Impact of using different ET models in HYDRUS-1D on soil water dynamics and potato crop ET

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ABSTRACT

Soil water content (SWC) plays a critical role in crop yield, irrigation scheduling, and water resources management. In the Canadian Prairies, the SWC in the rootzone from rainfall is rarely sufficient to satisfy crop water requirements. Thus, an understanding of the soil water dynamics is important for effective water management. Hydrologic modelling helps us to understand the underlying processes controlling and affecting soil water movement and distribution. The reference evapotranspiration (ET_{ref}) is a key input in most hydrologic models; thus, the estimation method could affect simulation results and inferences. The FAO Penman-Monteith (FAO PM) is recommended as a standard model. However, it is limited by requiring too many weather variables that are not readily available. Thus, simple empirical ET_{ref} models have been developed as an alternative. Soil moisture sensors were installed at 0.2, 0.4, 0.6, 0.8, and 1 m depths to measure SWC. SWC was first modelled in a rainfed potato farm in Winkler, Manitoba, using the FAO PM equation as input in the HYDRUS-1D model. Statistical and graphical results showed that the HYDRUS model performed well in simulating SWC with R^2 ranging from 0.6 to 0.9, RMSE from 0.003 to 0.03 m^3/m^3, MAE varying between 0.00932 and 0.0197 m^3/m^3 and MPE from -1.91 to 1.67%. The impacts of different ET_{ref} equations with varying weather inputs on soil water dynamics and seasonal potato crop evapotranspiration (ET_c) were further investigated. The results showed that measured SWC and SWC predicted using Irmak, Priestly-Taylor, and the FAO PM equations were not statistically different. Similar results were also obtained for ET_c. Hence, under limited data, the Irmak and Priestly – Taylor ET_{ref} equations are suitable alternatives that could provide accurate and reliable results for water management in southern Manitoba.

RÉSUMÉ

La teneur en eau du sol (TES) joue un rôle essentiel dans le rendement des cultures, le calendrier d'irrigation et la gestion des ressources en eau. Dans les Prairies canadiennes, la TES dans la zone racinaire dues aux précipitations est rarement suffisante pour répondre aux besoins en eau des cultures. Ainsi, une étude sur la variation de la TES est importante pour une meilleure gestion de l'eau. La modélisation hydrologique nous aide à comprendre les processus sous-jacents qui contrôlent et affectent le mouvement et la distribution de l'eau du sol. L'évapotranspiration de référence (ET_{ref}) est une donnée clé dans la plupart des modèles hydrologiques; par conséquent, la méthode d'estimation pourrait affecter les résultats et les inférences des simulations. L'équation Penman-Monteith de la FAO (FAO PM) est recommandée comme modèle standard d'estimation de ET_{ref}. Cependant, ce modèle est limité par le fait qu'il nécessite beaucoup de variables météorologiques qui ne sont pas souvent disponibles. Ainsi, des modèles ET_{ref} empiriques simples ont été développés comme alternatives. Des capteurs d'humidité du sol ont été installés à 0,2; 0,4; 0,6; 0,8 et 1 m de profondeur pour mesurer la TES. TES a été modélisée dans une ferme de pomme de terre pluviale à Winkler, au Manitoba, en utilisant tout d'abord l'équation PM de la FAO comme input dans le modèle HYDRUS-1D. Les résultats statistiques et graphiques ont montré que HYDRUS a bien simulé TES avec R^2 allant de 0,6 à 0,9; RMSE de 0,003 à 0,03 m^3/m^3; MAE de 0,00932 à 0,0197 m^3/m^3 et MPE de -1,91 à 1,67%. Les impacts de différents modèles ET_{ref} empiriques simples sur la dynamique de l'eau du sol et l'évapotranspiration saisonnière de la pomme de terre (ET_c) ont été ensuite étudiés. Les résultats ont montré que la TES mesurée et celle simulée à partir des équations d'Irmak, de Priestly-Taylor et de PM de la FAO n'étaient pas statistiquement différentes. Des résultats similaires ont également été obtenus pour ET_c. Par conséquent, en cas de disponibilité limitée des données, les équations d'estimation de ET_{ref} d'Irmak et de Priestly – Taylor sont des alternatives appropriées qui pourraient fournir des résultats précis et fiables pour la gestion de l'eau dans le sud du Manitoba.

KEYWORDS

Evapotranspiration models, Hydrus model, Crop ET

MOTS CLÉS

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INTRODUCTION

Soil moisture is an important variable of the hydrologic cycle as it plays a vital role in agricultural, atmospheric, hydrologic, and biophysical processes (Bittelli, 2011). The soil water content in the root zone is a limiting factor in achieving the maximum potential yield in arid regions. Therefore, monitoring and understanding soil moisture dynamics through a robust process for effective water management is important. There are different methods for estimating soil moisture (Bittelli, 2011). However, simulation modelling has been identified as a better alternative to soil moisture measuring instruments (Panigrahi et al. 2003). The complex interactions and variability in climate, soil, and management practices have made modelling an attractive tool for water management. Hydrologic models provide a better understanding of the agro-hydrological processes, the basis for sustainable water management. Since the 1970s, many models have been developed and applied in various soil and water-related simulations, including yield, irrigation and drainage, salinization, water balance, nutrients transport, and trafficability (Phogat et al. 2014, Karandish and Šimůnek 2016, 2016, Mante et al. 2018, Haj-Amor and Bouri 2019).

