

# Numerical Assessment of Evapotranspiration Covers in Cold Climates

By

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## Abstract

In all landfill remediation methods, the idea is to modify the site so that as little seepage as possible can migrate into the landfill itself. Evapotranspiration (ET) cover is designed to prevent water from infiltrating to the waste by using soil and vegetation to store, evaporate, and transpire water. The ET cover system was identified to be effective in semiarid regions in the US but was not assessed in cold regions such as the Canadian Prairie. The previous assessment approach of ET covers was performed by analysing field measurements, such as lysimeter. The numerical simulation by vadose models offers another option and water balance model prediction can assess the effectiveness of ET covers. The numerical evaluation at cold climates conditions requires the analysis of numerical codes in terms representation of critical processes such as freeze-thaw events and the performance of the chosen vadose-zone model itself. In this study, HYDRUS-1D, GeoStudio SEEP/W and TEMP/W, and SABAE-HW were selected to assess the ET cover performance in cold climates. The study site was located at High River, AB, and the data was retrieved from a HOBO<sup>TM</sup> weather station installed at the site. The observation period was approximately one year (August 2016 to September 2017). Soil hydraulic and thermal properties were determined by laboratory tests. The calibration process was carried out by comparison of measured and simulated soil moisture using PA-DDS, which is a new multi-objective calibration algorithm. The measured soil moisture content was revised by a semi-empirical method to represent the actual unfrozen water content in the soil during phase change. Percolation through the cover system was 79.6 mm based on HYDRUS-1D, 86.2 mm derived from GeoStudio, and 101.1 mm calculated by SABAE-HW. The majority of the percolation was due to snowmelt during a Chinook event which allowed up to 90% of the snow water equivalent of the whole winter to percolate through the cover (HYDRUS-1D). The simulated soil moisture showed that HYDRUS-

1D had the best agreement of measured soil moisture, but SABAE-HW showed more reasonable soil moisture behavior during freeze-thaw events. Both HYDRUS-1D and GeoStudio were missing the capability to simulate the frozen soil behavior during the freeze-thaw events. The simulations based on these two software packages had the potential to overestimate the soil moisture variation in cold climates due to the change in soil properties at frozen condition. SABAE-HW was the only model that was able to represent the unfrozen water content during frozen conditions but was unable to estimate any leaching fluxes during winter. The soil hydraulic properties in SABAE-HW were rudimental represented by the soil composition, which limited the simulation ability for the complex situation of the landfill. In addition, the thermal properties of soil and snow were hard-coded and could not be calibrated during the simulations. In this research, the limitation due to the soil hydraulic properties in SABAE-HW became obvious during the spring thawing period and resulted into the largest flux of all models. Overall, the performance of all three models requires further calibration with sufficient soil temperature data.

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## Contributions of Authors

Wang, X., Woodbury, A.D., Holländer, H.M. (in preparation). Numerical assessment of evapotranspiration covers in cold climates.

- a. Wang, X.: Developed and implemented the methodology for numerical assessment of evapotranspiration cover and wrote the paper
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- c. Holländer, H.M.: Suggested and supervised this research and assisted with the editing of the paper

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# 1. Introduction

## 1.1 Overview

Landfilling of waste may contaminate the groundwater by leaching over a long-time period (Widomski et al. 2015). In landfill remediation, the idea is to modify the site so that as little seepage as possible can migrate down to the waste in a landfill. Evapotranspiration (ET) cover is designed to prevent the water from reaching the waste. The key idea is the mitigation of water to percolate to the waste using soil and vegetation to store, evaporate, and transpire water. The application of ET cover on municipal solid waste landfills demonstrated equivalent performance to conventional final cover systems (Hauser 2009; Madalinski et al. 2003; Zhang and Sun 2014; USEPA 2003). The greater the storage capacity and evapotranspiration properties at the site, the lower is the potential of water percolating through the cover system. Therefore, it is important that the designed ET cover at a site can be accurately assessed prior to its construction. This minimizes the environmental impact and leads to more efficient ET cover systems.

The previous assessment of ET cover was focused on the comparison between field measurements, such as lysimeter, and water balance model prediction (Zhang et al. 2009; Ogorzalek et al. 2008; Benson et al. 2005; Mijares and Khire 2012; Bohnhoff et al. 2009; Steeves 2016). The accuracy of lysimeter varied in different study areas and on the scale systems used. The field measurements were laborious and lysimeters were costly. Therefore, the prediction by numerical simulation was considered to assess the ET cover effectiveness (Hauser 2009). The accurate numerical prediction depended on many different factors of environmental conditions, such as weather, soil properties, and surface vegetation. The vadose-zone models were able to represent the interaction between those factors from environmental condition to

access the infiltration of ET cover. Previous researchers showed the effectiveness and reliability of different vadose-zone models regarding the assessment of ET cover system around the United States (Bohnhoff et al. 2009; Ogorzalek et al. 2008). However, the performance of those models was not tested in cold regions such as the Canadian Prairie. Therefore, two concerns had to be addressed in the assessment of ET cover in cold regions by vadose-zone models (1) which model is suitable for the assessment of ET cover and (2) how reliable is the infiltration/percolation estimated by this approach.

## 1.2 Scope and Objectives

This thesis is organized as follows; in chapter 2, a review of evapotranspiration and assessment of ET cover systems is presented. This section includes a review of previous literature on both direct measurements and empirical equations for evapotranspiration estimation, the assessment of ET cover system by different vadose-zone models, and calibration efficiency of different algorithms. In chapter 3, a paper styled chapter contributes towards the main objectives, which was the assessment of ET cover performance by three different vadose-zone models and data from a low-cost weather station in High River, Alberta, Canada. In chapter 3, the laboratory measurement and the measurement procedure which contained details on soil hydraulic and thermal properties are described. Moreover, governing equations for three different vadose-zone models and their boundary conditions were discussed in this chapter. Calibration results and discussions were also covered in the paper section, respectively. Specifically, the comparison of soil moisture under different precipitation/snowfall and monthly estimated percolation was discussed, followed by the results of the simulation to address which vadose-zone model should be used for further optimization. The major conclusions from the current study and recommendations for future work were presented in chapter 4.

The main objective of the study was to evaluate the performance of evapotranspiration cover system in cold regions by three different vadose-zone models, HYDRUS-1D, SABAE-HW, and GeoStudio (Seep/W and Temp/W), which followed the two concerns addressed previously: (1) are these model suitable for the assessment of ET covers and (2) how reliable is the infiltration/percolation estimated by these models

## 2. Literature Review

### 2.1 Evapotranspiration

Evapotranspiration is a key process in the hydrologic cycle and the precision of estimation is an essential requirement for water resource management. Since the last century, several reliable measurements and calculation methods for evapotranspiration were developed. The purpose of this section is to explore aspects of those methods and discuss how to select an appropriate method for different applications. There are two general approaches for estimating ET: direct measurement and estimation based on empirical methods.

Direct measurements offer more accurate results compared to the empirical methods. However, the direct measurement is generally expensive, laborious, and includes complex instrumentation (Vaughan and Ayars 2009). The lysimeter is the most common direct measurement method and can directly measure the amount of actual evapotranspiration (AET) and the percolation. However, the measured ET in specified time interval contained errors due to wind or other factors, such as the mechanical vibration of the device itself (Schrader et al. 2013). An alternative approach is the use of an atmometer, which significantly reduced the amount of work and cost compared to a lysimeter (Magliulo et al. 2003).

Lysimeter directly measures changes in mass of a soil container with plants positioned on a scale or another weighing device (Bryla et al. 2010). The accuracy of lysimeter ET measurements varies depending on the study area and the scale of the device used. The device needs to be placed within a flat field and away from any obstruction that potentially influences radiation and wind speed. The location is being recommended as upwind with a uniform crop of at least 10,000 m<sup>2</sup> size. There is one case study performed by the TERENOSoilCan network at the Wüstebach creek,

Bad Lauchstädt, Germany. Artificial generated and real data from lysimeters were evaluated. There were four steps to evaluate of ET (Schrader et al. 2013): i) correction of measured data, ii) noise reduction by data smoothing, iii) calculation of fluxes and cumulative fluxes, and iv) validation. For correction of raw data, singular events such as wildlife or human factors were automatically removed by a plausibility control of data and suitable filters. The noise reduction was performed by the Savitzky-Golay filter which is a method based on the moving average and local regression. The validation step was comparing the measured data with synthetic data. The synthetic data were generated by an HYDRUS-1D simulation with 4.5 years of unsaturated water transport in a homogeneous 3 m profile consisting of silt loam. The results were promising and the cumulative flux for the atmospheric boundary was virtually indistinguishable.

An atmometer is an easily installed device for ET measurement and requires less cost than lysimeters. Atmometers basically consists of a wet ceramic cup mounted on top of a cylindrical water reservoir and the ceramic cup is covered with a green fabric that simulates the canopy of a crop (Livingston 1915). A case study by Magliulo et al. (2003) carried through several stages. The first stage was conducted at the Vitulazio field station of CNR ISAFoM during irrigation seasons of the years 1995 and 1996. In 1999, the trial was carried out at a location (WC2) close to the Tyrrhenian Sea at the west coast of Italy. In 2000, the atmometer was placed in the middle of a 10 ha alfalfa field of a commercial farm located 20 km south of the Torre Lama station. The research purpose was to verify the feasibility of using atmometer for estimating evapotranspiration in a Mediterranean environment. The results were compared with FAO Penman-Monteith prediction and measurements from a lysimeter and a Class A evaporation pan. The evapotranspiration results suggested that atmometer had similar results compared to the Penman-Monteith equation. The atmometer ET was also very close to grass ET as measured by the

lysimeter. Another study indicated the feasibility of lysimeter systems in Quebec, Canada (Proulx-McInnis et al. 2014).

Empirical methods range from simple temperature-based (e.g., Hargreaves method, Hargreaves and Samani 1985) to data-extensive combination methods (e.g., Hargreaves method, Allen et al. 1998; Azhar and Perera 2011). Note the Penman-Monteith equation is adopted and recommended for crop evapotranspiration ( $ET_c$ ) estimation (Allen et al. 1998). However, the Penman-Monteith (PM) model (Monteith 1965; Penman 1948) requires a large number of meteorological parameters which are generally incomplete or not available at different temporal scales (Djaman et al. 2015).

The Hargreaves method is a radiation model revised from the original Hargreaves equation (Hargreaves 1975). This method can be applied when radiation, humidity, and wind speed data are partially, or fully missing, and data quality cannot be guaranteed. Those data parameters can be altered based on regression or fitting at different climate conditions. Therefore, calibration is necessary for accurate results (Valipour 2015).

The FAO Penman-Monteith method, is a simplified form of PM models, a combination-type equation, and one of the most physically based evapotranspiration estimation methods (Allen et al. 1998). The PM method requires lots of input data but is the most accurate estimation among other existing methods, such as the Hargreaves method (Azhar and Perera 2011). The PM method requires not only the meteorological parameter such as solar radiation, air temperature, air humidity, and wind speed data, but also the canopy surface resistance, and bulk surface aerodynamic resistance for water vapor. The surface and aerodynamic resistance are difficult to measure, and the FAO PM method simplifies those parameters from the original PM equation by using the Leaf Area Index (LAI) and the above-given assumptions on the reference surface. The

reference surface is a hypothetical grass reference crop with a height of 0.12 m, a fixed surface resistance of  $70 \text{ sm}^{-1}$  and an albedo of 0.23 (Allen et al. 1998). The FAO Penman-Monteith method is the recommended method for the definition and computation of reference crop evapotranspiration ( $ET_o$ ) (Allen et al. 1998).

Magliulo et al. (2003) concluded that for selecting the suitable evapotranspiration estimation method, there were three factors required: i) site characteristics, ii) available meteorological data, and iii) precision and accuracy for results. The direct measurement provided the most precision and accuracy estimation of ET and required less amount of meteorological data comparing with the empirical method. Meanwhile, a certain type of devices, such as atmometers, were more sensitive to the site condition (e.g. wind direction, slope) comparing to a lysimeter. However, regardless of the techniques of direct measurement, the installation of those devices can disturb the soil layer and might change the hydraulic gradient at the lower boundaries (Thurman et al. 1998). Specifically, the distortion of soil layers in a landfill can reduce or limit the performance of a current cover system. For the empirical method, there are limitations due to different site characteristics, but large amounts of meteorological are required. Continued research (Gavilán and Castillo-Llanque 2009; Djaman et al. 2015; Valipour 2015; Azhar and Perera 2011) indicated the empirical method can provide an accurate estimation of ET, and FAO Penman-Monteith method was one of the benchmark evapotranspiration estimation methods (Lamont-Black et al. 2002). Hargreaves method showed the tendency of under predicting  $ET_o$  at high wind speeds and of over prediction under conditions of high relative humidity compared to the FAO PM method (Allen et al. 1998). The Hargreaves method was less impacted by meteorological data in a semiarid region since only air temperature data were required (Hargreaves and Allen 2003). However, the temperature measurement had the highest impact on



ET estimation and can lead to large ET fluctuation at a daily scale (Meyer et al. 1989; Ley et al. 1994).

In summary, the best option for evapotranspiration estimation is the FAO-PM equation and will be adopted in this study. All meteorological data required for empirical methods were recorded by a HOBO<sup>TM</sup> U30 weather station at our case study site. The direct measurement approaches in a landfill could potentially expose the waste and damage the cover system. Also, the temperature variation caused by Chinook events could impact the performance of atmometers and ET estimation by the Hargreaves method. Specifically, strong wind conditions and rapidly ascending air temperature over short time periods can lead to strong variation in the estimated evapotranspiration.

## 2.2 Assessment of ET Cover of Landfills in Cold Regions

A landfill cover system is designed as a barrier to prevent the infiltration over a long-time period (Widomski et al. 2015). ET cover is designed to mitigate water transfer from deep percolation by using soil and vegetation to store, evaporate, and transpire water. The larger the storage capacity and evapotranspiration at the site, the lower the potential of water percolating through the cover system. The interest over ET cover is rising, e.g. over 400 ET cover systems were reported in the United States (USEPA 2003). These sites included municipal solid waste as well as hazardous waste landfills. Critically for the evaluation is that the landfills show equivalent performance to conventional final cover systems (Albright et al. 2004). Therefore, it is important that landfills are accurately assessed to minimize the environmental impact.

