19.9°C. The end of the growing season was assumed to occur when the weekly average air temperature dropped below 4.3°C. The lushness of the vegetation was estimated from observations.

Presentation of Results

Figures 7 through 10 compare the measured volumes of water stored in the D1 cover to the modeled results calculated using the unimodal and multi-modal equations. These figures show that the multi-modal model improves the prediction capabilities of the SoilCover program. The effect of running the multi-modal model without vegetation is also presented, showing that vegetation has a profound effect on the volume of water contained within a soil cover.

The unimodal soil-water characteristic curves used to calculate the model results, shown in Figures 7 through 10, were created using just the in situ soil-water characteristic data. If the porosity measurements are also added, the modeled results improve significantly. However, the multi-modal model still produces a better match. Also, the multi-modal model is much easier to calibrate because specific parts of the soil-water characteristic curve can be changed, leaving sections that are known unaltered.

Figure 7. Water volumes per unit area in the shallow peat layer of the D1 cover.

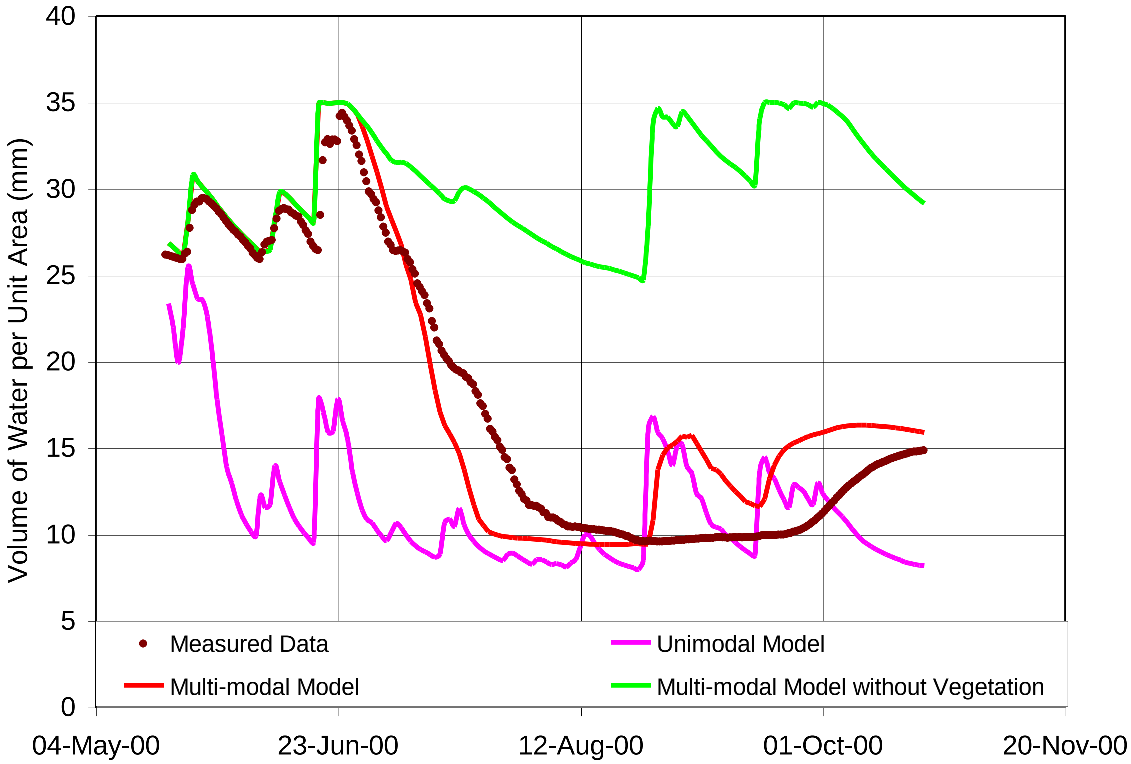

Figure 8. Water volumes per unit area in the deep peat layer of the D1 cover.

