HYDRUS-1D Simulation of Soil Water Dynamics and Response of Different ET_o Models to Crop Evapotranspiration (ET_c) Under a Rainfed Condition in Southern Manitoba

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Research Article

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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 water content in the rootzone replenished by rainfall is rarely sufficient to satisfy crop water requirements. Thus, the need for robust and effective water management. Hydrologic modelling provides the opportunity to understand the underlying processes controlling and affecting soil water movement and distribution. Evapotranspiration (ET) is an important input of hydrologic models; thus, the estimation of ET could have significant consequences on modelling outcome and inference. The FAO Penman-Monteith (PM) is the recommended model for estimating the reference crop evapotranspiration (ET_o). However, it is limited by requiring too many weather variables that are not readily available. Simple empirical ET_o models have been developed as an alternative. In this study, six ET_o models with different inputs were used to simulate soil water dynamics in a rainfed potato farm in Winkler, Manitoba, using the HYDRUS-1D model. The results showed that when used to simulate SWC, all the models followed a similar pattern, although a significant difference was observed at shallow depth (20 cm). Specifically, a significant difference ($p < 0.05$) was observed between observed and simulated SWC from Hargreaves Samani, Romanenko, Penman, and FAO-PM (missing) models. When used to simulate the crop evapotranspiration (ET_c), there was no significant difference ($p > 0.05$) between observed and simulated ET_c from FAO PM, Irmak, and Priestly – Taylor models. Hence, ET_o models with fewer data inputs such as Irmak and Priestly – Taylor models can provide accurate and reliable results for water management in southern Manitoba.

1.0 Introduction

Soil moisture is an important variable of the hydrologic cycle as it plays a vital role in agriculture, atmospheric, hydrological, and biophysical processes (Bitelli, 2011). The soil water content in the root zone is a limiting factor in achieving maximum potential yield in the arid regions. Therefore, it is important to monitor and understand soil moisture dynamics through a robust process for effective water resources management. There are different methods for determining soil moisture (Bitelli, 2011), although simulation modelling has been identified as a better alternative (Panigrahi et al. 2003). The complex interactions and variability in climate, soil, and management practices have made modelling an attractive tool for effective water management. When calibrated and validated, models provide an understanding of the agro-hydrological process, which is 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, Šimůnek et al. 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 hydrological models. It is also one of the most challenging

variables to determine accurately and least understood parameters (Xiang et al. 20202) because of the complex soil-plant-water interaction. In most hydrologic models, the reference evapotranspiration (ET_o) 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 model for determining ET_o (Allen et al. 1998). Nevertheless, it is limited to areas having access to complete 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 (Maule 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 inputs. However, the problem with such a method is that it is location-specific. Thus, it is recommended to evaluate the suitability of an empirical ET_o model before use in new environments (Tabari et al. 2013).

Numerous studies on ET_o 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_o models on simulation results has also been evaluated. For example, Oudin et al. (2006) assessed the effect of 27 ET_o models on discharge. Their results showed an insignificant impact of ET_o models on discharge. Malakshahi et al. (2020) evaluated the effect of 17 ET_o models in simulating water table depth using the DRAINMOD model. They reported that the Rohwer model and the pan ET model gave the best simulations. Mastrocico et al. (2010) simulated soil water content using the HYDRUS-1D model, taking inputs from 3 ET_o models. Their results showed that the FAO PM model performed better than the Turc and Hargreaves Samani models. In determining the actual crop water use in the Canadian Prairies, Martel et al. (2018) compared 8 ET_o models. They found that the Turc and Makkink ET_o models performed better than the FAO PM model.

From the literature, there is no clear consensus on the most appropriate ET_o model. The simulation of soil water dynamics taking ET_o from different ET_o 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 (ii) evaluate the impact of 6 ET_o models, including under limiting conditions, on soil water dynamics and crop evapotranspiration (ET_c). Although automatic weather stations (AWS) 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.

2.0 Methodology

2.1 Study Area

A field study was conducted on an experimental site belonging to a private commercial farmer (Hespler Farms) in southern Manitoba (latitude 56.5 N, long 45.93 E, elevation, 283 m) in 2011. The topography is almost flat, with a slope of < 2.5%. The area has a large deposit of fertile soil; thus, it is known for the commercial agricultural production of major crops, including potato, corn, canola, and soybeans. The

area's climate is semiarid with a 30-yr average annual precipitation, minimum temperature, and maximum temperature of 533.3 mm, 16.21 °C, and 17.64 °C, respectively (Satchithanantham 2013). The soil in the region belongs to the sandy loam textural class, with an average bulk density of 1450 kg/m³, 67.7% sand, 20.8% silt, and 11.5% clay fractions (Satchithanantham 2013).

