Soil water regimes of reclaimed upland slopes in the oil sands region of Alberta

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Leatherdale, J., Chanasyk, D. S. and Quideau, S. 2012. **Soil water regimes of reclaimed upland slopes in the oil sands region of Alberta**. Can. J. Soil Sci. **92**: 117–129. Large oil sands deposits in the Athabasca oil sands region of Alberta, Canada, are recovered through surface mining, creating a large-scale disturbance. Reclamation requires reconstruction of soil profiles to return the land to equivalent land capability and support the required end land use. Soil water regimes must be understood to allow for planting of appropriate vegetation species. This study quantified soil water regimes on reclaimed upland slopes of various reclamation prescriptions and determined whether soil water was affected by slope position. Slope position did not have a consistent effect on soil water. Spatial variability in soil characteristics and vegetation distribution likely had a greater influence on soil water than did slope position. The upper slope soil profiles had highly dynamic water regimes and a greater response to precipitation events than the lower soil profiles. Differences in water-holding capacity among sites were attributed to differences in clay, sand and organic matter content. Overwinter soil water recharge varied dramatically by site. Capillary barriers resulting from the textural discontinuities created by the reclamation prescriptions enhanced soil water retention within the profiles in at least two sites, and hence are desirable in reclamation scenarios, especially where reclamation material is coarse textured.

Key words: Peat mineral mix, oil sands, volumetric water content, reclamation, topographical position, soil water regime, soil texture, water-holding capacity

Leatherdale, J., Chanasyk, D. S. et Quideau, S. 2012. **Hydrologie des sols sur les pentes restaurées en hauteur de la région des sables bitumineux, en Alberta**. Can. J. Soil Sci. **92**: 117–129. Dans la région des sables bitumineux de l'Athabasca, en Alberta, on récupère de vastes dépôts de sables bitumineux par extraction à ciel ouvert, ce qui perturbe considérablement la surface. La restauration des sols exige la reconstruction du profil pédologique en vue de lui rendre une capacité équivalente à celle du sol d'origine et de favoriser diverses vocations des terres. Il faut comprendre l'hydrologie du sol avant de planter les espèces qui en assureront la végétalisation. La présente étude quantifie le régime hydrologique des sols sur les pentes en hauteur restaurées selon diverses méthodes, et détermine si l'emplacement le long de la pente modifie ou pas l'hydrologie. L'emplacement le long de la pente n'a aucune incidence cohérente sur l'eau dans le sol. La variabilité spatiale des paramètres du sol et de la répartition de la végétation influe sans doute plus sur l'hydrologie que l'emplacement le long de la pente. Les profils situés au sommet de la pente se caractérisent par un régime hydrologique très dynamique et réagissent mieux aux précipitations, comparativement aux profils situés plus bas. La capacité de rétention de l'eau varie d'un site à l'autre, phénomène qu'on attribue à une variation de la concentration d'argile, de sable et de matière organique. Durant l'hiver, la manière dont la réserve d'eau du sol se renouvelle varie de façon draconienne avec le site. Les obstacles capillaires résultant de la structure discontinue caractéristiques aux méthodes de restauration ont permis aux sols de mieux conserver l'eau dans le profil à au moins deux endroits. Cet aspect est donc souhaitable dans certaines situations, principalement quand le matériau servant à la restauration a une texture grossière.

Mots clés: Mélange de tourbe minérale, sables bitumineux, humidité volumétrique, restauration, emplacement topographique, régime hydrologique, texture du sol, capacité de rétention d'eau

Large oil sands deposits in the Athabasca oil sands region of Alberta, Canada, are recovered through surface mining, creating a large-scale disturbance. Surface mining operations remove vegetation, soil and subsoil from the earth's surface, disrupting natural hydrologic and nutrient cycles at a landscape scale (Fung and Macyk 2000). The process of mine reclamation often alters the natural landscape topography by creating hillslopes with excess overburden and mine waste products (Carroll et al. 2000; Salazar et al. 2002). Thus, successful mine reclamation requires constructing landforms and creating a soil medium overlying the tailings sand to supply sufficient water and nutrients for development of a desired plant community (Li and Fung 1998). In the oil sands region, existing landforms, generally flat and depressional areas, are replaced with upland landforms as the extraction and processing of oil sands creates overburden piles and tailings sand ponds. Soil substrates can be developed in various combinations of reclamation materials, called prescriptions. The key to successful reclamation at a site is selection of an appropriate soil prescription, which includes depths, composition and configuration of reclamation materials (Huang et al. 2011). One such prescription is developed by overstripping muskeg to include 25–50% mineral overburden to create a peat-mineral mix, which is then placed and spread on overburden or tailings sands dykes (Alberta Environmental Protection 1998; Fung and Macyk 2000). The fundamental goal of reclamation is to re-establish maintenance free, self-sustaining ecosystems with land capability equivalent to, or better than, pre-disturbance conditions (Alberta Environmental Protection 1998).

Previous research has documented that reclaimed hillslopes constructed after surface mine disturbance have altered hydrologic responses compared with those of undisturbed areas. Negley and Eshleman (2006) found increased storm runoff coefficients, greater total storm runoff and higher peak hourly runoff rates in two watersheds that were surface mined and reclaimed in the Appalachian region (USA). They attributed the increase in runoff to soil compaction as a result of land reclamation. Nicolau (2002) and Nicolau et al. (2005), studying a reclaimed coal mine area in central-eastern Spain, found that loam overburden developed a surficial crust, which reduced infiltration capacity, increased runoff and lead to the creation of a rill network. The consequence was that upper slope positions had a water deficit and vegetation was unable to colonize, which they attributed to low water content of the soils on the hillslope. Salazar et al. (2002) investigated steep hill-slopes of a reclaimed coal mine in north-eastern Spain and found that as slope gradients increased, runoff increased and when slopes were greater than 33%, lower slope positions had higher water contents than upper slope positions.

There is some evidence suggesting that hydrologic regimes of reclaimed areas are more dynamic during early reclamation years and become more constant with time. Guebert and Gardner (2001), studying a reclaimed surface coal mine in Pennsylvania (USA), found that newly reclaimed hillslopes had low infiltration rates resulting in overland flow. Four years following reclamation, increased infiltration rates were similar to pre-disturbance ones. Loch and Orange (1997) investigated the temporal change in physical properties at a reclaimed coal mine in Australia. They found that the water balance of the reclaimed area changed with time since reclamation; infiltration increased and runoff decreased within the first 4 yr following reclamation, which they attributed to establishment of vegetation. In contrast Yarmuch (2003), studying reclaimed sites in the oil sands regions of Alberta, found that bulk densities of the reclaimed peat-mineral mix topsoil horizons were significantly lower than those of undisturbed Ae horizons, and that bulk densities of different textured reclaimed upper subsoil horizons were statistically similar to those of similarly textured undisturbed Bt horizons, and also for lower subsoil horizons.