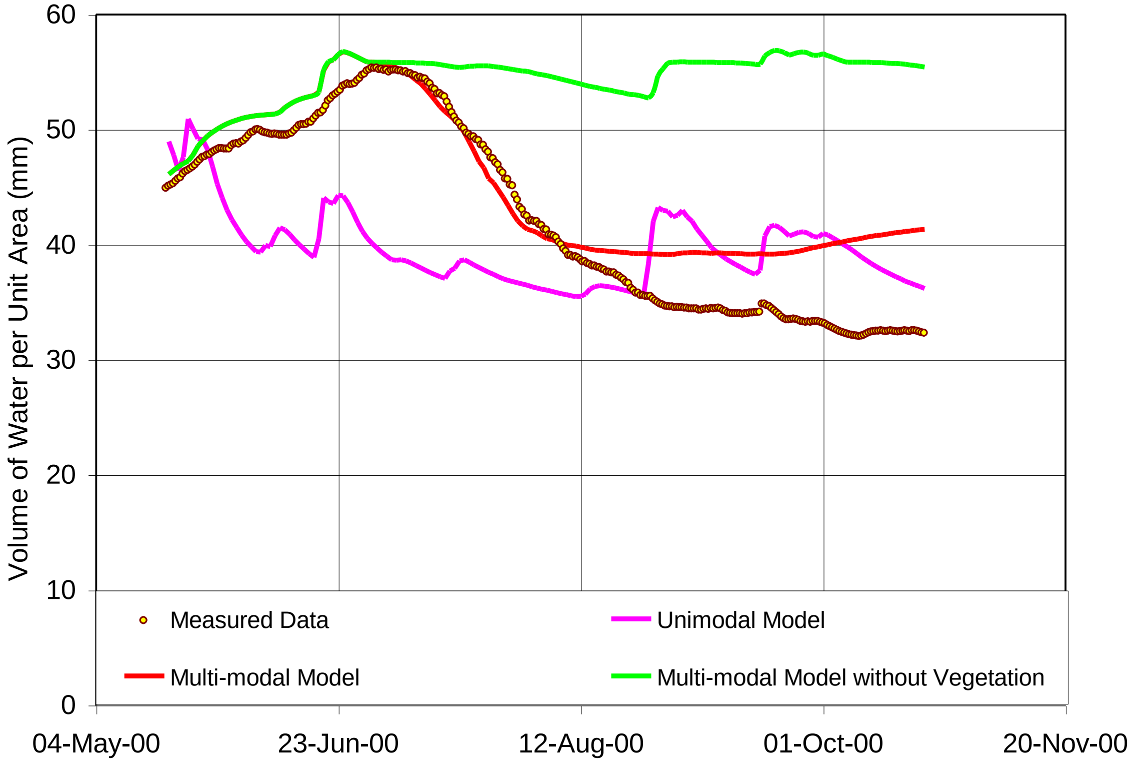

Figure 9. Water volumes per unit area in the till layer of the D1 cover.

