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Developing a tile drainage module for Cold Regions Hydrological Model: Lessons from a farm in Southern Ontario, Canada

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Abstract

Systematic tile drainage is used extensively in agricultural lands to remove excess water and improve crop growth; however, tiles can also transfer nutrients from farmlands to downstream surface water bodies, leading to water quality problems. There is a need to simulate the hydrological behavior of tile drains to understand the impacts of climate or land management change on agricultural runoff. The Cold Regions Hydrological Model (CRHM) is a physically based, modular modeling system that enables creating comprehensive models appropriate for cold regions by including a full suite of winter, spring, and summer season processes and coupling these together via mass and energy balances. A new tile drainage module was developed for CRHM to account for this process in tile-drained landscapes that are increasingly common in cultivated basins of the Great Lakes and northern Prairies regions of North America.

A robust multi-variable, multi-criteria model performance evaluation strategy was deployed to examine the ability of the module with CRHM to capture tile discharge under both winter and summer conditions. Results showed that soil moisture is largely regulated by tile flow and lateral flow from adjacent fields. The explicit representation of capillary rise for moisture interactions between the rooting zone and groundwater greatly improved model simulations, demonstrating its significance in the hydrology of tile drains in loam soils. Water level patterns revealed a bimodal behaviour that depended on the positioning of the capillary fringe relative to the tile. A novel aspect of this module is the use of field capacity and its corresponding pressure head to provide an estimate of drainable water and thickness of the capillary fringe, rather than a detailed soil retention curve that may not always be available. Understanding the bimodal nature of soil water levels provides better insight into the significance of dynamic water exchange between soil layers below drains to improve tile drainage representation in models.

Keywords: tile drainage, cold regions, hydrological model, capillary fringe, drainable water, water level fluctuations

1. Introduction

Harmful algal blooms and eutrophication in large freshwater lakes surrounded by agricultural lands are major environmental challenges in Canada and globally. The transport of nutrients, particularly phosphorus, in runoff from agricultural fields into rivers, ponds and eventually lakes is an important contributor to the increased frequency of algal blooms being experienced in

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North America and elsewhere (Sharpley et al., 1995; Correll, 1998; Filippelli, 2002; Ruttenberg, 2005; Schindler, 2006; Quinton et al., 2010). Nutrient transport from agricultural fields can occur via both surface runoff and tile drainage (Radcliffe et al., 2015), and recent increases in the frequency and magnitude of algal blooms in Lake Erie in North America have been attributed to tile drainage (King et al., 2015; Jarvie et al., 2017). Tile drain systems reduce the retention time of soil water, lessening waterlogging in fields and improving both crop growth and field trafficability for farmers (Cordeiro and Ranjan, 2012; Kokulan et al., 2019a). However, they are also important pathways for dissolved and particulate nutrients (Kladivko et al., 1999; Tomer et al., 2015). It has been estimated that 14% of farmlands in Canada (ICID, 2018) and 45% of fields in Southern Ontario, Canada (ICID, 2018; Kokulan, 2019) are drained by tile systems. In Alberta, tile drains have also been used to address salinity issues (Broughton and Jutras, 2013). Given their importance in hydrological budgets and biogeochemical transport, there is a need to understand the controlling mechanisms of water and nutrient export from tile systems as an integral part of the broader, modified hydrological system. The ability to integrate a dynamic quantification of tile drainage from fields in hydrological models can help understand the relative importance of this human-induced process as it interplays with an array of other phenomena, including energy and physical mass balance hydrological processes, climate change, and the impacts of modified land management practices on runoff and nutrient export.

There are several models that can represent tile drainage at the small basin scale, such as HYPE (Lindstrom et al., 2010; Arheimer et al., 2015), DRAINMOD (Skaggs, 1978, 1980a; Skaggs et al., 2012), MIKE SHE (Refsgaard and Storm, 1995) and SWAT (Arnold et al., 1998; Koch et al., 2013; Du et al., 2005; Du et al., 2006; Green et al., 2006; Kiesel et al., 2010). These models include conceptual components for many key hydrological processes, but research shows

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that they have been primarily designed and tested for temperate regions (Costa et al., 2020a). In Canada and other cold regions, some unique hydrological processes such as frozen soil, snowmelt, rain on snow, and runoff over and infiltration into frozen or partially-frozen soils may be very important (Rahman et al., 2014; Cordeiro et al., 2017; Pomeroy et al., 1998, 2007; Fang et al., 2010, 2013). Many hydrological processes, such as the sublimation of snow, energy balance snowmelt, and infiltration into frozen soils, are strongly affected by temperature and the phase changes of water, which make many existing models developed for warm regions less appropriate for regions with cold seasons (Pomeroy et al., 2007; Pomeroy et al., 2013; Pomeroy et al., 2016; Fang et al., 2010, 2013). Even for temperate regions, the representation of cold season processes is often underrepresented in models (Costa et al., 2020a).