The accuracy of a model is affected by uncertainties originating from model inputs, model assumptions, structure, and parameter uncertainty (Seiller & Anctil 2016). Model inputs may include soil properties, plant characteristics, weather variables, and evapotranspiration (ET). The ET is one of the most important inputs to hydrologic models. It is also one of the most challenging variables to determine accurately and least understood parameter (Xiang et al. 2020) because of the complex soil-plant-water interaction. In most hydrologic models, the reference evapotranspiration (ET_{ref}) is used to quantify the atmospheric water demand of crops (Allen et al. 1998). The FAO Penman-Monteith (FAO PM) equation has been identified as the standard equation for estimating ET_{ref} (Allen et al. 1998). Nevertheless, it is limited to areas having access to complete set of weather variables, which is hardly the case for most weather stations. Across the globe, including Canada, weather stations are limited in number and measure only temperature (Maulé et al. 2006, Hooker et al. 2018, Martel et al. 2018). To overcome this challenge, researchers have developed simple empirical ET equations that require fewer weather data inputs. However, the challenge with such methods is that they are location specific. Thus, it is recommended to evaluate the suitability of an empirical ET_{ref} model before use in a new environment (Tabari et al. 2013).

Numerous studies on ET_{ref} model comparison abound in the literature (Maulé et al. 2006, Xing et al. 2008, Tabari et al. 2013, Martel et al. 2018, Gao et al. 2017, Djaman et al. 2019, Ndulue and Sri Ranjan 2020). In addition, the impact of different ET_{ref} models on hydrologic simulation has also been studied. For example, Oudin et al. (2005) assessed the effect of 27 ET_{ref} models on discharge. Their results showed an insignificant impact of ET_{ref} models on discharge. Meanwhile, Adjei et al. (2022) reported that the Hargreaves model performed better than the FAO PM equation in simulating discharge using the SWAT model. Malakshahi et al. (2020) evaluated the effect of 17 ET_{ref} models in simulating water table depth using the DRAINMOD model. They reported that the Rohwer and pan ET models gave the best simulations. Mastrocico et al. (2010) simulated soil water content using the HYDRUS-1D model, taking inputs from 3 ET_{ref} models. Their results showed that the FAO PM model performed better than the Turc and Hargreaves Samani models. Martel et al. (2018) compared eight ET_{ref} models to determine the actual evapotranspiration in the Canadian Prairies. They found that the Turc and Makkink ET_{ref} models performed better than the FAO PM model. Kumar et al. (2020) developed different irrigation threshold based on inputs from different ET_{ref} models.

From the literature, there is no clear consensus on the most appropriate ET_{ref} model. The simulation of soil water dynamics from different ET_{ref} models using the HYDRUS-1D model has not been evaluated in southern Manitoba. Therefore, the objectives of this study were to (i) simulate soil water dynamics using the HYDRUS-1D model under a rainfed condition in a potato farm in Winkler, Manitoba, and (ii) evaluate the impact of different ET_{ref} models on soil water dynamics and crop evapotranspiration (ET_c). Although automatic weather stations are expanding in southern Manitoba, historical data from Environment Canada shows missing and incomplete weather data, posing a severe challenge to the long-term study required for improved soil and water management.

MATERIALS AND METHODS

Study Area

A field study was conducted on an experimental site belonging to a private commercial farmer (Hespler Farms, Winkler) in southern Manitoba (latitude 56.5 N, long 45.93 E, elevation 283 m) in 2011. The topography is almost flat, with an average slope of < 2.5%. The soil in the region belongs to the sandy loam textural class, with an average bulk density of 1450 kg/m^3, 67.7% sand, 20.8% silt, and 11.5% clay fractions (Satchithanantham 2013). The area has highly productive soils for large commercial agricultural production of major crops, including potatoes, corn, canola, and soybeans. The region is semiarid with a 30-yr average annual growing season rainfall (May-September) of 342 mm and a minimum temperature, and maximum temperature of, 10.6 ºC, and 22.6 ºC, respectively.

The field area covers approximately 5.16 ha, on which potatoes and corn were planted on rectangular fields separated by an alleyway and rotated for three years. Each side is separated by a buffer zone consisting of 12 plots with a 300 m x 84 m dimension. Details of experimental design and water and crop management are presented in Satchithanantham (2013). The experiment was set up to evaluate the agronomic and environmental impacts of four different water management, namely, No drainage-No Irrigation treatment (NDNI), No Drainage-Overhead Irrigation (NDIR), Free Drainage–Overhead Irrigation

Table 1. ET_{ref} equations and their input requirements

S/No	Model	Equation	Inputs
1	Hargreaves Samani (1985)	$ET_{ref} = 0.0023 * R_a * 0.408 * (T_a + 17.8)^{0.5}$	T_a
2	Priestly-Taylor	$ET_{ref} = \propto \frac{\Delta}{\Delta + \gamma} * \frac{R_n}{\lambda}$	T_a, Rs
3	Romanenko (1961)	$ET_{ref} = (0.0018 * (T_a + 25)^2 * (100 - RH))$	T_a, RH
4	Penman (1948)	$ET_{ref} = \left(\frac{0.000479}{U_2} + 2.625\right)(e_s - e_a)$	RH, U_2
5	Irmak et al. (2003)	$ET_{ref} = -0.611 + 0.149R_s + 0.079T_a$	T_a, R_s
6	FAO-PM (incomplete)	$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}[e_s - e_a]U_2}{\Delta + \gamma * (1 + 0.34 * U_2)}$	T_a, RH^*, U_{2}^{*}, R_s^*
7	FAO-PM (complete)	$ET_{ref} = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}[e_s - e_a]U_2}{\Delta + \gamma * (1 + 0.34 * U_2)}$	T_a, RH, U_2, R_s

(FDIR), and Controlled Drainage-Subirrigation (CDSI). The NDNI represented the control and rainfed with no drainage and no irrigation. In this study, field data from the NDNI replicate 1 (NDIR-Rep1) was used to simulate soil water content using the HYDRUS-1D model. The NDIR-Rep1 has an area of 50 m by 40 m. Potato seedlings (*Russet Burbank*) were planted on ridges of about 12.5 cm height with row spacings of 90 cm, seeding depth of about 5-10 cm, and intra-row spacing of 35 cm. Complete details of crop and management are contained in Satchithanantham (2013)

Field data – Soil water content

Field data collection started 15 days after planting (DAP) and lasted till harvest. SWC was measured throughout the growing season using the EC-5 sensor (Decagon Devices, Inc., Pullman, WA, USA), installed vertically at 0.2, 0.4, 0.6, 0.8, and 1 m, set on 3-hr intervals. The EC-5 probes measured volumetric SWC at an operating frequency of 70 MHz and were calibrated in a previous study (Satchithanantham 2013). The three-hour SWC values were averaged to obtain daily volumetric SWC for each depth and used for the model simulation.