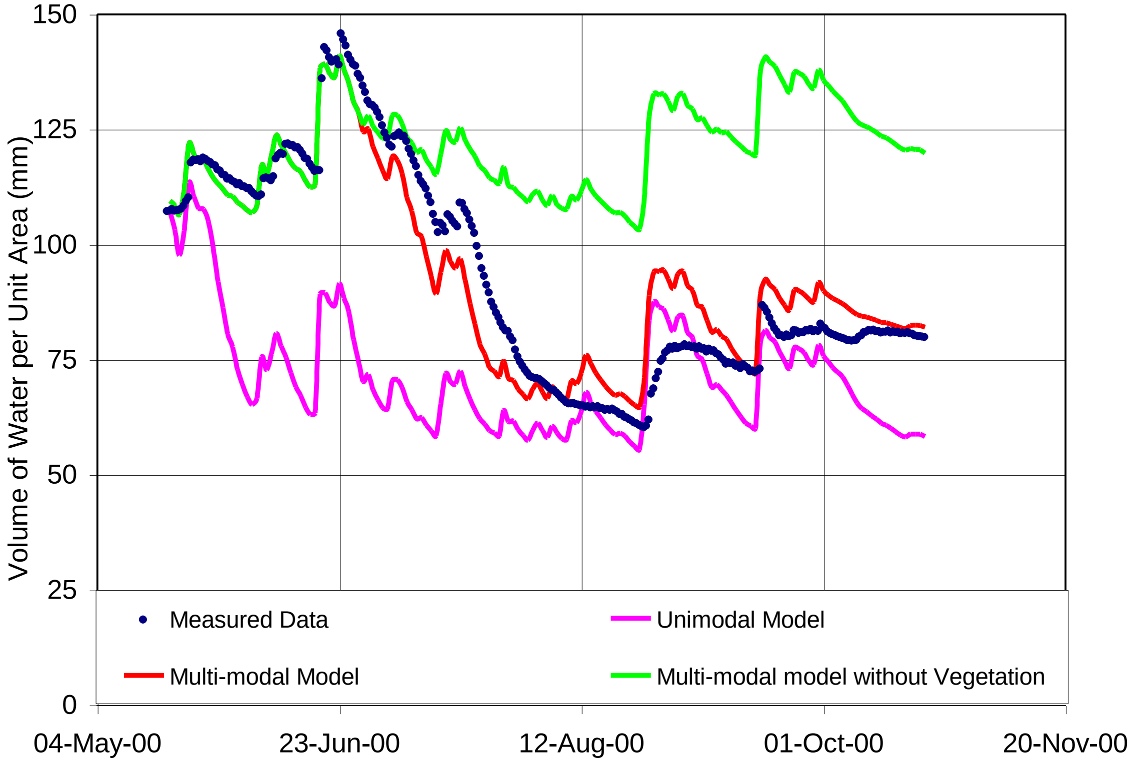

Figure 10. Total water volume per unit area in the D1 cover.

The volume of water stored in the shallow peat layer of D1 is shown in Figure 7. This layer is the most dynamic due to its exposure to the atmosphere. Figures 8 and 9 show the water stored in the deep peat and till layers of D1, respectively. These layers are less dynamic because the soil above dampens the effects of the atmosphere. The modeled volume of water within the till layer diverges after August 8. This happens because the soil-water characteristic curves and hydraulic conductivity functions were created to adequately simulate similar soils used for the four soil cover systems. The till used for the D1 cover, however, had slightly lower residual water content than that of the generalized soil-water characteristic curve. Figure 10 shows the change in the total water volume stored within the D1 cover. Note that the measured data and model results show the greatest divergence following the rain event on August 28. This event occurs after a long drying period, during which time the suctions within the soil drop below the standard moisture wilting point for plants of 1500 kPa (Figure 11). The reason for the divergence has not been fully explained but is likely due to a higher rate of canopy interception and runoff than the model predicted.

