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A comparison of the hydrological role of two reclaimed slopes of different age in the Athabasca Oil Sands Region, Alberta, Canada

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Abstract

Establishing hydrological connectivity in reconstructed landscapes, and understanding how this connectivity evolves over time, is critical for the development of effective water management strategies after oil sands extraction. In the current study, the dominant controls on the soil water regimes and runoff generation mechanisms on two contrasting reclaimed slopes (two and six years after reclamation) in the Athabasca Oil Sands Region are investigated. The most recently reclaimed slope demonstrated a hydrologic regime with limited soil water storage due to a low surface infiltration capacity that constrained percolation of rainfall. Accordingly, this slope generated a substantial amount of surface runoff controlled primarily by precipitation intensity. Conversely, the older slope had a greater surface infiltration capacity, more dynamic soil water regime and infrequent surface runoff. Topography controlled soil water distribution on the older slope more strongly than the newer slope due to more efficient water redistribution. This suggests that changes in the hydrophysical properties of reclamation materials following construction result in a shift in the hydrological role of reclaimed slopes at the watershed scale. Thus, over time, reclaimed slopes produce less overland flow and shift from water conveyors to water storage features in constructed watershed systems.

Keywords: oil sands; mine reclamation; constructed watershed; hydrology; reclaimed overburden slopes
**Introduction**

Large-scale disturbances caused by oil sands extraction activities in the Athabasca Oil Sands Region (AOSR) in Canada require the reconstruction of individual ecosystems and landforms at the scale of whole landscapes (Johnson and Miyanishi 2008). Understanding the connectivity between individual landforms within the reclaimed landscape is fundamental in re-establishing ecosystem functioning. Soil covers used during land reclamation and mine decommissioning at oil sands mining operations are designed to mitigate percolation into stockpiled overburden or waste (Elshorbagy et al. 2005; Kelln et al. 2007; Meiers et al. 2011) and to provide an adequate water supply for vegetation over dry summer periods (Carey 2008; Meiers et al. 2011). Accordingly, most reclamation soil cover research has focused on assessing the performance of these soil covers at the hillslope (i.e., individual landform) scale and do not explicitly consider their hydrologic function within the context of larger-scale landscapes (i.e., watershed-scale). Although some studies (e.g., Kelln et al. 2007; Shurniak and Barbour 2002) quantify downslope movement of water (interflow) and other studies have documented soil water distribution and temporal variability within reclaimed upland slopes (e.g., Kelln et al. 2008; Leatherdale et al. 2012), there is a need to couple the controls on soil water distribution to the storage and transmission of water through reclaimed slopes to their hydrologic role (i.e., storage or conveyor) within the larger-scale watershed.

In natural landscapes within the AOSR, deep glaciated substrates result in extremely complex surface and groundwater interactions and topography does not always control watershed hydrology (Devito et al. 2005; Smerdon et al. 2005). However, the hydrologic regime of the reclaimed landscape has been highly altered relative to natural areas (Elshorbagy et al. 2005). Consequently, the hydrologic response of reclaimed landscapes is quite different than the
responses of undisturbed areas (Negley and Eshleman 2006); though the dominant controls on soil water distribution within reclamation soil covers are not fully understood. For example, the influence of topography (i.e., slope position) on soil water distribution in reclaimed slopes is unclear. Kelln et al. (2008) found that soil moisture conditions were wetter at lower slope positions on a reclaimed slope landform in the AOSR during the wet spring season as well as throughout the comparably dry summer and fall seasons. Conversely, Leatherdale et al. (2012) determined that lower slope positions rarely exhibited higher soil moisture contents than upper slope positions and concluded that soil water distribution was not consistently influenced by slope position on a reclaimed saline-sodic overburden dump (also in the AOSR). Net percolation rates on reclaimed slopes are, however, influenced by topography, and can be an order of magnitude higher at plateau locations compared to slope locations (Huang et al. 2015b). Further, the presence and nature of vertical textural layering can influence the amount of water stored within reclamation soil covers (Zettl et al. 2011). Understanding the controls on water distribution within reclaimed slopes is a necessary step in evaluating the hydrological importance of these slopes on the performance and behaviour of the larger watershed-scale reconstructed landscape. Accordingly, there is an ongoing need to discern the dominant controls on water storage and distribution within reclaimed slopes.

Since the hydrophysical properties of reclaimed slopes can undergo substantial changes in the first few years following their construction (e.g., Guebert and Gardner 2001; Kelln et al. 2007; Meiers et al. 2011), the soil water regime and, thus, the hydrologic role of reclaimed slopes will change over time. The development of a secondary soil structure (i.e., macropores) contributes to the evolution of the hydraulic properties of reclaimed soils. For example, preferential flowpaths can develop around large rock fragments in reconstructed soils (Guebert
and Gardner 2001). Also, freeze/thaw cycling can contribute to the observed changes in the properties of reclaimed soils. Meiers et al. (2011) observed an increase in the saturated hydraulic conductivity of reclamation cover soils of one to two orders of magnitude over the first two years following soil placement and attributed these changes to the occurrence of an annual freeze/thaw cycle in the AOSR. Further, reclaimed slopes are typically vegetated with pioneer plant communities that transition through several successive vegetation communities in the years following reclamation (Carey 2008). The growth of vegetation and the establishment of root infrastructure in the shallow subsurface can contribute to the evolution of the hydrophysical properties of reclaimed soils as well (Loch and Orange 1997), although this effect is constrained to within the rooting zone and, thus, is not considered to be a primary control on the evolution of soil properties (Meiers et al. 2011). Nonetheless, insufficient consideration has been given to evaluating the importance of these changes and how they relate to hydrological regime shifts on reclaimed slopes over time. Accordingly, an understanding of how the evolution of the hydrophysical properties of reclamation soil materials relates to the hydrological role of reclaimed slopes in the reconstructed landscape is required.

Soil materials used in the construction of these landscapes (e.g., peat/mineral mix soils) have also demonstrated some hydrophobic tendencies. For example, Leatherdale et al. (2012) noted difficulty saturating samples of oil sands reclamation soils (including peat/mineral mix) in the laboratory and suggested that this was caused by the hydrophobic properties of the materials. Hunter et al. (2011) also measured a high degree of hydrophobicity on some reclaimed landscapes in the AOSR, although the extent of hydrophobicity was found to be highly variable within and between sites. The water content and peat/mineral mix composition can also influence the hydrophobicity of reclamation materials, with water repellent conditions when the soil is dry.
and a high water storage capacity under wet conditions, as influenced by a critical water content (Chau et al. 2014). Hydrophobic soils tend to have lower surface infiltration rates and are often associated with enhanced overland flow (Doerr et al. 2000). Consequently, the soil water regime of reclaimed slopes could be influenced by the presence and extent of soil hydrophobicity. For this reason, it is preferable to target materials with less hydrophobicity (i.e., wettable) for the construction of the sloping portions of reclaimed landforms, with the placement of materials with higher hydrophobicity on flat landscapes, in an attempt to minimize the potential for runoff and erosion of reclaimed landscapes (Hunter et al. 2011). Regardless, increased surface runoff and decreased infiltration was observed from a reclaimed slope capped with peat/mineral mix materials with hydrophobic tendencies (Leatherdale et al. 2012). Further quantification of the extent of the hydrophobicity of materials used to construct reclaimed slopes and the potential impact on the hydrologic function of reclamation soil covers is required.

