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Determination of Unsaturated Hydraulic Properties for Low Impact Developments

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ABSTRACT
With the increase in extreme rainfall events and rapid urbanization, the risk of flooding has increased substantially. Low Impact Developments (LIDs) can assist in decreasing this risk within certain areas. The soil is generally considered to be completely saturated when designing for the LIDs. However, this may not always be an accurate or realistic approach, as the soil could be variably unsaturated leading to inaccurate designs. To analyze the flow under variably unsaturated conditions, Richards' equation can be used. In order to solve the Richards' equation, two nonlinear hydraulic properties namely, soil water characteristic curve (SWCC) and the unsaturated hydraulic conductivity function are required. Laboratory and field measurements of unsaturated hydraulic properties are cumbersome, expensive and time-consuming. An alternative approach is to estimate unsaturated hydraulic properties using pedotransfer functions. Pedotransfer functions estimate soil hydraulic properties using routinely measured soil properties, such as soil texture, grain size distribution, bulk density, or porosity. This research presents a comparison between the direct measurement obtained through experimental procedures and the use of pedotransfer functions to estimate soil hydraulic properties for two green roof and three bioretention soil medias. Design implications are also part of this research effort.

RÉSUMÉ
Avec l'augmentation des épisodes pluvieux extrêmes et l'urbanisation rapide, le risque d'inondation a considérablement augmenté. Les développements à faible impact (LID) peuvent aider à réduire ce risque dans certains domaines. Le sol est généralement considéré comme complètement saturé lors de la conception des LID. Cependant, il ne s'agit pas toujours d'une approche précise ou réaliste, car le sol peut être insaturé de façon variable, ce qui conduit à des conceptions inexactes. Pour analyser l'écoulement dans des conditions d'insaturation variable, l'équation de Richards peut être utilisée. Afin de résoudre l'équation de Richards, deux propriétés hydrauliques non linéaires, à savoir la courbe caractéristique de l'eau du sol (SWCC) et la fonction de conductivité hydraulique insaturée sont nécessaires. Les mesures en laboratoire et sur le terrain des propriétés hydrauliques insaturées sont lourdes, coûteuses et longues. Une autre approche consiste à estimer les propriétés hydrauliques insaturées à l'aide des fonctions de pédotransfert. Les fonctions de pédotransfert estiment les propriétés hydrauliques du sol en utilisant des propriétés du sol mesurées en routine, telles que la texture du sol, la distribution de la taille des grains, la densité apparente ou la porosité. Cette recherche présente une comparaison entre la mesure directe obtenue par des procédures expérimentales et l'utilisation des fonctions de pédotransfert pour estimer les propriétés hydrauliques du sol pour deux toitures végétalisées et trois milieux de sol à biorétention. Les implications de conception font également partie de cet effort de recherche.

1 INTRODUCTION

With the increase in urbanization, the risk of flooding rises due to the increase in impervious surfaces. Climate change has also resulted in an increase in both intensity and frequency of extreme rainfall events leading to a higher probability of flooding. To counter the impacts of urbanization and climate change, engineers have developed ingenious solutions to reduce flooding and capture contaminants through the use of Low Impact Developments.

Low Impact Developments (LIDs) are defined as a stormwater management strategy that aims to mitigate the impacts of increased runoff and stormwater pollution by managing runoff as close to its source as possible (U.S. EPA, 2007). With LIDs, stormwater can be treated as a resource in helping to preserve and recreate natural landscapes, rather than as a waste that needs to be re-routed from its source (U.S. EPA, 2018). LIDs assist in developing sustainable cities and include systems such as permeable pavements, green roofs, bioretention cells, rain barrels and so on.

When designing for LIDs, it is traditionally assumed that the substrate is completely saturated allowing for the use of Darcy's equation. One key reason for assuming saturated conditions is possibly due to the difficulty in obtaining the unsaturated hydraulic properties or the lack of adequate modelling tools (Brunetti et al. 2016).