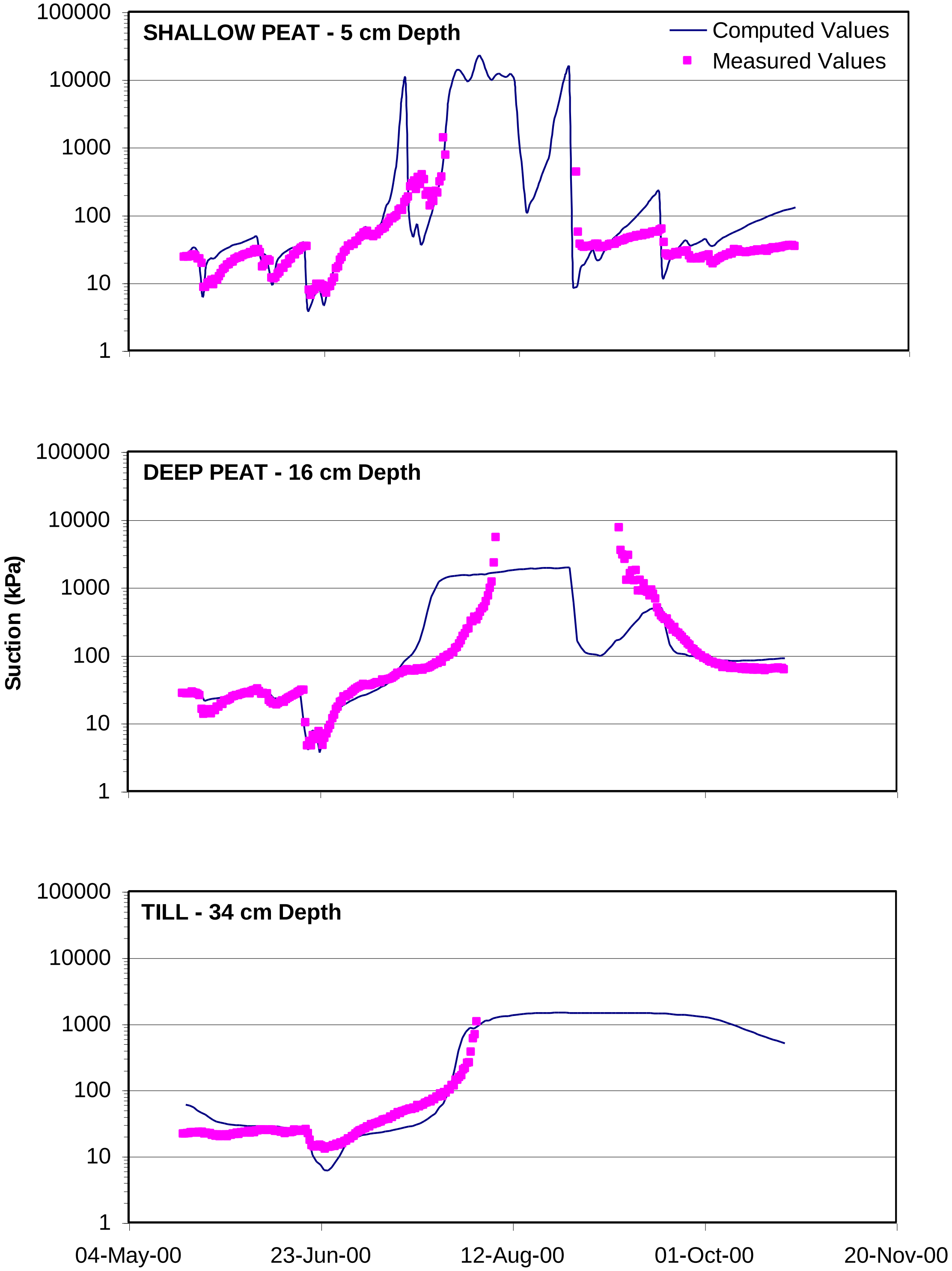

Figure 11. Measured and modeled suction data at three depths within the D1 cover.

Figures 12 through 14 show the volume of water stored within the D2, D3 and BL soil covers, respectively. The D2 cover behaved quite similarly to D1, which is not surprising since they share the same layering pattern. At first glance, the measured and modeled water volumes for the D3 cover differ substantially. However, the model calculates a lower water volume within the till layer than the measured data indicates. This discrepancy can be explained as in the previous paragraph for the D1 till, except that the till used for the D3 cover has higher water contents than the generalized soil-water characteristic curve describes. Taking this discrepancy into account, the modeled results accurately predict the measured data. Finally, Bill's Lake shows large divergences after major rainfall events. These divergences are likely due to macropores that extend the entire depth of the cover. These macropores act as conduits for the rainfall, quickly transporting the water deep within the cover and substantially lowering the amount of runoff.