This research examines the dominant controls on the soil water regimes of two reclaimed slopes in the AOSR. The approach is to compare the soil hydrophysical properties, soil water dynamics and runoff generation mechanisms on two reclaimed slopes that were reclaimed five years apart using the same prescribed soil-placement and revegetation approach. The discussion includes an evaluation of the role that existing slopes can play in watershed-scale landscape reclamation. Accordingly, the specific objectives of this research are to: 1) validate existing and identify new controls on soil water dynamics within two reclaimed slopes with differing reclamation timelines; 2) quantify the downslope movement of water; and 3) examine the function of reclaimed slopes in the context of landscape-scale design.
Site Description

Constructed watershed

This study was conducted in a constructed watershed (the Nikanotee fen watershed) within the Millennium mine lease at Suncor Energy Inc. oil sands mining operations approximately 40 km north of Fort McMurray, Alberta (56°55.944’N 111°25.035’W; average watershed elevation ~288 masl; Figure 1). The individual landforms within the constructed watershed (total watershed area = 32.1 ha) include: an upland aquifer (7.7 ha) constructed from tailings sand materials; a fen peatland (2.9 ha) built using fen peat from newly developed lease areas; a sloping natural remnant of the pre-mining landscape (2.8 ha; the “natural slope”); and three reclaimed slopes of varying age and character (combined area = 18.7 ha). An earthen berm was constructed around much of the perimeter of the watershed in an attempt to hydrologically isolate the catchment from the surrounding mining landscape. Beyond the berm, mining infrastructure (e.g., haul roads, service roads, equipment laydown yards and pipeline corridors) encase the majority of the watershed. Accordingly, water inputs from beyond the catchment boundary (Figure 1) are highly unlikely and were not observed.

Within the constructed watershed, the upland aquifer and fen peatland are situated in a gently sloping valley bottom (constructed upland grade is ~3% towards the 0% grade fen peatland) surrounded by the other relatively steep landforms and isolated from the underlying hydrogeological units by a geosynthetic clay liner. The natural slope is composed of natural soils characteristic of the AOSR, with a thin ~0-20 cm organic forest floor layer (bulk density = 0.2 g cm\(^{-3}\); porosity = 0.79) overlying a sandy silt mineral soil layer (bulk density = 1.2 g cm\(^{-3}\); porosity = 0.55), and is not included in this study. The two reclaimed slopes that are adjacent and
run parallel to the upland-fen valley (i.e., sloping to the west and east; see Figure 1) are the focus of this study. The final watershed design is described in detail by Daly et al. (2012) and Pollard et al. (2012).

**Reclaimed slopes**

The east slope (8.1 ha) was reclaimed in 2007 (soils placed) and revegetated in 2008 (herein referred to as the 2007 slope). In contrast, the west (2.4 ha) slope was reclaimed in 2011 and revegetated in 2012 (herein referred to as the 2011 slope). A third reclaimed slope (located in the southeast portion of the watershed, also reclaimed in 2011 and revegetated in 2012) is also occasionally discussed in this study. Planting on the slopes was guided by the Cumulative Environmental Management Association (CEMA) Revegetation Manual (Alberta Environment 2010) and consisted primarily of white spruce (*Picea glauca*), aspen (*Populus tremuloides*), white birch (*Betula papyrifera*), green alder (*Alnus viridis*), as well as an assortment of shrubs (e.g., Saskatoon berry (*Amelanchier alnifolia*), pin cherry (*Prunus pensylvanica*) and chokecherry (*Prunus virginiana*). The vegetation cover was more mature on the 2007 slope (average height ~1.5 m; >75% vegetation coverage) than the 2011 slope (average height 0.8 m; ~20 – 40% vegetation coverage; Table 1). Both slopes are composed of overburden substrate from the Cretaceous Clearwater formation, which is dominated by shale and siltstone (Hackbarth and Nastasa 1979). The Clearwater overburden material is overlain by a ~100 cm secondary capping layer of suitable overburden material and capped with a ~40 - 50 cm thick ‘peat/mineral mix’ cover soil. A summary of some of the slope attributes as well as a more detailed description of the reclamation material properties is presented in Table 1. Overburden material is typically salvaged from deeper within the soil profile (below the solum) and is considered to be suitable for use as a secondary capping layer by Suncor Energy Inc. if the pH is less than 8, the electrical
conductivity is less than 5 dS m\(^{-1}\) and the sodium adsorption ratio, which is a measure of the sodicity of the soil, is below 8 (J. Martin, personal communication). The ‘peat/mineral mix’ reclamation soil type is typically an amalgamation of organic peat and mineral soils obtained by over-stripping natural peat deposits underlain by glacial mineral soils (Meiers et al. 2006).

The secondary capping and peat/mineral mix soil layers were each directly placed (i.e., not from stockpile) during the construction of the reclaimed slopes in this study. To minimize soil compaction, each soil layer was placed as a single lift and construction of both slopes was completed primarily during the winter. For both lifts on the 2007 slope, the material was hauled to the top or mid-bench of the slope and pushed downgrade with a heavy dozer. Due to the presence of pipelines at the top of the 2011 slopes, the individual soil lifts were pushed upgrade from the slope base or mid-bench on the 2011 slopes. Any differences in soil properties caused by the different direction (i.e., up or down grade) that the soils were pushed during construction should be minimized by the winter soil placement period. Both slopes were reclaimed using a similar reclamation prescription. The current study focuses on comparing and contrasting the 2007 slope primarily with the west 2011 slope. The southeast 2011 slope in the constructed watershed (8.2 ha; see Figure 1) was reclaimed at the same time and using the same material and technique as the west 2011 slope. The southeast 2011 slope is not explicitly addressed (although included in one dataset, as expressed below) in this study, however, it is expected that the processes operating on this slope are similar to those of the west 2011 slope, given their simultaneous construction timeframe, source material and reclamation prescription.

Methods:

Field methods
Meteorological stations were deployed on each of the 2007 and 2011 (west) slopes in June 2012. Measurements of net radiation (NR-LITE net radiometer; 2.5 m height), ground heat flux (REBS HFT-3; 0.01 m depth) wind speed and direction (R.M. Young Wind Monitor; 2.75 m height), relative humidity and air temperature (Hobo U23 Pro v2 dataloggers; 1.0 and 2.3 m heights) were taken every minute and average values were recorded every 30 minutes using Campbell Scientific CR5000 dataloggers and Hobo dataloggers (relative humidity and air temperature data only). Soil moisture probes (CS-650) were installed horizontally into the peat/mineral mix reclamation surface soil layer at 2.5, 10 and 32.5 cm depths, as well as within the underlying secondary capping material at depths of 75 and 60 cm on the 2007 and 2011 slopes, respectively. Independent volumetric water content (VWC) calibration curve functions were derived for soils from each of the 2007 and 2011 slopes in the laboratory using minimally disturbed soil samples extracted in the field. The calibration process is intended to empirically determine the relationship between the reading from the soil moisture probe (the dielectric permittivity reading for the CS-650 probe) and an independently determined VWC of the soil. Prior to calibration, the soil samples were saturated, drained and weighed. Soil samples were allowed to evaporate while the probe response to the changing water content (i.e., permittivity reading) was measured every minute and recorded every 15 minutes with a Campbell Scientific CR1000 datalogger. The VWC of the soil sample was determined gravimetrically at 25 – 35 different VWC steps (~0.5 to 0.1 VWC) and a polynomial function was used to relate the reading from the soil moisture probe to the actual (i.e., gravimetric) VWC. This polynomial calibration curve equation was then applied to in-situ VWC measurements made using the CS-650 probes in the field.
Transects of soil moisture profile access tubes were installed across the mid and lower portions of each slope (Figure 1). A Troxler Sentry 200AP capacitance moisture probe was used to measure soil moisture at depths of 7.5, 15, 25, 35, 50 and 75 cm within the access tubes (5.08 cm I.D. PVC pipe; n = 9 and 14 locations on the 2007 and 2011 slopes, respectively) on a weekly basis (May – August 2012 – 2014). Calibration curves were developed for both the 2007 and 2011 slope soils. Due to equipment failure, a Delta-T Devices PR2 Soil Moisture Profile probe replaced the Troxler moisture probe in June 2014. Both of these soil moisture probes measure the dielectric permittivity of the soil, which is then related to the soil VWC. A custom calibration curve was developed for the Troxler moisture probe out of necessity, because this was an older model probe and the calibration provided by the manufacturer was no longer available. The procedure for this calibration was similar to that outlined for the CS650 probes, except this was completed in the field throughout the 2013-2014 seasons by periodically weighing a bucket containing an intact soil monolith (for gravimetric determination of VWC) and an access tube to facilitate concurrent permittivity measurements by the Troxler probe. The soil calibration provided by the manufacturer was used for the VWC measurements made with the PR2 Soil Moisture Profile probe, which is accurate to within ~±0.06 (including installation and sampling errors). New access tubes (2.8 cm I.D.) appropriate for the PR2 probe were installed within ~1 m of the Troxler access tubes. The depth intervals of the VWC measurements made using the PR2 probe (10, 20, 30, 40, 60, 100) are slightly different than those made previously with the Troxler probe. However, for illustrative and consistency purposes, they are shown and grouped as being made at the same depth for some of the analyses in this study. It is clearly stated that this has been done wherever relevant. Since this change applied to all measurements in the 2007 and 2011 slopes concurrently, they remain comparable. Shallow soil moisture
surveys were conducted along transects through the 2007, 2011 (southeast) and 2011 (west) slopes approximately every ten days (2013 only; Figure 1). Measurements of the average VWC in the upper 7 cm (i.e., 0 - 7 cm) of the soil were made every 20 m using a Delta-T Devices WET Sensor (type WET-2) portable water content probe, which measures the dielectric permittivity of the soil. Slope-specific calibration curves were developed in the laboratory to relate the dielectric permittivity measurement to volumetric water content (using similar methods as outlined previously) and applied to these measurements using intact soil samples extracted from the field.

Soil pits coupled with the access tube measurements at three locations on each slope were used to measure the in-situ infiltration rate (f) using a single-ring infiltrometer at the surface, at 10 and 30 cm depths as well as at the top of the secondary capping soil layer on each slope. Infiltrometers were installed to a minimum of 1 cm depth and tests were conducted until a steady-state infiltration rate was observed (indicated by a minimum of 4 consecutive measurements within ±15%). The time to reach steady state varied widely depending on the infiltration capacity of the soil layer being measured. Soil cores were also extracted at the same depth intervals for laboratory estimation of standard soil parameters and hydrophobicity (see details on laboratory methods below). In-situ f measurements were completed in both 2012 and 2013 while soil cores were only extracted in 2012. In 2014, two shallow trenches (each ~7 m long) were dug near the toe (lower slope) of the 2007 slope to estimate water movement via subsurface interflow. Trenches were dug to just below the top of the secondary capping material (~50 cm depth), lined with polyethylene and perforated PVC pipes that drained into 80 L buckets for collection of water and covered at the surface with plywood boards. Following rain events that produced interflow, the total volume of water in the buckets was measured and the buckets were emptied. A logging pressure transducer (Schlumberger Mini-Diver) was installed in one of
the trench buckets to provide information on the timing and duration of interflow generation. A surface runoff flume was installed near the toe of each of the 2007 and 2011 slopes, which consisted of plastic resin landscape edging set and sealed (with hydraulic cement) approximately 5-10 cm into the ground. This edging directed water flowing along the surface through a trough and into a bucket containing a v-notch and a logging pressure transducer (Schlumberger Mini-Diver). Manual measurements of discharge made during the spring freshet in 2013 provided independent rating curves for each flume. The surface runoff flume on the 2011 slope was only monitored during the 2014 season (in addition to the spring freshet period in 2013, when the rating curve was developed), while the 2007 slope flume was monitored throughout 2013 and 2014.

Detailed topographic surveys were completed for delineation of the sub-catchment gross drainage area for each of the runoff flumes. However, accurate delineation of the gross drainage area for the 2011 slope runoff flume was not possible due to dynamic erosional rill development and evolution during rainfall events and throughout the study period, which spontaneously directed water flows out of the topographically derived flume ‘catchment’ (this was not an issue on the 2007 slope due to the absence of rill erosion). The uncertainties associated with deriving a gross drainage area for the flume on the 2011 slope prevented accurate conversion of volumetric flow measurements to runoff depths. Thus, it was unclear what proportion of the slope was contributing to the volumetric flows measured at the flume, so these data could not be used to quantify surface runoff from the 2011 slope. However, these measurements provided useful information with respect to the frequency and timing of surface runoff events from this slope (i.e., the flume data was used to identify when surface runoff occurred, but quantifying it was not possible). These data were used to relate the occurrence of surface flow at the 2011 slope flume
to the maximum precipitation intensity of each storm event. Specifically, the volumetric flow of water through the flume was plotted against the maximum precipitation intensity for every rainfall event in 2014 (n = 37 individual P events). This approach provided the field-based empirical information on the minimum precipitation intensity required to produce a surface runoff response from the 2011 slope (i.e., precipitation intensity threshold). The depth flux of runoff generated from the 2011 slopes was derived empirically based on a combination of precipitation event data, the precipitation intensity threshold, the soil water storage capacity of the near-surface (0 – 2 cm) soil layer ($S_{0-2}$) and the percolation of water deeper into the soil profile ($f_{10}$), where

$$ R_{surf} = S_{0-2} - (i - f_{10}) $$

Equation 1

The soil water storage capacity (i.e., $S_{0-2}$) represents the fillable porosity, or the amount of additional water that the upper 2 cm soil layer can hold before becoming saturated. This was calculated by subtracting the amount of water stored within the upper 0 - 2 cm soil layer at the start of the precipitation event (based on the pre-event VWC measurement) from the total soil porosity and was typically ~5 mm. The average infiltration capacity measured at 10 cm depth was used to represent precipitation event water that percolated into deeper soil layers (i.e., $f_{10}$). Accordingly, surface runoff generation from the 2011 slope was presumed to occur once the storage capacity of the near-surface layer was satisfied and the precipitation intensity exceeded the observed threshold from the runoff flume observations.

The location and elevation of all instrumentation was surveyed annually (± 0.005 m vertical accuracy) using a Topcon HiPER GL RTK GPS system (2012 and 2013) and a Leica Geosystems Viva GS14 GNSS RTK GPS system (2014).
Laboratory methods