Researchers have studied the hydrologic characteristics of peat-mineral mix on a tailings sand storage facility (Moskal 1999; Chaikowsky 2003; Naeth et al. 2011). Moskal et al. (2001) established that water-holding capacity of peat-mineral mix increased when organic carbon increased and that depth of peat-mineral mix significantly increased total soil water. Chaikowsky (2003) found peat-mineral mix held sufficient water, and that a textural discontinuity within the tailings sand influenced its hydrologic regime. Naeth et al. (2011) investigating interactions of soil water and plant community response found that vegetation and the textural discontinuity influenced the hydrologic regime and that peat-mineral mix soils were below wilting point during the growing season. These studies focused on one reclamation prescription employed in the Alberta oil sands region, namely, a peat-mineral mix over tailings sand.

Keshta et al. (2010), using a probabilistic model, determined that in the oil sands region of Alberta under high water demands, 100-cm covers released more water than 35- and 50-cm thick covers, which may fail to release the same amount of water under similar conditions. Each cover comprised a peat-mineral mix layer (0.15–0.20 m thick) overlying glacial till, overlying saline sodic overburden. Carey (2008) found little soil water variability below 25 cm in 0.2 m of peat-mineral mix overlying 0.8 m of reworked glacial till, overlying saline sodic overburden at the same site, with the water table never more than 50 cm below the surface. He found total season evapotranspiration rates of 224–283 mm in a 3-yr study.

The overall objective of this study was to quantify soil water regimes on reclaimed upland slopes of various reclamation prescriptions in the Athabasca oil sands region of Alberta, Canada, determining how soil water status is affected by slope position and characterizing the temporal variability of soil water at the slope level.

MATERIALS AND METHODS

Study Area

The study area is located approximately 50 km north of Fort McMurray in northwestern Alberta, within the Boreal Forest Natural Region, which is dominated by a continental climate with short summers and long, cold winters (Strong and Leggat 1981; Natural Regions Committee 2006). Mean annual temperature is 0.7°C; January is the coldest month with a mean temperature of −18.8°C and July is the warmest with a mean temperature of 16.8°C (Environment Canada 2004). Mean annual precipitation is 455.7 mm; 342.2 mm occurs as rainfall and 155.8 cm occurs as snowfall. The Boreal Forest Natural Region consists of upland mixedwood forests and extensive wetlands in low-lying areas (Natural Regions Committee 2006). The dominant upland mixed forest vegetation is aspen (*Populus tremuloides* Michx.), balsam poplar (*Populus balsamifera* L.) and white spruce [*Picea glauca*(Moench) Voss]. Lowland areas are treed fens, with black spruce (*Picea mariana* Mill.) the dominant tree species, shrubby fens and sedge fens. Jack pine (*Pinus banksiana* Lamb.) stands occur on well-drained, sandy soils. Luvisolic soils develop on well to imperfectly drained areas under upland mixedwood forest vegetation (Strong and Leggat 1981; Natural Regions Committee 2006). Brunisolic soils develop on well-drained to rapidly drained fluvial and eolian materials, and Gleysolic and Organic soils develop within poorly drained wetland areas.

Experimental Sites

This study quantified soil water regimes on four reclaimed slopes with different reclamation prescriptions (Table 1). Sites 1 and 2 were tailings sand storage facilities with 20 cm of peat-mineral mix over tailings sand and 20 cm of peat-mineral mix over 80 cm of secondary material, respectively. Site 3 was a reclamation trial slope for lean oil sands waste material and was developed using 50 cm of peat-mineral mix over 50 cm of tailings sand over lean oil sand. Site 4 was a saline sodic overburden dump with 20 cm of peat-mineral mix over 80 cm of secondary material over Cretaceous saline sodic overburden. Lean oil sands contain less than 6% bitumen. Secondary material is suitable quality upland soil or surficial geological material salvaged to a depth where the material is considered to be of poor quality for plants (Yarmuch 2003).

Meteorological Parameters

Meteorological data were collected at all four sites using instrumented weather stations. Site 1 was instrumented with a Texas Electronics TE525MM tipping bucket rain gauge and a Campbell Scientific Inc. (CSI) 107F air temperature sensor, which were monitored with a CSI CR510 datalogger. Sites 2, 3 and 4 were instrumented with a Vaisala HMP45CF probe to measure air temperature and a Texas Electronics TE525WS tipping bucket rain gauge with a CSI CS705 snowfall adapter. A CSI CR10X datalogger controlled and monitored the meteorological sensors. Canadian Climate Normal data (1971–2000) were obtained for the Fort McMurray Airport (Environment Canada 2004), approximately 40 km south of the study area. The 2005 and 2006 data from the Fort McMurray airport were compared with the Canadian Climate Normals from the same location to determine how representative the 2005 and 2006 study years were. The 2005 and 2006 data from the Fort McMurray airport were then compared with the data collected from the hillslopes for each of those 2 yr.

Soil Collection and Analyses

Soil pits were dug on sites 1 (six pits), 2 (nine pits) and 3 (nine pits), 1.5 m downslope and 1.5 m to the right of each Diviner 2000® access tube in August 2005. Soil samples were separated by depth increments based on the Land Capability Classification System for Forest Ecosystems in the Oil Sands (Leskiw 1998; Cumulative Environmental Management Association 2006): 0–20 cm, 20–50 cm and 50–100 cm, classified as topsoil, upper subsoil and lower subsoil, respectively. In some cases, topsoil depth was greater than 20 cm. In these cases a second topsoil increment was sampled or a composite sample for the complete depth was taken if there were no major visual differences within the topsoil to indicate separation into two intervals. If the topsoil was less than 20 cm thick, the composite sample was taken from the topsoil only and the depth increment was noted as being less than 20 cm. Composite soil samples were taken from each depth increment within each soil pit for physical and chemical analyses and placed in a 4.0 L bucket. They were air dried, crushed and sieved to 2 mm in the laboratory.

Site 4 sampling was modified from the above method as follows: at nine locations samples were collected in August 2006 using a 5-cm Eijkelkamp soil auger. No soil pits were dug due to industrial facility regulations. Samples were collected 1.5 m downslope and 1.5 m to the right of each experimental unit. Composite samples were obtained for each depth interval. Three adjacent auger holes were required to obtain an adequate amount of sample.