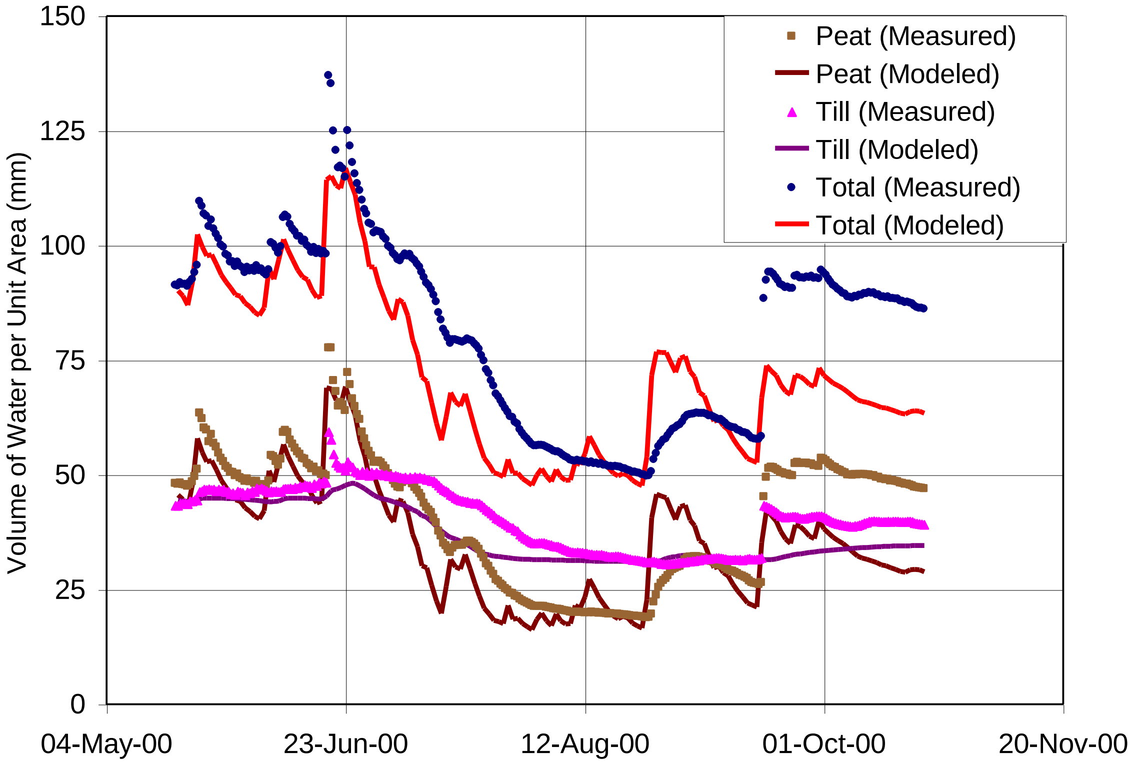

Figure 12. Water volumes per unit area within the D2 cover.