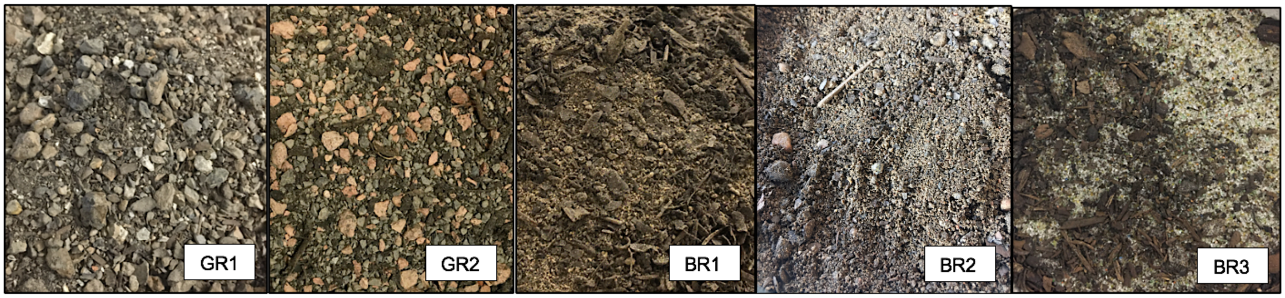

Figure 1: Two green roof and three bioretention substrates used in this study

However, with the assumption of saturated conditions, the use of Darcy's equation may lead to inaccurate results such as ponding or overflow within the soil media (Liu and Fassman-Beck, 2017).

Furthermore, it is more likely that unsaturated flow dominates in both green roof and bioretention systems, rather than saturated flow. Even though bioretention systems are designed for ponded conditions, it is noted that unsaturated conditions would prevail as most individual rainfall events are generally smaller than the design storm (Liu and Fassman-Beck, 2017). Green roofs, on the other hand, are not designed for ponded conditions as this will lead to an additional load to the building structure (Perelli, 2014). Therefore, green roof substrates are designed to have a saturated hydraulic conductivity larger than peak intensities to avoid ponding, thus decreasing the likeliness of saturated conditions.

Due to the difficulty in measuring the unsaturated hydraulic properties, some LID studies utilize estimated hydraulic properties which can lead to inaccurate results (Li & Babcock, 2015). An alternative approach is the use of pedotransfer functions. Pedotransfer functions estimate soil hydraulic properties using routinely measured soil properties, such as soil texture, grain size distribution, bulk density, or porosity. However, as LIDs are constructed with engineered materials that vary from place to place, the hydraulic properties for each individual design can vary. Factors such as field compaction, organic content, root growth and age can also impact the hydraulic properties and are crucial for accurate modelling (Li & Babcock, 2015). With improved accuracy, the models can assist in quantifying the impact of climate change or LID design, such as the optimal substrate depth that provides the best retention.

This research aims to assess the performance of various pedotransfer functions in predicting hydraulic properties of LID materials. The saturated hydraulic conductivity was measured using the constant head test. The soil water characteristic curves of two green roof and three bioretention soil medias were measured using the HYPROP measurement system (UMS, 2015). Regression models, physicoempirical models, and artificial neural network were the three types of PTFs used to predict the hydraulic properties in this study. This study also presents numerical modelling to highlight the importance of accurate representation of soil hydraulic properties in the assessment of LID facilities. Numerical modelling was carried out using HYDRUS-1D (Šimůnek et al. 2008). Thirty years of historic climate data for Toronto was used in numerical modeling.

2 THEORY

Richards' equation (1931) is utilized to describe the uniform flow of water under unsaturated conditions. Equation 1 shows the Mixed Form of Richards' equation for one-dimensional vertical flow,

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\psi)\left(\frac{\partial\psi}{\partial z} - 1\right)\right], \qquad [1]$$

where θ is the volumetric water content, ψ is the soil water pressure, z is the vertical coordinate, t represents time, and $K(\psi)$ is the unsaturated hydraulic conductivity which is the function of the soil water pressure.

In order to solve the Richards' equation, two nonlinear hydraulic properties are required. These are, the soil water characteristic curve (SWCC) and the unsaturated hydraulic conductivity function. The SWCC is the relationship between water content and pressure. Whereas the unsaturated hydraulic conductivity demonstrates a relationship of hydraulic conductivity with water content, $K(\theta)$, or pressure, $K(\psi)$. As unsaturated conditions increase, meaning a reduction in water content as a result of increasing suction, there is a decrease in hydraulic conductivity due to flow paths becoming more tortuous and flow through smaller pores.