Bulk density samples were collected from the upper part of each depth interval in each soil pit. At site 2 they were collected using a Uhland core with a length of 7.6 cm and an internal diameter of 7.5 cm. Coring in sandier substrates proved challenging as the sand particles became lodged between the Uhland core and the inner sleeves. Thus, at the other sites, bulk density samples were taken with a hammer corer 6.7 cm in

Table 1. Experimental site description

Site	Reclamation year	Organic capping	Peat type	Mineral substrate	Aspect	Slope (%)
Site 1	1992	20 cm PMM[z]	Humic	Tailings sand	South	25
Site 2	2003	20 cm PMM	Humic	80 cm 2°[y] over LOS[x] + OB[w]	West	25
Site 3	2003	50 cm PMM	Mesic	50 cm 2° over LOS	Northeast	24
Site 4	1999	20 cm PMM	Mesic	80 cm 2° over Saline/Sodic OB	North	20

[z]PPM, peat-mineral mix (a mix of organic and mineral soil material).
[y]2°, secondary material (unconsolidated mineral material).
[x]LOS, lean oil sands.
[w]OB, overburden.

length and 7 cm internal diameter. The hammer corer allowed for easy removal of an intact soil sample. Soil pits were not dug on site 4 and as a result, bulk density samples were collected for only the topsoil depth interval using the hammer corer described above. All bulk density samples were oven dried at 105°C for 48 h and bulk density was calculated by dividing the mass of the oven dried sample by the volume of the core.

Pressure plate apparatus (Topp et al. 1993) was used to determine water retention at 0.01, 0.033 and 1.5 MPa pressures. Water contents at 0.01 MPa are considered field capacity for coarse-textured soils (sands, sandy loams and loamy sands) and water contents at 0.033 MPa are considered field capacity for finer-textured soils (Cassel and Nielsen 1986). Water content at 1.5 MPa is considered wilting point for all soil textures. Water-holding capacity is the difference between field capacity and wilting point.

Bulk density was calculated for each individual sample after oven dry weight was determined. Gravimetric water content at these pressures was determined by oven drying the samples at 105°C for 48 h. Once the sample was oven dried and weighed it was crushed and re-sieved through a 2-mm mesh sieve then measured in a 25-mL graduated cylinder. Bulk density of the sieved sample was then determined. Both bulk densities of field-collected samples and those from the laboratory were used to convert gravimetric water contents from the pressure plate analysis to volumetric water contents (Mapfumo et al. 2003). Percent total organic carbon was quantified using dry combustion, after leaching with 8 M hydrochloric acid to remove the inorganic carbon, with a Costech Model 4010 Elemental Analyzer (Nelson and Summers 1996). Prior to analysis the samples were ball ground to less than 150 μm. Percent organic matter was calculated by multiplying percent total organic carbon by 1.724 (Hudson 1994).

Sentek Diviner 2000 Capacitance Sensor

The Diviner 2000 is a portable soil water monitoring system manufactured by Sentek Pty Ltd. The system is a combination of a data logger and a portable probe. The probe is inserted into a polyvinyl chloride access tube (55.5 mm outside diameter) and scaled frequency readings are taken at regular 10-cm intervals though the soil profile (Sentek Pty Ltd. 1999). This system uses measurements of the soil matrix dielectric constant to determine volumetric water content of a given soil (Groves and Rose 2004). The method has been accepted by researchers as a portable and cost-effective alternative to the conventional neutron probe (Groves and Rose 2004; Burgess et al. 2006). O'Kane Consultants Inc. installed Diviner 2000 access tubes on the four sites in August 2005. They developed material specific calibration curves for the soil materials monitored in this study. The access tubes had a maximum depth of 160 cm; however, installation depths of individual access tubes varied due to objects, such as rocks, interfering with installation.

At each site, Diviner 2000 access tubes were replicated three times across upper, mid and lower slope positions, approximately 25 m apart. Soil water readings were collected biweekly over the growing seasons, beginning in mid-May and continuing through September for the 2006 growing season. Diviner 2000 replicates were not installed until late in 2005; growing season biweekly water readings were not collected during the 2005 growing season and only the final measurement of 2005 was used for this study.

Soil water was expressed as volumetric water content and total soil water (TSW) to a given depth and for a given depth interval. Total soil water to a given depth for a given access tube was calculated by multiplying volumetric water content of a given depth increment by the thickness of that increment, then summing to the desired depth (Burk et al. 2000).

Depths and intervals were chosen to represent different sections of the soil profile. TSW35 represents the rooting zone for sites 1, 2 and 4, while TSW40 represents the rooting zone for site 3. TSW85–135 and TSW60–100 represent zones in the tailings sand at sites 1 and 3, respectively; TSW65–95 and TSW55–85 represent zones in the secondary material at sites 2 and 4, respectively. Each site had a unique reclamation prescription; as a result, the total soil water depths and depth increments differed among sites. Factors influencing depths and increments chosen were depth of the access tubes and variability in depths of the peat-mineral mix and underlying material.

A representative Diviner 2000 tube was chosen from each site to investigate over-winter soil water recharge and precipitation response at each site. Soil water recharge over winter was determined from the difference between the last soil water measurement of the 2005 growing season and the first soil water measurement of the 2006 growing season. During the 2006 growing season, a hot dry period was followed by a cooler wet period and measurement data from those time periods were used to determine soil water response to precipitation. These are denoted dry day and wet day, respectively.

Statistical Analyses

A repeated measures design was used since there were multiple measurements of a response variable on the same experimental unit (Littell et al. 2006). The treatment assigned to the experimental unit is slope position, and data were collected on the response variable of individual experimental units through time. The design is considered a mixed model because it contains both random (replicates) and fixed (slope position and time) effects; thus data were analyzed using the MIXED procedure in SAS 9.1 (Littell et al. 2006) with the statistical model for a repeated measures design.

Data Normality

Mixed models are linear statistical models and the assumption of the model is that response variable residuals follow a normal distribution (Littell et al. 2006). Residuals of the soil water data were negatively skewed when inspected visually and by determining skewness and kurtosis values (Quinn and Keough 2002). Soil water data were square root transformed to reduce skewness and kurtosis (Steel et al. 1997). In some cases the residuals continued to have a non-normal distribution following data transformation (Shapiro-Wilk ≤ 0.05). Attempts were made to remove outliers in the datasets but this resulted in removal of a large number of data points, in some cases an experimental unit's entire dataset, thereby reducing power of the statistical tests. Because of the complexity of the experimental design, a mixed model was chosen to analyze the data (normal and non-normal) and the results appear to be consistent with graphical representation of the data; caution was used in the interpretation of the results for the non-normal data.

RESULTS

Meteorological Parameters

Air temperature at the Fort McMurray airport was similar to the Canadian Climate Normals for the first 9 mo in 2005 and ranged from 1 to 8°C higher in the last 3 mo of 2005 (Table 2). Air temperature was higher than average in 2006 and the monthly average ranged from 0.5 to 7°C higher throughout the year.This trend was also evident when 2005 and 2006 air temperatures were compared. Air temperature at the sites were 1 to 4°C higher during the 2006 growing season than in 2005, with highest temperatures occurring in June.

