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Effect of Hysteresis of Soil-Water Characteristic Curves on Infiltration under Different Climatic Conditions

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Abstract

This paper presents the results of a numerical modelling exercise to investigate the role of the hysteresis of soil-water characteristic curve (SWCC) on the infiltration characteristics of soils subjected to four different climatic conditions from very dry to wet within the Canadian province of Alberta. Multi-year climate datasets from four different natural regions and sub-regions of Alberta are compiled and classified and applied as the soil-atmosphere boundary condition in one-dimensional finite element unsaturated flow models using the Hydrus-1D software. Multiyear simulations are carried out with and without the consideration of SWCC hysteresis. Simulation results are analyzed in terms of water balance at the ground surface and temporal distribution and storage of water within the soil domain. It is demonstrated that the hysteresis of SWCC can significantly affect the prediction of flow, redistribution and storage of water in the unsaturated zone. It is found that for soils that exhibit hysteretic SWCC, consideration of hysteresis in unsaturated flow modelling results in prediction of lower infiltration and less movement of water through the soil. It is also found that the use of wetting parameters results in prediction of increased infiltration and movement of water compared with the predictions using the drying or hysteretic parameters. It is concluded that, for soils that exhibit greater degree of SWCC hysteresis, it is important to measure both the drying and the wetting branches of the SWCC accurately and that accurate simulation of hysteretic behaviour requires climate datasets at appropriate resolution. The results presented in this paper highlight the importance of considering SWCC hysteresis for a wide range of geotechnical problems, such as soil cover design, prediction of groundwater recharge, contaminant transport through unsaturated soils, soil erosion, slope stability, and swelling/shrinkage of expansive soils.

1 **Keywords**

- 2 Unsaturated flow; soil-water characteristic curve; hysteresis; climate conditions; numerical
3 modelling; infiltration; surface run-off; moisture movement.

Draft

1. Introduction

Problems involving groundwater flow through unsaturated soils are often analyzed using numerical models. These models require reliable input data for the soil's hydraulic functions for accurate analysis of such problems. The two most commonly used hydraulic functions are: the soil-water characteristic curve (SWCC) and the unsaturated hydraulic conductivity relationship. Hysteresis in the SWCC refers to the non-unique relationship between the soil's matric suction and its water content, whereby the soil can have two different water contents at the same matric suction value, depending on the preceding sequence of wetting and drying. Such hysteresis is thought to be caused by various factors, such as variable and irregular cross-sections of the pores, the different contact angles in the advancing and receding soil-air interface menisci, and the difference in entrapped air volume at different matric suction values. Given that at any given pressure head the soil can have two different water contents – one on the wetting SWCC and the other on the drying SWCC and that the soil's hydraulic conductivity increases with its water content, it is expected that the hydraulic conductivity function will also exhibit hysteresis; however, there is not much evidence of hysteresis in the unsaturated hydraulic conductivity function to be of any practical significance (Stephens 1996).

The SWCC is assumed to be non-hysteretic in the numerical analysis of water and solute movement in the unsaturated zone. This assumption is valid when water content is monotonically increasing (e.g. infiltration) or decreasing (e.g. evaporation or gravity drainage); however, under both natural and irrigated environments, the change in soil's water content is affected by time-dependent processes at the surface and is transient and non-monotonic (Russo *et al.* 1989). That is, at any given time during water redistribution, some portions of the soil may be wetting while others may be drying. Consequently, hysteresis of the SWCC needs to be considered in numerical analysis. The importance of the SWCC hysteresis has been demonstrated in the laboratory and field studies (e.g. Lehmann and Ackerer 1988; Basile *et al.* 2003); however, hysteresis is usually ignored

1 using the rationale that the spatial variability of hydraulic properties may overwhelm the local
2 hysteretic effects (Royer and Vachaud 1975). Evidence contrary to this rationale has also been
3 observed (Stauffer and Dracos 1984). Kool and Parker (1987) have pointed out that in many cases
4 neglecting hysteresis is not based on knowledge that its effects are negligible, but rather on
5 expediency motivated by a lack of sufficient data to adequately calibrate the hysteresis model.

6 While neglecting the SWCC hysteresis may be justifiable under monotonic wetting or
7 monotonic drying conditions, it becomes very relevant for cyclic wetting and drying processes, such
8 as intermittent precipitation and evaporation. The importance of considering the SWCC hysteresis
9 needs to be assessed for applications such as the design of soil covers, where the design is based on
10 a number of years of climatic data consisting of intermittent precipitation and evaporation events.
11 Soil climate boundary has been cited as the most critical aspect of climate driven processes
12 affecting the stability of geotechnical infrastructure, especially from a climate change perspective
13 (Vardon 2014). Most of the published literature on the effect of the SWCC hysteresis on unsaturated
14 flow is based on controlled infiltration or evaporation events, with virtually no cases involving
15 multi-year climatic data consisting of intermittent precipitation and evaporation records.

16 This paper presents the results of a numerical modelling exercise to investigate the role of
17 the hysteresis of SWCC on the infiltration characteristics of soils subjected to different climatic
18 conditions within the Canadian province of Alberta. Multi-year climate datasets from four different
19 natural regions and sub-regions of Alberta are compiled and classified. These datasets represent
20 four different climates: wet to moist; neutral; dry; and, very dry. A one-dimensional finite element
21 unsaturated flow model is used to simulate the infiltration and redistribution of water in various
22 soil types. The climate datasets constitute the upper boundary conditions for these simulations.
23 Multiyear simulations are carried out with and without the consideration of hysteresis in the SWCC.
24 Hysteresis in the hydraulic conductivity function was not simulated. The results of the simulations
25 are analyzed in terms of water balance at the ground surface and the temporal distribution and

storage of water within the soil domain. It is demonstrated that the hysteresis of SWCC can significantly affect the prediction of flow, redistribution and storage of water in the unsaturated zone. This finding is also expected to have applications in other geotechnical problems, such as heaving associated with expansive soils, rainfall-induced slope instability, fate and transport of contaminants in the unsaturated zone, and the design of soil covers for waste containment.