Intact soil samples were extracted in the field using hollow steel (Shelby-type) soil tubes (5.5 cm I.D. x 5 cm height) driven into the ground at the specified depth intervals, wrapped in polyethylene film and carefully transported back to the laboratory. The bases of the soil samples were protected with screening to minimize loss of sediments during analyses. Soil samples were analysed for total porosity ($\phi$) and bulk density ($\rho_b$) following standard methods (e.g., Freeze and Cherry 1979; Klute 1986), with the exception that samples were oven-dried at 80°C. Saturated hydraulic conductivity ($K_{sat}$), soil water characteristic (retention) curves, specific yield ($S_y$) and hydrophobicity (see below) were determined for a sub-set of samples prior to oven drying. $K_{sat}$ was determined on each sample using a constant-head test. Specifically, a constant head differential ($H$) was set up by ponding water ~5 cm deep atop the soil sample of length ($L$) and cross-sectional area ($A$) and Darcy’s Law was applied to determine $K_{sat}$ according to

$$K_{sat} = \frac{Q L}{A H}$$  

Equation 2

where Q is the steady volumetric discharge through the system (Freeze and Cherry 1979). Samples with very low $K_{sat}$ that required Q measurements over several consecutive days were loosely covered with polyethylene film to limit evaporation of ponded water. Soil water characteristic curves were determined using a 5 bar (500 kPa) ceramic pressure plate extractor (Soil Moisture Equipment Corp. model #1600) and an air compressor controlled by a throttle valve and measured with a manometer tube. The pressure inside the chamber was raised above atmospheric pressure in incremental steps (1, 2, 5, 10, 20, 40, 60, 100, 200, 400 kPa), which forced water out of the soil samples via a porous ceramic plate on which the soil samples were placed. The soil samples were weighed approximately every day or two until the mass stabilized.
The final (i.e., stable) mass was recorded and used to determine the VWC of the soil samples gravimetrically at each pressure step. A ceramic plate with a 1 bar (100 kPa) air-entry pressure was used for the lowest pressure ranges (0 - 100 kPa) and a 5 bar (500 kPa) ceramic plate was used thereafter. Specific yield \( (S_y) \) was estimated for each of the soil samples as the difference between saturated VWC and the average of the soil sample VWC measured at both 20 and 40 kPa, since the VWC was not actually measured at the pressure typically used to represent field capacity (33 kPa).

Hydrophobicity (soil water repellency) was estimated at the stabilized VWC at several pressure steps using the water drop penetration time (WDPT) method (Letey 1969). This test involves recording the time taken for the complete penetration of a water drop placed on the surface of a soil (Letey 1969). The standardized WDPT test procedure followed that outlined in (Doerr 1998) and involved application of five drops of distilled water (at ~20°C) to the soil surface using a syringe and hypodermic needle. The median penetration time was considered to be representative of the WDPT of each sample (cf. Doerr 1998). Samples were categorized in terms of level of hydrophobicity severity according to Bisdom et al. (1993): <5 s WDPT (hydrophilic), 5 - 60 s (slightly hydrophobic), 60 - 600 s (strongly hydrophobic), 600 - 3600 s (severely hydrophobic) and >3600 s (extremely hydrophobic). Although somewhat arbitrary, the categorization of soil samples by level of hydrophobicity provides a useful summary and comparison between different soils (Doerr 1998) as well as demonstrates the effect of moisture content on soil hydrophobicity.

Statistical methods
A Shapiro-Wilk normality test was performed on the data ($\phi$, $\rho_b$, Troxler/PR2 access tube VWC measurements and shallow soil VWC survey data) and the results were verified by graphical assessment of quantile-quantile plots. For data with non-normal distributions ($\phi$, $\rho_b$, Troxler/PR2 access tube VWC measurements), Wilcoxon rank sum tests were conducted to determine if there was a statistical difference between VWC measurements on the 2007 and 2011 slopes ($H_0$: the differences between distributions of both populations is zero). The significance of linear regression models (shallow soil VWC survey data; normally distributed) was assessed using $t$-tests ($H_0$: the slope of the VWC and surface elevation relationship is zero, thus, they are independent). All statistical analyses were completed using the R Statistical Software (Version 0.98.1056; R Core Team 2013).

Results

Hydrophysical properties and hydrophobicity

Peat/mineral mix soils on the more recently reclaimed 2011 slope had a higher median $\rho_b$ and lower median $\phi$ than soils on the older 2007 slope (Figure 2). The results of the Wilcoxon rank sum tests indicate statistical differences in $\phi$ ($W = 115.5; p = 0.04$) but not $\rho_b$ ($W = 55; p = 0.23$) between the 2011 and 2007 slope soils. However, differences in $\rho_b$ between slopes were significant ($W = 6; p = 0.03$) in the upper 20 cm of the soil profile (i.e., when depths greater than 20 cm were excluded from the statistical analyses). The $\rho_b$ for both slopes are higher than those reported for peat/mineral mix soils by Meiers et al. (2011) of 0.9 g cm$^{-3}$, although the $\phi$ are similar to that of Meiers et al. (2011; 0.59). The secondary capping material, which exhibited similar hydrophysical properties on both slopes, had a much higher $\rho_b$ (average = 1.7 g cm$^{-3}$; $n =$
6) and lower $\phi$ (average = 0.36; n = 6) than the overlying peat/mineral mix soils on both slopes. The range of values reported in Kelln et al. (2007) and Meiers et al. (2011) for $\rho_b$ and $\phi$ of secondary capping materials is 1.3 – 1.7 g cm$^{-3}$ and 0.40 – 0.55, respectively, which places the materials in the current study slightly more dense and less porous than comparable materials in the AOSR. Average $S_y$ (±standard deviation) for the peat/mineral mix material on the 2007 and 2011 slopes was 0.28 (±0.10) and 0.12 (±0.06), respectively, and 0.08 (±0.03) for the secondary capping material.

The infiltration rate, $f$ (geometric mean values stated), at the surface of the 2007 slope was 195 mm hr$^{-1}$. This was more than five times greater than $f$ at the surface of the 2011 slope (35 mm hr$^{-1}$), which declined sharply to 1 mm hr$^{-1}$ in the upper 10 cm (Figure 2). Similarly, the near-surface $K_{sat}$ ($9 \times 10^{-5}$ m s$^{-1}$) of the 2007 slope was nearly two orders of magnitude greater than that of the 2011 slope ($1 \times 10^{-6}$ m s$^{-1}$). $K_{sat}$ and $f$ declined with depth in the upper 30 cm of both slopes, but with $K_{sat}$ on the 2011 slope increasing deeper in the profile. The lowest $K_{sat}$ and $f$ on the 2007 slope was within the secondary capping soil layer (~60 cm depth), whereas these minima occurred closer to the surface within the peat/mineral mix soil layer (~20 – 30 cm depth) on the 2011 slope (Figure 2).

For the lowest pressure tested (~400 kPa), soil water retention followed the trend of 2011 slope > 2007 slope (for the same depth) and deeper soils > surficial soils (for the same slope; Figure 3). Surface soil samples (i.e., 0 – 5 cm) from both slopes had a higher saturated VWC but lower water retention than soils from deeper within the soil profile (i.e., 20 – 25 cm). For example, the VWC of surface soil samples from the 2007 and 2011 slopes declined from saturated VWC by 0.45 and 0.24, respectively, while the VWC of deeper soil samples was only reduced by 0.22 and 0.09 (from saturated VWC) for the 2007 and 2011 slopes, respectively. The
secondary capping material displayed a similar trend to that of the 2011 slope deep peat/mineral mix soil (i.e., WS 22.5 cm), however, at a consistently lower VWC than the peat/mineral mix soils.

Soil hydrophobicity decreased rapidly with increasing VWC for all soils (Figure 4). Soils from both the 2007 and 2011 slopes were classified as strongly hydrophobic at the lowest soil water pressure tested (~25 – 40% VWC, depending upon the soil water characteristic curve). At the same moisture content, the surface soils (0 – 5 cm) on the 2011 slope were more hydrophobic than the surface soils on the 2007 slope. Surface soils on both slopes exhibited less hydrophobicity than soils deeper in the soil profile. The most hydrophobic soil was the secondary capping soil layer, which was classified as extremely or strongly hydrophobic across the range of moisture contents tested, with the exception of the highest VWC where it was classified as only slightly hydrophobic.