Various methods can be used to directly measure the SWCC. These include, using a hanging water column, pressure cells, pressure plate extractors, suction tables, soil freezing and others. Once a series of water content and pressure data point are measured for a porous medium, analytical functions such as van Genuchten (1980) function can be fitted to the data to represent the SWCC mathematically. The van Genuchten function can be described as:

$$S_e = \frac{\theta(\psi) - \theta_r}{\theta_s - \theta_r} = (1 + |\alpha\psi|^n)^{-(1-1/n)} \qquad [2]$$

where S_e is the effective water saturation, α and n are empirical parameters, and θ_r and θ_s are the residual and saturated volumetric water contents, respectively.

Analytical functions are fitted in order to assist in predicting the unsaturated hydraulic conductivity function. As direct measurement of unsaturated hydraulic conductivity can be both costly and time-consuming, these mathematical functions, along with the saturated hydraulic conductivity, can be utilized to predict the unsaturated hydraulic conductivity function.

3 MATERIALS AND METHODS

3.1 Physical Properties

Two green roof media (GR1, GR2) and three bioretention media (BR1, BR2, BR3) were characterized and their soil properties were determined. The five substrates are shown in Figure 1. Visual inspection indicated that, the green roof materials were coarser in comparison to the bioretention materials. The bioretention materials have a more uniform appearance with sand and wood chips being the most distinct constituents. Furthermore, the glass sand substrate (BR3) had a very strong odor indicating a large organic content.

Table 1 shows the measured organic content and specific gravity of the 5 substrates. The organic content was determined by placing the sample in a muffler oven set to 550°C for approximately 2 hours (ASTM D2974-14; Perelli, 2014). The addition of organic material acts as a lightweight component and is beneficial in decreasing the load on the green roof (Sandoval et al. 2017). Moreover, the organic material provides a large water storage volume (Li and Babcock, 2015) and helps deliver nutrients for plant growth (Sandoval et al. 2017).

Furthermore, it is noted that the addition of organic material also assists in the reduction of the soil density (Sandoval et al. 2017). As shown in Table 1, the specific gravities of the green roof media are smaller compared to the bioretention media. The specific gravity was determined using the pycnometer method (ASTM D854–14).

Table 1. Organic content and specific gravity of the tested media

Substrate	Organic Content (%)	Specific Gravity
GR1	7.03	2.02
GR2	5.16	2.24
BR1	5.06	2.80
BR2	6.80	2.70
BR3	7.81	2.36

To determine the particle size distribution curve (PSD), the sieve test and hydrometer test were performed. The PSD of all five substrates are shown in Figure 2. From the PSD, both green roof media contains a large percentage of gravel (>2mm) in comparison to the bioretention media, which is consistent with the visual inspection done initially. The bioretention materials contain a large percentage of sand (0.05 – 2 mm), with BR3 having 97% sand. All of the substrates analyzed were quite coarse and are expected to have high saturated hydraulic conductivity values leading to good drainage during flooding conditions.

3.2 Hydraulic Properties

3.2.1 Saturated Hydraulic Conductivity

To determine the saturated hydraulic conductivity, the constant head test was performed. In order to successfully measure the saturated hydraulic conductivity for these very coarse substrates, preparation of the sample was the key.

For this test, two side ports are installed into a compaction permeameter in order to attach the two open manometer tubes. A metal mesh and geotextile were placed at the bottom of the permeameter. The oven dried sample was split into four different bowls to help reduce the sample bias. To reduce segregation, water was added so that the sample reached a gravimetric water content of 2%. A packing procedure was adopted to avoid horizontal layering. When packing, the first lift was poured in and gently compacted. The top of the layer was then lightly scraped before pouring in the next lift to avoid horizontal layering of the sample. Once the permeameter was filled, the geotextile and metal mesh were placed at the top and then were sealed with an appropriate cover.

Carbon dioxide was passed though the permeameter to assist in flushing out the air. Once the sample has been flushed with CO_2, the permeameter was attached to a water reservoir and two manometers. In order to reduce air entrapment in the system, de-aired water was used. The saturated hydraulic conductivity was determined by obtaining the volumetric flowrate measured from the constant head test.