2. Climate Data Compilation and Classification

Climate is a critical factor that controls the infiltration characteristics and moisture distribution at any particular site. The ground surface may be subject to extreme weather conditions during a year - from being frozen throughout the winter to thaw and runoff during the spring and vegetation growth and wetting and drying during the summer. The timing, magnitude, and intensity of precipitation events significantly influence runoff generation, infiltration processes and thus the soil moisture regime in the upper portion of the ground.

In order to quantify the effect of climatic conditions on infiltration in soils with hysteretic SWCCs, four different climates from the province of Alberta, Canada were considered. Figure 1 shows the summer moisture index (SMI) for the natural regions and sub-regions for the province of Alberta (Natural Regions Committee 2006). SMI is a measure of precipitation effectiveness during the growing season. It is calculated by dividing growing degree-days greater than 5°C by the growing season precipitation (April through August). A high SMI value indicates a greater likelihood that at certain times during the growing season there will be less precipitation than the evaporative demand.

A SMI values greater than 4 indicates dry to very dry climatic conditions. Grassland Natural Region, Canadian Shield Natural Region, and Peace-Athabasca Delta Natural Sub-region all have SMI values in this range and are likely to have significant moisture deficits for extended periods during the growing season (Natural Regions Committee 2006). SMI values of between 3 and 4 indicate

neither dry nor wet climatic conditions. The likelihood of moderate moisture deficits for short periods during the growing season are expected for the regions with SMI values in this range. All of the Boreal Forest Natural Region except the Boreal Subarctic, Upper Boreal Highlands, and the Central and Peace River Parkland Natural Sub-regions have SMI values of between 3 and 4. An SMI value of less than 3 indicates moist to wet climate conditions, with no moisture deficits during the growing season. Foothills Parkland, Upper Boreal Highlands, and Boreal Subarctic Natural Sub-regions, and Rocky Mountain and Foothills Natural Regions, all have moist to wet conditions.

Four sites representing the moist, neutral, dry and very dry regions in Alberta as described above were selected for climate data compilation and classification. The online interactive tool of Alberta's AgroClimatic Information Service (ACIS) was used to select climate stations within these regions (ACIS 2014). The climate stations were selected based on the availability of daily-resolution continuous records of precipitation, net radiation, maximum and minimum air temperature, maximum relative humidity and wind speeds. It should be noted that these climatic variables not only form the upper boundary of the numerical models but are also required for climate classification of the sites under consideration.

Net radiation is measured only at a handful of locations in Alberta. Net radiation was either not measured at the climate station of interest or there were no continuous records for the years for which other climate variable records were available. As such, global solar radiation data from the nearby locations was used to estimate the net solar radiation at the selected location. Procedures have been developed for predicting net radiation based on equations formulated in terms of total solar radiation, relative humidity, and temperature (Allen *et al.* 1998; Irmak *et al.* 2003). Total solar radiation, relative humidity, and temperature measurements from the respective climate stations were used to estimate the net radiation. Four climate data sets corresponding to moist, neutral, dry and very dry regions were compiled. Five years of daily climate datasets comprising precipitation, maximum and minimum relative humidity and temperature, wind speed

and net radiation were compiled for neutral, moist and dry regions while the climate dataset for very dry region comprised 4 years of climatic records. Salient characteristics of the four climate data sets are given in Table 1. Daily values of the above mentioned variables were used to estimate the daily potential evaporation (PE) values. The Penman (1948) equation for PE can be written as following (Fredlund et al., 2012):

$$PE = \frac{\Gamma Q_n + \eta E_a}{\Gamma + \eta} \quad [1]$$

where PE is the potential evaporation, Q_n is the net radiation at the water (or saturated ground) surface, η is the psychrometric constant, Γ is the slope of saturation vapour pressure versus temperature curve), and E_a is as defined as:

$$E_a = 2.625(1 + 0.146W_w)(u_{vo}^{air} - u_v^{air}) \quad [2]$$

where W_w is the wind speed, u_{vo}^{air} is the vapor pressure in the air above the water (or saturated ground), surface, and u_v^{air} is the saturated vapor pressure at the mean air temperature.

The classification of the climate provides a general weather setting for the site. This is similar to the role that geology plays in understanding the soil conditions at a site. The Thornthwaite climate classification system is an empirical system that was developed from climatic data collected in United States (Thornthwaite 1948; Thornthwaite and Hare 1955). It forms an adequate basis for evaluating the climate for engineering purposes. The 1955 Thornthwaite Moisture Index is computed using Eq. [3] below:

$$I_m = 100 \left(\frac{P}{PE} - 1 \right) \quad [3]$$

where I_m is the 1955 Thornthwaite moisture index, P is the total annual precipitation, and PE is the total annual potential evaporation calculated as the summation of the Penman (1948) monthly potential evaporation values. An I_m of zero signifies that the annual precipitation and the potential evaporation are equal. While PE is used for climate classification, it is the Actual Evaporation (AE) and Actual Transpiration (AT) that are of greatest importance when assessing the actual loss of moisture from a soil surface. Figure 2 shows the I_m values for the four sites. It can be seen in Figure 2 that the compiled datasets cover a range of conditions from Semi-Arid to Moist Humid. It should also be noted that the data presented in Figure 2 also capture the year-to-year variations in climates for the four selected sites.

3. Methodology

3.1 Theoretical Background

Water flow in unsaturated porous media can be represented by Richards's equation (Richards 1928; 1931). For one-dimensional vertical flow, the mixed form of Richards's equation can be written as:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[K(\theta) \left(\frac{\partial \psi}{\partial z} - 1 \right) \right] \pm S \quad [4]$$

where θ is the volumetric water content, t is time, z is the spatial coordinate, $K(\theta)$ is the unsaturated hydraulic conductivity function, ψ is the suction or pressure head and S is a general sink or source term. An important aspect of the Richards's equation is that the water content and the unsaturated hydraulic conductivity are highly nonlinear functions of suction. The relationship between water content and suction is given by the SWCC. The relationship between unsaturated hydraulic conductivity and suction (or water content) is given by the unsaturated hydraulic conductivity

function, which is also commonly referred to as the K -function. One of the most commonly used closed-form empirical equation for the SWCC is the one proposed by van Genuchten (1980):

$$S_e = \frac{\theta(\psi) - \theta_r}{\theta_s - \theta_r} = [1 + |\alpha\psi|^n]^{-m} \quad [5]$$

For the K -function, the following equation proposed by Mualem (1976) is frequently used:

$$K(\psi) = K_s(S_e)^l \left[1 - \{1 - (S_e)^{1/m}\}^m \right]^2 \quad [6]$$

In Eqs. [5] and [6], K_s is the saturated hydraulic conductivity, S_e is the effective water saturation ($0 < S_e < 1$), θ_s is the saturated volumetric water content, θ_r is the residual volumetric water content, and α , n and m are empirical parameters that depend on the soil type and can be estimated by fitting Eq. [5] to the measured SWCC data. The parameter m is commonly assumed to be equal to $1 - 1/n$ (van Genuchten 1980). In Eq. [6], l is the pore interaction factor and its value has been found to be 0.5 for a wide variety of soils (Mualem 1976).