Soil water regimes

During 2013 and 2014, the near-surface VWC responded strongly to P events on the 2007 slope, with increasingly dampened responses deeper in the soil profile (Figure 5). The soil water regime of the 2007 slope also demonstrated seasonality, with wetter conditions apparent in the early to mid summer period and a drying trend during the later summer and autumn months of both years. In contrast, the VWC remained relatively stable at all depths throughout the soil profile on the 2011 slope during both 2013 and 2014, with a general trend of increasing VWC with depth. The secondary capping soil layer VWC remained slightly below saturation on both slopes during both years. The only notable exception was when this layer briefly reached saturation during a very wet period in early June 2013.
Similar to the time-series VWC measurements, the spatially distributed VWC access tube measurements made across the slopes (n = 9 and 14 locations on the 2007 and 2011 slopes, respectively; Figure 1) indicated that the 2011 slope VWC generally increased with depth in the soil profile (Figure 6). However, the greater measurement resolution with depth revealed that the 2011 slope exhibited a fairly uniform soil moisture distribution at depths greater than ~25 cm. In contrast, the VWC on the 2007 slope was lower in the upper layers and tended to increase with depth throughout the soil profile. The VWC within the secondary capping soil layer on both slopes (75 cm depth in Figure 6) demonstrated more variability than the overlying peat/mineral mix soil layers, which was an artefact of a higher amount of spatial variability in VWC between individual measurement points (i.e., large differences amongst commonly grouped access tubes) as opposed to variations driven by temporal or soil textural changes. These distinct trends were consistent at the upper and lower slope positions on both slopes. However, the VWC at lower slope positions on the 2007 slope was consistently higher than the VWC at upper slope positions at the same depth (Figure 6). These differences were statistically significant (p < 0.02) at all depths except 75 cm on the 2007 slope, while no significant differences were observed on the 2011 slope (Table 2). A similar trend was not observed on the 2011 slopes where there was no discernable difference in VWC at upper and lower slope positions. Furthermore, the near-surface (0 – 7 cm depth) VWC survey measurements made along transects that spanned the entire topographic range of the slopes (see Figure 1) indicated that VWC within the upper 7 cm of the soil was typically highest at topographically low slope positions on the 2007 slope (i.e., lower VWC / drier conditions towards the slope crest, Figure 7). Conversely, the near-surface VWC tended to increase with increasing surface elevation (i.e., higher VWC / wetter conditions towards the slope crest) on the 2011 slopes (note that the southeast 2011 slope is included in this analyses.
to increase the topographic range of the data from the 2011 slope. \( t \)-tests indicated that the slope of this relationship was significant \( (p < 0.01) \) on both slopes.

The influence of topography on slope response to precipitation events also varied between the 2007 and 2011 slopes. For example, the 2007 slope demonstrated differing responses at upper and lower slope positions following a 60 mm precipitation event (8/9-June-2013) whereas the 2011 slope responded in a similar (and more muted) manner irrespective of slope position (Figure 8). Soil water storage changes, which were estimated by multiplying the change in VWC by the soil layer thicknesses and integrating over the measurement depths, at the lower slope position on the 2007 slope (69 mm) slightly exceeded precipitation inputs, which suggests some water input from upslope occurred following the event (via interflow). Soil water storage increased by \(~28\) mm at the upper slope position of the 2007 slope following the same \( P \) event. In contrast, soil water storage on the 2011 slopes responded in a similar manner at upper and lower slope positions, increasing by \(~14\) and \(~12\) mm, respectively. The secondary capping material (i.e., 75 cm depth in Figure 8) appeared to respond strongly to the precipitation event at both slope positions except at the lower 2011 slope). Percolation of rainwater via preferential flow paths (as observed by Kelln et al. 2007) would contribute to this; however, temporary ponding of water around the bottom of the access tube from preferential percolation between the access tube and the soil would result in an overestimation of VWC in this layer. Thus, the actual soil water storage change in this layer remains unclear.

*Runoff generation and interflow*

Monitoring of surface runoff flumes indicated that overland flow occurred infrequently on the 2007 slope and typically generated only small amounts of runoff (usually \(<\!<\! 1\) mm; Table
3). One anomalous exception to this occurred in the early summer period of 2014 under conditions of high antecedent soil VWC (30/31-May-2014; Figure 5) during a large (41 mm) rainfall event, which was preceded by an additional 20 mm of precipitation over the previous nine days. This event generated 6 mm of runoff from the 2007 slope and was the only substantial runoff observed from the 2007 slope in either 2013 or 2014 (excluding the spring freshet, when large amounts of surface runoff were observed (Ketcheson and Price 2016)). Conversely, overland flow from the 2011 slopes occurred more frequently. For example, during the period of 1-May to 1-October 2014, 14 separate surface runoff events were observed at the runoff flume on the 2011 slope, whereas only two surface runoff events were observed at the 2007 slope flume during the same time period (Table 3). These field measurements indicated that surface runoff was produced on the 2011 slopes during most precipitation events that exhibited a precipitation intensity \((i)\) greater than \(~3\ \text{mm hr}^{-1}\) (Figure 9). This field-based runoff threshold (3 mm hr\(^{-1}\)) is lower than the \(f\) measured at the surface of the 2011 slope (35 mm hr\(^{-1}\)) but higher than the \(f\) measured at 10 cm depth (1 mm hr\(^{-1}\); Figure 2). Thus, it can be considered as within the range of near-surface \(f\) measured on the 2011 slopes. Due to the uncertainties associated with deriving a gross drainage area for the 2011 slope flume discussed previously, and a lack of data at the 2011 slope flume during the 2013 field season, the depth flux of runoff generated from the 2011 slope was determined empirically for 2013 and 2014 using the \(i\) threshold derived from the flume observations (3 mm hr\(^{-1}\)) and the antecedent storage capacity of the near-surface (0 – 2 cm) soil layer (see Field methods section). In order for runoff to be generated in this analyses, both the near-surface soil storage capacity and \(i\) threshold must be exceeded. This empirical runoff generation analysis showed good agreement with the field-based runoff observed in the flume (Table 3) and revealed that infiltration-excess (Hortonian) overland flow generation events
were short in duration (<1.5 hrs) but capable of producing substantial surface runoff (Figure 5). The empirical method resulted in an underestimation of the number of runoff events measured with the flume by three events in 2014, which indicates that this could be a slightly conservative estimate of the true runoff generated from these slopes. These surface runoff events occurred more frequently and generated considerably more runoff on the 2011 slope (19 occurrences, 125 mm total in 2013 and 2014 combined) than the 2007 slope (five occurrences, 7 mm total in 2013 and 2014 combined (Table 3). Interflow also occurred infrequently on the 2007 slope, with a total of 140 L of water measured in the two subsurface interflow collection pipes between 20-June and 18-August 2014, which represented a flux of < 1 mm. This estimate of interflow does not include flow through the secondary capping soil layer and, thus, is underestimated. The limitations of this estimation of interflow are addressed in the discussion section.