Estimating reference evapotranspiration (ET_{ref})

Hourly meteorological data, including rainfall, minimum and maximum air temperature (ºC), solar radiation (MJ/m^2/day), relative humidity (%) and wind speed (m/s) at 10 m, were collected from an on-site weather station. This study estimated ET_{ref} using the FAO PM equation and six other simple empirical ET_{ref} models (Table 1). Table 1 shows the selected ET_{ref} models, the equations, and their data requirements. Under limited data availability, ET_{ref} was estimated following Allen et al. (1998) recommendations.

ET_{ref} is the reference evapotranspiration [mm day^{-1}]; R_n is the net radiation [MJ m^{-2} day^{-1}]; R_a is the extraterrestrial radiation [MJ m^{-2} day^{-1}]; R_s is Solar radiation (MJ m^{-2} day^{-1}), G is the soil heat flux [MJ m^{-2} day^{-1}]; T_a is the average daily air temperature at the height of 2 m [°C]; U_2 is the wind speed at a height of 2 m above ground [m s^{-1}]; RH is relative humidity (%); e_s is the saturation vapour pressure [kPa]; e_a is the actual vapour pressure [kPa]; e_s -e_a is the vapour pressure deficit [kPa]; Δ is the slope of the saturation vapour pressure-temperature curve [kPa °C^{-1}]; γ is the psychrometric constant [kPa °C^{-1}], φ is latitude (rad); RH^* is relative humidity estimated from minimum temperature; R_s^* is solar radiation determined from the Hargreaves equation (Allen et al. 1998); and U_2^* is a constant windspeed value of 2 m/s

Determination of crop evapotranspiration (ET_c)

Crop (potato) evapotranspiration (ET_c) was determined using the crop coefficient approach (Allen et al. 1998), as shown in Equation 1

$$ET_c = K_c * ET_{ref} \qquad (1)$$

The K_c values of potatoes were determined following Ojeda-Bustamante et al. (2004), which computes K_c values using the CGDD (cumulative Growing Degree Days) as shown in equations 2-3

$$K_c = K_{max}\,\mathrm{erfc}\left(\left(\frac{x - x_{k\,max}}{\alpha_1}\right)^2\right) \qquad (2)$$

If $K_c < K_{c0}$, then $K_c = K_{c0}$

$$x = \frac{CGDD}{\alpha_o} \qquad (3)$$

where K_{c0} is the crop coefficient for the first phenological stage, K_{max} is the maximum K_c value, K_{c0} is the initial crop coefficient where soil evaporation is the major ET component, $x_{k\,max}$ is the auxiliary variable when the crop coefficient is maximum, erfc is the complementary error function, x is an auxiliary variable, and α_o is the CGDD required to reach phenological maturity. In this study, K_{max} = 1.15, α_o = 0.45, $x_{k\,max}$ = 0.45, α_1 = 0.45, and K_{c0} = 0.3, as reported by (Satchithanantham 2013).

The HYDRUS model simulates actual evaporation and transpiration, from which the simulated ET_c is computed as the sum of actual evaporation and actual transpiration. The HYDRUS model determines the actual crop ET by considering the ET_{ref}, and potential root water uptake, and pressure head, which is directly related to the soil water content. In this study, the ET_c calculated using the crop coefficient method is compared with the actual crop ET predicted by the HYDRUS model.

HYDRUS-1D Model

The HYDRUS model is one of the popular models used in hydrologic studies. The HYDRUS-1D model simulates water, heat, and solute transport in variably saturated media (Simunek et al. 2008). In this study, the HYDRUS-1D was used since soil water is assumed to move in one direction (upward or downward) under a rainfed condition. Soil water dynamics in the model is represented by the Richard's equation given below:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z_i}\left[K(h)\left(\frac{\partial h}{\partial z_j} + 1\right)\right] - S\,(h) \tag{4}$$

where h is the pressure head (L), θ is the volumetric water content (L^3/L^3), z is the vertical coordinate axis (L), K (h) is the hydraulic conductivity (L/T), S(h) is the sink term ($L^3/L^3/T$). The van Genuchten (1980) model was selected to describe the soil hydraulic and retention parameters using the equations:

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h|^n]^m}, & h < 0 \\ \theta_s, & ,\ h \geq 0 \end{cases} \tag{5}$$

$$K(h) = K_s S_e^l [1 - (1 - S_e{}^{1/m})^m]^2 \tag{6}$$

where θ_r is the residual water content ($cm^3\ cm^{-3}$), θ_s is saturated water content, K_s is saturated hydraulic conductivity (cm/day), *l* is shape factor, *m, α, n* are empirical shape factors in the water retention function (m = 1 – 1/n), S_e is relative saturation, and is given as:

$$s_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{7}$$

Model setup and model inputs The soil profile was discretized into 500 nodes of 0.005 m each to represent a grid of 2.5 m depth and a surface area of 1 m^2. The grid was subdivided into four layers: 0-0.4m, 0.4-0.6m, 0.6-1.0m, and 1.0-2.5 m as adopted from Mante et al. (2018). The first and second layers represents depth under the influence of field machinery and maximum root water use since potato is a shallow-rooted crop. The third layer represents depth below active root zone while the fourth represents deeper depth with limited or no interaction with the potato roots. The initial conditions were measured volumetric SWC of 0.35, 0.38, 0.39, 0.37, and 0.39 m^3/m^3 respectively for 0.2, 0.4, 0.6, 0.8, and 1.0 m respectively. Boundary conditions were assigned on the profile as observed in the field and from the literature. An atmospheric boundary condition with a surface layer was assigned to the top while a constant flux of 0 was assigned to the bottom profile because the water table was within the model domain. This is similar to the no-flux boundary reported by previous studies (Mante and Sri Ranjan 2017; Mante et al. 2018). The time variable inputs include effective rainfall, evaporation, and transpiration.