Since the use of tile drainage is becoming popular in many cold regions, it has become important to integrate such human-induced process in specialized hydrological modelling tools for these regions, such as the Cold Regions Hydrological Modelling platform (CRHM, Pomeroy et al., 2007; 2013; 2022). CRHM was initially developed in 1998 to assemble and explore the hydrological understanding developed from a series of research basins spanning Canada and elsewhere into a flexible, modular, object-oriented, multiphysics platform for simulating hydrological processes and basin response in cold regions (Pomeroy et al., 2007; 2022). The modular CRHM platform allows for multiple representations of forcing data interpolation and extrapolation, hydrological model spatial and physical process structure and parameter values. Many existing models typically operate at default daily or monthly time intervals, which is inadequate for the prediction of many short-duration "flashy" hydraulic responses often observed in tiles (Pluer et al., 2020; Vivekananthan, 2019; Vivekananthan et al., 2019; Lam et al., 2016a, 2016b; Macrae et al., 2019). Indeed, the ability to simulate shorter time intervals (e.g., hourly)

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facilitates the ability to capture both the rising and falling limbs of tile flow hydrographs, as well as the magnitude of peak flows, both of which are important to tile drain chemistry and export (Rozemeijer et al., 2016; Williams et al., 2015, 2016; Macrae et al., 2019).

Hydrological process models such as DRAINMOD, MIKE SHE and SWAT use a combination of empirical and physically based formulations for the simulation of tile flow derived by Hooghoudt (1940), Kirkham (1957), van Schilfgaarde (1974), Bouwer and van Schilfgaarde (1963) and Skaggs et al., (1978). Such formulations contemplate both cases where the soil water level is below and above the ground surface (Kirkham, 1957). In contrast, simulations of tile drainage in other models such as HYPE use empirically-derived recession curves (Eckersten et al., 1994) to simulate tile flow and water levels. In cases where there is a need for more focus on soil matrix hydrology and less need for understanding the relative contribution of tiles (and its interplay) with other catchment-scale mass balance hydrological processes, modellers tend to use specialised porous-media PDE-based (partial differential equation-based) numerical models such as HYDRUS (Simunek et al., 2011) and MACRO (Larsbo and Jarvis, 2003).

The amount of water transported by tiles depends on soil moisture dynamics and the positioning of the water table, which are in turn affected by many factors, including soil type, surface topography and morphology, as well as the local climate and the hydrologic characteristics of the field (Frey et al. 2016; Klaiber et al., 2020; Coelho et al., 2012; King et al., 2015). Thus, to provide reliable estimations of water from farmland via surface runoff and tile flow, models must be able to predict soil moisture and the soil water level accurately (Brockley, 1976; Rozemeijer et al., 2016; Javani-Jouni et al., 2018). Many studies have shown that in some soil types, including silty loam and clay loam soils, the drainable water is less than expected

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based on the effective porosity (*e.g.*, Skeggs et al., 1978; Raats and Gardner, 1974). Raats and Gardner (1974) have argued that the calculation of drainable porosity requires knowledge of the soil water level position and the distribution of soil moisture above the water level. Skeggs et al. (1978) added that the calculation of drainable porosity should take into account "the unsaturated zone drained to equilibrium with the water table". However, because the soil column is often composed of different soil layers with varying physical characteristics, drainable porosity varies with evapotranspiration rate, soil water dynamics and the water level depth (Logsdon et al., 2010; Moriasi et al., 2013). In a sandy loam soil, Lam et al. (2016a, 2016b) demonstrated that tile drainage was not initiated until soils were at or above field capacity. Williams et al. (2019) observed in the American Midwest that tile drainage was not initiated until the field storage capacity had been exceeded. It has also been shown that despite the presence of tile drains, the soil above the tile may not drain appreciably into the tile following an event and may remain at or above field capacity (Skaggs et al., 1978; Lam et al., 2016a). Therefore, the soil drainable water content may be considerably smaller than the storage capacity. This is related to matric potential within the vadose zone, which is driven by the soil characteristics but can also be due to the development of a capillary fringe that reduces the rate of vertical percolation through the unsaturated zone, reducing tile flow (Youngs, 2012). Despite this evidence, some saturated flow models that simulate tile flow overlook the effect of capillary rise and over-estimate the soil drainable water. Other models that represent unsaturated flow (i.e. HYDRUS 3D, Simunek et al., 2011) using Richard's Equation (Richards, 1931) capture the effect of capillary rise and saturation-pressure variation within the soil profile and assess the soil drainable water more accurately. Although the effect of capillary rise is considered in DRAINMOD through the concept of drainable porosity (that is represented as a "water yield") (Skaggs, 1980b), and is