Discussion

This study demonstrates that water distribution, storage and release from reclamation soil covers are strongly controlled by the soil hydrophysical properties. For example, the differences in $\phi$ and $\rho_b$ exhibited by the slopes (Figure 2) contributed to the contrasting storage properties, as evidenced by differing soil characteristic curves (Figure 3). These demonstrated that water was released from the 2007 slope soils more easily than soils from the same depths on the 2011 slope (Figure 3). The higher $\phi$ on the 2007 slope can be attributed to a greater proportion of large pores than on the 2011 slope. Additionally, the higher $f$ on the 2007 slope contributed to greater percolation and storage of precipitation inputs than the more recently constructed 2011 slope, which had a surface $f$ that was 20% that of the 2007 slope (Figure 2). The $f$ of a soil is directly related to the saturated hydraulic conductivity of the soil profile (Dingman 2002) and, in turn, to
soil parameters such as $\phi$ and $\rho_b$. Peat/mineral mix soils on the 2007 slope had a consistently higher $K_{sat}$ with depth than the 2011 slope (except for the underlying secondary capping soil layer, which had similar properties on both slopes), in spite of similar $\rho_b$ at depths greater than ~20 cm. Additionally, the 2011 slope materials demonstrated a higher degree of hydrophobicity than the 2007 slope (Figure 4), despite comparable amounts of organic materials in the materials on both slopes (Table 1). According to the classification of Bisdom et al. (1993), surface soils on the 2011 slope were classified as strongly hydrophobic at the lowest VWC tested (~31%), whereas surface soils on the 2007 slope at the same VWC were only classified as slightly hydrophobic (Figure 4). Since soil hydrophobicity is generally higher under dry soil moisture conditions (Doerr et al. 2000), and near-surface VWC measurements from both slopes were typically lower in the field than the moisture conditions under which hydrophobicity was assessed in the laboratory, soils in the field were likely more strongly hydrophobic than the estimates reported in the current study (i.e., drier soils in the field would produce more severe hydrophobicity). Nevertheless, reclamation soils from both slopes were classified as strongly hydrophobic at the lowest VWC tested. Reclamation soils with hydrophobic tendencies can contribute to decreased infiltration and increased runoff from reclaimed slopes capped with peat/mineral soil mixes in the AOSR (Leatherdale et al. 2012). The severe hydrophobicity of the 2011 slope soils likely contributed to the low near-surface $f$ and the higher frequency and larger amount of surface runoff generated from this slope (Table 3). Thus, the differences in $f$ between slopes are a reflection of both the contrasting hydrophysical properties and the differences in hydrophobicity.

The contrasting properties of the 2007 and 2011 slopes are also reflected in the observed VWC regimes. For example, the greater near-surface $K_{sat}$ and $f$ of the 2007 slope resulted in a
moisture regime that was more variable than that of the 2011 slope (Figure 5). Consequently, the 2007 slope was more closely coupled to atmospheric processes (e.g., precipitation). In contrast, the 2011 slope moisture regime was relatively stable and only responded to precipitation events under extreme conditions. Further, the relatively high $K_{sat}$ on the 2007 slope enabled more efficient downslope water redistribution, as evidenced by the stronger topographic control on moisture distribution on the 2007 slope relative to the 2011 slope (Figures 6 and 7). For example, the VWC was consistently greater (often with statistical significance; Table 2) at lower slope positions on the 2007 slope relative to the VWC at upper slope positions (Figure 6). This concurs with the results of Kelln et al. (2007), who observed higher VWC at lower slope positions on reclaimed slopes that had been reclaimed for ~seven years. However, the VWC was similar at upper and lower slope positions on the more recently reclaimed 2011 slope because the lower $K_{sat}$ (Figure 2) restricted water redistribution downslope. Topography also had a statistically significant and contrasting influence on the VWC of the near-surface soil (i.e., upper 7 cm) on each slope (Figure 7). Leatherdale et al. (2012) found that slope position did not have a consistent effect on moisture distribution on reclaimed slopes that ranged in age from ~2 to 13 years. In terms of the underlying materials, only one of the four slopes included in the Leatherdale et al. (2012) study was similar to the slopes in the current study; however, slope position did not consistently influence the soil water distribution on any of the reclaimed sites reported in that study. Since the $K_{sat}$ of reclamation materials can increase substantially in the first few years following reclamation (Meiers et al. 2011), it can be expected that topography will have an increasing influence on soil water distribution on the 2011 slope as the $K_{sat}$ increases over the following few years.
Similar topographic patterns are also apparent in the response and subsequent drainage of precipitation inputs from the 2007 and 2011 slopes. For example, soil water storage at the lower slope position on the 2007 slope increased by ~69 mm following a large (60 mm) precipitation event in early June 2013 (Figure 8). The water storage increase in excess of precipitation inputs near the toe of the 2007 slope provides evidence of interflow contributing to soil water storage change at lower slope positions. This was not evident on the 2011 slope, which exhibited a similar response at both upper and lower slope positions (soil water storage increase of ~12 - 14 mm). The increase in VWC within the secondary capping layer indicates that some precipitation water percolated into the slope via preferential flow paths, similar to that observed by Kelln et al. (2007). Since secondary porosity develops over time following soil placement (Guebert and Gardner 2001; Kelln et al. 2007), infiltration via preferential flowpaths was likely greater on the 2007 slope relative to the 2011 slope due to the greater time since reclamation, though temporary ponding of water around the bottom of access tubes would result in the VWC of this layer being overestimated. The VWC profile on the 2007 slope slowly returned to the pre-event conditions over the following several weeks at the lower slope position, as the water stored in the slope was lost to the atmosphere or seeped further downslope.

Slope aspect is not explicitly considered in this study; hence, it cannot be completely ruled out as a contributing factor in the different hydrophysical properties and soil water regimes observed on the reclaimed slopes. In the short-term, aspect-driven differences in insolation can influence soil water regimes, with enhanced drying on southern aspect slopes (Geroy et al. 2011). Similarly, the long-term development of soil properties on slopes with varying aspect has also been observed (Geroy et al. 2011). However, the greatest differences can be expected between north and south-facing slopes (e.g., Carey and Woo 1998; Carey and Woo 1999; Geroy
et al. 2011; Redding and Devito 2011). Differences in the insolation received on the slopes in the current study (eastern and western aspects) are small, which minimizes the potential for discernable differences in insolation-driven soil water regimes between slopes as a consequence of aspect. Further, the construction of these reclaimed slopes was recent, which negates the possibility of differences in the long-term development of soil properties on the slopes driven by aspect.

Although the vegetation cover on the 2007 slope is more extensive (~75% coverage) and mature than that of the 2007 slope (~20 – 40% coverage; Table 1), it did not vary substantially with slope position, so was not an influencing factor in the topographically driven VWC trends. It is also unlikely that snow distribution influenced the near-surface VWC trends, since these slopes became >75% snow-free by early April and mid-March in 2013 and 2014, respectively (Ketcheson and Price 2016).

Surface infiltration capacity and rainfall intensity and quantity are the strongest controls on runoff generation from reclaimed slopes. Surface runoff was generated on the 2011 slope more frequently than the 2007 slope, which had a much higher surface infiltration capacity. Visual observations of occasional near-saturated conditions at several locations along the toe of the 2007 slope suggested that some downslope interflow occurred when the storage capacity of the 2007 slope was exceeded during precipitation events. Infiltration measurements made at depth within the 2007 slope suggest that this interflow likely occurred as perched shallow subsurface stormflow development over underlying layers with low f (e.g., the top of the secondary capping material). However, Kelln et al. (2007) observed that interflow developed at the base of the secondary capping soil layer. Since the interflow trenches in the current study were installed to the interface between the base of the peat/mineral mix and the top of secondary
capping soil layers, the measurement of interflow reported here is likely an underestimation of the true value. However, this is unlikely to be a factor here because the \( K_{sat} \) of the secondary capping material was low (~\( 10^{-7} \) m s\(^{-1} \)). Although extended periods of sustained saturated conditions within the secondary capping soil layers would produce higher interflow fluxes, data from the trenches indicated that interflow duration was typically short (median interflow duration at base of peat/mineral mix ~15.5 hrs). Cumulative interflow along the top of the secondary capping layer between June and August 2014 was less than 1 mm, thus was not a hydrologically substantial flux of water. Similarly, Kelln et al. (2006) found that interflow on reclaimed slopes during the snow-free period occurred infrequently; however, interflow can continue intermittently throughout the summer and fall of an exceptionally cool and wet year (Kelln et al. 2007). Interflow on the 2011 slope (not measured) was likely less than the 2007 slope, since the \( K_{sat} \) of the peat/mineral mix material was typically two to three orders of magnitude lower than that of the 2007 slope (Figure 2). Further, the soil profile on the 2011 slope responded weakly to precipitation events (e.g., low variability in VWC profile in Figure 5), indicating that percolation was low, precluding the occurrence of substantial interflow.