The field area covers approximately 5.16 ha, on which Potato and Corn were planted on rectangular fields separated by an alleyway and rotated for three years. Each side, separated by a buffer zone, consisting of 12 plots with a dimension of 300 m x 84 m. Details of experimental design and water and crop management are presented in Satchithanantham (2013) and Cordeiro (2014). 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 (FDIR), and Controlled Drainage-Subirrigation (CDSI). The NDNI represented the control and rainfed irrigation with no drainage. 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)

2.2 Field data

Field data collection started 15 days after planting (DAP) and lasted till harvest. Soil water content and water table depth were observed throughout the growing season. These were used as model inputs, initial conditions, and boundary conditions. Measurement of soil water content was set at 3-hr intervals. It was continuously measured using the EC-5 sensor (Decagon Devices, Inc., Pullman, WA, USA), installed at five depths, 20 cm, 40 cm, 60cm, 80 cm and 100cm. Averaged daily values of water content was obtained at each depth and used for model simulation.

2.3 Estimating reference evapotranspiration (ET_o)

Hourly meteorological data including rainfall, minimum and maximum air temperature (°C), solar radiation (MJ/m²/day), relative humidity (%) and wind speed (m/s) at 10 m was collected from an on-site weather station. In this study, ET_o was estimated using the FAO PM equation and six other simple empirical ET_o models (Table 1). The selected models included: Valiantzas 2015, Valiantzas 2018, Hargreaves Samani, Turc, Priestly – Taylor and FAO PM (limiting). Table 1 shows the selected ET_o models and their equations, and their data requirements. Under limited data availability, ET_o was estimated following Allen et al. (1998) recommendations.

Table 1
ET_o models and their input requirements

S/No	Model	Equation	Inputs
1	Hargreaves Samani (1985)	$ET_o = 0.0023 \cdot R_a \cdot 0.408 \cdot \left(T_a + 17.8\right)^{0.5}$	T _a
2	Priestly-Taylor	$ET_o = \alpha \frac{\Delta}{\Delta + \gamma} * \frac{R_n}{\lambda}$	T _a , R _s
3	Romanenko (1961)	$ET_o = \left(0.0018 \cdot \left(T_a + 25\right)^2 \cdot (100 - RH)\right)$	T _a , RH
4	Penman (1948)	$ET_o = \left(\frac{0.000479}{U_2} + 2.625\right) (e_s - e_a)$	RH, U ₂
5	Irmak et al. (2003)	$ET_o = -0.611 + 0.149R_s + 0.079T_a$	T _a , R _s
6	FAO-PM _(limiting)	T _a , RH*, U ₂ *, R _s *	
7	FAO-PM	T _a , RH, U ₂ , R _s	

where ET_o is the reference crop evapotranspiration [mm day⁻¹]; R_n is the net radiation [MJ m⁻² day⁻¹]; G is the soil heat flux [MJ m⁻² day⁻¹]; T is the average daily air temperature at the height of 2 m [°C]; u₂ is the wind speed at a height of 2 m above ground [m s⁻¹]; 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] and is the psychrometric constant [kPa °C⁻¹], T_a is the average daily air temperature (°C), RH is relative humidity (%), φ is latitude (rad), R_s is Solar radiation (MJ m⁻² day⁻¹). RH*, U₂*, and R_s* refers to limiting conditions when relative humidity, windspeed, and solar radiation data respectively are missing; and were estimated following Allen et al. (1998).

2.4 Determination of actual crop evapotranspiration (ET_c)

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

$$ET_c = K_c * ET_o$$

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

$$K_c = K_{max} \operatorname{erfc} \left(\left(\frac{x - x_{kmax}}{\alpha_1} \right)^2 \right)^2$$

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

$$x = \frac{CGDD}{\alpha_o} 3$$

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_{kmax} 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, $K_{max} = 1.15$, $\alpha_o = 0.45$, $x_{kmax} = 0.45$, $\alpha_1 = 0.45$, 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. Therefore, simulated ET_c from the Hydrus model was compared to the observed actual ET_c .