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calculated for layered soil profiles (Badr,1978), it requires detailed information surrounding the soil water characteristic curve (Skaggs, 1980b). It is indeed optimal to use soil-specific water characteristic curves; however, Twarakawi et al. (2009) found that it was possible to employ average representative values from the soil water characteristic curve to represent soil drainable water where a soil-specific curve is not available.

In this study, a new tile drainage module was developed and incorporated within the physically based, modular Cold Regions Hydrological Modelling (CRHM) platform (Pomeroy et al., 2022) to enable hydrological simulations in tile-drained farm fields in cold agricultural regions. In this module, considerations were explicitly included for the effect of capillary rise and annual groundwater water table fluctuations on drainable soil water storage. The use of field capacity and pressure head (Twarakawi et al., 2009) to modulate soil drainable water across the soil profile, including the capillary fringe region, is an innovative aspect of the model that has been demonstrated to negate the need for water characteristic curves.

2. Materials and Methods

2.1 Study area

The study site is a ~10 ha farm field located near Londesborough, LON (UTM 17T 466689m E, 4832203m N), Ontario (Fig. 1a). Mean annual precipitation recorded in this region is 1247 mm (ECCC, 2020). Mean air temperature is 7.2 ^{o}C, with annual maxima in July (25.9 ^{o}C) and minima in January (-10.2 ^{o}C), (ECCC, 2020). Soil texture has been identified as Perth clay loam (Gr. Br. Luvisolic), with a slope between 0.2 and 3.5%. The field is systematically drained with a tile depth of 0.9 m and a spacing of 14 m (laterals). The tile network collects infiltrated water from about 75% of the field (~ 7.6 ha), which is discharged via a common tile outlet (main). The

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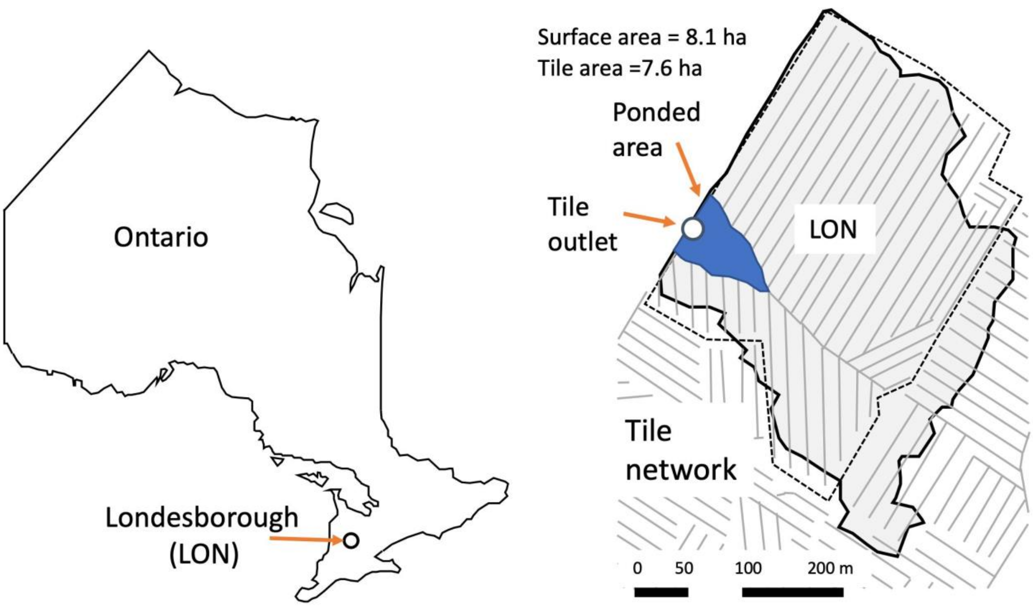
field is a corn-soy-winter wheat rotation with cover drops and rotational conservation till (shallow vertical tillage every three years). Additional details related to farming practices are provided in Plach et al. (2019) and soil characteristics are provided in Plach et al. (2018a) and Plach et al. (2018b). The outlets of the surface and tile flows are located at the edge of the field and drain into an adjacent field (Fig. 1b). Water tends to accumulate in a topographic low in the field, in front of the field outlet during snowmelt or high-intensity rainfall events (see ponded area, Fig. 1b). This zone coincides with the tile drain main pipe and is not a zone of groundwater discharge.



a) b)

b) Figure 1. (a) Location of the study area in South of Ontario and the (b) Londesborough (LON) farm with its tile network.