The ET cover system is effective in arid or semiarid regions in the U.S. (Bohnhoff et al. 2009; Nyhan 2005), or even humid regions with high precipitation, such as Ohio (Barnswell and Dwyer 2011). The evaluation was performed by comparing field measurements (e.g. lysimeter) with different numerical model prediction (Zhang et al. 2009; Ogorzalek et al. 2008; Benson et al. 2005; Mijares and Khire 2012; Bohnhoff et al. 2009). Since lysimeters having the shortcomings of being laborious and being costly, the prediction from numerical simulations was considered as a basic tool to assess the ET cover effectiveness. The purpose of this review is to explore the appropriateness of those numerical models and discuss the potential application in cold regions. The following models are discussed during the literature review i) HYDRUS-1D, ii) UNSAT-H, iii) LEACHM, iv) Vadose/W, and v) SHAW.

Previous researchers compared field data with different vadose-zone numerical models to indicate the feasibility of prediction (Zhang et al. 2009; Ogorzalek et al. 2008; Benson et al. 2005; Mijares and Khire 2012; Bohnhoff et al. 2009; Benson 2007). HYDRUS, UNSAT-H,

LEACHM, and Vadose/W were the most popular models used in previous studies. Two detailed studies on comparison of field data and water-balance prediction from UNSAT-H v3.0 (Fayer 2000), Vadose/W v6.02 (Krahn 2004), HYDRUS v2.007 (Šimůnek et al. 2005), and LEACHM v4.0 (Hutson and Wagenet 1992) were carried out continuously (Bohnhoff et al. 2009; Ogorzalek et al. 2008). The performance of the numerical models was evaluated by comparing the prediction for a monolithic water-balance cover in a semiarid climate (Bohnhoff et al. 2009) and for a capillary barrier in a sub-humid climate (Ogorzalek et al. 2008). In the capillary barrier study, the simulation was conducted with UNSAT-H, HYDRUS, and LEACHM with four different soil hydraulic properties sets. For the surface runoff, HYDRUS and LEACHM showed reasonable predictions matching the field measurements. UNSAT-H constantly over-predicted runoff. The key factor influencing the prediction was the precipitation rate applied to each model. UNSAT-H applied the total precipitation direct to the surface, while HYDRUS applied only the net precipitation. Therefore, UNSAT-H applied more water to the surface with higher intensity, which yielded to over-prediction of surface runoff (Scanlon et al. 2002). In addition, runoff from snowmelt was not included for those predictions and consideration of snow hydrology is mandatory in cold regions (Ogorzalek et al. 2008). For evapotranspiration, all three models represented the variation during seasonal changes. However, HYDRUS predicated field ET ranging from 99 – 105% of measured ET and LEACHM slight over predicated ET. UNSAT-H constantly under-predicted ET due to the over-prediction of surface runoff. In addition, all three models over-predicted ET during snowmelt. This was due to the difficulties to parametrize the surface vegetation, which included thickspoke, bluebunch, slender, wheatgrass and so on and their behavior during the early spring (Scanlon et al. 2005). The percolation predictions from all three models were reasonable in matching with field measurements. At last, different hydraulic

properties showed a strong influence on surface runoff and ET. HYDRUS showed the most promising results on runoff and ET.

The following research (Bohnhoff et al. 2009) evaluated the performance of UNSAT-H, HYDRUS, LEACHM, and Vadose/W. Overall, Vadose/W showed similar results compared to HYDRUS. The predictions for surface runoff were close to field measurements and slightly too high for ET. In summary, the parametric simulations indicated the sensitivity of each model prediction to precipitation rate, hydraulic properties, and the lower boundary condition. The prediction on the surface runoff was more accurate under two conditions: the precipitation rate was uniform, and the surface layer was set with higher hydraulic conductivity. Evapotranspiration was critical to accurately predict runoff. The percolation prediction was similar among all models, but Vadose/W was least sensitive to the lower boundary condition. The prediction by numerical simulation was considered as a tool to assess the ET cover effectiveness but not as a design tool (Hauser 2009).

The previous research showed the feasibility of different numerical models, while HYDRUS and Vadose/W showed a more accurate prediction. However, the numerical simulation lacked representation of freeze-thaw event. There were only limited studies assessing the ET cover effectiveness in cold regions. There were three continuous studies that were conducted in Alaska with permafrost soil layers (Schnabel et al. 2005; Schnabel et al. 2012a; Schnabel et al. 2012b). The evaluation of the ET cover effectiveness was performed in three areas: Juneau, Anchorage, and Fairbanks (Schnabel et al. 2005). The prediction was done with SHAW (Simultaneous Heat and Water) (Flerchinger 2000). SHAW simulates the heat, water and solute transfer within a one-dimensional soil column. It is a finite different approach applied with Richard's equation for simulating subsurface water movement. The prediction was based on soil, vegetation, and

meteorological data from different sources. The model predicted the variation of precipitation, evapotranspiration, percolation, and runoff due to the temperature and precipitation changes. However, the results lacked parametric analysis with different types of soil or numerical models. Other works directly compared conventional compacted soil covers (CSC) with ET covers by lysimeter (Schnabel et al. 2012b), assessment of ET covers by lysimeter, and electrical resistivity tomography (Schnabel et al. 2012a). Therefore, there was only few comprehensive numerical simulation comparing with the field measurement regarding snowmelt events in early spring that could lead to large flux in percolation (e.g., Hejazi and Woodbury 2011).

The simulation of infiltration during the snowmelt is considered more complicated than at normal weather conditions. First of all, the upper boundary condition for model simulation became complex during snowmelt (Zornberg and McCartney 2007). In addition, there were two key factors that affected the simulation of infiltration during snowmelt: the hydraulic conductivity and thermal property of soil. The hydraulic conductivity of a soil layer is altered by changes of the unfrozen water content during a freeze-thaw event. Specifically, water in large soil pores is frozen or crystallized faster comparing with small ones (Kane and Chacho 1990), to block the water movement and reducing hydraulic conductivity (Kane 1980). This phenomenon reduces the infiltration rate by at least one order of magnitude (Stähli 2006; Granger et al. 1984; Hayashi et al. 2003). Moreover, heat transport between air temperature and ground surface also has a serious impact on infiltration. The sensible and latent heat effect caused by energy/temperature changes can extend the time of the infiltration process significantly (Pomeroy and Brun 2001). In addition to the numerical challenges, snowmelt in cold regions due to the temperature rapidly increasing requires consideration. A special meteorological phenomenon that occurs frequently in Southern Alberta is the so-called Chinook, which is a

warm, dry wind from the Rocky Mountain east slope. This meteorological phenomenon causes a significant increase in temperature over a short period of time, yielding to snow melting and evaporation in the cold winter time. As a result, infiltration caused by snowmelt occurs frequently and randomly in the study area. Therefore, the snowmelt was a key aspect to consider for prediction of ET cover effectiveness in the cold region.

The previous studies evaluated three modeling tools for simulating the infiltration process, HYDRUS, Vadose/W (now as Seep/W with Temp/W), and SHAW. However, input requirements for SHAW included soil, vegetation, site characteristic, and meteorological data from different sources. More specifically, biomass, leaf dimension, stomatal resistance parameters were required for input and difficult to measure and time-consuming. On the other hand, HYDRUS, and Vadose/W were both capable of simulating infiltration under semi-arid climate conditions with less input requirements compared to SHAW.

SABAE-HW, Soil Atmosphere Boundary Accurate Evaluations of Heat and Water (Loukili et al. 2008), is a numerical package focused on simulating the vertical water and heat flux between atmosphere and soil layers. SABAE-HW was able to represent the freeze-thaw event and frozen soil moisture along the whole soil profiles (Loukili et al. 2008). Also, SABAE-HW was used to simulate the soil moisture in the BOREAS site, Saskatchewan (Hejazi and Woodbury 2011). The simulated soil moisture showed a general agreement with the observation data. However, its application in landfill cover design has not been yet attempted. Therefore, a lateral comparison among three different model software is desired to evaluate the feasibility of ET cover systems in the Canadian Prairie.

## 2.3 Calibration

HYDRUS-1D is one of the most popular models for estimating fluxes in the vadose-zone. The built-in calibration method in HYDRUS-1D is based on the Marquardt-Levenberg method (Marquardt 1963). It is a local optimization gradient method which requires initial parameters in order to process the optimization (Šimunek et al. 2012). The software requires soil parameters, specifically hydraulic conductivity, for calibration. However, the optimization process is relatively sensitive to the initial parameters. Generally, multiple trials for searching a local minimum of the objective function are recommended and the final solution is not guaranteed to be a global minimum (Šimunek et al. 2012). Since the beginning of this century,

Different reliable calibration methods were coupled with HYDRUS-1D to identify numerically the recharge or percolation since the early 2000s. The purpose of this review was to explore the insufficient aspects of those methods and discuss the potential application of those methods to calibrate the model. The following methods were discussed during the literature review i) PEST, ii) UCODE, iii) GA, iv) NSGA-II, MOSCEM-UA, and AMALGAM – Multi-objective Optimization Algorithms.

PEST, the model-independent Parameter Estimation and Uncertainty Analysis (Doherty 2016) was used to simulate water salinity by coupling it with HYDRUS-1D (Singh and Wallender 2011). The estimated recharge was calibrated with different soil salinity levels in western Fresno Country, California using 5-years of observed data (Singh and Wallender 2011). In the initial stage of the calibration, van Genuchten-Mualem (VGM) (Mualem 1976; van Genuchten 1980) parameters two transport parameters, and five time-averaged constant flux rates (*i.e.* recharge) were indicated as the decision variables. The objective function was based on the unsaturated soil hydraulic function (Mualem 1976). The saturated and residual water content

were fixed during the first trial to reduce the calibration parameters. For further calibration, the time-averaged based recharge was specified as decision variables. RMSD (root mean square deviation) was used for evaluating the model performance. The simulations using these two periods showed a reduction in RMSD ranging from 32 to 77% for different time series.

UCODE, a Computer Code for Universal Inverse Modeling (Poeter and Hill 1999) was used to calibrate hydrological, transport and geochemical parameters for transient unsaturated soil water flow and solute transport (Jacques et al. 2012). The UCODE programme was written in MATLAB (MathWorks 2016) to perform calibration. The decision variables were the geochemical parameters which were indicated by HP1, a coupled software of HYDRUS-1D and PHREEQC (Parkhurst and Appelo 1999). The objective function was based on the weighted sum of squared differences (SSD) to minimize the differences for each data types (Jacques et al. 2012). The SSD results for the Rothmund–Kornfeld approach were 20% lower than for the Gapon approach, which are two general approaches for chemical exchange. As a limitation for PEST and UCODE, both methods were inefficient in modeling large numbers of parameters during optimization. Therefore, an alternative method is necessary for models having a large number of parameters to be calibrated.

GA (Genetic Algorithm) (Goldberg 1989) was used to calibrate the hydraulic parameters based on the analysis of the soil water relationship with precipitation and evaporation. The calibration was done by a GA method for global optimization. Two new objective functions were used to fit the measured soil water content. The model efficiency (EF) coefficient, RMSD, and mean absolute error (MAE) were used to evaluate the model performance. The RMSD, MAE, and EF values were slightly different regarding different population size in this research. The decision variables showed large variations and proved that the non-uniqueness phenomenon was



highly non-linear and their results had multiple solutions (Hopmans and Šimuněk 1999). The GA method was powerful to determine a global minimum for each of the chosen multiple parameters situations. However, the overall efficiency was limited by finding the global minimum of all trials. The algorithm process might generate a global minimum value that only considered optimal in a certain population size. Therefore, the GA method required to restart the process which can potentially lead to a significant computational consumption. Therefore, an alternative method is needed for calibrating models under complex situations but also highly efficient for finding the global minimum.

Previous research (Wöhling et al. 2008) compared three multi-objective optimization algorithms: NSGA-II, MOSCEM-UA, and AMALGAM. The calibration efficiencies were determined by comparison of measured heads and simulated heads generated by HYDRUS-1D. The model simulated the vadose-zone with calibration data at three different depths from the Spydia experimental field site in New Zealand. It was known from former studies that the residual water content was least affecting the model. Therefore, the residual water content was set as zero. Five VGM parameters at three different layers combined as a 15-dimensional optimization problem (Wöhling et al. 2008). For a better comparison of the efficiency of the algorithms, Pareto sets were also included in this study. The pareto efficient is a method to represent the preference of each single solution without losing an good candidate solution and pareto set is the set of parameterizations of the pareto efficient. The optimal solutions generated by NSGA-II, MOSCEM-UA, and AMALGAM algorithms had a similar Pareto set of solutions. However, the AMALGAM outstood others algorithms in finding the overall best parameter sets with an averaged root mean square error (RMSE) of 0.14 m (Wöhling et al. 2008) following by MOSCEM-UA and NSGA-II. The reason was that AMALGAM builds on a population-based search procedure with

a highly efficient approach to find a well-distributed set of Pareto solutions within a single optimization run (Wöhling et al. 2008). In addition, this research also compared the three multi-objective algorithms (NSGA-II, MOSCEM-UA, and AMALGAM) with a single-objective SCE-UA method. All multi-objective algorithms showed significantly high processing speeds and low RMSE values. Wöhling et al. (2008) concluded “Hence, it might prove more efficient to run a multi-objective algorithm to find single-objective solutions. This is important results deserves more attention in future work.”

All of the discussed calibration methods showed their significance in different fields. PEST and UCODE were highly efficient in terms of the computation budget. However, both methods are based on the Marquardt-Levenberg method. The optimization was relatively sensitive to the initial parameters indicated and multiple trials for searching local minimum were necessary. In addition, grade-based algorithm showed its limitation when the calibration was performed with different soil layers, root water uptake, evapotranspiration, surface runoff, and/or additional large number of parameters. The GA method was powerful for determining the global minimum with multiple parameters. However, the efficiencies were limited by finding the global minimum and required restarting the algorithm. Both factors can potentially lead to significant computational budgets. Therefore, an alternative method is necessary for simulating model under complex situations but needs to be also highly efficient for searching for a global minimum. The multi-objective optimization algorithms NSGA-II, MOSCEM-UA, and AMALGAM showed their sufficiency of finding decision variables for multiple dimensional optimization problems. The disadvantage for those methods was the computational budget and that the optimal solution may not have a physical meaning. Even with advanced computational power, the multi-objective algorithms still requires more time than other methods.