Precipitation at the Fort McMurray airport was below the Canadian Climate Normal for 2005, with the exception of July which received approximately 55 mm more precipitation than the Canadian Climate Normal (Table 3). Precipitation was below the Canadian Climate Normal for January through March, June and August through December. This precipitation trend was evident at the study sites that had low amounts of precipitation from October 2005 through March 2006. May through September 2006 had less precipitation than the same time in the previous year. All sites had a large precipitation event in July, which accounted for 41 to 56% of the precipitation during the growing season.

Soil Water Dynamics

The peat-mineral mix at sites 1, 2 and 3 had a sandy loam texture and that at site 4 had a clay loam texture (Table 4). Sites 2 and 3 had greater water-holding capacity, 21.7 and 28.6%, respectively, than sites 1 and 4, which were 13.1 and 10.5%, respectively. Organic matter contents of peat-mineral mix at sites 1, 2, 3 and 4 were 6.7, 23.8, 10.7 and 8.5%, respectively.

At site 1, field capacityfor the uppermost 35 cm was not reached or exceeded during the 2006 growing season and soil water fell below wilting point for 72% of the dates measured (Fig. 1a). TSW85–135 exceeded field capacity for 91% of the total measurements in 2006 (Fig. 1b). At site 2, TSW35 was within the available water range (between field capacity and wilting point) on all dates measured during the 2006 growing season (Fig. 1c), while TSW65–95 was greater than field capacity for all measurements in 2006 (Fig. 1d). At site 3 TSW40 was within the available water range on all dates measured during the 2006 growing season (Fig. 2a). The TSW60–100 depth interval, which was within tailings sand, was above field capacity for all measurement dates during the 2006 growing season (Fig. 2b). The TSW35 at site 4 was within the available water range for 2006 with the exception of the final measurement date in 2006, which

Table 2. Mean monthly air temperatures in the study region for all four sites, including Environment Canada Climate Normals

	CCN[z]	Airport		Site 1		Site 2		Site 3		Site 4	
	1971–2000	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
Month	°C										
January	−18.8	−19.1	−11.3	−18.0	−10.8	−18.3	−10.8	−18.8	−11.6	−18.6	−11.3
February	−13.7	−11.6	−13.0	−10.1	−10.5	−10.4	−10.7	−11.1	−10.9	−10.9	−11.0
March	−6.5	−4.9	−4.4	−3.5	−3.4	−3.6	−3.4	−4.4	−3.6	−4.7	−4.3
April	3.4	5.3	7.3	6.6	9.3	6.2	8.6	5.8	8.4	5.5	8.1
May	10.4	10.0	10.9	11.1	12.4	11.1	12.1	10.7	12.1	10.3	11.5
June	14.7	13.8	17.1	15.4	19.1	15.1	18.7	14.8	19.2	14.3	17.8
July	16.8	16.2	17.2	17.4	18.6	17.1	18.2	17.0	18.3	16.4	17.5
August	15.3	14.1	15.5	14.9	16.9	14.7	16.7	14.5	16.5	14.2	15.9
September	9.4	8.9	11.2	10.1	12.7	10.1	12.6	9.7	12.4	9.5	11.8
October	2.8	3.9	1.5	5.1	2.3	4.9	2.4	4.5	2.0	4.3	NA[y]
November	−8.5	−3.8	−15.1	−3.0	−13.2	−2.8	−13.2	−3.5	−13.6	−3.3	NA
December	−16.5	−8.1	−10.0	−7.8	−8.0	−7.9	−8.9	−7.6	−8.8	−8.1	NA

[z]Environment Canada Climate Normals from the Fort McMurray Airport (1971–2000).
[y]NA, data unavailable.

Table 3. Total monthly precipitation in the study region for all four sites including Environment Canada Climate Normals

	CCN[z]	Airport		Site 1		Site 2		Site 3		Site 4	
	1971–2000	2005	2006	2005	2006	2005	2006	2005	2006	2005	2006
Month	(mm)										
January	19.3	14.5	10.0	3.6	0.8	16.3	2.5	1.8	0.2	33.6	1.0
February	15.0	11.0	16.0	4.3	1.3	8.9	0.3	0.8	2.0	0.0	3.0
March	16.1	15.0	24.5	7.4	12.7	11.7	17.0	1.9	0.5	0.0	10.4
April	21.7	16.5	23.5	43.7	8.6	21.8	14.7	19.4	0.0	13.7	5.3
May	36.9	22.5	49.5	31.2	51.3	24.6	52.1	61.4	20.4	27.2	41.3
June	74.8	61.0	50.0	65.5	38.9	64.3	28.7	65.1	24.2	56.9	36.0
July	81.3	136.0	88.5	90.9	138.9	70.6	106.9	120.3	110.2	87.3	107.8
August	72.7	64.5	37.0	86.4	46.5	59.4	35.8	91.1	25.9	56.1	35.5
September	46.8	17.0	23.0	17.5	45.5	18.8	34.8	17.3	15.1	9.5	34.4
October	29.6	3.5	8.5	1.5	2.8	1.5	9.4	5.9	2.9	1.1	NA[y]
November	22.2	1.0	21.5	5.1	0.0	4.8	0.0	0.0	0.0	1.3	NA
December	19.3	0.0	7.5	20.6	0.0	7.6	0.0	0.0	0.3	0.0	NA
October–March	121.5	45.0	88.0	42.5	17.6	50.8	29.2	10.4	5.9	36.0	NA
May–September	312.5	301.0	248.0	291.5	321.1	237.7	258.3	355.2	195.8	237.0	255.0

[z]Environment Canada Climate Normals from the Fort McMurray Airport (1971–2000).
[y]NA, data unavailable.

was below wilting point (Fig. 2c). The TSW55-85 was within the available water range for all measurements during the 2006 growing season (Fig. 2d). Soil water response at sites 1, 2 and 4 closely followed major precipitation events, while at site 3 the response was much lower than at the other three sites.

It was hypothesized that lower slope positions would have higher soil water contents than upper slope positions; however, this was generally not found on any of the reclaimed sites (Table 5). Sites 1 and 3 did not have any slope position effects during either the 2005 or the 2006 growing season, while sites 2 and 4 only showed

Table 4. Mean soil physical properties of the different depth intervals at the study sites