Root water uptake In Richard's equation, the sink term S (h) represents the root water uptake. The root water uptake rate is defined in terms of water stress factor and a potential uptake rate according to the Feddes model given as:

$$S\,(h) = \alpha(h)\beta(z)T_p \tag{8}$$

where $\alpha(h)$ is the root water uptake stress function, prescribed by soil water pressure head ($0 \leq \alpha \leq 1$), $\beta(z)$ is the function of root water uptake distribution, and T_p is potential transpiration.

The HYDRUS-1D model computes water uptake rate as a function of soil water pressure head. The coefficient in the Feddes model describes the reduction of water uptake due to stress. Feddes parameters (h_1 = - 0.1 m, h_2 = - 2.5 m, $h_{3(high)}$ = - 3.1 m, $h_{3(low)}$ = - 6.2 m, and h_4 = - 160 m) were obtained from Mante et al. (2018). ET was partitioned into evaporation (E_p) and transpiration (T_p) using Belman's formula, with an extension coefficient of k = 0.5 and leaf area index, LAI = 2.88 (Mante and Sri Ranjan 2017).

Model Parameterization

Calibration was done using the soil hydraulic parameters obtained from inverse modelling. Inverse modelling is an indirect method of obtaining soil hydraulic properties and water retention parameters. Researchers have adopted this approach (Zhang et al. 2018, Hou et al. 2018, Slama et al. 2019) since it is inexpensive, fast, and eliminates the difficulty of getting field measurements (Panigrahi and Panda, 2003). The HYDRUS-1D model uses the Levenberg-Marquardt non-linear minimization technique to fit soil hydraulic functions to observed data (Šimunek et al. 2012). In this study, the objective function was to maximize the R2 and minimize the error statistics. Model calibration was carried out using all the measured SWC obtained during the study period (June 3 to September 24). Shen et al. (2022) recommended that model calibration using full data and skipping validation is most robust and better than the traditional data split approach. This has been applied in related hydrologic studies (Arsenault et al. 2018, Shen et al. 2022, Arsenault et al. 2023).

Evaluation criteria

Model performance was assessed by qualitative and statistical analysis. Qualitative assessment involves a graphical plot of observed versus simulated on a 1:1 scale. Statistical tests such as Root Mean Square Error (RMSE), Mean Percent Error (MPE) and mean absolute error (MAE), and t-statistics were also used for model assessment. In addition to model performance, t-statistics was used to determine whether model estimates are statistically at a particular confidence interval. The significance test is read from standard statistical tables using the degree of freedom (df) and the critical values. A model is significant if the calculated t-value is less than the critical value.

The statistical indices are expressed as follows:

$$R^2 = \left(\frac{\sum_{i=1}^{n}(O_i-\bar{O})(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i-\bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i-\bar{P})^2}}\right)^2 \tag{9}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i-P_i)^2}{n}} \tag{10}$$

$$MPE = \frac{\sum_{i}^{n}(P_i-O_i)}{n} \times 100 \tag{11}$$

$$MAE = \frac{\sum_{i}^{n}|O_i-P_i|}{n} \times 100 \tag{12}$$

$$t = \sqrt{\frac{(n-1)(MBE)^2}{(RMSE)^2-(MBE)^2}} \tag{13}$$

where, O_i is Observed values, P_i is simulated values, $\overline{O_i}$ is the mean of observed values, and *n* is the total number of observed data points. Low RMSE, MPE, MAE, and t-stat and high R^2 values are indications of acceptable model performance (Stone 1993, Besharat et al. 2013, Moriasi et al. 2015).

RESULTS and DISCUSSION

Soil water content

Figure 1 shows the observed and simulated SWC at 0.2 m, 0.4 m, 0.6 m, 0.8 m, and 1m. Figure 2 shows the correlation between them. The optimized parameters used to match observed and simulated SWC are shown in Table 2. The model performance indicated by the statistical indices is presented in Table 3. Across the depths, the simulated and observed SWC followed the same pattern and trend, although larger deviations were observed at the 1 m depth. At the top layer and at the start of the simulation, both observed and simulated SWC gradually decreased in response to soil evaporation and, to a lesser extent, transpiration since the crop is at its developmental stage. Changes in soil water content were mainly due to rainfall. A 50 mm rain on June 15th caused soil water content to increase both in the observed and simulated content.

A higher and almost constant soil water content was observed at deeper depths (> 0.6 m). This can be explained by the management practice. In 2011, subsoiling was done before the start of the growing season to loosen the soil and reduce soil compaction in the field (Mante et al. 2018) This may have resulted in rainwater connecting with the ground water. As the season progressed, there was a closer match between simulated and observed soil water content, especially at the upper layer (0 - 0.4 m). This corresponds to the depth of the soil layer with the largest root density, given that potato has shallow roots with a maximum root depth ranging from 0.3 – 0.6 m (Allen et al. 1998, Iwama 2008).