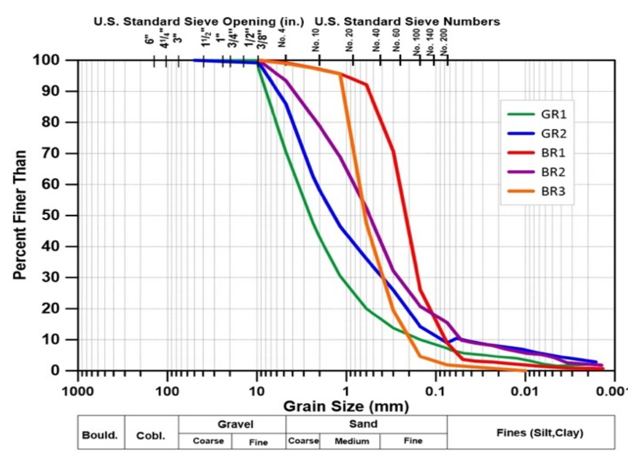

Figure 2. Particle size distribution curve of the substrates

3.2.2 SWCC

A popular method to measure the SWCC is the simplified evaporation method (Schindler, 1980). In this study, the HYPROP measurement system (UMS, 2015) which employs the evaporation method was used to measure SWCCs.

With the exception of the packing procedure, the measurements were made following the procedure as described by the manufacturer (UMS, 2015). For sample packing, a procedure similar to the one described for the hydraulic conductivity measurements was used. The sample was packed in three lifts. In order to reduce particle segregation during packing, the sample was wetted to a water content of 2%. The first lift is poured into the silver sample ring that is provided with the HYPROP equipment. The sample is compacted with 10 blows using a round shear box extruder and the side of the sample ring is tapped 5 times. The top of the layer was lightly scraped to avoid horizontal layering. Following a similar procedure, the second lift is poured into the sample ring. For the third lift, the excess sample at the top of the sample ring is scraped off with a straight edge.

3.3 Prediction of SWCC

For this study, 20 different pedotransfer functions (PTFs) were considered for each of the five substrates. Regression models, physicoempirical models, and the use of the artificial neural network were the three types of PTFs that were used to predict the SWCC. The ability of PTF to predict soil hydraulic properties of LID materials was assessed by comparing their predictions to measured hydraulic properties. Statistical analysis was used for these comparisons.

Guber and Pachepsky (2010) have developed a computer program, named CalcPTF, that utilizes regression equations to predict unsaturated hydraulic properties from routinely measured soil properties. CalcPTF contains 16 PTFs, where 7 estimate the Brooks and Corey (1964) parameters and 9 estimate the van Genuchten (1980) parameters. Depending on the PTF, soil inputs include the depth, the percentage of sand, silt, clay and organic content, the bulk density and the particle density.

Physicoempirical models utilize the particle size distribution to predict the SWCC as they are based on the similarity of shape. Arya and Paris (1981) model and the Modified Kovacs Model developed by Aubertin et al., (2003) are two physicoempirical models analyzed in this study.

Arya and Paris (1981) presented one of the first physicoempirical model and is especially preferred in practice as it works well with various soil types (Barbu, 2013). The Arya-Paris (AP) model divides the particle size distribution curve into fractions, where the larger particle sizes relate to a greater water content. The AP model attains the volumetric water content by estimating the pore volume and determines the soil pressure by converting pore radii using the capillary theory (Arya and Paris, 1981).

The other physicoempirical model analyzed is the Modified Kovacs (MK) Model developed by Aubertin et al., (2003). This model was found to work well with tailing materials, granular and cohesive soils (Fredlund et al. 2012). As the LID materials are highly granular, it is interesting to see if this model works well. The major difference between the MK model and the AP model is that the MK model only uses the coefficient of uniformity (C_u) from the particle size distribution, rather than directly using all of the points measured in the PSD. Moreover, both the capillary and adhesive saturation are considered to determine the amount of water held in the soil. In high suction ranges, the adhesive component would govern, whereas in the highly saturated range the capillary component would dominate.

Rosetta Lite DLL (Dynamically Linked Library) is a neural network prediction utility and is included within the HYDRUS software (Šimůnek et al. 2008) to help predict the van Genuchten (1980) parameters and saturated hydraulic conductivity (Schaap et al. 2001). Rosetta contains five models where the inputs depend on the data availability. The first model consists of a look up table for the textural class of the soil media being analyzed. The other four models use the percentage of sand, silt and clay along with additional inputs such as the dry density, the water content at 33 kPa and 1500 kPa suction values.

3.4 Statistical Analysis

The measured and predicted SWCC were compared using statistical analysis and through visual inspection. To confirm the validity of the statistical analysis, a visual inspection of the predicted to the measured data should also be completed (Schunn and Wallach 2005). To determine how well the trend in the data fit, the coefficient of determination (R^2) was calculated. Obtaining a R^2 of 1 refers to 100% of the predicted data matches the trend of the measured data. Nevertheless, a R^2 of 1 does not necessarily mean the predicted data matches the measured data. Thus, to determine the deviation from the actual value of the measured data, the mean square deviation (MSD) was estimated.