3.0 Hydrus-1d Model

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 is used since soil water moves 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:

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

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:

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

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

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:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} 7$$

3.1 Model setup and model inputs

The 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 1m². The grid was subdivided into four layers: 0-0.4m, 0.4m-0.6m, 0.6m-1.0m, and 1.0-2.5 m. The initial condition was derived from measured water content at five depths (0.2, 0.4, 0.6, 0.8, and 1m). Boundary conditions were assigned on the profile as observed in the field. An atmospheric boundary condition with a surface layer was assigned to the top. This includes a time variable boundary condition inputs of effective rainfall, evaporation, and transpiration.

3.2 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:

$$S(h) = \alpha(h)\beta(z)T_p$$

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 ($h_1 = -0.1\text{m}$, $h_2 = -2.5\text{m}$, $h_{3(\text{high})} = -3.1\text{m}$, $h_{3(\text{low})} = -6.2\text{m}$, and $h_4 = -160\text{m}$) were obtained from Mante et al (2018). ET was partitioned into evaporation (E_p) and transpiration (T_p) using the Belman's formula, with extension coefficient, $k = 0.5$ and leaf area index, $\text{LAI} = 2.88$ (Mante and Sri Ranjan 2017).

3.3 Model calibration and validation

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 R^2 and minimize the RMSE values. Observed soil water content in the treatment plot at five depths (0.20, 0.40, 0.60, 0.80, and 1m) was used to optimize the hydraulic functions.

The observed soil water content data was divided into two: The first series (June 3 to August 25) was used to calibrate the model using the inverse modelling technique in HYDRUS-1D to determine the soil hydraulic properties and water retention parameters. Thereafter, the model was validated (August 26 – September 24) by simulating the remaining soil water content data using the calibrated model.

3.4 Evaluation criterion

Model performance was assessed by qualitative and statistical analysis. Qualitative assessment involves a graphical plot of observed versus simulated on a 1:1 scale with zero intercepts. Statistical tests such as Root Mean Square Error (RMSE), Mean Bias Error (MBE) and mean absolute error (MAE) were also used for assessment. Good model performances are characterized by Low RMSE, MBE, and MAE values and a high coefficient of determination (R^2) (Moriasi et al. 2015). They are expressed as follows:

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

9

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

10

$$MBE = \frac{\sum_{i=1}^n (P_i - O_i)}{n} \times 100$$

11

$$MAE = \frac{\sum_{i=1}^n |O_i - P_i|}{n} \times 100$$

12

where, O_i is Observed values, P_i is simulated values, $\bar{O}$ is the mean of observed values, and n is the total number of observed data points. For SWC and crop ET (ET_c), a one-way analysis of variance (ANOVA) was used to test for significant differences between measured and modelled results. The means were compared at the 5% ($p < 0.05$) significance level.

4.0 Results And Discussion

4.1 Soil water content and ET_c simulation

Figure 1 shows the observed and simulated soil water content plots at different depths (0.2 m, 0.4 m, 0.6 m, 0.8 m, and 1m). The optimized parameters used to match observed and simulated SWC is shown in Table 2, and the model performance indicated by the statistical indices is presented in Table 3. Across the depths, the averaged simulated SWC was higher than the observed. At the start of the simulation, both observed and simulated SWC gradually decreased in response to evaporation and, to a lesser extent, transpiration since the crop is at its developmental stage. Changes in soil water content were also a result of response to rainfall. A 50 mm rain on the June 15 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 (> 60 cm). This can be explained by management practice and groundwater contribution. In 2011, subsoiling was done prior to the start of the growing season to loosen the soil compaction in the field (Mante et al. 2018). This may have also aided capillary action. Satchithanantham et al. (2014) reported that during a 4-day dry period, groundwater supplied and replenished 96% of the crop ET. As the season progressed, there was a closer match between simulated and observed soil water content at the upper depth (0–40 cm). This corresponds to the depth of the soil layer with the largest root density, given that potato is a shallow root crop with a maximum root depth of about 30–60 cm (Iwama 2008, Allen et al. 1998).

Overall, temporal plots of observed and simulated soil water content and statistical indices (Table 3) during calibration ($R^2 = 0.85$, RMSE = $0.0158 \text{ m}^3/\text{m}^3$, MBE = -0.003, and MAE = 0.0133) and validation ($R^2 = 0.741$, RMSE = $0.0243 \text{ m}^3/\text{m}^3$, MBE = 0.0102, and MAE = 0.0199) were acceptable, although the model performed better during calibration.