As a summary, the GA method was the least efficient algorithm for coupling with HYDRUS-1D due to the low processing speed and the uncertainty of the optimization solution. The choice between multi-objective algorithms and the Marquardt-Levenberg method with local optimization gradient method was highly dependent on the user purpose and research objectives. For simulation of six or less decision variables, Marquardt-Levenberg optimization satisfied the academic or commercial requirements. The usability and utility of multi-objective algorithms became suitable and efficient for a complex model with a large number of parameters. In addition, the multi-objective algorithms showed potential capability for calibrating not only recharge but also other processes such as heat or solute transport at the same time.

### 3. Numerical Assessment of Evapotranspiration Covers in Cold Climates

#### Abstract

In landfill remediation, evapotranspiration (ET) cover is designed to prevent water percolating to the waste. The key objective is the mitigation of water from deep percolation into the landfill using soil and vegetation to store, evaporate, and transpire water. The ET cover system has been proved effective in the semiarid region in the US, but not been assessed in cold regions such as the Canadian Prairie. The performance of ET cover was evaluated using three vadose-zone models, HYDRUS-1D, GeoStudio, and SABAE-HW. The study site was located at High River, AB and data were retrieved from a HOBO weather station. The observation period was from August 2016 to September 2017 and three undisturbed soil cores were taken close to HOBO weather station. The soil hydraulic and thermal characteristics were determined by laboratory tests and pedo-transfer functions. The model was calibrated by comparing measured and simulated soil moisture through PA-DDS, a new multi-objective algorithm. Percolation during the observation period was estimated 79.6 mm by HYDRUS-1D, 86.2 mm by GeoStudio, and 101.1 mm by SABAE-HW. The majority percolation was due to snowmelt during a Chinook event, which was up to 90% of total snowfall. HYDRUS-1D had the best agreement with measured soil moisture, but SABAE-HW showed more reasonable soil moisture behavior under freeze-thaw event. Furthermore, the performance of SABAE-HW required further investigation with sufficient soil temperature and snowfall information.

### 3.1 Introduction

Landfilling of waste can generate pollution which may reach aquifer systems by leachate infiltration over a long-time period (Widomski et al. 2015). In landfill remediation, the idea is to modify a site, so that as little seepage as possible can migrate into and through a landfill. Evapotranspiration (ET) cover is a relatively new concept in which the landfill cap is specifically designed as a porous layer (or layers) to isolate the waste from infiltrating water. The idea is that water from precipitation/snowmelt will be stored within the cap and allowed to evaporate and transpire back into the atmosphere. The greater the storage capacity and evapotranspiration at the site, the lower the potential for water percolating through the cover system. These ET caps could be installed at municipal solid waste and hazardous waste landfills when equivalent performance to conventional final cover systems can be demonstrated (Albright et al. 2004). Therefore, assessment of ET cover system is important, and improvement on its efficiencies could minimize the impact to the current, and future environments.

The ET cover system has been effective in arid or semiarid regions of the US (Bohnhoff et al. 2009; Nyhan 2005), and even humid region with high precipitation, such as Ohio in the US (Barnswell and Dwyer 2011). The previous assessment of ET cover systems was performed by comparing field measurements, such as lysimeters, with water balance model prediction (Zhang et al. 2009; Ogorzalek et al. 2008; Benson et al. 2005; Mijares and Khire 2012; Bohnhoff et al. 2009). The accuracy of lysimeters varied in the different study areas and the scale systems used but the field measurements were laborious and lysimeters are costly. Therefore, the predictions by numerical simulation were considered as a key tool to assess the ET cover effectiveness. In spite of all these efforts as noted above the performance of ET cover has yet been proven in cold climates with distinct freeze-thaw events such as in the Canadian Prairies.

The key challenge here is the prediction of infiltration/percolation rates due to complex boundary conditions (Zornberg and McCartney 2007) and soil characteristics during phase changes. Further, the complicated upper-atmospheric boundary can lead to large mass balance errors for numerical models. In addition to the numerical challenges, meteorological events in cold regions such as snowmelt during spring or precipitation over short time periods requires attention. The short term “Chinook” wind events in western North America, can occur quite often and can cause frequent snowmelt events during the winter. Therefore, the simulation of snowmelt infiltration is considered critical for describing the efficiency of ET cover systems. Soil characteristics, such as the hydraulic conductivity of the soil layer, is altered the phase change of water. Specifically, water in larger porous media is frozen or crystallized faster compared to small pores (Kane and Chacho 1990), serving to block water movement and reducing hydraulic conductivity (Kane 1980). This blocking phenomenon can reduce the infiltration rate by at least one order of magnitude (Stähli 2006; Granger et al. 1984; Hayashi et al. 2003). The heat transport between air temperature and ground surface also has a serious impact on the infiltration process. The sensible and latent heat effect caused by energy/temperature changes can extend the time of the infiltration process significantly (Pomeroy and Brun 2001). As a result, infiltration caused by snowmelt has a lower permeability rate and the boundary condition for model simulations can become complex during snowmelt. Therefore, numerical simulations require the additional of heat transport process to fully represent infiltration/percolation in cold regions. Note there are only limited studies regarding the assessment of the ET cover in cold regions, such as a study in Alaska on permafrost (Schnabel et al. 2005; Schnabel et al. 2012a; Schnabel et al. 2012b). The prediction was done by using the SHAW (Simultaneous Heat and Water) (Flerchinger 2000) numerical simulator and

results lacked parametric analysis with different types of soil or numerical models. One study of note compared conventional compacted soil covers (CSC) with ET covers by lysimeter and electrical resistivity tomography (Schnabel et al. 2012a). After a detailed review of the literature it can be concluded that there is definitely a knowledge gap with respect to assessments of ET cover in cold regions such as the Canadian prairies .

The main objective of this study was to evaluate ET cover systems in cold climates by three vadose-zone numerical models, which are HYDRUS-1D, SABAE-HW, and GeoStudio (Seep/W and Temp/W). The simulated soil moisture by HYDRUS-1D was compared with the measured one through calibration by PA-DDS, a multi-objective algorithm. The numerical simulation capability, soil moisture behavior and monthly estimated percolation from three models are discussed. Further research will focus on how to improve the application of ET cover systems in cold climate and how to improve the feasibility of chosen vadose-zone numerical models.

### 3.2 Study Area

The study area is a 70-year-old municipal dumping site which is located in the city center of High River, Alberta (Fig. 1). Several domestic water wells and an irrigation canal are adjacent to the dump site. The site was submerged by flooding in 2003 and was identified as a health risk for the environment and population by the local regulator. The landfill was equipped with a landfill gas barrier system constructed on the north, east, and south sides in 2011. The most common surface soil type is lean clay combined with organics, and the groundwater level (GWL) varies from 2 to 12 m below the surface with a flow direction towards the northeast. In the central portion of the study area, the GWL is close to 4 m below the surface or even less. The surface vegetation varied in different sections. For the upland section, the Idaho fescue, and Prairie

Junegrass were the major species. For the lowland section, the Northern Wheatgrass, Slender Wheatgrass, and Western Wheatgrass contributed the most to transpiration.

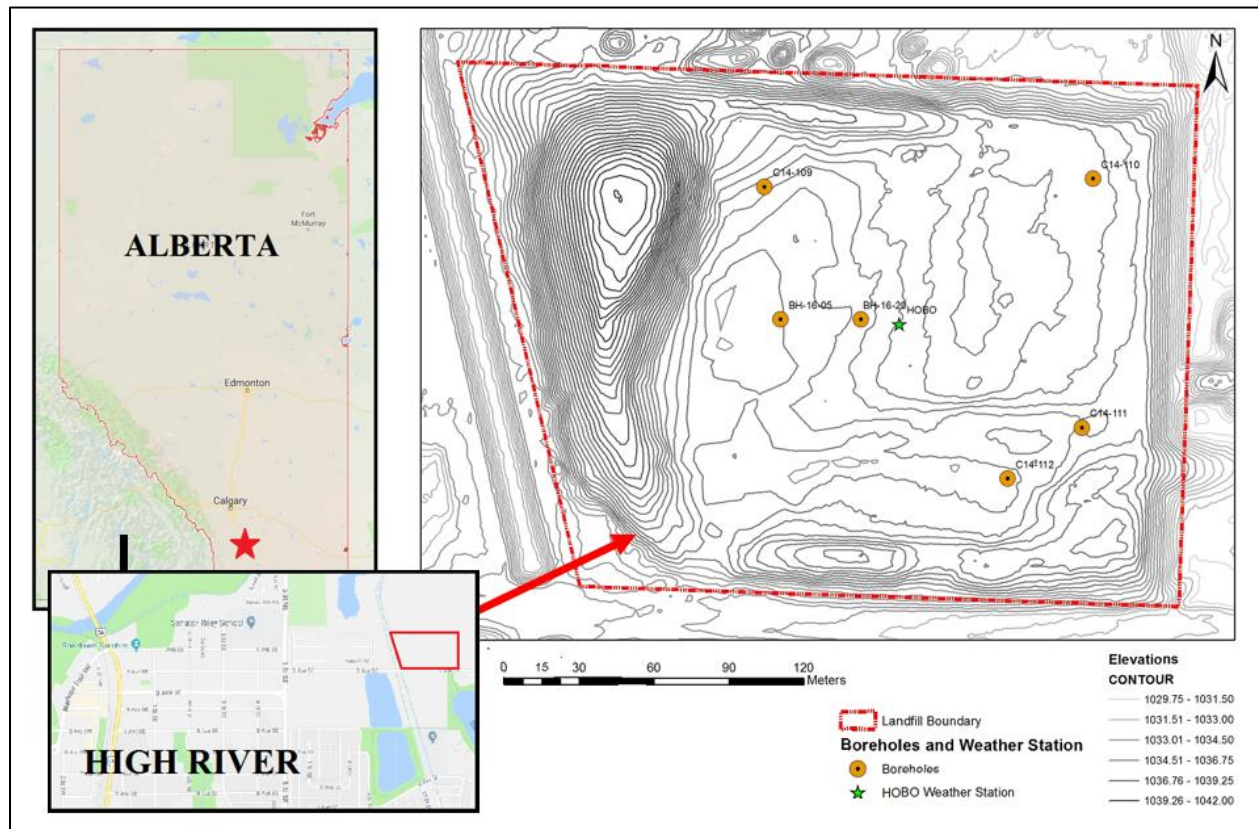


Figure 1. Map of the study area.

### 3.2.1 Data

A HOBOT<sup>TM</sup> U30 weather station was installed on August 2<sup>nd</sup>, 2016 on the landfill and was located at 5607235.76 m N, 298317.63 m E, 1038.95 m above mean sea level (MSL), UTM Zone 12N to provide weather and soil observations. The HOBOT<sup>TM</sup> weather station has been shown to be reliable and robust for measuring soil temperature, soil moisture, and climate data which included precipitation, air temperature, solar radiation, wind speed, and relative humidity (Holländer et al. 2016). The weather station included one frequency domain reflectometry (FDR) soil moisture sensors installed at 50 cm depth below the surface. Unfortunately, there were no



soil temperature sensors installed due to a limit in the number of ports. The data logging interval was set to 10 minutes to record the data for meteorological observation and 30 minutes for soil moisture.

The mean temperature recorded by the HOBO™ weather station (from August 2016 to February 2017) was 3.8°C and the mean daily temperatures varied from -33.2°C to 23.9°C (Fig. 2). Nearly 56% of the total precipitation (287 mm) occurred during the summer period. This is a typical semi-arid climate region identified as Köppen climate type BSk (Köppen 1884), having warm summers and cold winters. Furthermore, the recorded temperature varied significantly when a Chinook event occurred and temporarily caused a warm temperature in the winter period. Chinook events are a warm, dry wind from the Rocky Mountain east slope to southern Alberta. This meteorological phenomenon causes a significant increase in temperature during a short period of time, causing snow melt and evaporation in winter.

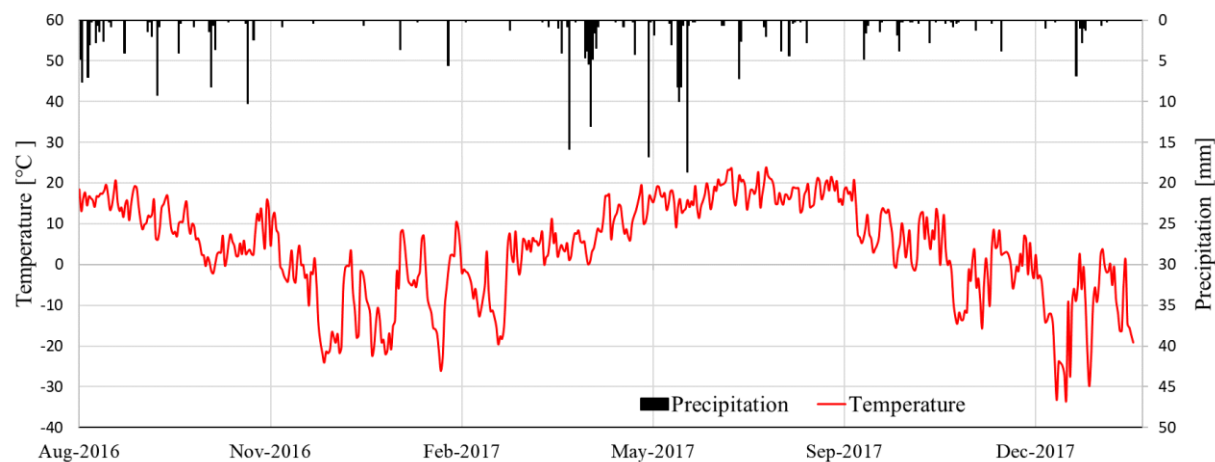


Figure 2. Daily average of measured air temperature and precipitation at the HOBO™ U30 weather station (August 2016– February 2018)

The satisfactory quality of the measurements from this type of low-cost weather station was proven in the Okanagan Valley and in Abbotsford B.C. under normal climate conditions (Assefa and Woodbury 2013; Holländer et al. 2016), but not yet been evaluated under cold climate conditions typical of the Canadian prairies. Note the rain gauge of the HOBO weather station was not equipped to measure snow fall (Holländer et al. 2016). Precipitation recorded during winter period was due to snow melting caused by Chinook event. The precipitation or snowfall in winter period was compared with the nearest government weather station within a 25 km radius, Okotoks, (5627592.47m N, 291257.92m E, 1081 m MSL) (Environment Canada 2018).