A number of models for hysteresis in the SWCC and the K -function have been proposed over the past several decades. Comprehensive reviews of these hysteresis models have been provided by Viaene *et al.* (1994), Pham *et al.* (2005), and Bashir (2007). One of the most widely used hysteresis models for the SWCC and the K -function was proposed by Kool and Parker (1987). They combined the van Genuchten (1980) K - θ - ψ model with the empirical hysteresis model of Scott *et al.* (1983) to derive a new model of capillary hysteresis, which is capable of taking into account the effect of air entrapment. The model provides closed-form expressions for hysteretic SWCC and K -function.

The Kool and Parker (1987) hysteresis model predicts the drying and wetting scanning curves by scaling the main curves. The main hysteresis loop, which is composed of the main drying curve (MDC) and the main wetting curve (MWC), is defined by Eq. [5]. This leads to a parameter

vector $\{\theta_s^d, \theta_r^d, \alpha^d, n^d\}$ for the MDC and $\{\theta_s^w, \theta_r^w, \alpha^w, n^w\}$ for the MWC, resulting in 8 unknown parameters. The simplest formulation for the Kool and Parker (1987) model assumes $\theta_s^w = \theta_s^d = \theta_s$ and $\theta_r^w = \theta_r^d = \theta_r$, thereby ensuring that the main hysteresis loop is closed and the total number of unknown parameters is reduced to 6. Once the parameters for the main hysteresis loop are known, the drying and wetting scanning curves can be scaled from the MDC and the MWC, respectively.

Drying scanning curves can be predicted by scaling the MDC to pass through the residual volumetric water content θ_r and the last reversal point from wetting to drying $(\Delta\theta, \Delta\psi)$ by replacing the saturated volumetric water content θ_s^d in the parameter vector $\{\theta_s^d, \theta_r^d, \alpha^d, n^d\}$ by:

$$\theta_s^* = \frac{\Delta\theta(\theta_s - \theta_r) - \theta_r[\theta_s - \theta^d(\Delta\psi)]}{\theta^d(\Delta\psi) - \theta_r} \quad [7]$$

Similarly, wetting scanning curves can be predicted by scaling the MWC to pass through the saturated volumetric water content θ_s and the last reversal point from drying to wetting $(\Delta\theta, \Delta\psi)$ by replacing the residual volumetric water content θ_r^w in the parameter vector $\{\theta_s^w, \theta_r^w, \alpha^w, n^w\}$ by:

$$\theta_r^* = \frac{\Delta\theta(\theta_s - \theta_r) - \theta_s[\theta^w(\Delta\psi) - \theta_r]}{\theta_s - \theta^w(\Delta\psi)} \quad [8]$$

By setting $n^w = n^d = n$, a non-hysteretic K -function is obtained from the Kool and Parker (1987) model and the size of the parameter vector gets reduced by 1; however, doing so results in a loss of flexibility in terms of specifying the MDC and the MWC as α is the only parameter left that can be used to define the differences between the MDC and the MWC.

One of the shortcomings of the Kool and Parker (1987) model is its inability to produce scanning hysteresis loops that are closed. For example, in a scanning hysteresis loop consisting of the primary wetting and secondary drainage scanning curves, the secondary drainage curve does

not pass through the point where the wetting scanning curve departs the main drying curve. As a result, a pumping effect occurs when the system undergoes the cyclic variations in pressure head. Such cyclic variations exist in systems such as transport above a tidally-forced water table and infiltration and redistribution under periodic irrigation as pointed out by Werner and Lockington (2006).

The model of Parker and Lenhard (1987) uses a scaling procedure similar to that used by Scott *et al.* (1983) and Kool and Parker (1987); however, in this model, the scaling procedure enforces the closure of scanning loops by scaling the scanning curves to pass back through the reversal points. Similar to the Kool and Parker (1987) model, the MDC and the MWC for the Parker and Lenhard (1987) model are described by the van Genuchten (1980) equation (Eq. [5]). The wetting scanning curves are predicted using the following equation:

$$S(\psi) = \frac{[S_e^w(\psi) - S_e^w(\Delta\psi^{wd})](\Delta S_e^{dw} - \Delta S_e^{wd})}{S_e^w(\Delta\psi^{dw}) - S_e^w(\Delta\psi^{wd})} + \Delta S_e^{wd} \quad [9]$$

where S_e^w is the effective saturation calculated using the van Genuchten (1980) equation (Eq. [5]) with parameter vector $\{\theta_s^w, \theta_r^w, \alpha^w, n^w\}$. The superscript Δ indicates a reversal point value, and superscripts wd and dw indicate reversal from wetting to drying and drying to wetting, respectively. Similarly, drying scanning curves are predicted using:

$$S(\psi) = \frac{[S_e^d(\psi) - S_e^d(\Delta\psi^{wd})](\Delta S_e^{wd} - \Delta S_e^{dw})}{S_e^d(\Delta\psi^{wd}) - S_e^d(\Delta\psi^{dw})} + \Delta S_e^{dw} \quad [10]$$

where S_e^d is the effective saturation calculated using the van Genuchten (1980) equation (Eq. [5]) with parameter vector $\{\theta_s^d, \theta_r^d, \alpha^d, n^d\}$. The Parker and Lenhard (1987) model eliminates the

pumping effect but at the cost of increased memory storage requirements because it requires the storing of previous reversal points so as to be able to pass the scanning curves through them.