Site	Depth interval (cm)	Clay[z] (g kg^{-1})	Sand[z] (g kg^{-1})	Texture	Field bulk density[y] (Mg m^{-3})	Lab bulk density[y] (Mg m^{-3})	Field capacity[x] (m^3 m^{-3}; MPa)[v]	Wilting point[x] (m^3 m^{-3}; 1.5 MPa)	Total organic carbon[w] (g kg^{-1})
Site 1	0–19.7 (0.3)	140 (12)	711 (1)	Sandy loam	1.32 (0.05)	1.04 (0.02)	0.228 (0.007)	0.097 (0.005)	39 (5)
Site 1	19.7 (0.3)–48.4 (4.6)	142 (13)	734 (27)	Sandy loam	1.21 (0.10)	1.03 (0.02)	0.261 (0.016)	0.089 (0.004)	NA[u]
Site 1	>48.4 (4.6)	24 (6)	930 (12)	Sand	1.65 (0.06)	1.37 (0.01)	0.048 (0.009)	0.018 (0.003)	NA
Site 2	0–24.9 (2.3)	57 (11)	563 (20)	Sandy loam	0.62 (0.12)	0.59 (0.06)	0.339 (0.009)	0.122 (0.004)	138 (41)
Site 2	24.9 (2.3)–82.6 (4.9)	53 (10)	647 (35)	Sandy loam	1.30 (0.70)	1.00 (0.02)	0.249 (0.011)	0.092 (0.003)	NA
Site 2	>82.6 (4.9)	55 (11)	640 (61)	Sandy loam	1.50 (0.30)	1.07 (0.02)	0.226 (0.023)	0.071 (0.004)	NA
Site 3	0–20.0 (0.0)	142 (7)	678 (2)	Sandy loam	0.90 (0.02)	0.90 (0.01)	0.396 (0.009)	0.11 (0.002)	62 (2)
Site 3	20.0 (0.0)–56.9 (5.0)	138 (9)	652 (23)	Sandy loam	0.86 (0.03)	0.86 (0.01)	0.327 (0.007)	0.117 (0.001)	NA
Site 3	56.9 (5.0)–119.9 (5.8)	14 (8)	926 (11)	Sand	1.23 (0.01)	1.34 (0.02)	0.062 (0.003)	0.008 (0.001)	NA
Site 4	0.0–20.0	355 (78)	374 (67)	Clay loam	0.84 (0.07)	0.70 (0.03)	0.23 (0.005)	0.125 (0.003)	49 (8)
Site 4	20.0–50.0	241 (15)	346 (13)	Loam	NA	0.99 (0.01)	0.252 (0.004)	0.140 (0.005)	NA
Site 4	50.0–100	201 (17)	400 (36)	Loam	NA	1.04 (0.01)	0.274 (0.004)	0.150 (0.009)	NA

Values reported as mean (standard error).
[z]$n = 3$ for each clay and sand measurement for each depth interval.
[y]$n = 6$ for depth interval and bulk density at each depth interval for site 1; $n = 9$ for depth interval and bulk density at each depth interval for sites 2 through 4.
Note: depth interval samples for site 4 were taken at exactly 0–20, 20–50 and 50–100; therefore, at this site there was no mean (standard error) for the depth interval values.
[x]$n = 18$ for volumetric watercontent at a given pressure for each depth interval for sites 2 to 4; $n = 12$ for volumetric water content at a given pressure for each depth interval for site 1. Field and laboratory bulk density are provided for comparison; laboratory bulk density values were used to calculate volumetric water content at field capacity and wilting point.
[w]% organic matter = % total organic carbon × 1.724.
[v]0.01 MPa was used to determine field capacity for sites 1, 2 and 3 and 0.03 MPa was used to determine field capacity for site 4.
[u]NA, data unavailable/inapplicable.

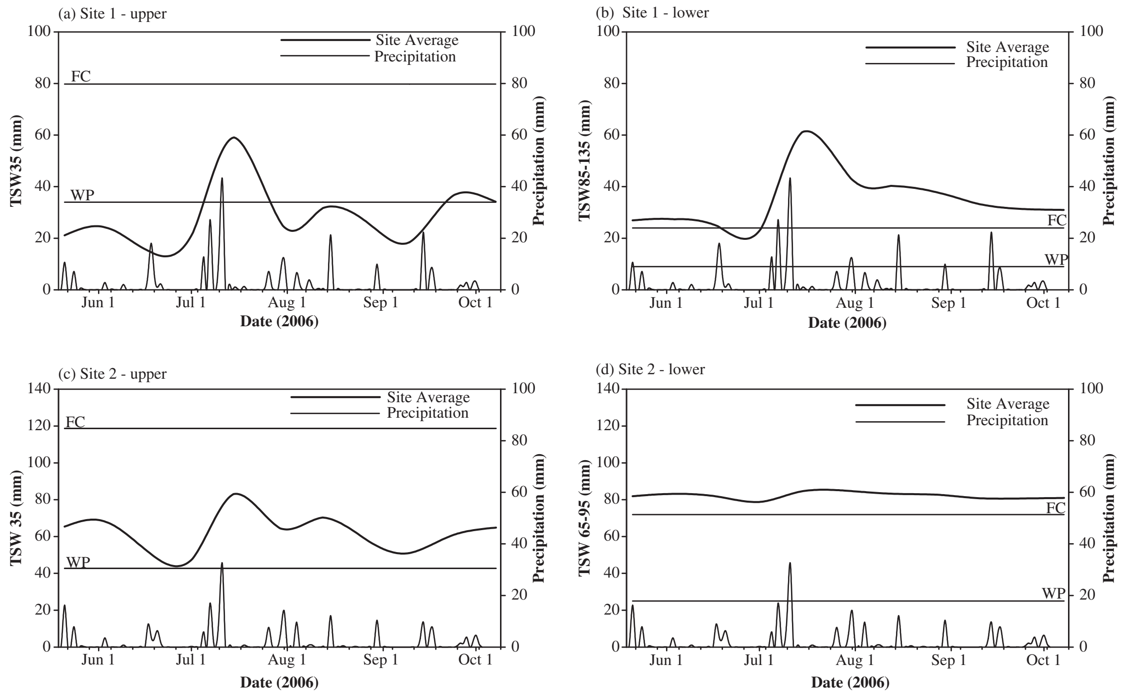

Fig. 1. Mean total soil water (TSW) (mm) for (a) the upper soil profile at site 1; (b) the lower soil profile at site 1; (c) the upper soil profile at site 2; (d) the lower soil profile at site 2. FC = field capacity 0.01 MPa at sites 1, 2 and 3 and 0.03 MPa at site 4; WP = wilting point 1.5 MPa at sites 1, 2, 3 and 4.