3.5 Modelling using HYDRUS 1D

The HYDRUS 1D software (Šimůnek et al. 2008) was used to evaluate the performance of the hydraulic properties from PTFs to the measured hydraulic properties. HYDRUS is a modelling software used in the analysis of water flow and solute transport in variably saturated soils. Thirty years of Toronto historical climate data was used for the analysis. In total, 8250 active days were modelled, where the active period represents the time when the ground is thawed thus allowing water to infiltrate into the soil. The inactive period is when the ground is frozen and the precipitation is in the form of snow.

The models for the bioretention medias were simulated with a 100 cm deep soil profile. A 15 cm soil profile was simulated for the green roof substrates, which corresponds to an extensive green roof (CVC and TRCA, 2011). The lower boundary condition was set to free drainage. The upper boundary condition was set to atmospheric boundary condition with a surface layer. Thirty years of daily records of precipitation and potential evaporation values constituted the atmospheric boundary. The allowable ponding was taken as zero for the green roof. On the other hand, bioretention are designed for ponded conditions as they cater to a greater catchment area in addition to precipitation that directly infiltrates the system. According to Credit Valley Conservation and Toronto and Region Conservation Authority (2011), the maximum ponding depth should be between 15-25 cm. Therefore, the allowable surface ponding was set to 20 cm in the models that were representative of bioretention facilities.

4 RESULTS AND DISCUSSION

4.1 Hydraulic Properties

The averaged saturated hydraulic conductivity (K_s) for the five LID media as well as their error bars are shown in Figure 3. Overall, the K_s measured for the green roof materials is one magnitude higher than the bioretention materials. These results are consistent with the PSD which shows that the green roof materials are coarser compared to the bioretention materials.

GR1 contains a greater percentage of gravel in comparison to GR2 resulting in slightly higher K_s due to the increased void space to assist in water mobility. On the other hand, the bioretention media is designed to undergo ponding and assist in the reduction of storm water pollutants in addition to flood prevention. Thus, to capture the contaminants whether through sorption, volatilization, or filtration, a lower K_s in comparison to the green roof media is preferred (Pitt et al. 1999).

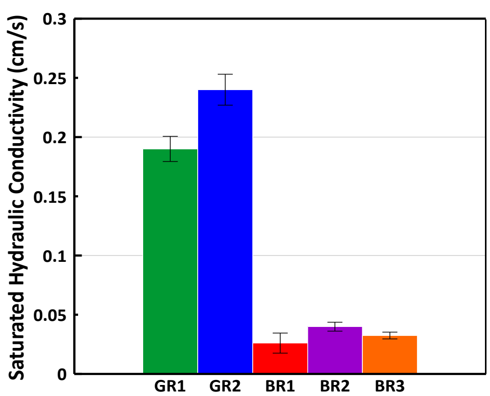

Figure 3. Averaged saturated hydraulic conductivity (K_s) values with error bars

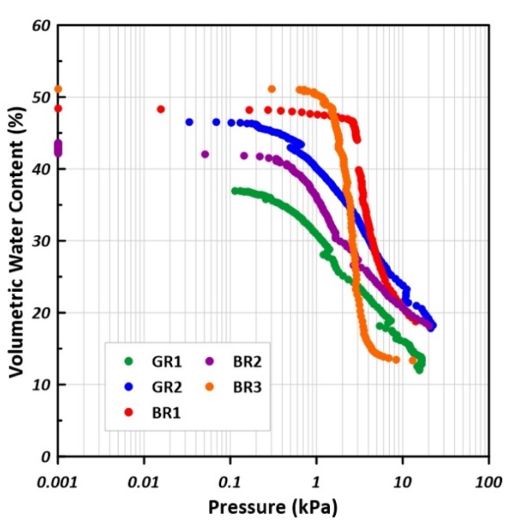

Figure 4. Soil Water Characteristic Curves (SWCC) for the five tested substrates

The SWCC for the 5 LID materials were measured using HYPROP and are illustrated in Figure 4. The fitted van Genuchten parameters to the measured SWCC data are presented in Table 2. The air entry value (AEV) is when air first enters the saturated soil. From Figure 4, it is observed that BR1 and BR3 have a larger AEV compared to the other substrates. From Table 2, the α parameter in the van Genuchten equation is roughly equal to the inverse of the AEV. The α parameter is smaller for the bioretention materials in comparison to the green roof materials, with the exception of BR2.