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2.2 CRHM: The modelling platform

The modular CRHM platform includes options for empirical and physically based calculations of precipitation phase, snow redistribution by wind, snow interception, sublimation, sub-canopy radiation, snowmelt, infiltration into frozen and unfrozen soils, hillslope water movement, actual evapotranspiration, wetland fill and spill, soil water movement, groundwater flow and streamflow (Pomeroy et al., 2007; 2022). Where appropriate, it calculates runoff from rainfall and snowmelt as generated by infiltration excess and/or saturated overland flow, flow over partially frozen soils, detention flow, shallow subsurface flow, preferential flow through macropores and groundwater flow. Water quality can also be simulated (Costa et al., 2021). Modules of a CRHM model can be specific to basin setup, such as delineating and discretizing the basin, conditioning observations for extrapolation and interpolation in the basin, or are process-support algorithms such as for estimating longwave radiation, complex terrain wind flow, or albedo dynamics, but most commonly address hydrological processes such as evapotranspiration, infiltration, snowmelt, and streamflow discharge. CRHM discretizes basins into hydrological response units (HRU) for mass and energy balance calculations, each with unique process representations, parameters and position along flow pathways in the basin. HRU are connected by blowing snow, surface, subsurface and groundwater flow and together generate streamflow which is routed to the basin outlet. CRHM does not require a stream within a modelled basin. The feature allows CRHM to model the hydrology of regions dominated by storage and episodic runoff, such as agricultural fields.

Although CRHM has capabilities to represent many different processes, not all processes must be represented in all situations. The modular design of the CRHM platform enables the user to activate or inactive specific processes to optimize the model for a particular situation. For example, in the current study, blowing snow was not employed as it does not appear to be

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significant at the study site (periodic snow surveys showed relatively uniform snow cover). Preferential flow into tile drains was not developed for the current simulation as although it is a key process in heavy clay soil, as it does not appear to be a significant driver of preferential flow into tile drains in coarse textured soil (Pluer et al., 2020; Macrae et al., 2019). Freeze-thaw processes in soil were also not employed here as there is very little seasonal soil frost in the temperate Great Lakes region due to the persistent snow cover, and where soil frost occurs, it is restricted to brief periods and shallow depths (above 10 cm depth) (Macrae unpublished data).

2.3 Observations and input data for the model

Tile flow, soil water level (water table position) and surface flow were measured at the site between Oct. 2011 and Sept. 2018 at 15-minute intervals. It was not possible to install more than one measuring station at the site due to farming activity, so water table position and soil moisture were measured at the field edge, approximately at the midpoint of the field. Tile flow rates were determined using simultaneous measurements of flow velocity and water level in the tile main pipe at the edge of the field (Table A1, Appendix A), with an additional barometrically-corrected pressure transducer (Table A1) for periods when the flow sensor did not function. Surface runoff naturally exits the field at one location. However, to facilitate its measurement, the edges of the field were equipped with berms (1/2 plywood sheets, installed vertically above and below the ground), directing surface runoff through a culvert (45 cm diameter). Surface runoff through the culvert was also measured using a Hach Flo-tote sensor and FL900 logger. The soil water level in the field was measured at the edge of the field, located midway between the topographic high and low points of the field, using a baro-corrected pressure transducer.

Air temperature, wind speed, air relative humidity, incoming solar irradiance and rainfall were also measured at the site at 15-minute intervals and used to force the model. Variable names and their symbols in CRHM are listed in Appendix B. The air temperature, wind speed and incoming solar radiance measurements were collected 1 m above ground using a Temperature Smart Sensor S-THB-M002, Wind Smart Sensor Set S-WSET-M002 and a Solar Radiation Sensor (Table A1). Rainfall and relative humidity were measured via a tipping bucket rain gauge (Table A1) and a RH Smart Sensor (Table A1). These observations were continuously recorded throughout the study period, with the exception of brief periods of instrument failure and maintenance, when data from nearby stations (Table T1, Supplementary Material) was substituted using the double mass analysis method (Searcy and Hardison, 1960).