3.2 Development of the Numerical Model

A one-dimensional numerical model of the soil profile was developed using the Hydrus-1D software (Šimůnek *et al.* 2013) to simulate the effects of hysteresis of SWCC and climatic conditions. Hydrus-1D is a finite element program for simulating the transport of water, heat and multiple solutes in a variably saturated porous media. It is capable of handling hysteretic soil hydraulic functions and soil-atmosphere boundary conditions. The profile depth of the numerical model was set at 1 m. Initially, the finite element models were developed by dividing the entire vertical profile into 100 1-cm-thick layers. Nodal spacing was adjusted in various models to achieve convergence.

A zero-gradient boundary condition was used at the bottom of the soil profile to simulate a freely draining soil profile. This boundary condition is most appropriate for situations where the water table lies far below the domain of interest (Šimůnek *et al.* 2013). One of the four different climatic datasets was applied as the top boundary condition of the soil profile. This boundary condition was implemented by providing Hydrus-1D with a daily time history of precipitation (P) and potential evaporation (PE) values. The PE values were calculated using the daily temperature, relative humidity, wind speed and net radiation data employing Penman (1948) method. It should be noted that climate data at the most sites was only available at a daily resolution.

The boundary representing the soil-air interface, which is also known as the soil-atmosphere boundary, is a special type of boundary where the flux, pressure or the gradient is not known *a priori*. The potential flux across this boundary is dependent on the soil atmospheric conditions, namely: precipitation; minimum and maximum relative humidity and temperature; wind speed; and, net radiation. The actual surface flux at this boundary also depends on the transient moisture condition in the soil near the ground surface. In instances where the moisture

availability in the soil at the surface is limited, the evaporation rate at the surface is reduced to a value commonly known as actual evaporation (AE). In instances when the head at the ground surface is greater than a critical minimum head value (ψ_A), a flux equal to potential evaporation rate is prescribed. For situations where the head at the soil surface falls below this critical value, actual evaporation rate at the soil surface is calculated by estimating the flux at the potential head at the soil surface (Vanderborght *et al.* 2010). Another important aspect of the soil-atmosphere boundary is that it can change from a prescribed flux to a prescribed head and *vice versa*. The other instance where the switch from prescribed flux to head and *vice versa* may happen is when the precipitation rate exceeds the infiltration capacity of the soil. Precipitation in excess of the infiltration capacity will either result in generation of instantaneous runoff or accumulation of water on the soil surface (ponding). Runoff generation or build-up of head at the soil surface depends on the maximum allowed pressure head at the soil surface (ψ_s) and is related to the soil surface condition. The soil-atmosphere boundary in Hydrus-1D is implemented by means of a system dependent boundary condition using the approach proposed by Neuman *et al.* (1974). The boundary condition limits the absolute value of the flux such that the following two conditions are satisfied:

$$\left| -K(\psi) \left(\frac{\partial \psi}{\partial x} + 1 \right) \right| \leq E \quad [11]$$

and,

$$\psi_A \leq \psi_s \quad [12]$$

where E is the maximum potential rate of infiltration or evaporation under the current atmospheric conditions, ψ is the pressure head at the soil surface, and ψ_A and ψ_s are, respectively, the minimum and the maximum pressure heads allowed under the prevailing soil conditions. The minimum pressure head at the soil surface allowed under the prevailing soil conditions, ψ_A , can be calculated from the air humidity, H_r , as follows (Šimůnek *et al.* 2013):

$$\psi_A = \frac{RT}{Mg} \ln(H_r) \quad [13]$$

2

3 where M is the molecular weight of water, g is the gravitational acceleration, and R is the gas
 4 constant, T is the temperature and the other variables are as described above. Details of the the
 5 methods for calculating E and ψ_A on the basis of atmospheric data have been discussed by Feddes
 6 *et al.* (1974).

7 Although the weather condition at the ground surface can be highly variable throughout the
 8 year, the infiltration numerical modelling can be simplified considerably by realizing that the soil-
 9 atmospheric analyses are most responsive during the period when the ground surface is thawed. As
 10 such, each year of the simulation can be divided into active and inactive time periods
 11 (Fredlund *et al.* 2013). The active period represents thawed ground conditions when precipitation
 12 can either make its way into the ground as infiltration, or can flow away as runoff. The inactive
 13 period represents the period when the ground is frozen and precipitation accumulates on the
 14 ground surface as snow. For each of the four sites the first date of freezing (i.e., the start of winter)
 15 was selected based on the review of multi-year air temperature records from the climatic data for
 16 that site. Spring-like conditions consists of a period where the precipitation that has accumulated
 17 over the winter is applied as a major infiltration event. The first date of spring (i.e., a date on which
 18 the soil is expected to be thawed) was also selected based on the review of multi-year air
 19 temperature records from the climatic dataset for that particular site. The number of days from the
 20 start of the spring to the start of the freezing period was identified as the active period and the
 21 simulations were run for this active period. The precipitation from the date of the previous year's
 22 freeze-up to the date of the current year's spring thaw was assumed to be snow. It was assumed
 23 that 50% of the snow was lost through sublimation and spring runoff. The other half of the snow
 24 was applied as a spring infiltration event in the first two weeks of spring.

25

3.3 Simulation Details

Simulations were designed to investigate the effects of climate type, degree of hysteresis in SWCC, and precipitation intensity on the infiltration behaviour. The effect of climate type was quantified by carrying out twelve different simulations. A set of three simulations were carried out, for each of the four different climate types, namely: wet, neutral, dry and very dry. For each of the climate type three simulations were run with soil hydraulic properties corresponding to drying, wetting and hysteretic parameters. For these simulations a loamy soil was selected from the UNSODA database (soil U4910 from Gebrenegus and Ghezzehei 2011 or Nemes *et al.* 1999) and was labelled Soil 1. The van Genuchten (1980) parameters for Soil 1 are provided in Table 2. The hysteretic SWCC curves for Soil 1 are shown in Figure 3. Hysteresis was simulated using the model of Parker and Lenhard (1987). An inspection of the wetting and drying SWCCs for Soil 1 indicates that hysteresis could be significant for this soil if flow reversals were to occur, given the relatively large separation between the main draining and wetting branches of the curves. For all the models, the initial volumetric water content was specified to be $0.4 \text{ cm}^3/\text{cm}^3$ constant with depth, in order to ensure that the hysteretic and non-hysteretic models have similar initial storages. Setting the initial condition in suction would have resulted in different storages owing to the different water holding capacities at similar suction values. This would have complicated the comparing of change in storage for different models.