Overall, temporal plots of the observed SWC matched the simulated with R^2 of 0.65 to 0.92, RMSE of 0.018 to 0.022 m^3/m^3, MPE = -1.9 to 1.7%, and MAE = 0.0009 to 0.0196, and NSE ranging from -0.7 to 0.88). The best model performance was observed at the top layer (0.2 and 0.4 m

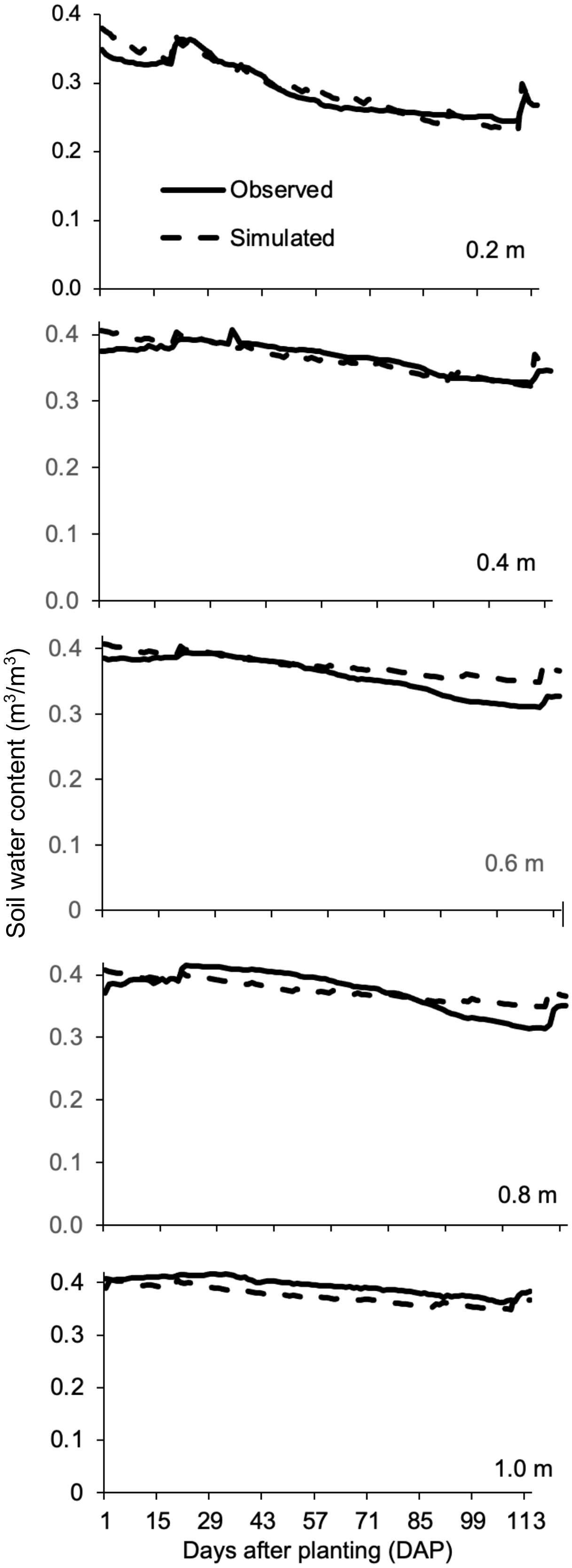


Fig. 1. Simulated and observed soil water content during the study period across the soil profile (0 -1 m).

Table 2. Optimized soil hydraulic parameters based on inverse modelling.

Depth (m)	θ_r (m^3 m^{-3})	θ_s (m^3 m^{-3})	α	n	K_s (m/day)	l
0 – 0.4	0.069	0.40284	0.07655	1.293	1.4627	0.5
0.4 – 0.6	0.042	0.42075	0.02825	1.576	1.1626	0.5
0.6 – 1.0	0.042	0.42026	0.01670	1.442	3.0676	0.5
1.0 – 2.5	0.040	0.42881	0.03596	1.173	3.50	0.5

depths), which decreased with depth. Based on the MPE values, the model underestimated SWC at the 0.4 and 1 m depths. The statistical indices of the HYDRUS model, as obtained in this study, are comparable with other related studies. For example, Mante and Sri Ranjan (2017) simulated SWC in the same study area for plots under the FDIR treatment. They reported R^2 ranging from 0.68 to 0.89 and NSE ranging from 0.75 to 0.99. Slama et al. (2019) simulated water content over the 0.90 m depth using the HYDRUS-1D model in Tunisia and reported R^2 ranging from 0.75 to 0.93 and RMSE ranging from 0.003 to 0.01 m^3/m^3. Gabiri et al. (2018) reported R^2 ranging from 0.36 to 0.92 and RMSE ranging from 0.02 to 0.13. González et al. (2015) applied the HYDRUS model to simulate soil water content under full and deficit irrigation in Brazil. They reported $R^2 > 0.92$, RMSE < 0.025, and model efficiency of > 89%. The results from this study suggest that the HYDRUS model is an effective model for SWC simulation; thus, it can be used as a water management tool in the region.

The discrepancies between observed and simulated SWC in Fig. 2 may be due to soil profile heterogeneity. In the HYDRUS model, Richard's equation expresses temporal changes in SWC to ET and unsaturated soil hydraulic properties. In the field, soil properties are highly variable in vertical and horizontal directions (Hou et al. 2018, Maheu et al. 2018). Soil hydraulic properties controlling soil water dynamics and redistribution vary from point to point. This study selected the van Genuchten model to determine the soil hydraulic properties and water retention variables (θ_r, θ_s, α, n, K_s). Through inverse modelling, observed and simulated SWC were fitted. Model parameterization is subject to uncertainty which can significantly affect simulation results. Baroni et al. (2011) reported that pedotransfer functions (PTFs) are the most significant source of uncertainty affecting soil water simulations. They reported that the saturated conductivity (Ks) and alpha (α) parameters caused the highest variability. Similarly, Holländer et al. (2016) reported that n is the most sensitive parameter affecting soil water content simulation results.