The weak response to precipitation events in the near-surface soil moisture on the 2011 slope (-2.5 cm; Figure 5) is coupled to the occurrence of surface runoff from this slope. In principle, the precipitation depth and change in soil water storage within the reclaimed slope cover layers could be used to estimate the amount of surface runoff expected on an event-by-event basis using a water budget approach. This could be accomplished by subtracting the change in soil water storage of the cover layers before and after a rainfall event from the total precipitation received, with the residual representing the amount of surface runoff generated (i.e., surface runoff = P – change in storage). However, due to the minimal responses in the logging
VWC measurements on the 2011 slope (i.e., small estimated change in storage), this approach resulted in the majority of precipitation being reported as surface runoff. This showed poor agreement with the timing of surface runoff measured with the flume and often contradicted field observations. However, comparisons of the empirically derived estimate of surface runoff from 1-May to 1-October 2014 VWC (11 runoff events) and field observations of runoff measured in the flume over the same time period (14 events) showed good agreement (Table 3).

The current study does not account for the influence of different interception rates on surface runoff generation. General conclusions about interception losses from vegetation communities are difficult to make since interception typically depends on several climatic factors (e.g., amount/intensity/duration of rainfall, wind speed) in addition to characteristics of the vegetation canopy (e.g., canopy storage capacity, leaf area index; Crockford and Richardson 2000). The vegetation community on the 2007 slope is more mature and has a higher leaf area index than the 2011 slope (data not shown), which likely results in a higher canopy storage capacity that could contribute to higher rates of interception on the 2007 slope. Canopy interception on reclaimed slopes in the AOSR can vary between 15 – 26% of precipitation (Huang et al. 2015a). However, the near-surface VWC on the 2007 slope responded strongly to P events (Figure 5), which suggests that a substantial amount of P was still reaching the soil surface on this slope. On the 2011 slope, the empirical estimation of surface runoff uses a threshold that is based upon unintercepted rain (i.e., throughfall), so interception on this slope is implicitly accounted for. In addition, rainfall in the AOSR is often delivered as convective storms of high intensity and short duration (Carey 2008). Since rainfall events with these characteristics result in lower interception values than low intensity long duration events (Crockford and Richardson 2000), interception differences between slopes would be minimized.
during the intense rainfall events that generated surface runoff on the 2011 slope. Thus, interception rates likely had a negligible impact on the surface runoff generation observed in the current study. Detailed information regarding differences in rooting depth was not collected, although this has been shown to vary widely between sites (e.g., from 19 to 110 cm (Zettl et al. 2011)). Based on the differences in vegetation community (Table 1), the rooting depth on the 2007 slope is greater than that of the 2011 slope, which would contribute to the greater variability of VWC on the 2007 slope.

It is prudent to note that the hydrological processes and trends identified herein represent those measured on two reclaimed slopes within the AOSR, as replication at additional reclaimed slopes was not possible. Data were collected at various locations throughout each slope, as specified in the Methods section and throughout the paper. This provided the requisite information on the variability of the hydrological processes operating on each slope so inferential statistics could be validly applied to test the null hypothesis that the parameter in question was the same on both slopes (Hurlbert 1984). Thus, the sample sizes reported throughout this paper represent the sampling locations within each of the two reclaimed slopes, while the overall comparison of the hydrological processes presented in this paper is limited to those operating on the two slopes (i.e., n = 2).

**The role of reclaimed slopes in constructed watershed hydrology**

The contrasting hydrophysical properties of the materials on the 2011 and 2007 slopes produced differing hydrological roles on a watershed scale. The importance of near-surface $f$ and $i$ as controls on runoff generation from reclaimed slopes appears to diminish with time since reclamation. For example, the near-surface $f$ of the older 2007 slope, which produced limited
surface runoff, was more than five times greater than that of the 2011 slope, which produced a substantial amount of surface runoff. Higher net percolation on the 2007 slope resulted in infrequent downslope fluxes of water via interflow. The hydrophysical properties of materials used in mine reclamation can change substantially over the first several years following placement (e.g., Guebert and Gardner 2001; Kelln et al. 2007; Meiers et al. 2011). The observed differences in water distribution and runoff generation between the older 2007 and more recently reclaimed 2011 slopes can be considered a surrogate for the changes that can be anticipated in the years following reclamation. For example, Meiers et al. (2011) found that $K_{sat}$ increased by one to two orders of magnitude over the first two years following reclamation of an overburden dump in the AOSR. In the current study, soils on the older 2007 slope exhibited a $K_{sat}$ two orders of magnitude higher than the soils on the 2011 slope, which is consistent with the findings of Meiers et al. (2011). Changes to the $K_{sat}$ on the 2011 slope, similar to those observed by Meiers et al. (2011), are probable over the subsequent several years following reclamation. Furthermore, the surface $f$ of the 2011 slope could also increase as preferential flow paths and secondary porosity develop, which can occur in as little as three to four years (Guebert and Gardner 2001). Hence, it is reasonable to anticipate a shift in the properties of the soils on the 2011 slope towards those exhibited by the 2007 slope over time. In this hypothesized scenario, which is supported by observations from studies in similar reclaimed landscapes (Guebert and Gardner 2001; Kelln et al. 2007; Meiers et al. 2011), the 2011 slope could begin to behave in a similar manner as the 2007 slope within a few years.

Although these potential changes would ultimately result in less water being conveyed from these landforms (due to reduced surface runoff generation) to adjacent low-lying systems in the constructed landscape, increased percolation and subsequent storage of precipitation water
would result in greater available water for vegetation establishment and maturation on the reclaimed slope itself. From an ecosystem creation perspective, integrated landscape reconstruction is important (Devito et al. 2012; Johnson and Miyanishi 2008), hence interconnectivity of landforms is desired. However, the likely evolution of reclaimed slopes appears to favour water storage within landforms over hydrologic landscape connectivity. Nevertheless, recently reclaimed slopes can provide substantial amounts of water to adjacent, low-lying/downstream ecosystems in the first few years following construction. This additional water from reclaimed slopes would serve to alleviate water availability issues (i.e., supplement limited precipitation inputs) associated with reclamation projects that occur at the beginning of a dry climate cycle.

**Summary and conclusions**

Soil water storage characteristics and hydrophysical parameters control the soil water regime of reclaimed slopes and thereby influence the transmission of water within the reconstructed landscape. Soils on the recently reclaimed 2011 slope had a higher bulk density, lower saturated hydraulic conductivity and a low near-surface infiltration capacity. Consequently, the soil water regime was less variable with time (less water infiltrated) and topography did not influence water distribution. Accordingly, more frequent and substantial surface runoff was generated from the 2011 slope relative to the older 2007 slope, which exhibited a lower bulk density, higher saturated hydraulic conductivity and increased near-surface infiltration capacity relative to the 2011 slope. Hence, the 2007 slope was more closely coupled to atmospheric processes (more variable soil water regime) and stored most of the precipitation inputs received during the snow-free period. Both slopes exhibited hydrophobicity at low moisture contents. Soils on the 2011 slope tended to be more hydrophobic and, thus,
contributed to the low surface infiltration rates. If the anticipated changes in hydrophysical properties of soils on recently reclaimed slopes are realized, these landforms could start to produce less overland flow and shift from water conveyors to water storage features in constructed watershed systems.