Twenty-four additional simulations were conducted to assess the effect of degree of hysteresis on the infiltration behaviour. In addition to Soil 1 used for the set of simulations conducted to investigate the effect of climate type, two other soils labelled Soil 2 and Soil 3 were used. Soil 2 was a silty sand reported by Yang *et al.* (2004). Soil 3 was soil K0004 reported by Gebrenegus and Ghezzehei (2011) and had the texture of silty loam. The drying and wetting SWCCs for Soil 2 and Soil 3 are shown in Figure 3. The van Genuchten (1980) parameters for Soil 2 and Soil 3 are given in Table 2. In terms of the degree of hysteresis in their respective SWCCs as defined by

$\{\max(\theta^d - \theta^w)\}$ in Figure 3, Soil 1 had the highest and Soil 2 had the lowest degree of hysteresis. Twelve simulations were carried out using hydraulic properties of Soil 2 and other twelve simulations were conducted using hydraulic properties of Soil 3. Drying, wetting and hysteretic simulations were conducted for each soil type. Each set of drying, wetting or hysteretic simulations for each soil type used the four different climatic conditions. The other details of these simulations were the same as those described above for the initial set of simulations conducted to investigate the effect of climate type. The initial conditions of these models were set at 50% saturation volumetric water content.

The climate records used in the present study were only available at a daily resolution, which means the precipitation (P) and the potential evaporation (PE) were applied as distributed over a 24-hour period. In reality, precipitation events can and do occur over a time interval much shorter than 24 hours. Such intense precipitation events may overwhelm the infiltration capacity of a soil and result in generation of surface run-off. It is hypothesized that these shorter-duration precipitation events may also result in more significant moisture content reversals, resulting in more pronounced hysteretic behaviour. Three additional simulations were carried out using Soil 2 to test this hypothesis. For these three simulations, dry climate type was used but the intensity of the precipitation event was increased by applying the total daily precipitation over a 6-hour period while applying the daily PE values over the 24-hour period. The saturated hydraulic conductivity of Soil 2 was reduced by a factor of 10 to further increase the possibility of run-off generation. These simulations were run using both hysteretic and non-hysteretic SWCCs.

4. Results and Discussion

The results of the simulations are presented in many different ways such as: water balance at the ground surface, overall water balance of the complete soil domain, and temporal information on moisture distribution with depth. The results are presented in this manner to highlight the

importance of these simulations results to actual engineering applications. The water balance at the ground surface is of interest to those involved with soil cover design or predicting ground water recharge as it provides information on the quantity of the meteoritic water that moves past the ground surface overcoming evaporation and runoff. Similarly temporal information on moisture distribution with depth is important for studies regarding contaminant transport or shrinkage and swelling behaviour of expansive soils.

4.1 Effect of Climate Type

In this section, the results from the set of simulations conducted to investigate the effect of climate type on infiltration behavior with and without hysteretic SWCC are presented and discussed. For the sake of brevity, the results for the hysteretic and non-hysteretic simulations corresponding to one climate type (dry climate) are presented first and explained in detail. The comparisons between hysteretic and non-hysteretic simulations for all climate types are then presented to provide the reader an insight on the importance of hysteresis for various climate types. The simulations run with hysteretic, drying and wetting SWCCs are referred to as HC, DC and WC simulations, respectively.

Water balance for the hysteretic and non-hysteretic simulation with dry climatic conditions is shown in Figure 4 in which the net infiltration (NI) is the quantity of meteoric water that overcomes the evaporation and makes its way into the soil profile. It is calculated as follows:

$$NI = P - AE - RO \quad [14]$$

where RO is the surface runoff and the other quantities have been defined previously. Similarly, the bottom flux in Figure 4 refers to the quantity of water that flows through the soil profile and drains through the bottom boundary of the soil domain. With the exception of RO , all quantities were

considered positive into the soil domain and negative out of the soil domain. RO is always considered positive. It should be noted that daily values of P and PE are plotted in Figure 4 instead of plotting their cumulative values in order to achieve a reasonable resolution for the cumulative AE , RO , NI and bottom flux plots.

A number of important observations can be made from Figure 4. Firstly, the cumulative AE for all the simulations is around 1400 mm, which is nearly half of the cumulative PE of 2709 mm. This is because of the soil-atmosphere boundary, which reduces the evaporation from the potential value depending on the prevailing water conditions in the soil layer at the ground surface. Secondly, the AE values for the HC and DC simulations are similar and substantially higher than the WC simulation. The lower AE value for the WC simulation implies that less water was retained in the soil layer near ground surface for the WC simulation compared with the HC and DC simulations, resulting in reduced evaporation. Such result is expected because for the same soil the water-entry value (WEV) for the MWC is lower than that for the air entry value (AEV) of MDC. As such, for the WC simulation, smaller amount of water was retained by the soil near the ground surface compared with the HC and DC simulations, which, in turn, reduced the quantity of water available for evaporation. This observation is also consistent with the general understanding that coarse-grained soils are good evaporation barriers owing to their lower water retention characteristics.

The WC simulation had the largest cumulative NI whereas the HC simulation had the lowest cumulative NI (Figure 4). The WC simulation showed largest cumulative NI because of the lowest cumulative AE as per Eq. [14]. The HC simulation showed lowest cumulative NI because it had the highest cumulative AE and nearly as much cumulative RO as the WC simulation (close to 100 mm). The DC simulation predicted the lowest cumulative RO (around 30 mm) among the three simulations. The differences in cumulative RO values for the three simulations can be explained with the help of Figure 5, which shows temporal distributions of volumetric water content θ , cumulative RO and $(P-PE)$ for the three simulations. The numerical model predicts surface runoff

1 when the soil near the ground surface gets saturated (i.e., $\theta = \theta_s$) and the potential surface flux
2 intensity is greater than the saturated hydraulic conductivity of the soil (i.e. $(P - PE) > K_{sat}$). As
3 seen in Figure 5, this condition is achieved more frequently for the HC and WC simulations than for
4 the DC simulation because in the HC and the WC simulations the soil follows either the MWC or the
5 scanning wetting curve whereas the soil follows the MDC in the DC simulations. Soil that is
6 following a wetting curve will get saturated more quickly and more frequently than the soil that
7 follows a drying curve, thereby triggering surface runoff conditions more frequently.