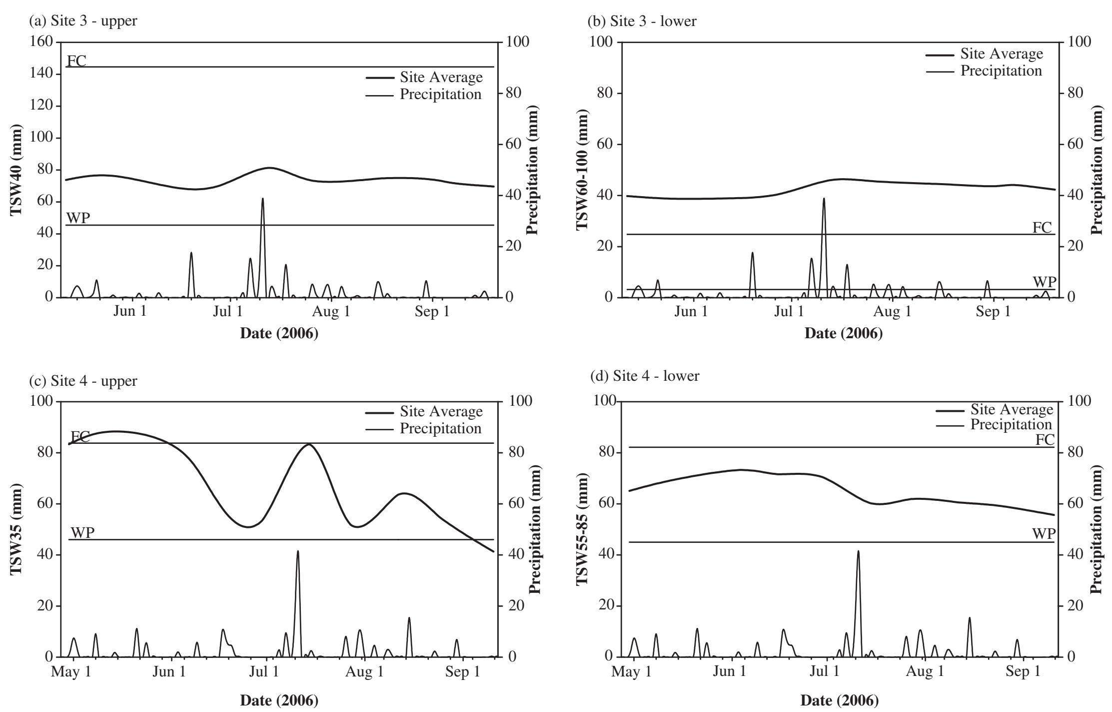

Fig. 2. Mean total soil water (TSW) (mm) for (a) the upper soil profile at site 3; (b) the lower soil profile at site 3; (c) the upper soil profile at site 4; (d) the lower soil profile at site 4. FC = field capacity 0.01 MPa at sites 1, 2 and 3 and 0.03 MPa at site 4; WP = wilting point 1.5 MPa at sites 1, 2, 3 and 4.

Table 5. Statistical slope position results for Sites 1, 2, 3, and 4

	2005	2006
Site 1 (peat-mineralmix over tailings sand)		
TSW35 (mm)	N[z]	N
TSW85–135 (mm)	N	N
Site 2 (peat-mineral mix over secondary material)		
TSW35 (mm)	N	N
TSW65-95 (mm)	N	Y[z]
Site 3 (Peat-mineral mix over tailings sand)		
TSW40 (mm)	N	N
TSW60–100 (mm)	N	N
Site 4 (peat-mineral mix over secondary material over overburden)		
TSW35 (mm)	N	Y
TSW55-85 (mm)	N	N

[z]Y, statistically significant slope position effect ($P \leq 0.10$), N, no significant slope position effect detected ($P \leq 0.10$).

slope position effects during the 2006 growing season for TSW65–95 and TSW35, respectively (Table 4).

Site 1 had a loss of soil water in the upper soil profile and a gain of soil water in the lower subsoil from the final measurement in 2005 to the initial measurement in 2006 (Fig. 3a). At sites 2 and 3 there was relatively little change in soil water within the soil profile over this period (Fig. 3b and 3c), while site 4 was characterized by a gain of soil water throughout the soil profile (Fig. 3d). At Sites 1 and 2 considerable soil water recharge of the rooting zone and lower subsoil occurred following a large precipitation event when approximately 104 and 74 mm fell on these sites, respectively (Fig. 4a and 4b).

At site 3 little soil water recharge of the soil profile followed a large precipitation event of approximately 75 mm (Fig. 4c). Site 4 had considerable soil water recharge of the rooting zone following a large precipitation event with approximately 76 mm of precipitation (Fig. 4d). However, the lower subsoil at this site did not respond to this precipitation event and there was a loss of soil water.

Textural discontinuities at sites 2 and 4 appeared to influence soil water retention in the topsoil. At site 2 there was a bulge 10 cm above the peat-mineral mix secondary material interface where volumetric water content was highest, then a reduction of volumetric water content deeper within the soil profile (Figs. 3b and 4b). At site 4 a bulge of greatest volumetric water content occurred below the peat-mineral mix interface then there was a reduction of volumetric water content at a depth of 50 cm, then a large increase at a depth of 70 cm (Figs. 3d and 4d).

DISCUSSION

Soil texture influences water retention within the soil and its ability to infiltrate and transmit water through the soil profile (Hillel 1998). Soils that are predominantly coarse-textured typically have high infiltration rates and saturated hydraulic conductivities and low water-holding

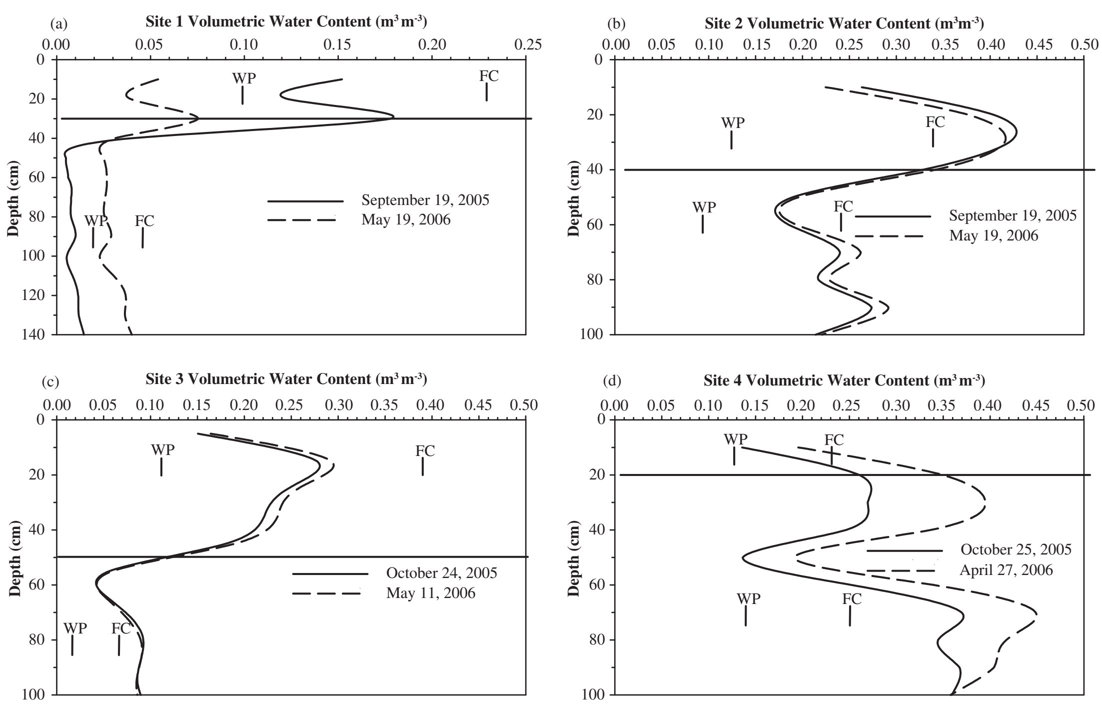

Fig. 3. Representative over winter soil water profile response for (a) site 1; (b) site 2; (c) site 3; (d) site 4. FC = field capacity 0.01 MPa at sites 1, 2 and 3 and 0.03 MPa at site 4; WP = wilting point 1.5 MPa at sites 1, 2, 3 and 4. The horizontal line represents the interface between the PPM and the 2° or the tailings sand.