The n parameter presented in Table 2 correlates with the pore size distribution. A high n value signifies a narrow pore size distribution, leading to a steeper SWCC as the water content drains over a narrow suction range. As observed in Figure 4, both BR 1 and BR3 have steep curves, thus a greater n value. The green roof substrates have a smaller n value which allows the system to retain water over a greater suction range.

The water storage volume is determined by the difference between the saturated and residual water content. GR2 has the greatest available water and BR2 has the smallest. GR1 also contains a large water storage volume, however the saturated water content is much smaller in comparison to the other substrates. This may be due to not allowing the material to saturate long enough, thus not allowing for a completely saturated material during testing. The porosity of GR1 can further prove this, as it measured a porosity of 0.67. This demonstrates the difficulties in measuring the SWCC of these LID materials as they are very coarse and require time to properly saturate.

Table 2. Fitted van Genuchten parameters

Media	θ_s (cm^3/cm^3)	θ_r (cm^3/cm^3)	α (1/cm)	n
GR1	0.38	0.006	0.13	1.34
GR2	0.47	0	0.09	1.31
BR1	0.49	0.21	0.03	5.23
BR2	0.43	0.16	0.11	1.73
BR3	0.50	0.13	0.04	5.75

4.2 Predicted versus Measured SWCC

After conducting the statistical analysis of the predicted to the measured SWCC, it was found that some PTF methods work better for certain substrates compared to others. In general, the CalcPTF program and Rosetta better predicted the green roof materials used in this study in comparison to the bioretention materials. On the other hand, the AP method works better for the bioretention materials.

This observation can be seen in Figure 5, which compares the PTFs to the measured SWCCs for GR2 and BR2. As there is a large number of estimations that were considered from the CalcPTF program, the PTF developed by Vereecken et al. (1989) is shown in Figure 5 as it produced the closest prediction to the measured SWCC.

The statistical analysis for the selected PTF from the CalcPTF program as well as Rosetta, and both physicoempirical methods are presented in Table 3.

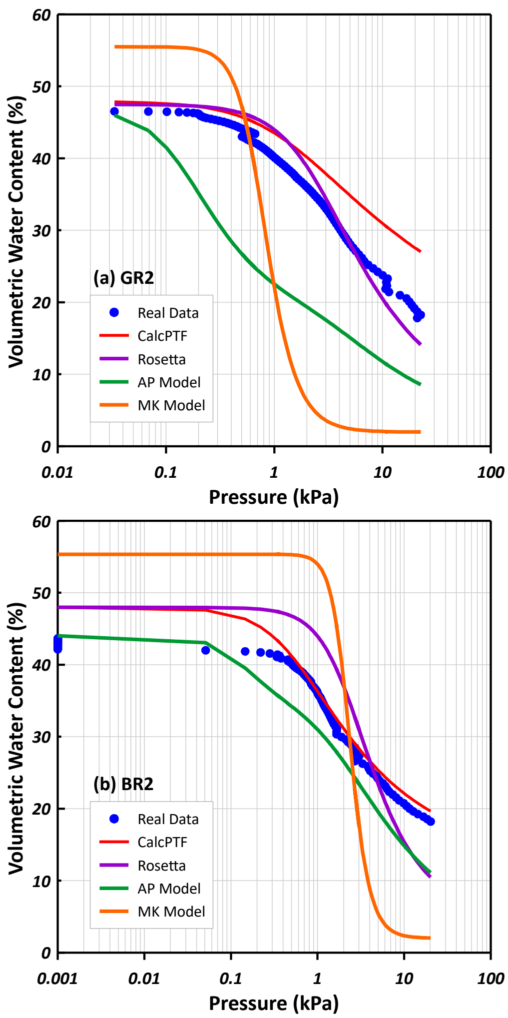

Figure 5. Comparison of predicted to measured SWCC for (a) GR2 and (b) BR2

Upon closer investigation, CalcPTF and Rosetta did poorly with the materials that contain the largest percentage of sand. This may lead to the conclusion that the PTFs are dependent on the percentage of the particle sizes. Nevertheless, it is important to note that both the CalcPTF program and Rosetta do not take into consideration the percentage of gravel.