The FDR soil moisture sensor was installed at 50 cm below the surface. The accuracy of the soil moisture sensor was  $\pm 3\%$  in water content in a temperature range between 0 and 40°C (Holländer et al. 2016). However, soil moisture recorded at frozen condition does not show realistic results due to the phase change and the accompanying change in dielectric permittivity. Therefore, measured soil moisture content required to be evaluated due to the accuracy measurements in cold climates. Previous studies reported different empirical or semi-empirical equations to estimate the frozen water content (Mark and Xubin 2006; Qin et al. 2009; Liu and Li 2012; Kozlowski 2003). The semi-empirical equation (Kozlowski 2007) used to estimate the unfrozen water content:

$$\theta_u = \begin{cases} \theta & \text{for } T > T_f \\ \theta_{nf} + (\theta - \theta_{nf}) \exp \left[ -3.35 \left( \frac{T_f - T}{T - T_m} \right)^{0.37} \right] & \text{for } T_m < T < T_f \\ \theta_{nf} & \text{for } T \leq T_m \end{cases} \quad (1)$$

Where  $\theta_u$  [ $\text{cm}^3 \text{cm}^{-3}$ ] is the unfrozen water content,  $\theta_{nf}$  [ $\text{cm}^3 \text{cm}^{-3}$ ] is the water content which cannot be frozen,  $T_m$  [°C] is the temperature below at which the unabsorbed water is all frozen,

$T_f$  [°C] is freezing point of soil, and  $\theta$  is the soil water content above 0°C. Details of this equation can be found in Kozlowski (2007).

### 3.2.2 Laboratory Measurements

There were three soil cores taken by a direct push probe within a radius of 5 meters from the weather station. Sieve analysis according to ASTM-C136-06 (ASTM 2014) and laser diffraction tests (Malvern Panalyticals's Mastersizer 2000 particle size analyzer) were performed to determine the soil texture and classification. There were two layers for each soil sample: the top soil was present from 0 to 40 cm and a fine textured cover soil below 40 cm. The USDA textual classification was used as a reference for determining the soil type. The top soil was classified as silty loam and the cover soil as loam (Table 1 and Appendix 1). The hydraulic conductivity was determined in a triaxial cell following ASTM D5084 - 16a (ASTM 2016), and DIN 18130 - 1 (Scholz et al. 2003). The hydraulic conductivity for both soil layers ranged between 8.8 and 18.9 cm/d (Table 2).

Table 1. Soil composition

| Soil samples | Depth [cm] | Sand [%] | Silt [%] | Clay [%] | Soil texture    |
|--------------|------------|----------|----------|----------|-----------------|
| W506-1       | 0 – 44     | 29.2     | 49.4     | 21.4     | Silty loam      |
|              | 44 - 50    | 48.5     | 39.0     | 10.4     | Loam            |
| W506-2       | 0 - 42     | 42.0     | 42.2     | 15.8     | Silty loam/Loam |
|              | 42 - 50    | 55.0     | 37.0     | 8.0      | Loam            |
| W506-3       | 0 – 38     | 27.6     | 50.4     | 22.0     | Silty loam      |

|  |         |      |      |      |      |
|--|---------|------|------|------|------|
|  | 38 - 50 | 50.2 | 36.9 | 12.9 | Loam |
|--|---------|------|------|------|------|

ROSETTA (Schaap et al. 2001) was used to derive soil hydraulic parameters according to the van Genuchten-Mualem (VGM) relationship (Mualem, 1976; van Genuchten, 1980). ROSETTA are based on neural network analyses and USDA soil textural class to predict the VGM parameters. The VGM parameter are saturated water content  $\theta_s$  [ $\text{cm}^3 \text{cm}^{-3}$ ], residual water content  $\theta_r$  [ $\text{cm}^3 \text{cm}^{-3}$ ], and the empirical parameters  $\alpha$  [ $\text{cm}^{-1}$ ],  $n$  [-] and  $m$  [-] (Table 2).

Table 2. Soil parameterization based on ROSETTA with 95% confidence interval

| Soil samples | $\theta_r$                          | $\sigma \theta_r$                   | 95 % confidence interval |       | $\theta_s$                          | $\sigma \theta_s$                   | 95 % confidence interval |       | $\alpha$                            | $\sigma \alpha$                     | 95 % confidence interval |       | n                                   | $\sigma n$                          | 95 % confidence interval |       | Ks                    | $\sigma n$            | 95 % confidence interval |      |
|--------------|-------------------------------------|-------------------------------------|--------------------------|-------|-------------------------------------|-------------------------------------|--------------------------|-------|-------------------------------------|-------------------------------------|--------------------------|-------|-------------------------------------|-------------------------------------|--------------------------|-------|-----------------------|-----------------------|--------------------------|------|
|              | [cm <sup>3</sup> cm <sup>-3</sup> ] | [cm <sup>3</sup> cm <sup>-3</sup> ] |                          |       | [cm <sup>3</sup> cm <sup>-3</sup> ] | [cm <sup>3</sup> cm <sup>-3</sup> ] |                          |       | [cm <sup>3</sup> cm <sup>-3</sup> ] | [cm <sup>3</sup> cm <sup>-3</sup> ] |                          |       | [cm <sup>3</sup> cm <sup>-3</sup> ] | [cm <sup>3</sup> cm <sup>-3</sup> ] |                          |       | [cm d <sup>-1</sup> ] | [cm d <sup>-1</sup> ] |                          |      |
| W506-1       | 0.071                               | 0.001                               | 0.070                    | 0.072 | 0.425                               | 0.002                               | 0.424                    | 0.426 | 0.007                               | 0.000                               | 0.007                    | 0.007 | 1.550                               | 0.010                               | 1.544                    | 1.557 | 15.4                  | 4.1                   | 12.5                     | 18.3 |
|              | 0.040                               | 0.001                               | 0.040                    | 0.040 | 0.397                               | 0.001                               | 0.396                    | 0.397 | 0.011                               | 0.000                               | 0.011                    | 0.011 | 1.493                               | 0.001                               | 1.492                    | 1.494 | 8.8                   | 2.6                   | 6.9                      | 10.6 |
| W506-2       | 0.055                               | 0.001                               | 0.054                    | 0.055 | 0.399                               | 0.000                               | 0.399                    | 0.399 | 0.009                               | 0.000                               | 0.009                    | 0.009 | 1.518                               | 0.003                               | 1.515                    | 1.520 | 16.7                  | 2.6                   | 12.5                     | 18.1 |
|              | 0.055                               | 0.000                               | 0.055                    | 0.055 | 0.343                               | 0.000                               | 0.343                    | 0.343 | 0.018                               | 0.000                               | 0.018                    | 0.018 | 1.436                               | 0.000                               | 1.436                    | 1.436 | 9.1                   | 1.1                   | 8.3                      | 9.9  |
| W506-3       | 0.069                               | 0.001                               | 0.069                    | 0.070 | 0.424                               | 0.002                               | 0.423                    | 0.425 | 0.006                               | 0.000                               | 0.006                    | 0.006 | 1.580                               | 0.006                               | 1.576                    | 1.583 | 18.9                  | 4.3                   | 15.9                     | 21.9 |
|              | 0.048                               | 0.000                               | 0.048                    | 0.048 | 0.391                               | 0.000                               | 0.391                    | 0.391 | 0.014                               | 0.000                               | 0.014                    | 0.014 | 1.454                               | 0.001                               | 1.454                    | 1.455 | 11.3                  | 3.8                   | 8.7                      | 13.9 |

Thermal conductivity and volumetric heat capacity were recorded by a METER™ KD2 Pro Thermal Properties Analyzer. Sensor SH-1 was used to measure the soil thermal properties with an accuracy range of  $\pm 10\%$  for thermal conductivity and  $\pm 10\%$  for volumetric heat value above  $0.1^\circ\text{C}$  (Decagon Devices Inc. 2016). The soil samples were placed in a freezer at  $-20^\circ\text{C}$  for over 24 hours and then moved to the laboratory at constant  $23^\circ\text{C}$  air temperature. Both parameters were recorded every 15-minute during the transfer from frozen to unfrozen state and were evaluated in a temperature range between  $-10^\circ\text{C}$  and  $10^\circ\text{C}$ . The thermal properties were being recorded at two different soil moisture conditions: field capacity and wilting point. The thermal conductivity for top soil ranged between  $3.63$  and  $12.11\text{ Wcm}^{-1}\text{K}^{-1}$ . The thermal conductivity for cover soil ranged between  $5.61$  and  $8.02\text{ Wcm}^{-1}\text{K}^{-1}$ .

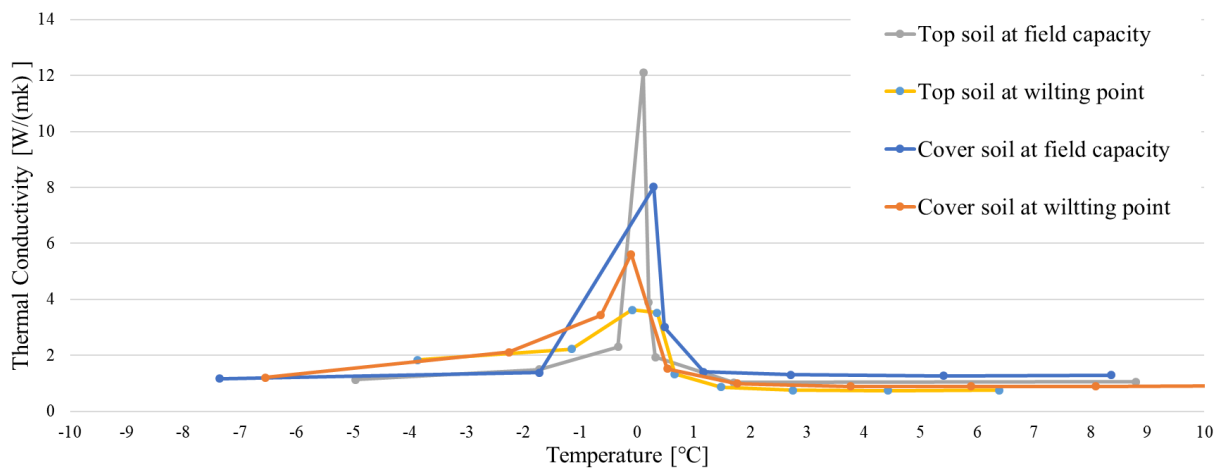


Figure 3. Thermal conductivity of top and cover soil samples

### 3.3 Vadose-zone Models

HYDRUS-1D version 4.16 (Šimůnek et al. 2013) was primarily used to evaluate the performance of the ET cover. The simulation was calibrated by comparing measured and simulated soil moisture at 50 cm depth. The calibrated soil hydraulic parameters from HYDRUS-1D were then used as input data for the other two other vadose-zone models (GeoStudio and SABAE-HW) which are described below

#### 3.3.1 HYDRUS-1D

The changes in soil moisture were simulated by the Richards equation (Richards 1931).

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left[ K(\psi) \left( \frac{\partial \psi}{\partial z} \right) - S \right] \quad (2)$$

Where,  $\theta$  is the volumetric water content [ $\text{cm}^3 \text{cm}^{-3}$ ],  $\psi$  is the pressure head [cm],  $t$  is the time [d],  $z$  is the elevation [cm],  $S$  is the sink term [ $\text{cm}^3 \text{cm}^{-3} \text{d}^{-1}$ ] and  $K(\psi)$  [ $\text{cm d}^{-1}$ ] is an unsaturated hydraulic conductivity function of  $\psi$  and of the saturated hydraulic conductivity  $K_s$  [ $\text{cm d}^{-1}$ ].

The soil water retention (characteristic) curves are represented by the VGM model (van Genuchten 1980; Mualem 1976).

$$\theta(\psi) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1 + |\alpha\psi^n|]^m} & \psi < 0 \\ \theta_s & \psi \geq 0 \end{cases} \quad (3)$$

$$K(\psi) = K_s S_e^L \left[ 1 - \left( 1 - S_e^{\frac{1}{m}} \right)^m \right]^2 \quad (4)$$

Where  $\psi$  [cm] is pressure head,  $\theta_s$  [ $\text{cm}^3 \text{cm}^{-3}$ ] is saturated water content,  $\theta_r$  [ $\text{cm}^3 \text{cm}^{-3}$ ] is residual water content,  $\alpha$  [ $\text{cm}^{-1}$ ],  $n$  [-] and  $m$  [-] are empirical parameters,  $K_s$  [ $\text{cm day}^{-1}$ ] is saturated hydraulic conductivity and  $S_e$  [-] is the effective saturation.

The heat transfer is modeled using the Chung and Horton equation (Chung and Horton 1987) and the FAO (Food and Agriculture Organization) Penman-Monteith method was used to compute the potential evapotranspiration (Allen et al. 1998). The FAO Penman-Monteith method requires radiation, air temperature, air humidity, and wind speed data. The potential evaporation and transpiration calculation were based on the Leaf Area Index (LAI) [-] and the soil cover friction [-] (Ritchie 1972; Ritchie and Burnett 1971). In addition, the root water uptake was determined by the Feddes model (Feddes et al. 1977) with default parametrization of pasture from the built-in dataset of HYDRUS-1D.