Crop (potato, ETc) evapotranspiration

Figure 3 shows the plot of predicted cumulative evaporation (E) (108.26 mm), transpiration (T) (242.16 mm), and total potato evapotranspiration (ET_c) (350.42 mm). Evaporation and transpiration represented 30.9 and 69.1% of the total ET_c. Overall, the predicted ET_c for potatoes compares well with related studies in the Canadian Prairies and other regions. Mante and Sri Ranjan (2017) reported a crop ET of 356.05 mm in the same study area. Kumar et al. (2020) reported a cumulative potato ET_c of about 400 mm in the humid subtropical climate. Similarly, Ghazouani et al. (2109) applied the HYDRUS-1D to predict the crop ET for potatoes under deficit irrigation as 135 – 175 mm. In the semiarid climate of Tunisia, Mguidiche et al. (2015) reported that the total measured crop water use for potatoes was 277.4 mm while Hou et al. (2018) reported 183 mm in China.

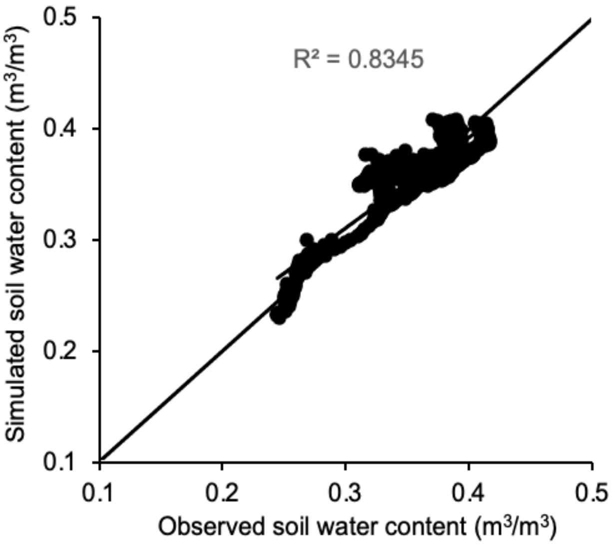
Impact of ET_{ref} models on SWC simulation

The impact of ET_{ref} models on SWC was analyzed only for the top layer (0.2 m) since potato is a shallow-rooted crop and it is also the depth with observable changes in SWC due to root water extraction, rainfall, and ET. Figure 4 compares observed and predicted water content from the selected ET_{ref} equations. Figure 4 showed that all the ET_{ref} equations overestimated SWC at the start of the simulation. After the 50 mm rainfall on June 22, a closer match was seen between the observed and predicted SWC from Irmak, Priestly-Taylor, and the FAO PM (complete) equations, while large deviations were observed for the Hargreaves Samani, Romanenko, Penman, and FAO-PM (incomplete). This could be because the Hargreaves Samani, Romanenko, Penman, and FAO-PM (incomplete) equations underestimated evaporation and transpiration (ET), leading to less soil water depletion and increased SWC.

Statistical analysis (Table 4) showed that all the ET_{ref} equations performed relatively well based on the R^2 values. However, RMSE and NSE values indicate that Irmak, Priestly-Taylor, and the FAO PM (complete) models are acceptable. This may be related to the fact that radiation-

Table 3. Statistical Indices across the soil profile (0 -1.0 m).

Depth (m)	R^2	NSE	RMSE (m^3/m^3)	MPE (%)	MAE (m^3/m^3)
0.2	0.92	0.88	0.0132	0.391	0.0106
0.4	0.77	0.71	0.0115	-0.061	0.0093
0.6	0.83	0.37	0.0225	1.677	0.0172
0.8	0.65	0.57	0.0211	0.095	0.0181
1.0	0.79	-0.70	0.0206	-1.907	0.0197
Overall	0.84	0.57	0.0183	0.039	0.0147



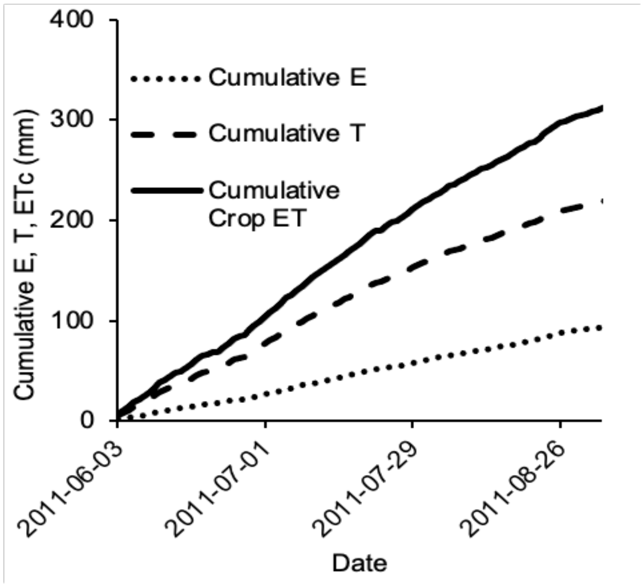


Fig. 2. **Overall simulated soil water content versus observed soil water content across the soil profile.**

Fig. 3. **Cumulative Evaporation, Transpiration and ET of potato.**

Table 4. Model performance of selected ET_{ref} models in comparison with measured soil water content at the 0.2 m depth.

