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Research papers

Fully coupled heat and water dynamics modelling of a reclamation cover for oil sands shale overburden

Mingbin Huang[a,c], Andrew Ireson[b,a], S. Lee Barbour[a,*], Shelby DeMars[a,b], Willemijn M. Appels[d]

[a] Department of Civil and Geological Engineering, 3B48 Engineering Building, 57 Campus Drive, University of Saskatchewan, Saskatoon, Saskatchewan S7N 5A9, Canada
[b] Global Institute for Water Security, National Hydrology Research Centre, 11 Innovation Boulevard, Saskatoon, University of Saskatchewan, Saskatchewan S7N 3H5, Canada
[c] State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Northwest Agriculture and Forestry University, Yangling 712100, China
[d] Lethbridge College, 3000 College Dr S, Lethbridge, AB T1K 1L6, Canada

A R T I C L E I N F O

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A B S T R A C T

Numerical models of soil-water dynamics have been widely used in the design of soil cover systems for mine site reclamation; however, in most cases these models only consider water dynamics without consideration of heat dynamics. For cover systems in northern climates, such as those associated with oil sands mines in northern Alberta, Canada, freezing conditions exist for approximately 6 months of the year and snow melt comprises approximately 25% of annual precipitation. This study attempts to assess whether a fully coupled water and heat flow model (CM) provides additional insights into cover performance as compared with a water flow model (FM). The CM and FM are developed for a monitored reclamation cover constructed over oil sands shale overburden. The validated results indicated that the key limitation of the CM was its inability to simulate frozen ground infiltration. This limitation results in an overestimate of snow melt runoff and does not replicate the development of perched conditions on the shale overburden surface as a result of snow melt infiltration. The FM is also unable to simulate the observed infiltration of snow melt deep into the cover when snow melt is represented simply as surface precipitation in early spring following ground thaw. Both models are improved if snow melt infiltration is represented in the model by the preferential filling of macropores across the full depth of the cover and oxidized shale prior to ground thaw. This methodology is incorporated with the CM to produce a coupled water and heat model with enhanced infiltration (CM-EI), and with the FM to produce a flow model with enhanced infiltration (FM-EI). The CM-EI provided an improved simulation of soil temperature dynamics under frozen and unfrozen conditions, as well as soil water dynamics under unfrozen conditions, including the improved representation of the annual water balance components over each water year. Given the small difference in annual water balance components between the CM-EI and FM-EI modelling approaches (~5 mm/year), it is concluded that a FM-EI provides the best tool with which to assess the performance of these reclamation covers.

1. Introduction

Snow melt is a crucial component of the water balance within semi-arid, cold regions of the world. Increases in soil water storage from snow melt infiltration into frozen soils are critical to meeting vegetation water requirements through the summer months; however, the simulation of snow melt infiltration remains a particularly challenging problem, involving coupled heat and water transport, phase change processes, and infiltration into macropores (Gray et al., 2001; Kelln et al., 2009; Suzuki, 2013). The distribution of water and ice in the soil profile at the time of melt determines the amount of infiltration, the distribution of infiltrating water within the soil profile, and drainage of water below the frozen zone (Flerchinger and Saxton, 1989; Hansson et al., 2004; Antonopoulos, 2006; Zhao et al., 2016).

In this paper, we attempt to quantify the water balance of reclamation covers placed over saline-sodic clay shale mine waste (overburden) at an oil sands mine in northern Alberta, Canada. The water balance has important implications for vegetation on the cover and the redistribution and export of salts produced within the overburden. Conventional practice has been to use numerical models to simulate soil water dynamics during the unfrozen time period (i.e. growing season) in order to interpret long-term (> 10 year) field monitoring data. The winter period, or snow

* Corresponding author.
E-mail addresses: andrew.ireson@usask.ca (A. Ireson), lee.barbour@usask.ca (S.L. Barbour), willemijn.appels@lethbridgecollege.ca (W.M. Appels).

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accumulation period, is neglected as the movement of water and solutes during this period is assumed to be negligible. The melt period is treated as an externally applied initial or boundary condition to the model (Carrera-Hernandez et al., 2011 and 2012; Huang et al., 2011). If applied as an initial condition, the soil moisture storage in the profile is increased by an amount equivalent to the snow water equivalent, SWE (mm). If applied as a boundary condition, the volume of SWE is applied as an infiltration flux over a specified period of time following ground thaw-usually one week. One factor that complicates this is the fact that snow melt and the concomitant infiltration of melt water on these reclamation covers is generally complete one to two months prior to complete ground thaw (Kelln et al., 2009). Models have been initialized from the completion of thawing (Carrera-Hernandez et al., 2011 and 2012; Huang et al., 2011), which removes the need to deal with frozen soils, but may lead to errors in the partitioning of snowmelt into infiltration and runoff. Here we term models adopting this approach flow models, FMs. FMs that have been applied to reclamation covers include system dynamics models (Elshorbagy et al., 2007; Keshta et al., 2010) and physically based models (Shurniak, 2003; Carrera-Hernandez et al., 2011; Huang et al., 2015a).