Table 2
Optimized soil hydraulic parameters

Depth (m)	$\theta_r (\text{m}^3 \text{m}^{-3})$	$\theta_s (\text{m}^3 \text{m}^{-3})$	α	n	$K_s (\text{m/day})$	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

Although Hydrus model performance was satisfactory (Table 3), discrepancies between observed and simulated SWC could be due to heterogeneities within the soil profile. 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. In this study, the van Genuchten model was selected to determine the soil hydraulic properties and

water retention variables (θ_r , θ_s , α , n , K_s). Through inverse modelling, observed and simulated soil water content was 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 found the saturated conductivity (K_s) 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.

Numerous studies have also reported the performance of the HYDRUS model in simulating SWC. 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 0.68–0.89, NSE ranging from 0.75–0.99, PBIAS ranging from –1.99 to 1.16% and RSR values ranging from 0.33–0.61. 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 0.75–0.93, RMSE ranging from 0.003–0.01 m³/m³. Gabiri et al. (2018) reported R^2 ranging from 0.36–0.92, RMSE ranging from 0.02–0.13. Gonzalez et al. 2015 applied the HYDRUS-1D 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%. These studies confirmed the versatility of the HYDRUS-1D model.

Table 3
Statistical Indices during calibration and validation across the soil profile (0-1m)

Calibration					Validation			
Depth (m)	R^2	RMSE	MBE	MAE	R^2	RMSE	MBE	MAE
Overall	0.8559	0.0158	-0.0030	0.0133	0.7413	0.0243	0.0102	0.0199

4.2 ET_c simulation

Figure 3 shows the plot of simulated cumulative evaporation (108.26 mm), transpiration (242.16 mm), and actual crop evapotranspiration (350.42 mm). Evaporation and transpiration represented 30.9 and 69.1% of the total ET_c. Overall, the simulated 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. Recently, 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 simulate the crop ET for potato under deficit irrigation as 135–175 mm. In the semiarid climate of Tunisia, Mguidiche et al. (2015) reported the total measured crop water use for potato was 277.4 mm while Hou et al. (2018) reported 183 mm in China.

4.3 ET_o model impact on SWC simulation

The impact of ET_o models on SWC was analysed for the upper layer (20 cm) since it is the depth where observable changes in SWC due to root water extraction, rainfall, and ET is the highest. Figure 4 shows the comparison between observed and simulated water content from the selected ET_o models. Figure 4 also showed that all the ET_o models followed a similar pattern in simulating SWC, with that all the models overestimating SWC at the start of the growing season. After the June 22 rainfall of 50 mm, a closer match between the observed and simulated SWC from Irmak, Priestly-Taylor, and the FAO PM models while large deviations were observed for the Hargreaves Samani, Romanenko, Penman, and FAO-PM (missing) models. This could be because these models underestimated evaporation and transpiration (ET), leading to less soil water depletion and increased SWC in the profile. T-test results also showed that there was no significant difference between the observed and simulated SWC using Irmak, Priestly-Taylor, and the FAO PM models, while a significant difference ($p < 0.05$) was recorded for Hargreaves-Samani, Romanenko, Penman, and FAO PM (limiting) models.

Statistical analysis (Table 4) showed that all the models performed relatively well based on the R^2 values. However, RMSE and NSE values indicate that only Irmak, Priestly-Taylor, and the FAO PM models are acceptable.

Table 4
Model performance of selected ET_o models in comparison to measured soil water content at the 20 cm depth

ET _o models	R ²	RMSE	MBE	MAE	NSE
Hargreaves- Samani	0.88	0.049	4.53	0.0453	-0.71
Irmak	0.92	0.0129	0.4	0.0105	0.882
Penman	0.88	0.043	4.00	0.04	-0.327
Priestly-Taylor	0.92	0.0127	-0.113	0.0106	0.89
Romanenko	0.86	0.0552	5.11	0.0511	-1.159
FAO PM (missing)	0.85	0.0577	5.33	0.0533	-1.358
FAO PM	0.92	0.0129	0.1	0.0107	0.883

Overall, the results showed that the ET_o model could affect soil water dynamics using the HYDRUS model.