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**Figure captions**

Figure 1 – TOP: location and general landform arrangement of the constructed Nikanotee fen watershed (including the shallow soil moisture survey transects) within the surrounding mining landscape. BOTTOM: detailed topographic maps of the 2007 (East) and 2011 (West) slopes. Minor contours (grey) are 2 m elevation increments. Subsurface flow trenches are not shown to scale (2007 slope only).

Figure 2 – A & B: boxplots of soil bulk density, $\rho_b$, (A) and porosity (B) for the peat/mineral mix soils on the 2007 and 2011 slopes (n = 12 for each slope). Note the boxplots do not include data from the secondary capping soil layer. C, D & E: infiltration rate, $f$ (C), saturated hydraulic conductivity, $K_{sat}$ (D) and $\rho_b$ (E) with depth for the 2007 and 2011 soils (n = 4 to 12 per depth for $f$ and n = 3 per depth for $K_{sat}$ and $\rho_b$). Horizontal bars on C, D & E indicate the range in data (i.e., maximum and minimum values) and the solid points represent the geometric (C & D) and arithmetic (E) mean. Note that the 60 cm depth on C, D & E is within the secondary capping soil layer and all other depths are within the peat/mineral mix reclamation soil layer.

Figure 3 – Soil water characteristic (retention) curves. 0 cm and 22.5 cm represent soil samples extracted from 0 – 5 cm and 20 – 25 cm depth intervals. The secondary capping soil material is denoted as “Secondary Cap”. Each curve represents the average of triplicate soil samples. Soil samples from both the 2007 (n = 2) and 2011 (n = 2) slopes comprise the secondary capping soil layer curve. Note that the saturated VWC appears on the figure at 0.1 kPa.
Figure 4 – The extent of soil hydrophobicity and the influence of soil water pressure (left) and soil water content (right). Hydrophobicity severity categorized according to Bisdom et al. (1993).

Figure 5 – In-situ VWC measurements on the 2007 (middle) and 2011 (bottom) slopes for the periods of May to October in 2013 and 2014. The black and gray bars (top) represent precipitation and surface runoff (2011 slope only), respectively.

Figure 6 – Soil water distribution profiles from VWC measurements made within access tubes located throughout both slopes (n = 9 and 14 locations on the 2007 and 2011 slopes, respectively; outliers removed from plot to increase clarity of trends). See Figure 1 for measurement locations. Data from May - August 2012 – 2014; 85 measurements per slope position over 29 sampling days during this time period. Note that the actual measurement depths of data collected between June – August 2014 are slightly, but consistently at all locations, different than the depths that appear on the y-axis (see Field methods section).

Figure 7 – Average VWC measurements in the upper 7 cm of the soil versus surface elevation of the 2007 and 2011 slopes during 2013 (2011 data include both the southeast and west 2011 slopes to increase the elevation range). Error bars represent the range (max, min) observed at each elevation. Dashed lines are the trendlines for the max and min data series.

Figure 8 – VWC profiles before (t = 0) and following (t = 1 through 39 days) a 60 mm precipitation event at upper and lower slope positions on the 2007 and 2011 slopes (8/9-June-2013).

Figure 9 – Maximum discharge measured in the runoff flume versus precipitation intensity (i) during each event on the 2011 slope.
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- **2007 Slope**
  
  \[ y = -0.0034x + 1.2952 \]
  
  \[ R^2 = 0.31 \]

- **2011 Slopes**
  
  \[ y = 0.0019x - 0.1616 \]
  
  \[ R^2 = 0.24 \]
Figure 8 – VWC profiles before (t = 0) and following (t = 1 through 39 days) a 60 mm precipitation event at upper and lower slope positions on the 2007 and 2011 slopes (8/9-June-2013).
Figure 9 – Maximum discharge measured in the runoff flume versus precipitation intensity ($i$) during each event on the 2011 slope.
Tables

Table 1 – Description of the reclaimed slopes and the particle size distribution and percent organic matter content (expressed as loss on ignition, LOI) of the different reclamation materials (summarized from data presented in Ketcheson (2015). The sample size for the 2007 slope peat/mineral mix and secondary capping soils were 17 and 4, respectively, while the sample size was 14 and 3 for the 2011 slope peat/mineral mix and secondary capping layers, respectively). Note that the soil samples were not pretreated for the removal of organic matter or carbonates before conducting the particle-size distribution analysis (c.f. Eshel et al. 2004); hence these particles are included within the percentages expressed for the mineral grain size classes.

<table>
<thead>
<tr>
<th>Slope</th>
<th>Size (ha)</th>
<th>Aspect</th>
<th>Grade (%)</th>
<th>Veg. Ht.* (m)</th>
<th>Soil Layer</th>
<th>% Sand</th>
<th>% Silt</th>
<th>% Clay</th>
<th>LOI (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007 Slope</td>
<td>8.1</td>
<td>West</td>
<td>13</td>
<td>1.5 (0.3 - &gt;4.0)</td>
<td>Peat/mineral mix Secondary capping</td>
<td>45</td>
<td>48</td>
<td>7</td>
<td>9</td>
</tr>
<tr>
<td>2011 Slope</td>
<td>2.4</td>
<td>East</td>
<td>19</td>
<td>0.8 (0.2 - 1.4)</td>
<td>Peat/mineral mix Secondary capping</td>
<td>38</td>
<td>56</td>
<td>6</td>
<td>10</td>
</tr>
</tbody>
</table>

* Average vegetation height expressed in bold, approximate range in vegetation heights shown in parentheses.
Table 2 – Wilcoxon rank sum tests of difference of $VWC$ between upper and lower slope position for the 2007 and 2011 slopes; absolute difference in median $VWC$ (fraction) and $p$-value results are shown (significant test results at $p < 0.02$ shown in bold). $W$ is the value of the ranked sums.

<table>
<thead>
<tr>
<th>Depth</th>
<th>2007 Slope</th>
<th>2011 Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$VWC$ Difference</td>
<td>$p$-value</td>
</tr>
<tr>
<td>7.5</td>
<td>0.02</td>
<td>0.017</td>
</tr>
<tr>
<td>15</td>
<td>0.02</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>25</td>
<td>0.02</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>35</td>
<td>0.03</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>50</td>
<td>0.02</td>
<td>0.002</td>
</tr>
<tr>
<td>75</td>
<td>0.01</td>
<td>0.53</td>
</tr>
</tbody>
</table>
Table 3 – Surface runoff and subsurface (interflow) event characteristics on the 2007 and 2011 slopes. Data includes the empirically derived infiltration excess runoff analyses (based on $i$ and antecedent soil storage capacity; 2011 slopes only), field measurements of runoff through the surface flumes (2007 and 2011 slopes) and the interflow trenches (2007 slope only).

<table>
<thead>
<tr>
<th>Slope</th>
<th>Method of runoff estimation</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>17-June to 20-August</td>
<td>1-May to 1-October</td>
</tr>
<tr>
<td></td>
<td>Number of events</td>
<td>Runoff total (mm)</td>
<td>Average duration (hr)</td>
</tr>
<tr>
<td>2011 Slope</td>
<td>Empirical</td>
<td>8</td>
<td>52</td>
</tr>
<tr>
<td>2011 Slope</td>
<td>Flume</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>2007 Slope</td>
<td>Flume</td>
<td>3</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>2007 Slope</td>
<td>Subsurface interflow</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>