### 3.3.2 GeoStudio (Seep/W and Temp/W)

GeoStudio 2018, Seep/W coupled with Temp/W (previously Vadose/W) (GEO-SLOPE International Ltd 2017) was also used to assess the ET cover performance. Seep/W simulated the water movement through the soil layer under unsaturated or saturated conditions. For consistency, the soil water retention was represented by the VGM model and evapotranspiration were estimated by the Penman-Monteith method. The root water uptake was conducted following the Feddes model (Feddes et al. 2001). Leaf Area Index (LAI) and soil cover friction data based on previous research (Ritchie 1972) were used to calculate potential transpiration flux from evapotranspiration estimated by the PM method. Temp/W simulated the heat transport through the porous media at frozen or unfrozen states and the measured soil thermal properties in various temperatures were used to simulate the sensible and latent heat transfer during phase change. This model required volumetric heat capacity parameters for the unfrozen and frozen states as a function of temperature.



### 3.3.3 SABAE-HW

SABAE-HW, (Soil Atmosphere Boundary Accurate Evaluations of Heat and Water), is a numerical code written in Fortran (Loukili et al. 2008). This numerical package focused on simulating the vertical water and heat flux between atmosphere and soil layers. The SABAE-HW code was based on the framework developed for the Canadian Land Surface Scheme (CLASS) version 2.6. CLASS was originally developed as a land surface scheme for the Canadian Global Climate Model (Verseghy 1991; Verseghy et al. 1993). The performance of CLASS was limited by the simple representation of the soil layer (Loukili et al. 2008). Therefore, SABAE-HW code used a finite volume discretization to improve the representation of soil layers and to resolve the soil heat flux terms by implementing them with the Generalized Minimal Residual (GMRES) approach (Saad and Schultz, 1986). The principle of one-dimensional moisture and heat transfer was represented by the water and energy balance between different soil layers.

$$T_i(t + \Delta t) = T_i(t) + [G(z_{i-1}, t) - G(z_i, t)] \frac{\Delta t}{C_i \Delta z_i} \pm S_i \quad (5)$$

where  $T$  [°C] is the average layer temperature,  $G(z_{i-1})$  and  $G(z_i)$  [ $\text{Wcm}^{-2}$ ] are the downward heat fluxes at the top and bottom of layer  $i$ ,  $\Delta t$  [day] is the time step,  $\Delta z_i$  [cm] is the thickness of soil layer,  $C$  [ $\text{Wcm}^{-2}$ ] the volumetric heat capacity of soil layer,  $S_i$  is a correction term stemmed from freezing, thawing or percolation. The details for all parameters can be found in the literature (Verseghy 2009; Loukili and Woodbury 2008).

$$\theta_i(t + \Delta t) = \theta_i(t) + [F(z_{i-1}, t) - F(z_i, t)] \frac{\Delta t}{\Delta z_i} \quad (6)$$

where  $\theta_i$  [ $\text{cm}^3\text{cm}^{-3}$ ] is the average volumetric liquid water content,  $F(z_{i-1})$  and  $F(z_i)$  [ $\text{cm}^3\text{d}^{-1}$ ] are the water flow rates at top and bottom of layer  $i$ . The water content will be considered as

freezing or melting based on soil temperature and amount of heat energy received. The liquid water content will be set as frozen while soil temperature reaches below zero-degree °C, or/and when heat energy exceeded the heat capacity of current soil layer.

The required data for meteorological input are identical to the requirement of the Penman-Monteith method. The potential evapotranspiration was estimated under different conditions.

$$E_p = \rho_a C_{DH} v_a [\varrho_{0,sat} - \varrho_a] \quad (7)$$

where  $E_p$  is potential evapotranspiration,  $\rho_a$  is the density of air,  $C_{DH}$  is the minimum ratio of drag coefficient for heat,  $\varrho_{0,sat}$  is the saturated specific humidity at the surface with a different condition. The detailed equations to estimate those parameters were given in previous documents (Verseghy 1991, 2009; Verseghy et al. 1993). The input for soil characteristics was based on index calculations from soil types, which were represented by the soil composition in terms of sand and clay.

### 3.4 Boundary and Initial Condition

Appropriate initial condition (IC) and boundary conditions (BCs) are necessary for numerical simulations to achieve stability and accuracy. For the case study landfill the simulation period was from August 2016 to September 2017 and the soil profile was defined with a depth of 100 cm.

#### 3.4.1 HYDRUS-1D

The numerical model simulation period was from early August 2016 to the end of September 2017. The external meteorological information such as solar radiation, temperature, and precipitation controlled the surface water flux and energy balance across the upper boundary. Based on the measured soil moisture, the infiltration process is sensitive to air temperature

variations and a sudden occurrence of snowmelt. Note the groundwater table was monitored and did not reach the top of the cover layer. Therefore, the upper hydraulic BC was defined as “atmospheric BC with surface runoff” within HYDRUS and the option of consideration of surface ponding and post-winter soil thawing was selected. The lower hydraulic BC was defined as free drainage at 100 cm since the measured groundwater table was more than 2 meters below the ground surface during the simulation period. For the thermal BC, the upper boundary was set as mean air temperature, and the lower boundary was defined as zero-gradient (free flux) since no soil temperature data was available. The IC of soil moisture was set as a constant value of 8% among the soil layers based on the measured soil moisture.

#### 3.4.2 GeoStudio (Seep/W and Temp/W)

The upper BC used the land climate interaction (LCI) boundary condition coupled with surface energy balance (SEB) boundary condition. The LCI boundary condition represented the ground surface condition during a potentially snow-covered or vegetated ground. This boundary condition was used to compute the water balance and net infiltration. The SEB boundary condition represented the thermal energy transferring between atmosphere and soil. This coupled boundary was used to simulate meteorological variances on the infiltration of surface soil cover. The SEB equation is:

$$(R_{ns} - R_{nl}) = R_{sens} + R_{lat} + R_g \quad (8)$$

Where  $R_{ns}$  [ $\text{Wcm}^{-2}$ ] is the net short-wave radiation,  $R_{nl}$  [ $\text{Wcm}^{-2}$ ] is the long-wave radiation,  $R_{sens}$  [ $\text{Wcm}^{-2}$ ] is the sensible heat flux,  $R_{lat}$  [ $\text{Wcm}^{-2}$ ] is the latent heat flux, and  $R_g$  [ $\text{Wcm}^{-2}$ ] is rest amount of energy transmitted to soil layers.

The SEB follows similar basic concepts in the calculation of the energy balance from the PM method (Dingman 2008) and the atmospheric stability correction (Saito and Šimůnek 2009; Koivusalo et al. 2001) in sensible heat flux. The “shadowing effect” represents the situation when the ground surface is partially blocked from direct sunlight. Note the atmospheric stability correction addresses the assumption that momentum and heat flow have the same resistance. The surface reflection factor, albedo was another key parameter to consider during the simulation. The value of albedo varied between 0.1 to 0.95 representing the reflection from a bare-ground surface to fresh snow (Allen et al. 1998). This coupled boundary was used to simulate meteorological variances on the infiltration of surface soil cover. The lower BC was defined as free drainage. The IC was based on the measured groundwater table.

### 3.4.3 SABAE-HW

The upper boundary was the soil atmosphere boundary with vegetation/snow pack. The land surface can be treated with different types (e.g. canopy and snow-covered ground, snow-covered ground) based on air temperature and amount of snow stored on the surface. The snowpack was considered as an extra layer above the ground surface and is unique to SABAE-HW. This snow layer had a variable thickness to represent the freeze-thaw process (Verseghy 1991, 2009; Verseghy et al. 1993). The lower boundary was set as unit gradient boundary since the groundwater table was far below the soil layer.

## 3.5 Sensitivity Analysis and Calibration

### 3.5.1 Sensitivity Analysis

Sensitivity analysis is a standard procedure to identify the impact and variation caused by decision variables to an objective function. It is also a way to assess the priorities of different parameters to achieve a manageable computational budget. In this research, a sensitivity analysis

was used to provide the upper and lower limits of different VGM parameters. Those VGM parameters were used to represent the soil water retention. A general approach was used, which allowed altering one parameter at each time to estimate the sensitivity of modeling results (Czitrom 1999). The feasibility and effectiveness of this approach was proven by previous studies (Oostrom et al. 2013; Holländer et al. 2016). This approach only estimated the local sensitivity of the parameters. An analysis by altering all VGM parameters at the same time may have different degrees of sensitivity. However, the range of soil hydraulic properties were also based on estimation using ROSETTA which included a 95% confidence interval (Table 3). Therefore, this local sensitivity approach combined with a search within the 95% confidence interval can be defined as a global optimization problem due to the preconditioning. The initial simulation results were considered as baseline. Each VGM parameter was altered by  $\pm 10\%$  and the hydraulic conductivity, which was measured in a laboratory test, was varied by  $\pm 10\%$  of the log-normal distribution of the hydraulic conductivity.

### 3.5.2 PA-DSS

HYDRUS has an automatic parameter estimation feature and is based on the Marquardt-Levenberg method (Marquardt 1963) which is a local optimization gradient-based method requiring initial parameters in order to conduct the optimization (Šimunek et al. 2012). The optimization is sensitive regarding the initial parameters. Generally, multiple trials for searching local minimum is recommended and the final solution cannot be guaranteed as the global minimum (Šimunek et al. 2012). Different reliable calibration methods were coupled with HYDRUS-1D (Zhang et al. 2010; Wöhling et al. 2008; Singh and Wallender 2011; Jacques et al. 2012). This study indicated that a multi-objective algorithm showed superior efficiencies and

results in a complicated model system. Therefore, a multi-objective algorithm was coupled with HYDRUS-1D to improve the calibration and this is described below.

PA-DDS is a multi-objective optimization algorithm which combines Dynamically Dimensioned Search and Pareto Archived Evolution Strategy (Asadzadeh and Tolson 2013). PA-DDS was successfully applied to a wide range of water resources engineering problems including watershed model calibration, reservoir operation, and water distribution network design problems (Jahanpour et al. 2018; Asadzadeh et al. 2015; Asadzadeh et al. 2016). In addition, PA-DDS showed promising results in a previous study when comparing the optimized results against the values for the single objective Marquardt-Levenberg method (Wang et al. 2017 ). In this work calibration performance was evaluated by comparing measured and simulated soil moisture at the study site.

### 3.5.3 Calibration

HYDRUS-1D computational modules were coupled with PA-DDS by MATLAB (MathWorks 2016) for calibration. Calibration performance was evaluated using measured and simulated soil moisture at 50 cm depth in terms of the root mean square error (RMSE) (Hyndman and Koehler 2006) and the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe 1970). The five VGM model parameters were estimated for each of the two soil layers, which generated in a 10-dimensional optimization problem. The objective functions contained measured and simulated soil moisture:

$$Max: f_{(NSE: 50cm)}(X) = 1 - \frac{\sum_{i=1}^n [\theta_{mea}(t_i) - \theta_{sim}(t_i, X)]^2}{\sum_{i=1}^n [\theta_{mea}(t_i) - \bar{\theta}_{obs}]^2} \quad (9)$$

$$Min: f_{(RMSE: 50cm)}(X) = \sqrt{\frac{\sum_{i=1}^n [\theta_{mea}(t_i) - \theta_{sim}(t_i, X)]^2}{n}} \quad (10)$$

where  $f_{(NSE: 50cm)}(X)$  and  $f_{(RMSE: 50cm)}(X)$  are the fitness functions,  $X$  is the parameter vector including  $\theta_{mea}$  and  $\theta_{sim}$  which are the measured and simulated soil moisture at depths 50 cm,  $t_i$  is the time step that the  $i^{th}$  measurement is taken,  $N$  is the number of measurements.

The lower and upper limits of the VGM parameters (Table 3) were set based on the sensitivity of each parameters to simulation. The optimization trials were processed for 2000 solutions at each evaluation and four trials were computed. The solutions of the combined runs generated a total of 8000 solutions. The local optimal solution was chosen from the trade-off line based on Pareto Front points.

Table 3. Lower and upper boundary for soil parameters

| Soil samples | Layers | $\theta_r$ [cm <sup>3</sup> cm <sup>-3</sup> ] | $\theta_s$ [cm <sup>3</sup> cm <sup>-3</sup> ] | $\alpha$ [cm <sup>3</sup> cm <sup>-3</sup> ] | n [cm <sup>3</sup> cm <sup>-3</sup> ] | Ks [cm d <sup>-1</sup> ] |
|--------------|--------|------------------------------------------------|------------------------------------------------|----------------------------------------------|---------------------------------------|--------------------------|
| W506-1 Top   | Upper  | 0.080                                          | 0.450                                          | 0.01                                         | 1.700                                 | 18.279                   |
|              | Lower  | 0.060                                          | 0.350                                          | 0.001                                        | 1.300                                 | 12.541                   |
| W506-1 Cover | Upper  | 0.050                                          | 0.420                                          | 0.03                                         | 1.800                                 | 10.562                   |
|              | Lower  | 0.040                                          | 0.380                                          | 0.010                                        | 1.400                                 | 6.938                    |
| W506-2 Top   | Upper  | 0.050                                          | 0.450                                          | 0.010                                        | 1.800                                 | 18.000                   |
|              | Lower  | 0.040                                          | 0.397                                          | 0.0010                                       | 1.400                                 | 12.507                   |
| W506-2 Cover | Upper  | 0.060                                          | 0.340                                          | 0.030                                        | 1.600                                 | 9.906                    |
|              | Lower  | 0.050                                          | 0.320                                          | 0.010                                        | 1.200                                 | 8.000                    |
| W506-3 Top   | Upper  | 0.070                                          | 0.450                                          | 0.010                                        | 1.700                                 | 19.00                    |
|              | Lower  | 0.060                                          | 0.390                                          | 0.0010                                       | 1.300                                 | 15.954                   |
| W506-3 Cover | Upper  | 0.050                                          | 0.420                                          | 0.030                                        | 1.650                                 | 13.930                   |
|              | Lower  | 0.040                                          | 0.380                                          | 0.010                                        | 1.400                                 | 8.710                    |

The soil moisture content at 50 cm depth was used as the reference to assess the outputs of the three vadose-zone models. Since this research focused on cold region application, the soil temperature at the observation point was another critical parameter requiring calibration. Unfortunately, soil temperature sensors were not installed at the study site. Therefore, calibration does not include soil temperature data.