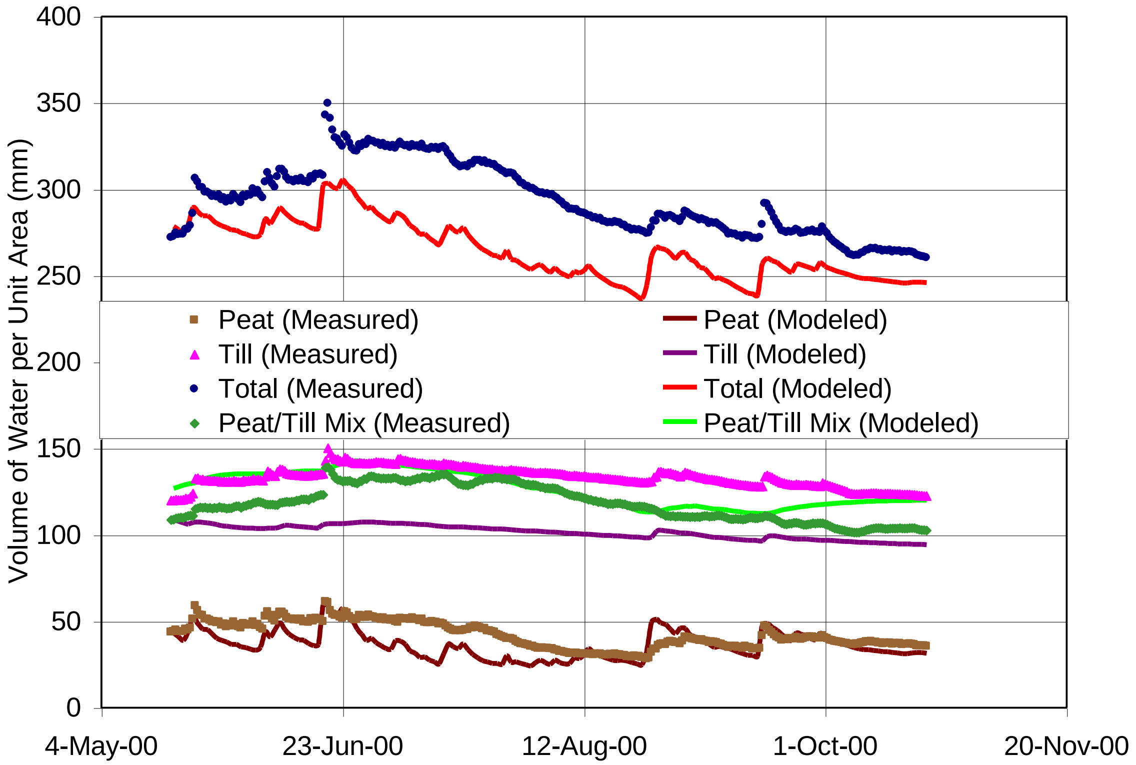

Figure 13. Water volumes per unit area within the D3 cover.

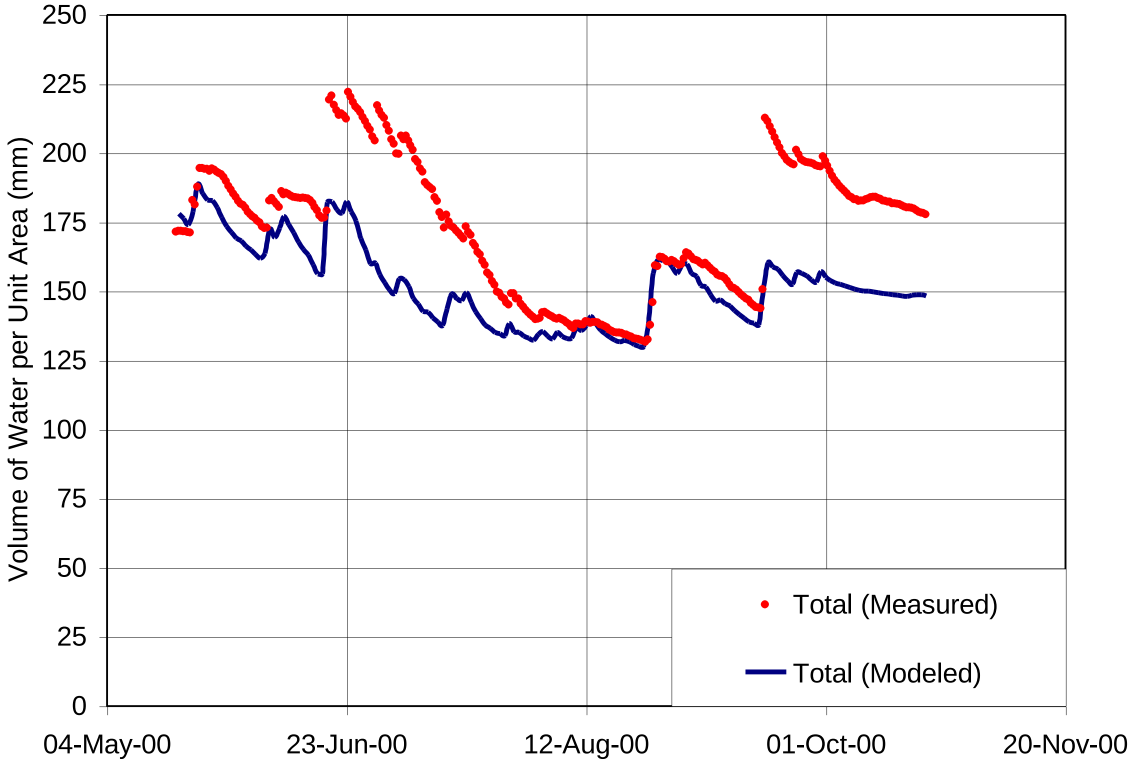

Figure 14. Water volumes per unit area within the Bill's Lake cover.