4.4 ET_c comparison

Figure 5 shows the cumulative daily observed and simulated ET_c . Table 5 shows the statistical indices of observed and simulated ET_c . Model performance results from ET_c comparison followed the same trend as the SWC simulation, with the Irmak, Priestly-Taylor, and the FAO PM models performing satisfactorily ($R^2 > 0.5$). Numerous studies have reported good agreement between observed and simulated results using the FAO PM model in hydrologic modelling studies (Mastrocico et al. 2010, Maranda and Ancil 2015, Tadesse et al. 2019). This justifies why FAO PM model is the globally accepted, recommended, and standard ET_o model. This has been attributed to the FAO PM being a physically-based model comprising both energy and aerodynamic factors 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 are viable alternative empirical ET_o models for the area. This could be related to the fact that they are radiation-based and the influence of radiation on ET in the study area (Martel et al. 2018, Ndulue et al. 2020). On the other hand, poor performance was recorded for Hargreaves Samani, Romanenko, Penman, and FAO-PM (missing) models based on their statistics indices (Table 5).

In comparison with SWC model performance, we observed decreased model performance. This may be due to the approach used in computing the observed ET_c . While observed ET_c was calculated using the crop coefficient approach, the HYDRUS model determines the actual crop ET_c by reducing the ET_o according to the simulated root water uptake and evaporation rates, dependent on the simulated soil water content (Hou et al. 2018). Other studies have compared simulated 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).

Table 5
ET_c statistical indices

Models	R ²	RMSE (mm/day)	MBE (%)	MAE	NSE	p-value
Hargreaves Samani	0.55	2.37	-179.7	1.82	-0.75	< 0.0000*
Priestly-Taylor	0.59	1.15	0.38	0.94	0.58	0.9853 ^{NS}
Irmak	0.61	1.18	-7.78	1.01	0.57	0.691 ^{NS}
Penman	0.29	2.10	-143.3	1.65	-0.38	< 0.0000*
Romanenko	0.22	2.27	-209.6	2.13	-1.22	< 0.0000*
FAO Limiting	0.38	2.84	-227.3	2.29	-1.51	< 0.0000*
FAO PM	0.57	1.18	4.46	0.98	0.57	0.8262 ^{NS}
* significantly different, ^{NS} Non-significant						

The t-test results also showed that the Hargreaves Samani, Romanenko, Penman, and FAO-PM (missing data) are statistically different from the observed ET_c while ET_c derived from Irmak, Priestly-Taylor, and the FAO PM models are not significantly different from the observed ET_c.

Our results agree with Utset et al. 2003, Xing et al. 2008, Tadesse et al. 2019, Akumaga and Alderman (2019). A simulation study using the SWAP model, Utset et al. (2003) 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), 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, Bia et al. 2016).

5.0 Conclusion

Effective water management is needed for a moisture-deficit region like the Canadian Prairies. This would require accurate estimate of evapotranspiration (ET). Hydrologic modelling offers the opportunity to understand the underlying processes controlling soil water dynamics in the field. In addition, the use of calibrated and validated model is a fast, accurate, and cost-effective strategy for water management. In this study, the performance of six simple empirical models for predicting ET were used for SWC simulation in the Hydrus-1D model. The models were used to simulate crop ET in a rainfed potato field, Winkler, southern Manitoba. The results showed that although all the ET_c models followed the same

pattern, the Irmak, Priestly-Taylor and FAO PM models performed well providing a close correlation with the observed SWC. In simulating the crop ET_c , results showed no significant difference ($p > 0.05$) between observed and simulated ET_c using the FAO PM, Priestly – Taylor, and Turc models. In conclusion, under limited availability of weather data, the Priestly – Taylor model could give accurate and reliable results for water management in the region.

Declarations

-Conflict of Interest

There is no conflict of interest associated with this publication

-Funding Statement

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-Author's Contribution

Mr. Ndulue did the data analysis and created the first draft. Dr. Mante assisted with data analysis manuscript review. Dr. Sri Ranjan provided the field data, review of the concepts and writing of the manuscript.

-Availability of data and material

Available upon request.

-Code availability

Not applicable

-Ethics approval

None required

-Consent to participate

Not applicable

-Consent for publication

The authors provide their consent to publish this article. No other subjects were involved.

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Figures

Figure 1

simulated and validated soil water content during calibration and validation across the soil profile (0-1m)

Figure 2

Correlation of simulated versus observed soil water content during calibration and validation

Figure 3

Cumulative Evaporation, Transpiration and ET of potato

Figure 4

Comparison of observed and simulated soil water content at the 20 cm depth using different ETo models.

Figure 5

Comparison of cumulative observed ETc and simulated ETc using different ETo models.