### 3.6 Results

#### 3.6.1 Sensitivity Analysis

The sensitivity of the parameters from the VGM model  $\theta_r$ ,  $\theta_s$ ,  $\alpha$ ,  $n$ , and  $K_s$  were evaluated during sensitivity analysis. The residual and saturated soil moisture content had the smallest impact on soil moisture estimation, while the parameters  $\alpha$  and  $n$  forced large variations (Figure 4). The VGM parameter  $\alpha$ , which was altered by -0.005 and +0.005, resulted in soil moisture variation by means of RMSE of 0.34 and 0.40 and NSE of 0.87 and 0.73 comparing to the initial simulated moisture at baseline. The VGM parameter  $n$  was altered by -0.15 and +0.15, which was approximately 10% of initial value. The soil moisture varied in terms of RMSE by 0.48 and 0.30 and NSE by 0.77 and 0.82 compared to the baseline. The impact of hydraulic conductivity  $K_s$  can be considered relatively minor compared to  $\alpha$  and  $n$ .



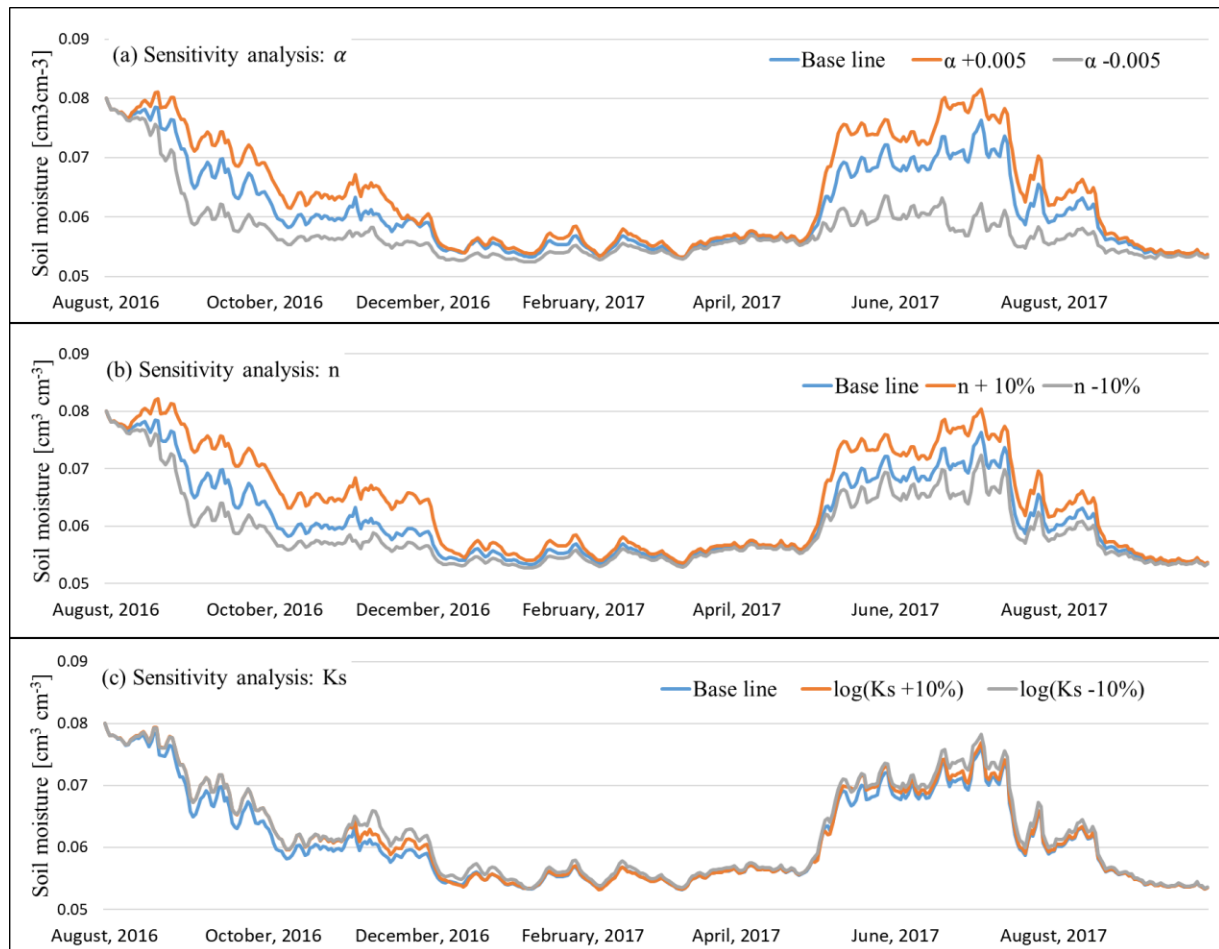


Figure 4. (a), (b), and (c): Sensitivity of  $\alpha$ ,  $n$ , and  $K_s$  on soil water content at 50 cm depth at W506-2

As shown on Figure 5, the measured air temperature reached below  $0^{\circ}\text{C}$  at 2016-11-15 and raised above  $0^{\circ}\text{C}$  until 2017-03-21. The simulated soil temperature at 50 cm reached below  $0^{\circ}\text{C}$  from 2016-11-24 and rose above  $0^{\circ}\text{C}$  at 2017-4-10 (Fig. 5). During this period, four Chinook events were measured, which occurred on 2017-01-18, 2017-01-28, 2017-02-13 and 2017-02-23. However, the soil temperature at 50 cm were still below  $0^{\circ}\text{C}$  during Chinook event and soil remained as partially or fully frozen. Therefore, measured soil moisture content required evaluation due to the measurements accuracy when soil temperature reached below  $0^{\circ}\text{C}$  at measured depth.

For the unfrozen water content, the water stored in porous media passed the freezing point and soil moisture content represented the freezing process as a rapid drying behavior in the soil. The semi-empirical equation (Equation 1) was used to calculate the unfrozen water content. The unfrozen water content varied from 3.8% to 6.2% based on Equation (1). The fully frozen temperature for soil was assumed as  $-12^{\circ}\text{C}$ , the frozen point was assumed at  $-0.15^{\circ}\text{C}$ , and the value for unfrozen water content was set as 3.8% based on Kozłowski (2007). The simulated soil temperature from HYDRUS-1D was used for calculation of unfrozen water content. As Figure 5 shown, the soil temperature reached below  $0^{\circ}\text{C}$  from 2016-11-24 and remained below  $-10^{\circ}\text{C}$  until the largest chinook event occurred at 2017-01-28. The unfrozen soil moisture content was constant at value of 3.8% while the soil temperature below  $-10^{\circ}\text{C}$ . During the Chinook event, the soil temperature at 50 cm slightly increased and reached to  $-5^{\circ}\text{C}$ . The soil temperature reached above the thawing point on 2017-4-10 and soil moisture content represented the thawing process as a rapid wetting behavior in the soil. The unfrozen water content based on Equation (1) showed minor changes during this winter period and it was not able to calculate the unfrozen water content change due to the infiltration process during Chinook events. Therefore, the unfrozen water content was only applied to revise the measured soil moisture before the Chinook event.

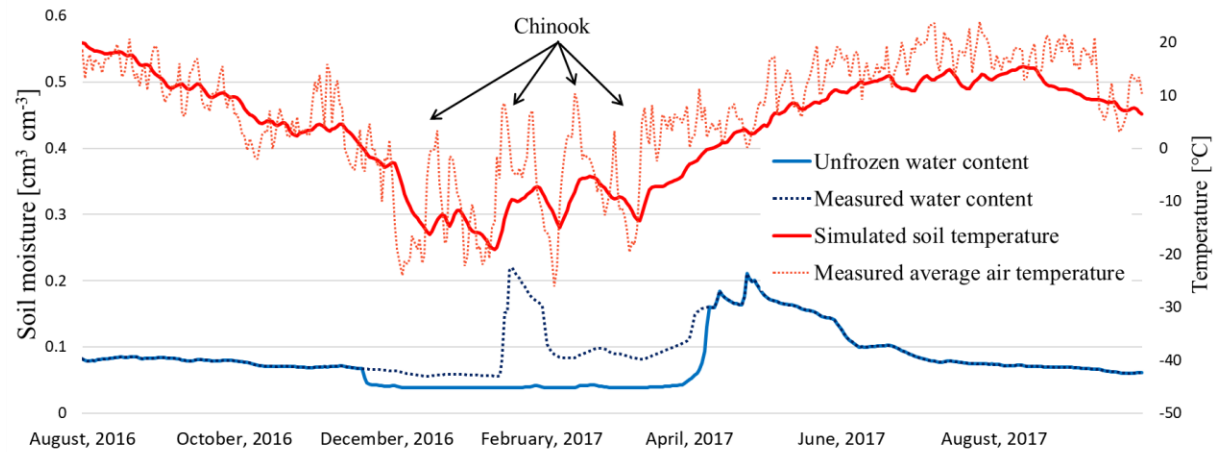


Figure 5. Air temperature and unfrozen soil water content at 50 cm depth

### 3.6.2 Calibration

The calibration process compared simulated soil moisture by HYDRUS-1D with the measured one through PA-DDS. The soil moisture content in the winter period had to be removed from the calibration process since the data were not measured directly but indirectly estimated using the semi-empirical equation from Kozłowski (2007). The difference in simulated and measured soil moisture showed large variation in different soil samples (Table 4).

Table 4. VGM parameter calibrated by PA-DDS

| Soil samples | Layers | $\theta_r$<br>[cm <sup>3</sup> cm <sup>-3</sup> ] | $\theta_s$<br>[cm <sup>3</sup> cm <sup>-3</sup> ] | $\alpha$<br>[cm <sup>3</sup> cm <sup>-3</sup> ] | n<br>[cm <sup>3</sup> cm <sup>-3</sup> ] | Ks<br>[cm day <sup>-1</sup> ] | RMSE  | NSE   |
|--------------|--------|---------------------------------------------------|---------------------------------------------------|-------------------------------------------------|------------------------------------------|-------------------------------|-------|-------|
| W506-1       | Top    | 0.060                                             | 0.425                                             | 0.001                                           | 1.446                                    | 18.0                          | 0.037 | 0.260 |
|              | Cover  | 0.047                                             | 0.380                                             | 0.015                                           | 1.334                                    | 8.5                           |       |       |
| W506-2       | Top    | 0.045                                             | 0.400                                             | 0.002                                           | 1.705                                    | 17.7                          | 0.003 | 0.680 |
|              | Cover  | 0.055                                             | 0.332                                             | 0.020                                           | 1.471                                    | 8.3                           |       |       |
| W506-3       | Top    | 0.069                                             | 0.424                                             | 0.007                                           | 1.415                                    | 14.4                          | 0.038 | 0.150 |
|              | Cover  | 0.048                                             | 0.391                                             | 0.016                                           | 1.500                                    | 13.0                          |       |       |

The simulated soil moisture based on soil samples from W506-1, W506-2, and W506-3 was compared with the measured soil moisture (Table 4). The difference between simulated and measured soil moisture noted by the RMSE was 0.037 and the NSE became 0.260 for soil sample W506-1, RMSE of 0.003 and NSE of 0.680 for W506-2, and RMSE of 0.038 and NSE of 0.150 for W506-3. Therefore, the soil samples from W506-2 showed better agreement with the measured data and was used for further analysis. However, all simulated results were not able to represent the large fluctuation that was caused by the Chinook event, which can be measured from 2017-01-18 to 2017-02-13. There were three potential causes that could lead to these results 1) the precipitation/snowfall data during the winter period were not correctly recorded, 2) the capability of calibration algorithm, and 3) the simulation ability of the chosen vadose zone model during freeze-thaw event.

### 3.6.3 Simulation of Soil Moisture

A total precipitation of 12.6 mm was recorded from 2016-11-03 to 2017-03-15 by the weather station. The precipitation recorded at Okotoks station during the same period showed 106.6 mm including 90.2 cm as snowfall (snow water equivalent of 90.2 mm). Although snowfall can be affected by location, the snowfall data measured at Okotoks station should be relatively similar with the study site in High River. Therefore, there were three different precipitation/snowfall scenarios simulated the influence caused by the weather data: 1) using the measured precipitation/snow by the onsite HOBO™ weather station, 2) manually adding certain amount of precipitation/snow to match the soil water observation, and 3) using snowfall data from the nearby Okotoks station.

As Figure 5 shown, the simulated water content (SWC) with measured precipitation/snowfall data in study site had a relatively constant value during the whole winter period. The SWC was around 7 % that slightly changed during the Chinook event. By manually adding a total of 21 cm snowfall, 15 cm before 2017-01-16 and 6 cm after the Chinook event, the soil moisture simulated by HYDRUS-1D became similar to the measured one, specifically at the peak flux during Chinook and early spring snowmelt. However, after the Chinook event, the SWC decreased slower compared to the measured one. By using the snowfall data from Okotoks station, the SWC by HYDRUS-1D increased during the Chinook event but was over-predicted in other periods. The SWC from Okotoks rapidly increased during early spring and the soil was almost saturated due to snowmelt (Fig. 6). All three different amounts of precipitation/snow were used for numerical simulation to represent soil moisture behavior. The comparison results showed that the ability to simulate water movement was limited with fully or partially frozen soil.