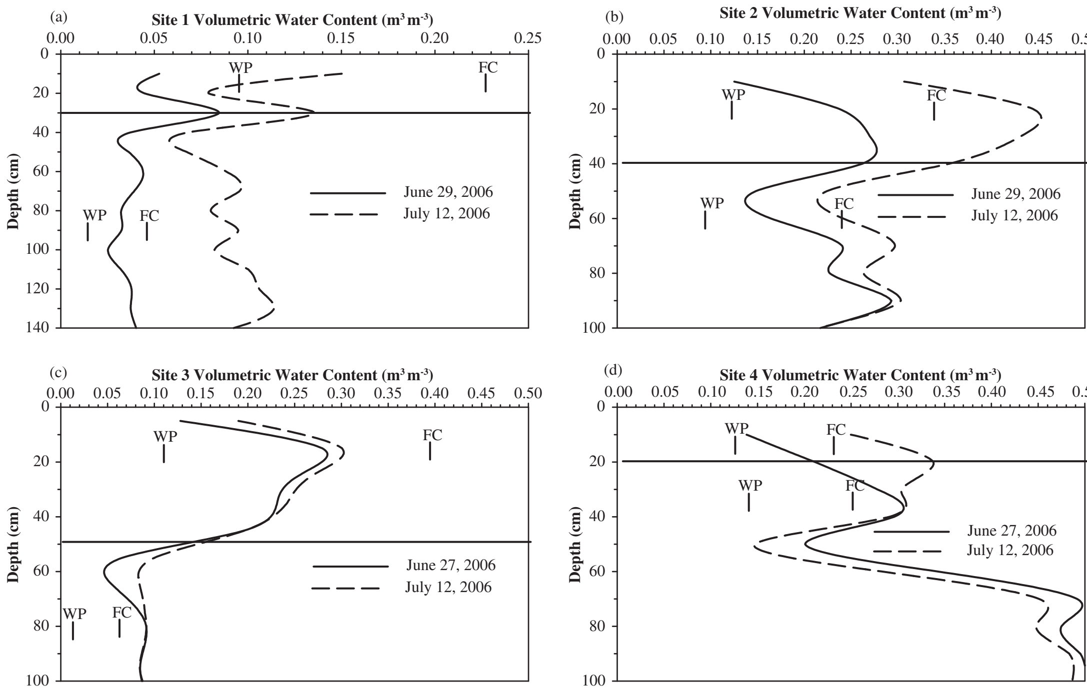

Fig. 4. Representative soil water profile response to precipitation at (a) site 1; (b) site 2; (c) site 3; (d) site 4. FC = field capacity 0.01 MPa at sites 1, 2 and 3 and 0.03 MPa at site 4; WP = wilting point 1.5 MPa at sites 1, 2, 3 and 4. The horizontal line represents the interface between the PPM and the 2° or the tailings sand.

capacity. Organic matter content increases the volume of water held by soil at field capacity, thereby increasing water-holding capacity (Hudson 1994). Bauer and Black (1992) found that increasing organic matter content in coarse-textured materials increased water-holding capacity to a greater extent than when organic matter was increased in fine-textured materials. There were differences in water-holding capacity among sites, likely due to differences in clay, sand and organic matter content. Sites 2 and 3 with higher organic matter contents had greater water-holding capacity. Thus, texture of the material and amount of organic matter likely influenced the amount of soil water that could be retained within a peat-mineral mix. During this study, sites 2, 3 and 4 appeared to hold sufficient water for vegetation while site 1 was subject to low soil water contents.

Field capacity and wilting point values for the tailings sand at sites 1 and 3 were low, as expected and as reported at another oil sands site (Naeth et al. 2011). The tailings sands at sites 1 and 3 and the peat-mineral mix at site 3 were difficult to saturate for pressure plate analyses, suggesting these materials were displaying some hydrophobic properties. Other studies on tailings sand storage facilities also found hydrophobic tailings sands (Chaikowsky 2003; Burgers 2005). Site 3 was unvegetated and if vegetation were established the soil water regime in the peat-mineral mix would likely change dramatically.

Precipitation was highly variable during the 2006 growing season and, in general, the rooting zones, as expected, had more dynamic soil water regimes than zones deeper within the soil profiles (Figs. 1 and 2). These results concur with previous studies in Alberta's boreal forest region, which have shown that temporal soil water fluctuations are greater in the upper soil profile than in the lower subsoil and that the upper soil profile responds strongly to local precipitation events (Whitson et al. 2005; Powell and Bork 2007). Variability in seasonal distribution of precipitation and the resulting soil water flux affects growth and development of boreal forest conifer species (Brooks et al. 1998). Thus, it is important to quantify the expected soil water regime of a reclaimed site as it may affect the ability to develop a self-sustaining ecosystem.

Conversely, the soil water regime at site 3 did not respond as strongly to precipitation events. Rills and channels were observed at this site, which is an indication of surface runoff, known to occur at reclaimed areas (Hillel 1998; Guebert and Gardner 2001; Nicolau et al. 2005). Overland flow was likely a function of lack of vegetation and the influence of a hydrophobic soil substrate, which was probably increasing surface runoff and decreasing infiltration. Vegetation protects the soil surface from the erosivity of rainfall and when not present soil removal by rill and sheet erosion may occur (Hillel 1998). The peat-mineral mix in the rooting zone and the tailings sand was difficult to saturate during pressure plate analyses, suggesting that these materials were displaying hydrophobic properties. The combination of these factors was likely contributing to little loss or gain of water within the soil profile at this hillslope.