Subsequently, as shown in Figure 5, the CalcPTF overestimates the saturated volumetric water content. This is due to the fact that the program calculates the porosity using the inputted dry bulk density and particle density. The AP method has a closer fit to the saturated water content as it uses the measured saturated water content to fit the predicted SWCC to the measured.

The MK model showed a very poor performance for the LID materials used in this study. This model uses the coefficient of uniformity, D_{10}, and D_{60} values from the PSD to perform the calculations. Whereas the AP method uses the complete measured PSD to estimate the SWCC, thus obtaining a better representation of the soil characteristics. Although the AP method performed better than the MK model for BR2, it did not predict the green roof media well. As the green roof media contains a large percentage of gravel, a gravel content correction would need to be applied as recommended by Barbu (2013).

Overall, the PTFs are not able to accurately estimate the SWCC of the engineered media. These substrates differ vastly when compared to natural, non-engineered soil as they are mixed to meet specific design criteria.

Table 3. Statistical analysis of the predicted SWCC

Media		Vereecken et al. (1989)	Rosetta	AP Method	MK Method
GR2	R^2	0.998	0.981	0.845	0.758
	MSD	24	7	216	399
BR1	R^2	0.233	0.806	0.622	0.780
	MSD	605	202	134	359
BR2	R^2	0.972	0.928	0.947	0.876
	MSD	6	40	21	239
BR3	R^2	0.322	0.927	0.971	0.329
	MSD	423	24	6	903

4.2.1 Predicting Hydraulic Conductivity

Pedotransfer functions are also used to estimate saturated hydraulic conductivity. Rosetta provides estimates for K_s in addition to estimates for water retention. Devlin (2015) has developed a program, called HydrogeoSieveXL, to estimate K_s from grain-size distributions curves using 15 different methods. Table 4 presents the estimated K_s from Rosetta and 6 methods included in the program by Devlin (2015). Note that the empty cells in Table 4 means that the material failed the criteria required for that model.

Table 4. Hydraulic conductivity estimates

Source	GR1	GR2	BR1	BR2	BR3
Measured	0.24	0.19	0.03	0.04	0.03
Rosetta	0.004	0.003	0.012	0.005	0.008
Terzaghi (1925)	0.004	0.001		0.001	0.031
Sauerbrei (1932)	0.025	0.004	0.008	0.001	0.044
Kozeny-Carmen (1953)	0.001	0.0003		0.0004	0.224
Zamarin (1928)	0.001	0.0002		0.0004	0.134
Barr (2001)	0.003	0.001	0.004	0.0004	0.025
Alyamani & Sen (1993)	0.25	0.067	0.003	0.006	0.018

Units for hydraulic conductivity are in cm/s

Overall, both Rosetta and the methods found in HydrogeoSieveXL underestimate the measured K_s for the

LID materials analyzed in this study. The predicted K_s underestimates the green roof substrates by a magnitude of 2 and the bioretention materials by a magnitude of 1. BR3 obtained the closest estimates, demonstrating that uniform-graded materials perform best when estimating using physicoempirical methods.

4.3 HYDRUS 1D Modelling Results

The water balance at the ground surface describes the water that moves across the soil-atmosphere boundary. Through the assessment of a water balance, relevant components such as water storage capacity, infiltration or drainage can be analyzed. This assists in the design and analysis of the substrates performance when used in LID applications.

Components of the water balance at the ground surface include precipitation (*P*), potential evaporation (*PE*), actual evaporation (*AE*), transpiration (*T*), surface run-off (*RO*), and net infiltration (*NI*). The *NI* refers to the amount of water that enters the soil and can be described as:

$$NI = P - AE - RO \quad [3]$$

The *AE* is also dependent on prevailing water quantity in nears surface soils layer and is therefore always less than the *PE*. Within HYDRUS, the *AE* is estimated by using a system-dependent atmospheric boundary condition at the top of the modeling domain. The potential flux is dependent on external conditions, such as precipitation or evaporation, while the actual flux depends on the soil moisture conditions.

As shown in Equation 3, if the evaporation demand is high, the *NI* decreases accordingly. Higher precipitation intensities might result in exceeding the infiltration capacity of the soil resulting in surface run-off, thus decreasing the *NI*. Generally, a high retention and low K_s tends to increase the *AE*, thus decreasing *NI*. A lower K_s and higher AEV implies that it would take longer for water to infiltrate into the soil, thereby allowing evaporation to occur as the water remains at the surface.