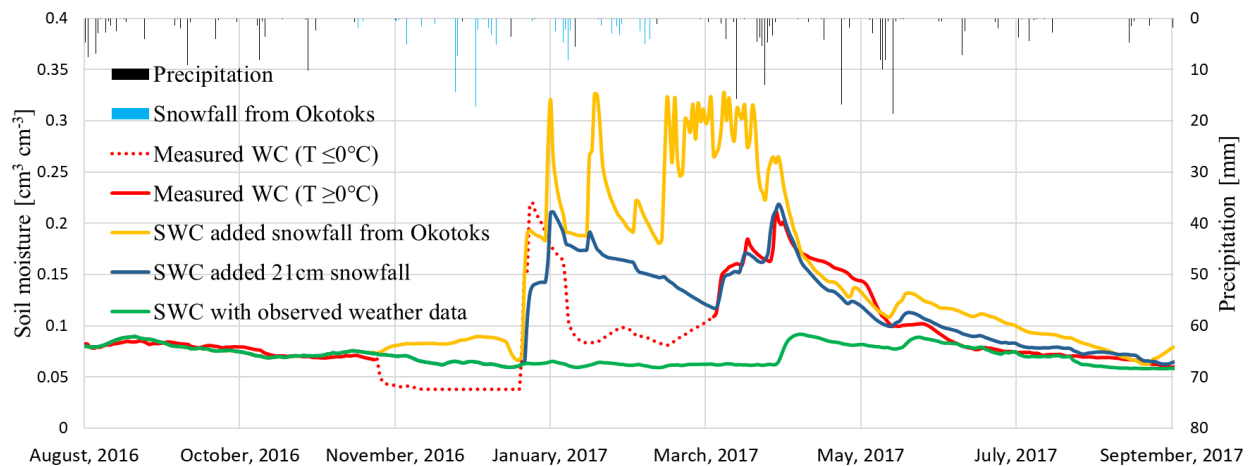


Figure 6. Simulated soil moisture with different precipitation data by HYDRUS-1D

Following the same procedure, three different precipitation/snowfall were used for simulation and the SWC by GeoStudio showed similar behavior (Figure 7). However, comparing the results from HYDRUS-1D by adding 21 cm of snowfall, the SWC showed an over-predicted peak during the Chinook event and under-predicted water content during the thawing period. In addition, with the snowfall data from Okotoks station, the soil reached full saturation during the Chinook event and early spring.

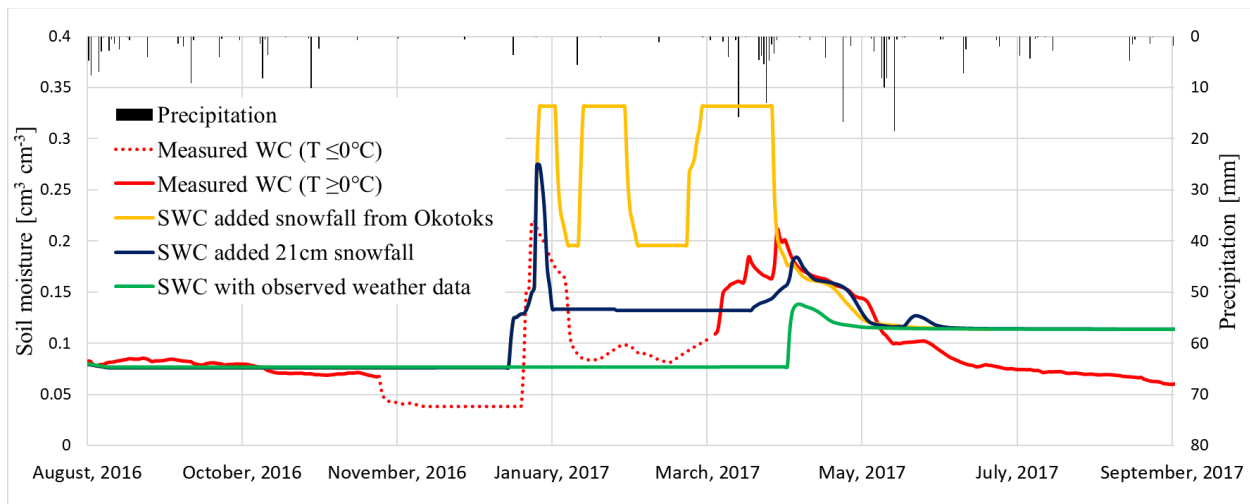


Figure 7. Simulated soil moisture with different precipitation data by GeoStudio

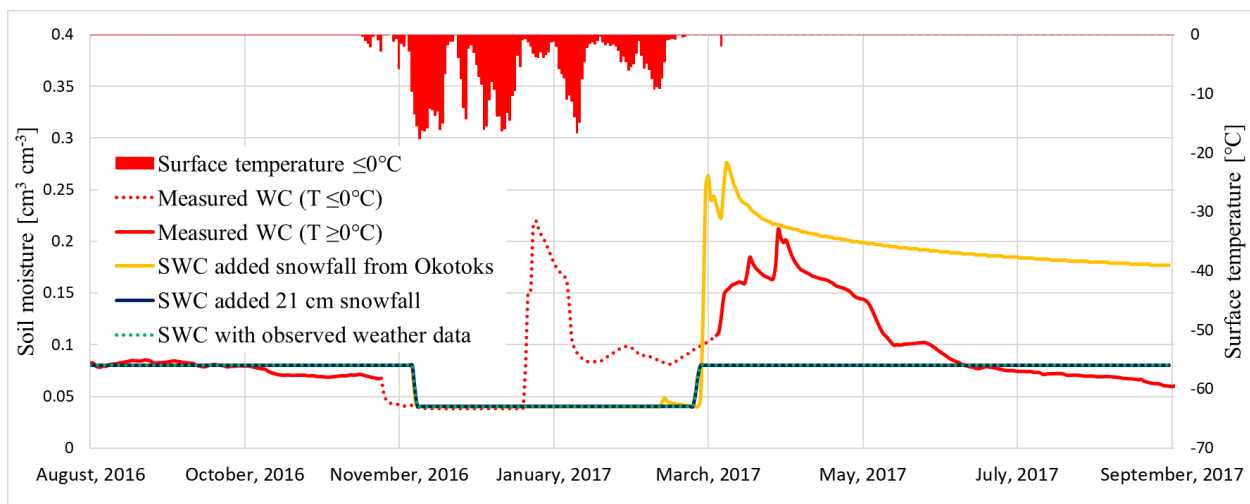


Figure 8. Simulated soil moisture with different precipitation data by SABAE-HW

For SABAE-HW, the SWC with the measured weather data showed a constant 8% water content from 2016-08-02 to 2016-12-07 (Figure 8). On 2016-12-08, the simulated temperature passed the freezing point and soil moisture content represented the freezing process as a rapid drying behavior in the soil. The soil moisture content remained at 4% constantly during the period when the surface temperature was below 0°C. On 2017-04-01, the soil moisture reacted on the thawing period and reached 8% and was constant until the end of the simulation. By adding 21 cm of snowfall, the simulation results showed the same soil moisture with SWC with measured weather data. By adding snowfall data from Okotoks station, the simulated soil moisture showed lower values compared with the HYDRUS-1D results. Specifically, the soil moisture did not represent the peak flux during the Chinook event with three different amounts of precipitation/snow added. The key reason was the simulated soil surface and snow layer temperature was below 0°C. The amount of water from precipitation/snow did not infiltrate into soil layer and remained as snow layer above surface.

The total percolation estimated during the measured period was simulated as 79.6 mm by HYDRUS-1D, 86.2 mm by GeoStudio, and 101.1 mm by SABAE-HW at the end of the simulated soil column. HYDRUS-1D and GeoStudio showed relatively similar overall percolation, while the GeoStudio had slightly higher rates in April 2017. SABAE-HW predicted negligible percolation during the winter period with a large peak value occurring during the spring thawing period. In addition, the SABAE-HW simulated percolation in May and June 2017, which matched with the major precipitation events.

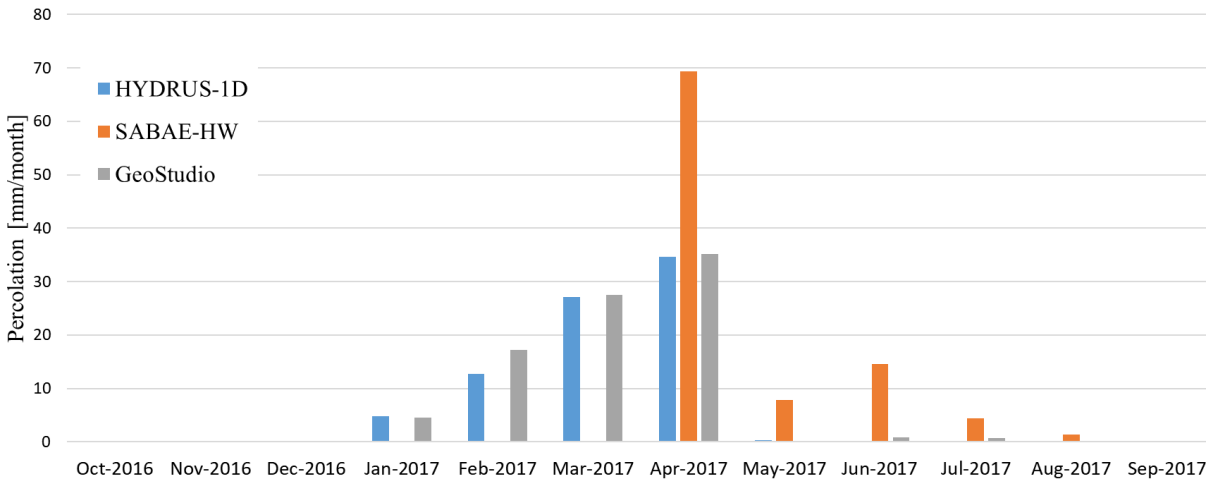


Figure 9. Monthly estimated percolation distribution from different models

### 3.7 Discussion

#### 3.7.1 PA-DDS Calibration

By coupling PA-DDS with HYDRUS-1D, a new and simple calibration method was developed, since the PA-DDS required fewer trials and was not affected by the initial parameters. The sensitivity analysis was used to determine the impact and variation of soil moisture by altering the VGM parameters. The results from sensitivity analysis lowered uncertainties of different soil parameters by reducing the range of values. Therefore, this method is for better heuristic searching and estimating the upper and lower limits of different parameters.

In this study, the calibration was only achieved before the Chinook events. The rest of the time, SWC did not represent any large fluctuation caused by Chinooks. Also, the SWC did not represent the soil moisture in a rapidly ascending/descending freeze/thaw phase change. The simulation was either numerically unstable or showed constant values when PA-DDS was used to calibrate over the whole simulation period. There were two potential causes that could lead to



these results. First, the results were not guaranteed as the global optimal solution with limited iteration, and the algorithm may require multiple trials. Second, the simulation ability of the chosen vadose-zone model (HYDRUS-1D) was limited and could not represent the water movement through the frozen soil. Note the calibration was performed with four trials and 2000 solutions each time to avoid the limitation of the algorithm itself. Therefore, the key reason for not matching SWC was the limited simulation ability of the vadose-zone model during freeze-thaw event.

The input data, specifically the snowfall data had a significant influence on the choice of the vadose-zone model. Since the weather station had limited performance of measuring snowfall, there were three different precipitation/snowfall scenarios simulated to evaluate the influence caused by the weather data: 1) the measured precipitation/snow by weather station in study site, 2) manually added 21cm of precipitation/snow, and 3) added snowfall data from Okotoks station. By manually adding additional 21 cm of snowfall to measured precipitation, the SWC had a better agreement with measured soil moisture comparing to the adding the precipitation recorded by the onsite and Okotoks weather stations (Figure 6). HYDRUS-1D showed better agreement compared to GeoStudio. Especially, the SWC simulated by HYDRUS-1D and GeoStudio showed a large flux during Chinooks and spring snowmelt events. However, the added amount of precipitation/snowfall was unrealistic compared to the recorded data from the closest weather station. Meanwhile, even the simulation by adding certain amounts of snowfall showed higher agreement with observation soil moisture. HYDRUS-1D and GeoStudio were still not being able to accurately simulate rapidly drawdown of soil moisture during the freezing cycle, as the soil moisture approaching to unfrozen water content after Chinook (event occurred at February 2017 of Figure 6 and 7). Therefore, the vadose-zone models, such as HYDRUS-1D and GeoStudio

over-predicted the infiltration due to the limited numerical representation and simplified soil water movement during the snowmelt.

### 3.7.2 Comparison of three vadose-zone models

The performance of all three vadose-zone models was evaluated based on the comparison between measured and simulated soil moisture. The measured soil moisture required additional evaluation due to the unfrozen water content being altered during the phase change period. The unfrozen water is the water remaining in liquid form under partially frozen condition due to the suction between water and soil particles. During freezing, water stored in the porous media is crystallized to ice, yielding to a freezing front. It is well-known that this phenomenon generates suction as rapid upward water flow, which significantly reduces the water content at the freezing front (Beskow 1935; Edlefsen and Anderson 1943; Hansson et al. 2004). In this study, a semi-empirical equation from Kozlowski (2007) was used to calculate the unfrozen water content. There were three parameters in this equation that affected the accuracy: 1) the temperature when the soil is fully frozen, 2) the freezing point, and 3) the amount of water between soil particles that cannot be frozen. The chosen parameters to identify the unfrozen water content were based on laboratory work on silty clay (Akimov 1978). In addition, the soil temperature had large uncertainty since it was estimated by numerical simulation using HYDRUS-1D. The simulation results were based on measured thermal conductivity and volumetric heat capacities, which also depended on the frozen and unfrozen water content. The accuracy of this estimation remained uncertain since calibration was not possible due to missing data. This uncertainty impacted the time of the freeze-thaw cycle, the location of the freezing front, and the unfrozen water content. Therefore, the estimated frozen water content based on semi-empirical equation required further

calibration. Such a calibration should be based on laboratory measurements of soil samples from the study site.

The measured soil moisture showed large soil water fluxes during the Chinook event. The freezing front moved upward during the Chinook event, which reduced the suction and increased the water content and therefore the unsaturated hydraulic conductivity. In addition, the soil water content was below field capacity before reaching frozen condition due to the large transpiration effect during the early vegetation period. The soil moisture started at 8% in August and reached approximately 6% by the end of October 2016 and remained constant (Fig. 5). The HYDRUS-1D simulation also showed constant 6% soil moisture during the winter period. The soil was dry and had a larger infiltration rate compared to soil having high water content. This situation increased the infiltration and its rate under frozen condition due to limited amount of ice existing between particles. Therefore, the soil moisture measured during Chinook reached peak value for two days only and reduced rapidly after this thawing event. During the thawing period occurred in April, the soil moisture ascended slowly due to a small infiltration rate. Since some water remained in the soil after the Chinook event, the infiltration rate was lower compared to situations when the soil was drier.