ET_{ref} models	R^2	RMSE	MPE (%)	MAE (m^3/m^3)	NSE	t-values
Hargreaves- Samani	0.88	0.049	4.531	0.0453	-0.71	25.334
Irmak	0.92	0.0129	0.396	0.0105	0.88	1.424
Penman	0.88	0.0433	4.002	0.0400	-0.33	25.718
Priestly-Taylor	0.92	0.0127	-0.113	0.0106	0.89	0.946
Romanenko	0.86	0.0552	5.109	0.0511	-1.16	25.873
FAO PM (incomplete)	0.85	0.0577	5.333	0.0533	-1.36	25.676
FAO PM	0.92	0.0129	0.145	0.0107	0.88	1.209

*Significantly different, NS Non-significant

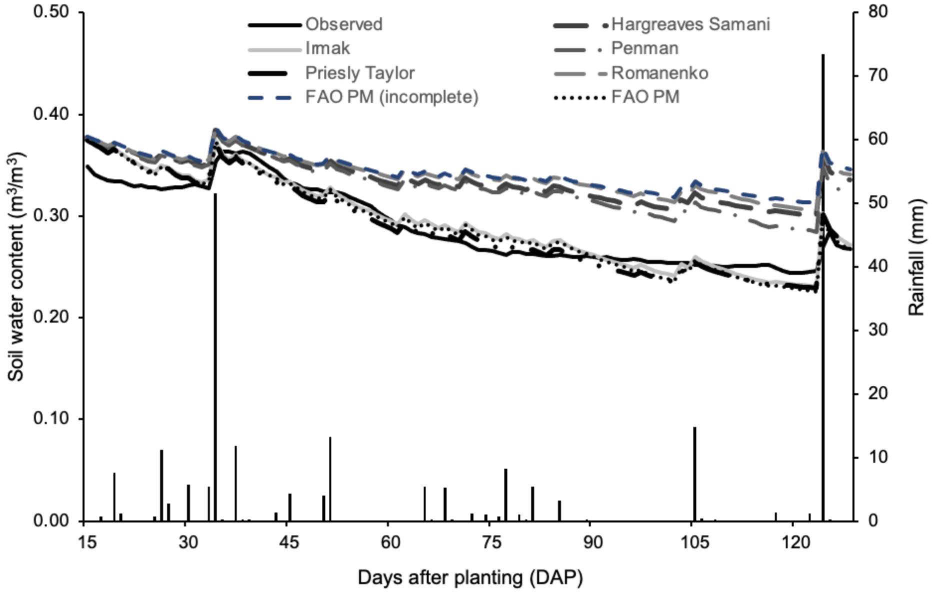


Fig. 4. **Comparison of observed and predicted soil water content at the 0.2 m depth using different ET_{ref} models.**

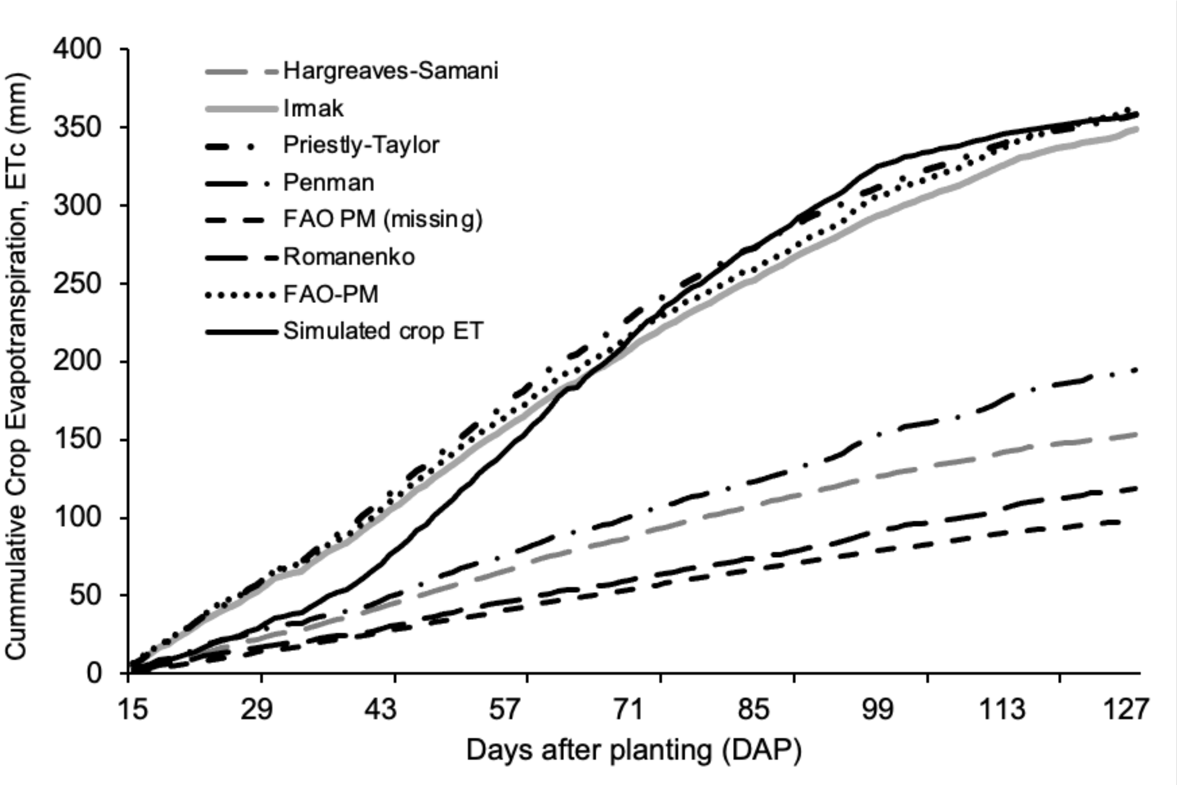


Fig. 5. Cumulative daily HYDRUS predicted potato crop evapotranspiration and calculated ET_c derived from the ET_{ref} models.

based models such as Priestly-Taylor and Irmak performed well in estimating ET_{ref} in the region (Martel et al. 2018, Ndulue and Sri Ranjan 2021). The results suggest that Priestly-Taylor and Irmak models are as good as the FAO PM (complete) equation despite requiring the use of fewer weather inputs. Therefore, under data scarce conditions, Priestly-Taylor and Irmak models are good alternatives. T-test results also showed that the predicted SWC using Irmak, Priestly-Taylor, and the FAO PM (complete) equations were not significantly different from the measured SWC at 95% confidence level, while Hargreaves-Samani, Romanenko, Penman, and FAO PM (incomplete) models were. The results agree with related studies. Utset et al. (2004) reported that SWC prediction using FAO PM and Priestly-Taylor produced similar results while Mastrocicco et al. (2010) reported that only the FAO PM performed well in simulating SWC while Turk and Hargreaves equations performed poorly. Overall, the results indicates that the choice of ET_{ref} equation could affect soil water dynamics using the HYDRUS model.