8 The WC simulation predicts the largest value of cumulative bottom flux (BF) among the
9 three simulations (Figure 4), which is expected since the WC simulation had the greatest quantity of
10 water entering the system (highest cumulative NI). Since the soil was following the MWC in the WC
11 simulation, it had lower WEV and hence lower water retention capacity compared with the soil in
12 the HC and DC simulations. The observation that the HC and DC simulations predicted lower
13 cumulative BF is significant from the viewpoint of soil cover design in which the control of water
14 infiltration is the primary objective.

15 The temporal changes in the storage in Soil 1 for the three simulations are shown in
16 Figure 6. The storage for the WC simulation is the highest throughout the time period, which is
17 consistent with its having the highest cumulative NI . The storage for the HC simulation is either
18 similar to or slightly lower than that for the DC simulation for most of the time period except
19 towards the end of the time period, where the storage for the HC simulation exceeds that of the DC
20 simulation. It is interesting to note that storage values for the three simulation are very similar at
21 the start and end of the simulation. However, it should also be noted that values vary within the
22 course of the simulations. As pointed out previously, a lot more water passes through the system in
23 the WC simulation compared with the HC or DC simulations. These differences in the change of
24 storage for the three simulations are important for the systems involving downward migration of
25 contaminants or for groundwater recharge estimates.

Figure 7 shows the driest and the wettest water content profiles with depth for the first year of the total simulated time period for the DC, HC and WC simulations. For driest profile, which is related to a drying event the HC simulation resembles the DC simulation whereas for wettest profile, which is related to a wetting event, the HC simulation resembles the WC simulation. Consequently, the HC simulation predicts the largest variation in water content with depth during a calendar year. Difference in moisture content variations would predict different estimates of movements in expansive soils due to swelling and shrinkage. In such instances, ignoring the effect of hysteresis of the SWCC could potentially lead to inaccurate estimates of such movements.

A comparison of the cumulative values of *AE*, *NI*, *RO* and *BF* for the DC, WC and HC simulations with different climatic condition is presented in Figure 8. It is evident from Figure 8 that observations similar to those made previously for the dry climate can be made for the wet, neutral and very dry climates. For all four climate types the cumulative *AE* is always the greatest for the HC simulation and the cumulative *NI* always the greatest for the WC simulation. The HC and the WC simulations predict nearly the same values for cumulative *RO* regardless of the climate type. The cumulative values of *NI*, *RO* and *BF* increase as the climatic conditions become wetter; this is because of higher cumulative *P* and higher TMI for wetter climatic conditions. Overall, the predictions from the HC simulations are significantly different from the DC and WC simulations. This observation emphasizes the importance of considering hysteresis irrespective of the climate type.

4.2 Effect of Degree of Hysteresis in SWCC

Figure 9 shows the cumulative values of *AE* and *NI* for the three soil types obtained from the DC, WC and HC simulations for the four different climate types. It is worth recalling that Soil 1 had the highest and Soil 2 had the lowest degree of hysteresis as defined by $\{\max(\theta^d - \theta^w)\}$ (Figure 3).

The cumulative AE and NI values for Soil 2 for the hysteretic and non-hysteretic simulations are very similar. This is an expected result since Soil 2 had the lowest degree of hysteresis in its SWCC. The greatest difference in cumulative AE and NI values between the hysteretic and non-hysteretic simulations was exhibited by Soil 1, which had the highest degree of hysteresis in its SWCC. For both Soil 2 and Soil 3, however, the cumulative AE and NI values obtained from the HC (hysteretic) simulation are very close to those obtained from the DC (drying) simulation.

It has been reported in the literature that, owing to the small time steps required for convergence of numerical solution, sometimes the hysteresis algorithm in Hydrus-1D may not be able to capture the moisture content reversals (Bashir *et al.* 2009). It was prudent, therefore, to confirm that the prediction of very similar cumulative AE and NI values by the HC and DC simulations was not because of problems with the hysteresis algorithm in Hydrus 1-D. Satisfactory performance of the hysteresis algorithm can be established by superimposing the paired water content-suction data points at a given node on the hysteretic SWCC for the soil.

Figure 10 shows the paired water content-suction data from the top node for the HC, DC and WC simulations for Soil 2, superimposed on the hysteretic SWCC for this soil. As seen in Figure 10, the paired data points from the DC simulation plot on the MDC and those from the WC simulation plot on the MWC. The paired data points from the HC simulation plot on the MDC, MWC or scanning curves depending on the drying and wetting history of the soil. It can also be observed from Figure 10 that Hydrus-1D generates scanning curves as the soil goes through the drying and wetting cycles in response to the infiltration and evaporation/drainage events.

As an additional check on the hysteresis algorithm, the switching of hysteresis at various spatial locations was compared with the reversal of water content. Hydrus-1D assigns a hysteresis index κ to each node (Šimůnek *et al.* 2013). Wetting is indicated by setting $\kappa = 1$ and drying is indicated by setting $\kappa = -1$. Figure 11 compares the hysteresis index to the moisture content time history at three different spatial locations for a part of the HC (hysteretic) simulation for Soil 2. It

can be seen in Figure 11(a) that the upper layer of the soil is exposed to atmospheric conditions and therefore undergoes numerous reversals. This gradually decreases with depth as can be seen in Figure 11(b) for 0.5 m depth and in Figure 11(c) for 1 m depth.

It is evident from the results presented in Figures 10 and 11 that the hysteresis algorithm in Hydrus-1D was working satisfactorily and was able to capture the moisture content reversals accurately. These results confirm the importance of hysteretic SWCC for accurate simulation of the effect of hysteresis and highlight the importance of the accurate measurement of the both the drying and the wetting branches of the hysteretic SWCC.