For HYDRUS-1D, the simulated results showed influences from three aspects: 1) upper boundary condition, 2) vegetation types, and 3) soil hydraulic properties. The boundary condition used in the model simulation had an error and limitation due to complex heat transport process. Specifically, the heat flux at the upper boundary condition had a significant influence and was calculated based on air temperature. Thus, the air temperature was not equal to soil temperature at the interface to the snow layer. During the snow thawing, the heat transport process in the snow layer was not correctly described in the model since latent heat and sensible

heat was not considered in HYDRUS-1D. The actual surface temperature was affected by those processes but not been simulated by HYDRUS-1D. In addition, the model boundary considered snow accumulation at the soil surface when the temperature was negative. The amount of snowmelt during the time when the temperature reached above zero was based on the average air temperature change in each simulation step. This condition forced a certain delay of water infiltrating during thawing periods, which can be observed as the delay of the soil moisture peak during the Chinook event (Fig. 6). Therefore, the upper boundary in HYDRUS-1D did not fully represent the actual surface temperature and water infiltration during thawing periods.

The surface vegetation contained several species and different growth periods. There were several different surface vegetation types, and each had somewhat different characteristics. It is difficult to identify which type of vegetation dominates in the long term after establishment (Schaaf et al. 2011). The root growth season generally starts with the last day of  $-4^{\circ}\text{C}$  temperature (Allen et al. 1998). Thus, the root growth season was assumed to start on April 15<sup>th</sup> and ended on October 15<sup>th</sup>. The LAI requires detailed monitoring and varies for each vegetation species. Such detailed data were not available in this study. Therefore, this simulation was based on approximate LAI and soil cover fraction to calculate the actual amount of transpiration on daily basis. The surface vegetation also affected the root water uptake and the root density distribution. Therefore, the surface vegetation had a significant impact on the thawing process in early spring, which affected the accuracy of infiltration.

The soil properties were changed under the partially or fully frozen condition, which led to numerical difficulties on simulating the infiltration process during thawing and freezing periods. The soil hydraulic properties were affected by the apparent phase of the liquid. The temperature was used to represent the percentage of ice in the porous media, which affected the pore water

pressure. Therefore, the freeze-thaw process showed a similar behavior as drying and wetting. However, the soil water content changes due to the infiltration in partially frozen soil showed different behavior. For example, the simulated water content showed a slow descent after the Chinook event, but the measured water content showed a rapid decline (Fig. 6). Therefore, HYDRUS-1D did not consider the soil hydraulic properties changes while simulating the soil water content during freeze-thaw event.

The simulation for water movement in the soil by HYDRUS-1D and GeoStudio are based on Richard's equation and similar upper boundary condition for evapotranspiration estimation. Therefore, soil moisture behavior and estimated percolation were almost identical. GeoStudio showed two additional limitations: 1) root uptake and 2) matric suction. GeoStudio only identified the surface vegetation by LAI and height of vegetation. Both parameters were difficult to measure in this study area. Therefore, the simulated soil moisture showed variations only during the transpiration period. The hydraulic conductivity was defined as a function of matric suction as a polynomial spline with linear interpolation. The changes in matric suction will be significant if the hydraulic function was high non-linear, and it was difficult to interpolate between two points. In this case, the matric function was not able to represent hydraulic conductivity during a freeze-thaw event. The advantage of GeoStudio was the slightly enhanced Penman-Monteith method and the improved thermal property function. The enhanced Penman-Monteith method considered the surface reflection factor which improved the calculation of albedo factor. The thermal function defined as polynomial spline function of thermal conductivity with temperature changes. However, the temperature variation was large on daily basis. Therefore, the performance of this thermal function was limited. Also, GeoStudio was not able to perform any automatic calibration on soil hydraulic or thermal parameters, and it had a

limited finite discretization. In summary, HYDRUS-1D was superior when compared with GeoStudio, which can be considered as a good candidate for further analysis or improvement.

SABAE-HW was able to represent the unfrozen water content when the soil passes the freezing point. The soil water content is based on the Clapp and Hornberger model (Clapp and Hornberger 1978), which is an empirical equation for estimating unfrozen water content by altering the pore water pressure. In addition, SABAE-HW considered snowfall as an additional layer located on the surface. This feature is unique to the other models in this comparison. The estimation of the infiltration rate and the soil thermal properties in SABAE-HW is based on the results of the surface temperature. This improved the accuracy for estimating the upper boundary comparing to HYDRUS-1D and GeoStudio. However, the soil hydraulic properties in SABAE-HW are represented by the soil composition only, which limited the simulation ability for a complicated situation. Moreover, the thermal properties of soil, water, and snow were hard-coded so that there was no possibility to change them. The missing possibility to calibrate this parameter generally accumulates potential errors during simulations. In this research, the limitation due to the soil hydraulic and thermal properties in SABAE-HW was clearly visible in the simulation results (Fig. 8). The calculated snow layer temperature was below 0°C during the whole winter period, yielding to no melted snow as water infiltrating into soil layer. Also, during the thawing period, infiltration continued until June which was not reasonable based on the measured data.

HYDRUS-1D and GeoStudio estimated almost identical monthly percolation rates when adding measured snowfall from Okotoks station. The total percolation estimated by HYDRUS-1D is 0.1 mm with measured precipitation from the rain gauge, 16 mm with adding certain amounts of snowfall, and 79.6 mm by adding snowfall from Okotoks station. The ratio showed

there were 0%, 76% and 89% of snowfall as precipitation transferred to percolation in the three situations. GeoStudio showed a similar ratio. However, SABAE-HW showed no percolation during the winter period, which was in disagreement with the measured water content. The key reason was that the simulated snow melting water was considered as ponding water and the snow layer temperature remained below 0°C during the whole winter period, yielded no infiltration process.

Thus, HYDRUS-1D showed a higher agreement with measured data and the meteorological phenomenon compared to GeoStudio and SABAE-HW. In addition, the two key factors affecting the percolation in cold regions to investigate the performance of ET cover were the amount of snowfall and the early spring transpiration. The actual amount of snowfall can be reduced by controlling the surface runoff. By increasing surface slope grade, the effective surface runoff can reach 80% (Sheng 1988). As the percolation/snowfall ratio showed, transpiration impacted approximately 10% of total percolation caused by total snowfall. The impact of this factor was limited but requires further analysis with sufficient data. As result, the ET cover performance in our study area was highly dependant on the elimination of the snowfall from the surface.

### 3.8 Conclusion

The research investigated the performance of three vadose-zone models for the assessment of evapotranspiration cover in cold regions. All input data were from a low-cost weather station equipped with soil moisture sensors. The calibration process became simple and robust for VGM parameters by combining HYDRUS-1D with PA-DDS. All three models adequately estimated soil moisture during the vegetation period (2016-08 – 2016-11). HYDRUS-1D showed slightly better results compared to GeoStudio due to the finer element discretization and capability of calibration. In addition, HYDRUS-1D contained different surface vegetation types that improved

the infiltration estimation. However, both HYDRUS-1D and GeoStudio were missing the capability to simulate the behavior of frozen soil during the phase-change period. These two simulators showed high potential to overestimate the soil moisture variation under the cold climate due to changes of soil properties under frozen condition. SABAE-HW was able to predict the unfrozen water content while the soil passing the freezing point. However, the soil hydraulic properties in SABAE-HW were roughly represented by the soil composition, which limited its ability in complex soil conditions. In addition, there was no access to alter the thermal properties of soil so that the calibration was impossible. The limitation due to the soil properties in SABAE-HW was clearly represented after the thawing period. Overall, the performance of all three models required further calibration with soil temperature. As a result, the SABAE-HW showed higher potentials to be applied in further ET cover assessment in cold regions, but the performance of this vadose-zone model requires further investigation.

Assessment of ET cover based on soil moisture observations showed limitations. The measured soil moisture content varies due to the freezing front and accuracy of soil sensor required calibration for specific soil samples. The semi-empirical equation used in this research can only estimate the unfrozen water content in steady state. The actual water content during the infiltration of partially frozen soil was difficult to identify due to the complex heat transfer and absorption process between particles and water. A soil moisture sensor in deeper depth is recommended in further studies to avoid the large variation caused by a freeze-thaw event. Furthermore, SABAE-HW had higher potentials to be applied in future analysis with proper update, such as rewritten code for option to modify thermal properties of soil.



#### 4. Recommendations for Future Research

- The soil moisture sensors and the semi-empirical equation used for calculating frozen water content required calibration. Those calibrations should be based on laboratory measurements for the soil samples in the study area.
- Additional soil moisture and temperature sensors should be installed in a transect along the landfill slope.
- The performance of HYDRUS-1D and SABAE-HW can be calibrated based on the soil temperature data and validated for the selected model based one year or longer time period of meteorological and soil data.
- The possibility of snow drifting should be investigated through a detailed site assessment.
- Snow accumulation and snow measurement should be performed to provide sufficient data for future analysis.
- Simulation of lateral flow and surface runoff along a 2D transect.
- SABAE-HW source code should be rewritten for the accessibility to change default thermal parameters of air, water, and soil.

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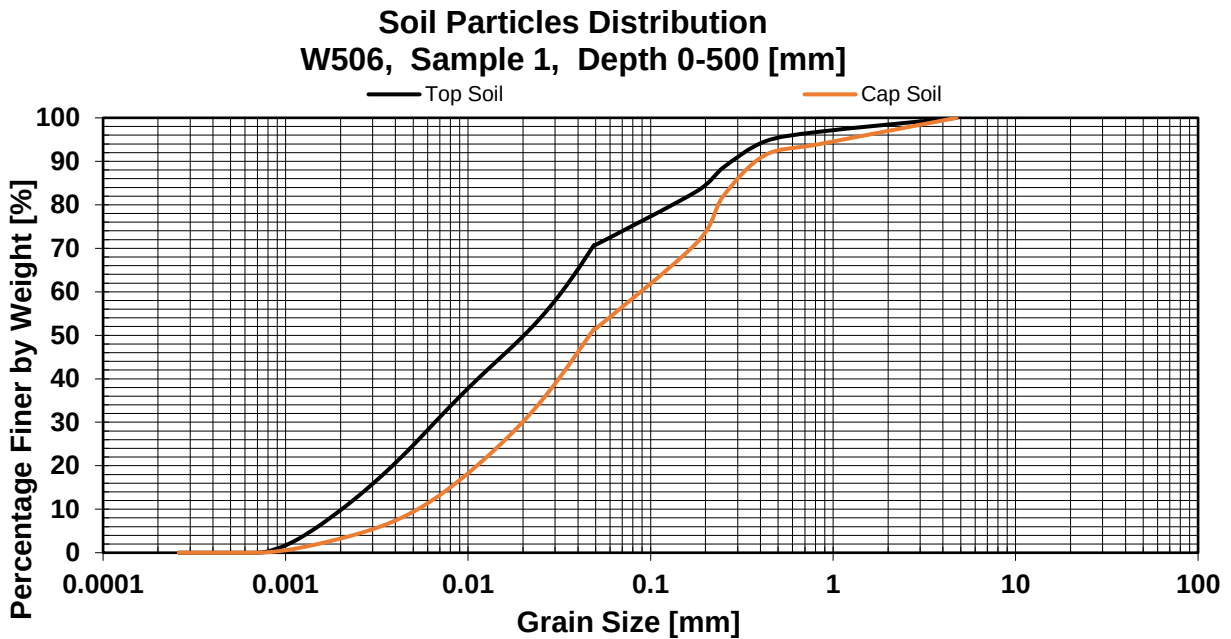
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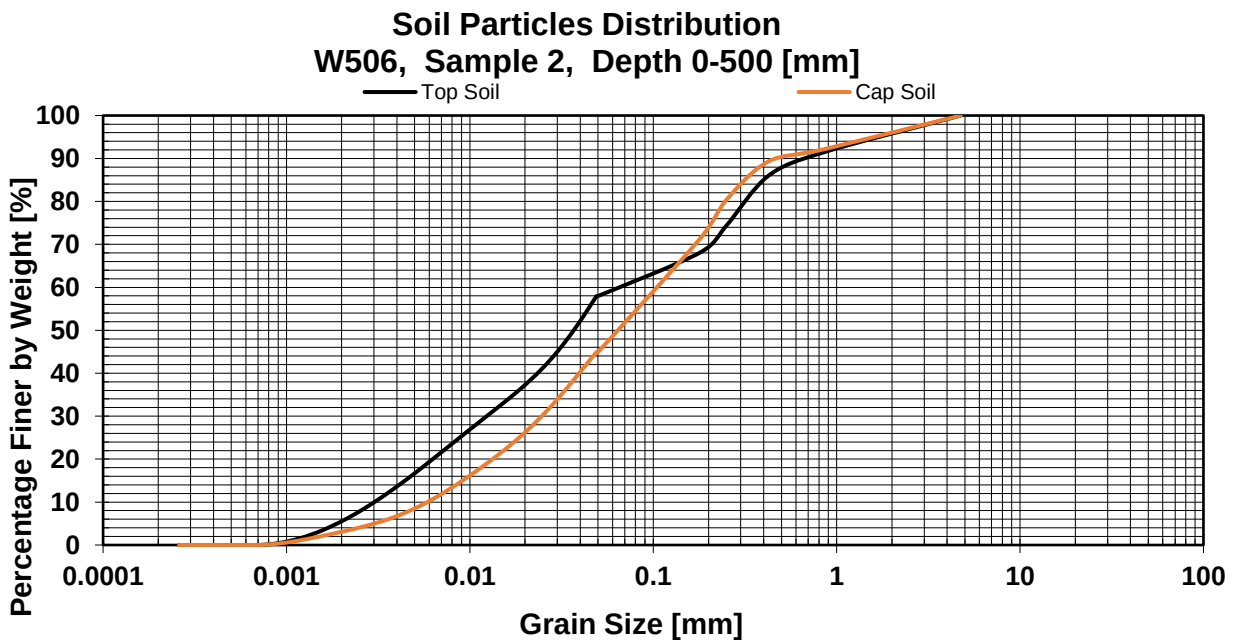
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## Appendix I Soil Particles Distribution



Appendix I.1: Soil particle sizes, W506-1, depth 0-500 mm





**Soil Particles Distribution**  
**W506, Sample 3, Depth 0-500 [mm]**