Figure 15 compares the measured actual evapotranspiration (AET) to the modeled results for the four cover systems. The measured AET was estimated using the Bowen Ratio Energy Balance (BREB) Method. This method is based on an evaluation of the ratio of sensible heat flux to latent heat flux, referred to as the Bowen Ratio. Engineering applications of the BREB method are described by Wilson (1990) and Woyshner and St-Arnaud (1994). The D1, D2 and BL models all calculated higher AET rates early in the season than the BREB method estimated. These higher AET rates were predicted because these three covers were well vegetated during the summer of 2000, creating high AET rates during the growing season. The vegetation on D3 was poor, therefore the AET rates were less than those on the other three covers and closely simulated the BREB method estimation. However, all four models calculated lower AET rates late in the season than the BREB method. This under-estimation of AET may be due to lower model calculations of plant transpiration rates than actually occurred. This is almost certainly true for BL since, as noted in the vegetation section of this paper, smooth brome has the ability to start to regrow late in the growing season.

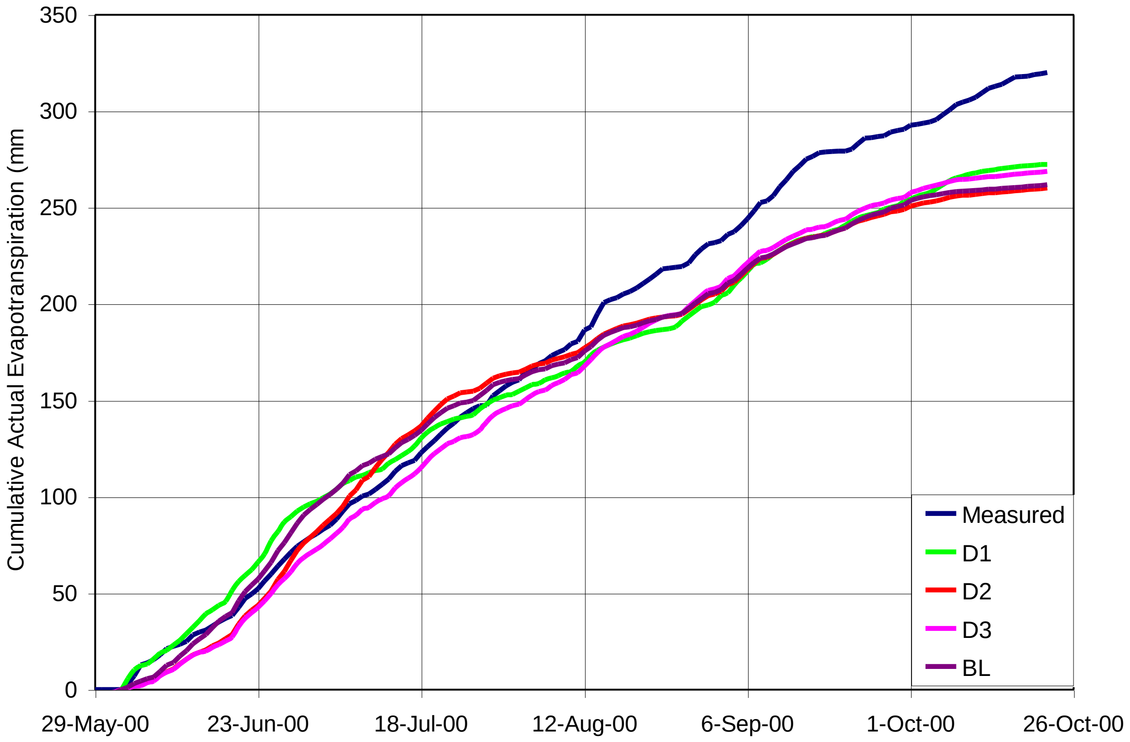

Figure 15. Cumulative actual evapotranspiration measured using the Bowen Ratio Energy Balance method compared to the model results for the four soil cover systems.

Conclusions

The use of multi-modal soil water characteristic curves and hydraulic conductivity functions increased the understanding of the physics of water movement within the soil. An improved match was realized using these factors to perform field response modeling. The model results also show that vegetation has a major effect on evapotranspirative rates and water storage. In order to improve the simulation of moisture movement with the soil cover systems further, two-dimensional models will need to be implemented.

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