4.3 Effect of Precipitation Intensity

The results presented in the previous section indicated that relatively small differences between the hysteretic and non-hysteretic simulations for Soils 2 and 3 were in part because of their lower degrees of SWCC hysteresis. However, part of the difference between the hysteretic and non-hysteretic simulations for Soil 1 can also be attributed to runoff generation. For Soil 1, the WC and HC simulations generated significantly more cumulative *RO* than that generated by the DC simulation (Figure 5). The saturated hydraulic conductivity values for Soil 2 and Soil 3 are, respectively, one and two orders of magnitude higher than that for Soil 1. Their higher hydraulic conductivity and the fact that the climatic conditions could only be obtained and applied at daily resolution resulted in no runoff generation for Soil 2 and Soil 3. In reality the precipitation events almost always occur over a shorter time interval than 24 hours and may overwhelm the infiltration capacity of the soil, resulting in runoff generation. Shorter duration of precipitation may also induce greater number of moisture content reversals, resulting in more pronounced hysteretic behaviour. In this section, the above hypothesis is tested using the results of three additional simulations using Soil 2 in which the precipitation intensity was increased by applying the total daily precipitation in 6 hours, but keeping the potential evaporation distributed over the 24-hour

1 period. Further details of these simulations have been provided previously in the Simulation Details
2 section.

3 The water balance the ground surface and water flux from the bottom of the domain for
4 these simulations are presented in Figure 12. It is evident from Figure 12 that the hysteretic and
5 non-hysteretic simulations show distinctly different values of cumulative AE , NI and BF for a more
6 intense (shorter duration) precipitation event. This observation also emphasizes the importance of
7 collecting and using climatic data at appropriate resolution in order to simulate the hysteretic
8 behaviour accurately.

9 5. Conclusions

10 This paper presented the results of a numerical modelling exercise to investigate the role of the
11 hysteresis of SWCC on the infiltration characteristics of soils subjected to different climatic
12 conditions within the Canadian province of Alberta. Multi-year climate datasets from four different
13 natural regions and sub-regions of Alberta were compiled and classified. These datasets represent
14 four different climates: wet to moist; neutral; dry; and, very dry. A one-dimensional finite element
15 unsaturated flow model was used to simulate the infiltration and redistribution of water in various
16 soil types. The climate datasets constituted the upper boundary conditions for these simulations.
17 Multiyear simulations were carried out with and without the consideration of hysteresis in the
18 SWCC. The results of the simulations were analyzed in terms of water balance at the ground surface
19 and the temporal distribution and storage of water within the soil domain. The following
20 conclusions can be drawn from the results presented in this paper:

- 21 1. The consideration of hysteresis in the SWCC of a soil will result in the prediction of significantly
22 different infiltration characteristics than those predicted using a non-hysteretic SWCC.
- 23 2. It is important to consider hysteresis of SWCC for all climate types ranging from very dry to wet.

- 1 3. The greater the degree of hysteresis in a soil's SWCC, the more pronounced the differences
- 2 between the predictions from hysteretic and non-hysteretic simulations.
- 3 4. In case of soils that exhibit hysteresis of SWCC, consideration of hysteresis results in prediction
- 4 of lower infiltration and less movement of water through the soil.
- 5 5. Regardless of the climatic conditions and the type of soil, the use of wetting hydraulic
- 6 parameters results in prediction of increased infiltration and movement of water compared with
- 7 the predictions using the drying or hysteretic hydraulic parameters.
- 8 6. For soils that exhibit greater degree of hysteresis, it is important to measure both the drying and
- 9 the wetting branches of the SWCC accurately.
- 10 7. Accurate simulation of hysteretic behaviour requires climate data records at appropriate
- 11 resolution.

12 The results presented in this paper highlight some very important considerations of
13 practical relevance and applications. The consideration of hysteresis will result in predictions of
14 lower infiltration of meteoric water and greater runoff generation, which will have implications for
15 soil cover design, prediction of groundwater recharge and fate and transport of contaminants in the
16 unsaturated zone. Similarly, prediction of greater runoff generation will be of interest to
17 practitioners involved in studying the erosion behaviour of soils. Differences in water distribution
18 with depth, its temporal physiognomies and severity between hysteretic and non-hysteretic
19 simulations will affect the prediction of swelling/shrinkage behaviour of expansive soils. The
20 differences in quantity and distribution of water will also have implications for slopes where
21 suction plays an important part in stability assessment.

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References

- ACIS 2014. AgroClimatic Information Service (ACIS) Portal. Alberta Ministry of Agriculture and Rural Development. Available on-line at <http://agriculture.alberta.ca/acis/> (accessed 31 Dec, 2014).
- Allen, R. G., Pereira, L. S., Raes, D., and Smith, M. 1998. Crop Evapotranspiration: Guidelines for Computing Crop Water Requirements. FAO – Food and Agriculture Organization of the United Nations, Rome, Italy, 24 – 47.
- Bashir, R. 2007. *Quantification of surfactant induced unsaturated flow in the vadose zone*. Ph.D. dissertation, McMaster Univ., Hamilton, ON, Canada.
- Bashir, R., Smith, J., Stolle, D., and Henry, E. 2009. On the importance of hysteresis in numerical modelling of surfactant-induced unsaturated flow. *Soil Sediment Contamination: An International Journal*, 18(3): 264-283.
- Basile, A., Ciollaro, G., and Coppola, A. 2003. Hysteresis in soil water characteristics as a key to interpreting comparisons of laboratory and field measured hydraulic properties, *Water Resources Research*, 39(12): 1355, doi:10.1029/2003WR002432, 12.
- Feddes, R. A., Bresler, E., and Neuman, S.P. 1974. Field test of a modified numerical model for water uptake by root systems, *Water Resources Research*, 10(6): 1199-1206.
- Fredlund, D.G., Rahardjo, H. and Fredlund, M.D. 2013. *Unsaturated Soil Mechanics in Engineering Practice*, Wiley, Hoboken, NJ, USA.