Fully coupled water and heat models, CMs, have been developed to simulate flow processes in frozen soils, and such models can, in principle, be applied to simulate snowmelt infiltration. These models allow the timing of ground freezing/thaw, as well as water redistribution during the winter period to be simulated (Stahli et al., 1999). There are a number of numerical models capable of simulating water and heat transport, including the phase change that occurs during freezing and thawing. Some of these models were developed for specific applications, such as the ICM (Lytton et al., 1993) and FrostB (Guymon et al., 1993) models designed for roads, airstrips, or similar environments. Other models are more general and incorporate advanced treatment of the energy transfer between the atmosphere and the soil surface. Examples of these models include SOIL (Jansson and Halldin, 1980), SHAW (Flerchinger, 2000), COUP (Jansson and Karlberg, 2001), a modification of HYDRUS (Hansson et al., 2004), GeoTop (Endrizzi et al., 2014), and SEEP/W (Geo-Slope International Ltd., 2018). Most of these models are not generally designed to represent macropores, and are expected to overestimate snowmelt runoff in soils which contain macropores, such as the clay rich, fractured soils in reclamation covers (Kelln et al., 2009). Although some of models such as HYDRUS do have dual porosity formulations, their formulations are not able to simulate the situation in which a high water content matrix is frozen while the macropores remain empty and potential flow paths for infiltrating snow melt water.

Aside from these limitations, CMs are able to track heat and water dynamics within unsaturated soil during both frozen and unfrozen conditions, including the energy balance associated with the latent heat of fusion during freezing and the surface energy balance between the atmosphere and the soil.

The overarching aim of this study is to determine whether CMs provide additional insights into cover performance compared with simpler FMs. The specific objectives of this paper are: (1) to validate CM and FM models for a monitored reclamation cover constructed over oil sands shale overburden; (2) to assess how snow melt infiltration into frozen ground can best be represented in these models, recognizing the limitations in both approaches; and (3) to evaluate the comparative performance of these different approaches.

2. Materials and methods

2.1. Site description

This study was conducted at South Bison Hill (SBH), a reclaimed shale overburden dump constructed between 1980 and 1996 at Syncrude's Mildred Lake Mine (Fig. 1). The dump is 2 km^2 in area with a plateau rising about 60 m above the surrounding landscape. After construction, the overburden dump was contoured into a number of discrete watersheds and was capped with different prototype soil cover designs. All the reclamation covers are comprised of an upper layer of salvaged peat mixed with glacial clay (i.e. peat-mineral mixture, PMM) overlaying salvaged glacial clay till (GC).

Three soil test covers were constructed in 1998/99 on a north facing 5H: 1 V slope as part of a reclamation cover research program. Each is 50 m wide and 200 m long in the downslope direction. The three covers are defined by their nominal thicknesses of PMM overlying GC. A fourth soil test cover was established at a site on the plateau of SBH in 2001. The PMM, GC and shale are classified as sandy loam, silty loam and silty clay, respectively, based on the Unified Soil Classification System (Huang et al., 2015a). The physical properties of three materials have been described in detail by Meiers et al. (2011), Huang et al. (2015a), and Appels et al. (2017). Following the placement of the soil covers, the reclaimed area was planted with trembling aspen (*Populus tremuloides* Michx) and white spruce (*Picea glauca (Moench)* Voss) (Kessler et al., 2010), but has also developed a rich understory of a wide variety of other vegetation.

Each cover is instrumented to monitor volumetric water content, soil temperature, and matric suction across the cover profile and the upper portion of the underlying shale overburden. Volumetric water content and matric suction are monitored using calibrated CS615 time domain reflectometry (TDR) sensors and CS229 thermal conductivity suction sensors (Campbell Scientific Lt. USA), respectively. Soil temperature is measured using thermistor sensors.

This study only focuses on the D3 cover with 20 cm of PMM overlying 80 cm of GC, which represents the base case for the reclamation design being considered for this landform. The model development and assessment are based on the D3 field monitoring profile which has instrumentation located at 5, 20, 30, 55, 90, 115, 125, 145, and 170 cm soil depths (Fig. 1c). The measured soil water contents at three nodes of 125, 145, and 170 cm soil depths, however, appeared abnormal and are not used for water dynamic model assessment.

Interflow along the cover-shale interface was measured using an interflow collection system constructed in June 2000, while surface runoff was measured using v-notch weirs equipped with sonic sensors and data acquisition systems. The v-notch weirs are installed at a total of 4 locations along the surface drainage system for the dump, including weirs within the drainage swale upstream and downstream of the cover sites. The detailed descriptions of the interflow and surface runoff collection systems can be found in Kelln et al. (2009).

A meteorological tower in the approximate centre of SBH was used to monitor air temperature, relative humidity, wind speed, radiation, and precipitation (TE525WS tipping bucket rain gauge, Campbell Scientific Lt. USA). The average temperature was 1.7 °C and the average annual precipitation was 365 mm, 74 mm as snow based on SBH climate data observed from 2001 to 2015. The monitoring study period (Nov. 1, 2000 to Oct. 31, 2015) was divided into 15 water years with each water year extending from November 1 of one year to October 31 of the following year.

2.2. Evolution of soil properties and vegetation

The hydraulic conductivity of the cover soils, as well as the shallow shale overburden, evolved over the first few years following cover placement due to dry/wet and freeze/thaw cycling (Meiers et al., 2011). The measured field saturated hydraulic conductivity (K_s) values of cover materials increased by one to two orders of magnitude over the first five monitoring seasons, while the K_s of the shallow shale increased approximately one order of magnitude over the same time period. No significant change was apparent in the water retention curves (WRC), and hence, these were assumed to remain constant during the study period. The temporal variations of K_s in the first five seasons (2001–2005) were incorporated into our simulations to calculate hydraulic conductivity using the van Genuchten-Mualem equations (van Genuchten, 1980) therefore, while the value of K_s was treated as a constant after 2005.