The water balance at the surface using the measured and predicted soil hydraulic parameters are presented in Figure 6. Note that the water exiting the system is negative and the water entering the system is positive. The van Genuchten fitted parameters shown in Table 2 were inputted into the HYDRUS-1D model to acquire the water fluxes for this water balance. Additionally, no surface run-off was observed for any of the substrates.

From Figure 6a, it can be observed that the PTFs overestimate the *NI* for green roof material. The difference in *NI* calculated from measured and estimated (MK method) hydraulic properties is 500cm at the end of the 30-year period. This corresponds to the statistical analysis for GR2, where the MK model performs poorly in comparison to CalcPTF. The difference between CalcPTF and the measured for *NI* is 50cm, which is quite small in comparison. The greater *NI* results in a greater bottom flux (*BF*) leading to overdesign for a green roof.

The *BF* describes the outflow at the bottom of the substrate as free drainage was set for the bottom boundary condition. During a storm event, it is ideal to mitigate the water travelling out of the green roof. As reducing peak flow during storm events is a key design criterion for LIDs, a decreased *BF* for green roofs is preferred.

Figure 6b presents the water balance for BR2. The water balance of the predicted and measured shows similar results. Whereas the PTFs overestimated the *NI* for GR2, the PTFs for BR2 underestimate the *NI*, with the exception of the MK model. CalcPTF has the closest results to the measured simulation, with a *NI* difference of 165cm at the end of the 30-year simulation. The performance of the PTFs is consistent with their ability to predict hydraulic properties as shown by the statistical evaluation results in Table 3.

Similar observations were made for BR1 and BR3, where simulations using predicted and measured hydraulic properties resulted in relatively close *NI* values. Therefore, *NI* estimates are less sensitive to soil hydraulic properties for LID systems that accept a large quantity of water.

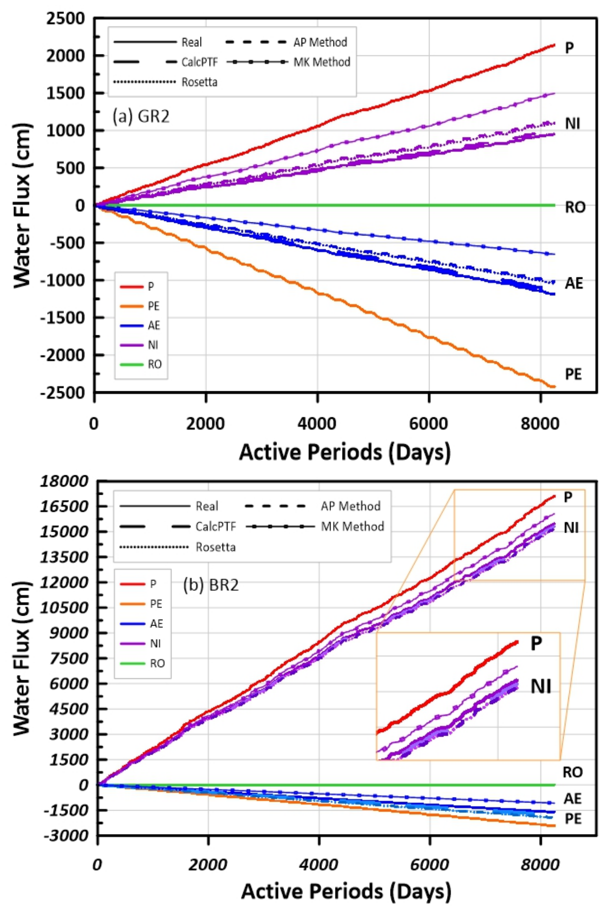

Figure 6. Water balance of measured and predicted SWCC for 30-year Toronto historic climate data for (a) GR2 and (b) BR2

5 CONCLUSIONS

In this study, the predicted SWCC using PTFs were compared to the measured SWCC of 5 LID substrates.

Overall, the PTFs were not able to fully capture the measured soil hydraulic properties for the LID substrates considered in this research. However, through numerical modelling, it was determined that measured soil hydraulic properties are more relevant for green roof systems in comparison to bioretention systems.

As field and laboratory measurement of unsaturated hydraulic can be expensive and cumbersome, the use of PTFs can be seen as a great advantage. However, from a design perspective, accurate soil hydraulic properties are more important for systems that manage less water, such as green roof systems.

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