Sites 2, 3 and 4 held sufficient soil water in the rooting zone for plant growth during most of the growing season. Conversely, soil water content at site 1 was below wilting point for most of the growing season, reflective of the shallow cover at this site, underlain by tailings sand. This was a south-facing warm and dry slope with coarse-textured soils, which are known to have low soil water contents. In the southern boreal forest of Saskatchewan warm summer seasons coupled with low water-holding capacity and high hydraulic conductivity of sandy soils associated with jack pine sites can lead to soil water at wilting point in the upper soil during dry seasons (Kljun et al. 2006; Grant et al. 2007). Previous studies have shown that peat mineral mixes on tailings sands storage facilities are prone to volumetric water content below wilting point (Naeth et al. 2011). Soil water was not a function of slope position on the reclaimed hillslopes. This unexpected outcome may be the result of soil water patterns responding to the heterogeneity of soil properties and spatial patterns of vegetation rather than slope position. The peat-mineral mix is generally placed on site while still frozen and broken up and evened out to the prescribed application depth by large equipment, once the material has thawed. Handling and placement of the reclamation material by large-scale equipment creates immense spatial variability in depth and distribution across a site. Salazar et al. (2002) found lower slope positions had greater soil water than upper ones only when slopes were greater than 33%.

Spatial variability occurs in application depth and distribution of peat-mineral mix. For the sampled soil profiles, coefficients of variation suggest a high degree of variability for soil water for a depth interval among soil profiles within a slope position. The coefficient of variation is a measure of the variation within a dataset and the larger the percentage the greater the variability of the parameter (Dollhopf 2000). Coefficients of variation of total soil water within the rooting zone for sites 1, 2, 3 and 4 ranged from 17 to 58, from 13 to 67, from 1 to 38 and from 6 to 34%, respectively, and for total soil water within the subsoil interval for the four sites ranged from 2 to 71, from 11 to 75, from 12 to 67 and from 1 to 62%, respectively.

The measurement positions may have been too far apart and/or the Diviner 2000 access tubes may not have been installed deep enough into the soil profile to detect changes in soil water content as a result of slope position. The variation in peat-mineral mix depths was hypothesized to be a factor in soil water variability. Chaikowsky (2003), using regression analysis with topsoil depth, found no direct relationship between soil water status and topsoil depth; however, she suggested that the variability of peat-mineral mix depth had some influence on soil water distribution through the profile. Peat mineral mix depth was added into the repeated measures model for the study sites, but was not significant (data not shown).

This study could not establish what was causing the soil water variability. Grayson et al. (1997) proposed the existence of two states for soil water patterns: a wet state and a dry state. The wet state occurs when precipitation is greater than evapotranspiration and the dominant control on the spatial patterns of soil water is topography, which was referred to as a non-local control. The dry state occurs when precipitation is less than evapotranspiration and soil water spatial patterns are a function of soil and vegetation variability, which they refer to as local control. The researchers further suggested that soil water patterns are less sensitive to topographic factors under dry conditions. When soil water distribution is dominated by local controls, soil water contents are more random and exhibit greater dispersion. Numerous studies have found that during dry periods, soil water variability increases and the influence of topography on soil water distribution decreases (Western et al. 1999; Gómez-Plaza et al. 2001; Teuling and Troch 2005; Choi et al. 2007).

Potential evapotranspiration was calculated using the Penman-Monteith equation for site 2, and indicated a soil water deficit of 284 mm during 2006 (data not shown). The site had a water deficit during this study and it is likely that the other three sites also had water deficits during the 2006 growing season. Following the Grayson et al. (1997) theory, when these sites had a water deficit, the soil water patterns would largely be controlled by local conditions, such as vegetation and soil variability, and slope position effects may not be detected. Spatial and temporal heterogeneity are inherent properties of hillslope soil water systems and as a result are scale dependent across space and time (Grayson et al. 1997).

Aspect is known to influence the rate of thaw, with southern aspects thawing faster than northern aspects (Carey and Woo 1998). The loss of soil water from the end of 2005 to the beginning of the 2006 growing season within the rooting zone at site 1 is likely the result of this site facing south, and the 2006 spring being warmer than average and having below-average precipitation, leading to high evaporation rates. Spring snowmelt likely led to the increase in soil water in the lower subsoil. Following a large precipitation event there was a significant increase in soil water throughout the profile, indicating percolation. The small change in soil water at Site 2 within the soil profile indicates that there was no significant loss or recharge of soil water from spring snowmelt. Similar to site 1 the increase of soil water in both the upper soil and lower subsoil at site 2 indicates that, following periods of large precipitation events, percolation may increase water in the secondary material.

The soil water increase in the rooting zone at site 3 following the large precipitation event observed during the 2006 growing season was smaller than those at sites 1 or 2. This site was unvegetated and had been subject to loss of topsoil from the upper slope positions to the lower slope positions via water erosion. Rills and channels were observed on this site, an indication of surface runoff.

Spring snowmelt coupled with spring precipitation likely led to the increase in soil water within the soil profile at site 4. Prior to the large precipitation event, soil water in the rooting zone was approaching wilting point at this site. Vegetation may have been drawing water from deeper in the soil profile since there was little in the rooting zone for vegetation, thereby reducing soil water in the lower subsoil. This site was developed using finer-textured materials than were the other sites, which would have lower soil hydraulic conductivities (Hillel 1998). The rapid vegetation uptake of soil water as it became available, also likely reduced the amount of soil water to percolate between the two dates.

Capillary barriers occur when a fine-textured soil overlies a coarse-textured soil creating a texturally distinct interface (Miyazaki 1988; Heilig et al. 2003). Sites 2 and 4 are likely characterized by capillary barriers to water flow as the peat-mineral mix exhibited volumetric water contents higher than field capacity above the interfaces of the peat-mineral mix and the underlying materials. Similar results have been found on other studies of tailings sands storage facilities in the region (Chaikowsky 2003; Naeth et al. 2011). Zettl et al. (2011), using a physically based model, found that field capacity for a texturally heterogeneous profile could be 110–330 mm higher than that for a homogeneous profile with the same average texture, and postulated that these differences could account for differences in observed ecosite productivity in the oil sands region.

The capillary barriers created by textural discontinuities created by fine-textured peat-mineral mix material overlaying coarse-textured material, overburden or tailings sand would increase water retention within the peat-mineral mix, and hence within the entire reconstructed soil profile. Thus, the creation of these capillary barriers fortuitously via prescriptions would be beneficial to vegetation due to increased soil water supply, providing a perched water table is not created.

CONCLUSIONS

Lower slope positions, on the four reclaimed upland slopes under study, did not have greater soil water contents than upper slope positions. Local controls, such as soil and vegetation variability, could be influencing spatial variability of soil water at a hillslope scale. There was evidence to suggest that the textural discontinuity on reclaimed slopes influenced soil water within the peat-mineral mix. Sites that had a greater fraction of coarse-textured material in the peat-mineral mix had percolation during large precipitation events. The upper soil profiles had highly dynamic water regimes, with a greater response to precipitation events than the lower subsoils. Site 3 was an anomaly as it exhibited very limited response to precipitation events and little temporal change in the soil water profiles, likely the result of a hydrophobic substrate on an unvegetated slope, which decreased infiltration and thus increased runoff.

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