- Gebrenergus, T., and Ghezzehei, T.A. 2011. An index for degree of hysteresis in water retention, *Soil Sci. Soc. Am. J.*, 75(6): 2122-2127.
- Irmak, S., Irmak, A., Jones, J. W., Howell, T. A., Jacobs, J. M., Allen, R. G., and Hoogenboom, G. 2003. Predicting Daily Net Radiation Using Minimum Climatological Data. *Journal of Irrigation and Drainage Engineering*, 129(4): 256 – 269.
- Kool, J. B. and Parker, J. C. 1987. Development and evaluation of closed-form expressions for hysteretic soil hydraulic properties. *Water Resources Research*, 23(1):105 – 114.
- Lehmann, F. and Ackerer, P. 1998. Comparison of iterative methods for improved solutions of the fluid flow equation in partially saturated porous media. *Transport in Porous Media*, 31(3): 275 – 292.
- Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, 12(3): 513-522.
- Natural Regions Committee. 2006. *Natural Regions and Sub-regions of Alberta*. Compiled by D.J. Downing and W.W. Pettapiece. Government of Alberta Pub. No. T/852. Edmonton, Alberta. Available on-line at http://www.cd.gov.ab.ca/preserving/parks/anhic/Natural_region_report.asp (accessed 31 Dec 2014).
- Nemes, A., Schaap, M.G. and Leij, F.J. 1999. UNSODA database of unsaturated soil hydraulic properties. v. 2.0 ed. USDA Agric. Res. Serv., Washington, DC.
- Neuman, S. P., Feddes, R. A., and Bresler, E. 1974. Finite element simulation of flow in saturated-unsaturated soils considering water uptake by plants. Third Annual Report, Project No. A10-SWC-77, Hydraulic Engineering Lab., Technion, Haifa, Israel.
- Parker, J. C. and Lenhard, R. J. 1987. A model for hysteretic constitutive relations governing multiphase flow: 1. Saturation-pressure relations. *Water Resources Research*, 23(12): 2187–2196.

- Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. London A(194): 120-145.
- Pham, H.Q., Fredlund, D. G., and Barbour, S. L. 2005. A study of hysteresis models for soil-water characteristic curves. Canadian Geotechnical Journal, 42(6):1548 - 1568
- Richards, L. A. 1928. The usefulness of capillary potential to soil moisture and plant investigators. J. Agric. Res., 37(12): 719-742.
- Richards, L. A. 1931. Capillary conduction of liquids through porous mediums. Physics (N.Y.), 1(5): 318-333.
- Royer, J.M. and Vachaud, G. 1975. Field determination of hysteresis in soil-water characteristics. Soil Sci. Soc. Am. J.: 39(2): 221-223.
- Russo, D., Jury, W.A., and Butters, G.L. 1989. Numerical analysis of solute transport during transient irrigation: 1. The effect of hysteresis and profile heterogeneity. Water Resources Research, 25(10): 2109-2118.
- Scott, P., Farquhar, G., and Kouwen, N. 1983. Hysteretic effects on net infiltration. In *Advances in infiltration*. American Society of Agricultural Engineers Publication 11-83, St. Joseph, Michigan, pp 163-170.
- Šimůnek, J., Šejna, M., Saito, H., Sakai, M., and van Genuchten, M.Th. 2013. *The Hydrus-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media, Version 4.17*. Hydrus Software Series 3, Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, 342 pages.
- Stauffer, F. and Dracos, T. 1984. Local infiltration into layered soils and response of the water table, experiment and simulation. In *Frontiers in Hydrology*, (W. Maxwell and L. Beard, eds.) pp 228-242. Water Res. Publ. Littleton, Colorado.
- Stephens, D.B. 1996. *Vadose Zone Hydrology*. CRC Press Inc., Boca Raton, FL, USA.

- Thorntwaite, C.W. 1948. An approach toward a rational classification of climate. *Geographical Review*, 38: 55-94.
- Thorntwaite, C.W., and Hare, F.K. 1955. Climatic Classification in Forestry. *Unasylva*, 9: 50-59.
- van Genuchten, M. Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* 44:892-898.
- Vanderborght, J., Graf, A., Steenpass, C., Scharnagl, B., Prolingheuer, N., Herbst, M., Franssen, H.-J., and Vereecken, H. 2010. Within-Field Variability of Bare Soil Evaporation Derived from Eddy Covariance Measurements Special Section: Patterns. *Vadose Zone Journal* 9 (4): 943.
- Vardon PJ 2014. Climatic influence on geotechnical infrastructure: a review. *Environmental Geotechnics*. DOI: 10.1680/envgeo.13.00055
- Viaene, P., Vereecken, H., Diels, J., and Feyen, J. 1994. A statistical analysis of six hysteresis models for the moisture retention characteristic. *Soil Science*, 157(6): 345-355.
- Werner, A. D. and Lockington, D. A. 2006. Artificial pumping errors in the Kool-Parker scaling model of soil moisture hysteresis. *Journal of Hydrology*, 325(1-4):118 -133.
- Yang, H., Rahardjo, H., Leong, E.C., and Fredlund, D.G. 2004. A study of infiltration on three sand capillary barriers. *Canadian Geotechnical Journal*, 41(4): 629-643.

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Tables

Table 1: Salient characteristics of the four climatic conditions modelled in the present study

Climate	Very Dry	Dry	Wet	Neutral
Period	1996-1999	2004-2008	1965-1969	2003-2008
Number of years	4	5	5	5
Active days per year	212	201	202	193
Cumulative precipitation (mm)	774	1698	2324	1920
Averaged cumulative precipitation per year (mm)	194	340	465	384
Cumulative potential evaporation (mm)	1830	2710	1798	1903
Averaged cumulative potential evaporation per year (mm)	458	542	360	380.6
1955Thornthwaite Moisture Index (I_m)	-64.1	-46.8	11.9	-13.9

Table 2: The van Genuchten (1980) parameters for the three soils modelled in the present study

Soil ID	Soil 1 (Loam)	Soil 2	Soil 3
Description	Loam	Silty sand	Silty loam
θ_r [-]	0.21	0.07	0.03
θ_s [-]	0.52	0.38	0.4
n [-]	1.704	2.02	1.228
K_s [mm/d]	19.15	259.2	1373
α^d [1/mm]	0.0015	0.002	0.0091
α^w [1/mm]	0.008	0.003	0.0503

[Note: θ_r – residual volumetric water content; θ_s – saturation volumetric water content; K_s – saturated hydraulic conductivity; n , α^d and α^w – van Genuchten (1980) parameters.]

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