ET_c comparison

Figure 5 shows the cumulative daily calculated and HYDRUS predicted ETc. Table 5 shows the statistical indices of calculated, and HYDRUS predicted ETc. Results from ETc comparison were similar to the SWC results (Table 5); with the Irmak, Priestly-Taylor, and the FAO PM (complete) equations performing satisfactorily, with $R^2 > 0.5$, low RMSE and MPE values. The t-test results showed that the ETc estimates considering Irmak, Priestly-Taylor,

Table 5. ET_c statistical indices.

Models	R^2	RMSE (mm/day)	NSE	MPE (%)	MAE (mm/day)	t-value
Hargreaves Samani	0.55	2.37	-0.75	-179.70	1.82	12.38*
Priestly-Taylor	0.59	1.15	0.59	0.38	0.94	0.036^{NS}
Irmak	0.61	1.18	0.57	-7.78	1.01	0.71^{NS}
Penman	0.29	2.10	-0.38	-143.30	1.65	10.95*
Romanenko	0.22	2.27	-1.22	-209.60	2.13	13.55*
FAO PM (incomplete)	0.38	2.84	-1.51	-227.30	2.29	14.27*
FAO PM (complete)	0.57	1.18	0.57	4.46	0.98	0.40^{NS}

*Significantly different, ^{NS} Non-significant and the FAO PM equations were not statistically different at 95% confidence level from the HYDRUS predicted potato ET, while Hargreaves-Samani, Romanenko, Penman, and FAO PM (incomplete) models were. Figure 5 and MPE values in Table 5 showed that the Hargreaves-Samani, Romanenko, Penman, and FAO (incomplete) models overwhelmingly underestimated ETc. Based on the NSE values, poor performance was recorded for Hargreaves Samani, Romanenko, Penman, and FAO-PM (incomplete) equation. This may be due to their poor SWC simulation.

Numerous studies have reported close matches between predicted and measured hydrologic variables using the FAO PM equation (Mastrocico et al. 2010, Maranda and Anctil 2015, Tadesse et al. 2019). This has been attributed to the fact that it is comprised of both energy and aerodynamic terms controlling the ET process (Allen et al. 1998).

The results also showed that despite requiring lesser data compared to the FAO PM, the Irmak and Priestly-Taylor models performed well; thus, they are better alternative empirical ETref equations for the region. This could be related to the fact that they are classified as radiation based ETref models and highlights the influence of solar radiation on ET in the study area (Martel et al. 2018, Ndulue et al. 2020).

Our results agree with Utset et al. (2004), Xing et al. (2008), Tadesse et al. (2019), Akumaga and Alderman (2019). In a simulation study using the SWAP model, Utset et al. (2004) found no significant difference between the Priestly – Taylor model and the FAO PM. Similarly, Xing et al. (2008) found out that there was an insignificant difference between the Priestly – Taylor model and the FAO PM despite requiring fewer inputs, while Martel et al. (2018) reported that the Turc and Priestly-Taylor models performed well in estimating ET_c, ranking first and third, respectively, with an NSE > 0.7 for both models. On the other hand, our result disagrees with Oudin et al. (2005) and Wang et al. (2006). They reported that simple temperature-based models such as Hargreaves Samani gave similar results as the complex FAO PM model. This has been attributed to model parameter calibration, which can fit observed and simulated (Paturel et al. 1995, Bai et al. 2016).

In comparison with SWC using the different $ET_{ref,}$ we observed decreased performance. This may be due to the approach used in computing the calculated ET_c. While calculated ET_c was obtained using the crop coefficient approach, the HYDRUS model determines the crop ET_c by reducing the ET_{ref} according to the simulated root water uptake, evaporation rates, and simulated soil water content (Hou et al. 2018). Other studies have compared predicted ET_c with ET_c obtained from soil water balance or lysimeter (Allen et al. 1998, Utset et al. 2004, Lopez-Urrea et al. 2006, Gervais et al. 2010).

CONCLUSIONS

Effective water management is needed for a moisture-deficit region like the Canadian Prairies. Hydrologic modelling offers the opportunity to understand the underlying processes controlling soil water dynamics in the field. In addition, hydrologic modelling is a fast, accurate, and cost-effective strategy for water management. In this study, the HYDRUS-1D model was first used to simulate SWC in a rainfed potato field, in Winkler, southern Manitoba, using the standard ET_{ref} equation as input in the HYDRUS-1D model. Statistical and graphical results show that the HYDRUS-1D model performed well. Thereafter, the impacts of other empirical ET_{ref} models on SWC simulation and crop evapotranspiration were investigated. When simulating SWC, the results showed that although all the ET_{ref} models followed the same trend, the Irmak, Priestly-Taylor and FAO PM (complete) models performed well with high R^2 and low error indices. Also, for the potato crop ET, results showed that the Irmak, Priestly-Taylor and FAO PM (complete) estimates were not statistically different from the HYDRUS predicted crop ET while Hargreaves-Samani, Romanenko, Penman, and FAO PM (incomplete) models were. In conclusion, under data-scarce conditions, the Priestly – Taylor and Irmak models could give accurate and reliable results for water management in the region.

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