Although rainfall was recorded continuously at the field site, snowfall data was not. Snowfall data was obtained from nearby stations (Wroxeter-Davis and Wroxeter, Environment Canada, 2021), located 31.7 km from the field site. Periodic snow surveys done at the site found that data from the nearby stations was a close approximation of snow at the field site. Hourly precipitation data from Wroxeter-Geneor were used for the period between 2015 and 2018, whereas daily data from the Wroxeter station and the daily pattern of snowfall from Wroxeter-Geoneor were combined for the period between 2011 and 2014 for reconstruction of the missing hourly snowfall time series based on the method presented by Waichler and Wigmosta (2003).

2.4 Development of the new tile module

A Tile Drainage Module (TDM) was developed within CRHM with the goal of adding the ability to simulate tile flow and the resulting soil water levels at an hourly time scale. CRHM was forced with hourly precipitation, air temperature, solar radiation, wind speed and relative

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humidity to calculate hydrological states and fluxes in HRUs and the basin. The model requires parameterizations that specify the hydraulic and hydrological properties of the soil, including its thickness, saturated hydraulic conductivity (K), and surface cover. CRHM calculates water storage and fluxes between HRUs, as well as vertical fluxes amongst different hydrological compartments (within each HRU) that include snow, depressional storage, different soil layers, and groundwater.

Based on the simulation of soil moisture performed by the original CRHM "*Soil*" module, TDM calculates the dynamic tile flow rate that, in turn, feeds back to soil moisture at each time step. The presence of a capillary fringe (sometimes referred to as the tension-saturated zone within the soil profile) and its effects are considered by limiting the amount of drainable soil water. TDM uses specific site-specific information about the tile network, such as the tile depth, diameter and spacing, together with a parameterisation that translates the hydrological effect of the soil capillary fringe (CF), if present, into two state variables, CF thickness and CF drainable water. These two state variables are used to limit the fraction of the soil moisture that can freely drain to the tiles.

2.4.1 Soil moisture and water level

The TDM uses the water quality soil module or soil module (*WQ_soil* or *Soil*), which divides the soil column into two layers: a recharge layer where evapotranspiration and root uptake generally take place and a deeper layer that connects to the groundwater system. Since CRHM's state variable for soil moisture is soil water storage volume (Fig. 2a), the model results were converted into water level elevation above the semipermeable layer (Table B1, Appendix B; see Fig. 2b for comparison with soil water level observations) by dividing volumetric soil moisture content

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(Table B1) by soil porosity (Table B1) for the cases with no capillary fringe above the soil water level. Additional steps were taken for periods when a capillary fringe developed (discussed below).

2.4.2 Capillary fringe and drainable water

Soil moisture in the capillary fringe is equal to the field capacity (θ_{fc}) (Bleam, 2017, Sect. 2.4). Therefore, while the positioning of the capillary fringe responds dynamically to the matric potential, the saturation profile within the capillary fringe remains constant, as well as its thickness because it only depends on the pressure head (capillary forces) that are related to the grain size distribution and field capacity (h_{fc}) as introduced by Twarakawi et al. (2009). Therefore, the drainable water in the capillary fringe becomes the difference between saturation (θ_s), computed dynamically in CRHM, and θ_{fc}, which corresponds to the water held by capillary forces at field capacity (Fig. 2). Accordingly, Fig. 2 shows the schematic soil characteristic curve for the three water level conditions contemplated in the model.

1. *Condition 1* is when the matric head is at the surface and the soil is completely saturated;
2. *Condition 2* is when the matric head drops but the upper boundary of the capillary fringe is at the soil surface; and
3. *Condition 3* is when water level drops further and the upper boundary of the capillary fringe drops beneath the surface.

In essence, the soil is completely saturated (θ_s) in *Condition 1*. Between *Conditions 1* and *2*, the capillary fringe occupies the entire soil column above the water level; thus, it can only release the volume of water corresponding to θ_s-θ_{fc} or φ_c (dimensionless). Between *Conditions 2* and *3*, two layers with distinct hydraulic characteristics develop: (1) the top one at θ_{wp} that releases

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water up to θ_{fc}-θ_{wp}, and (2) the lower one that corresponds to the capillary fringe and can release up to the volume of water corresponding to θ_s-θ_{fc} or φ_c.

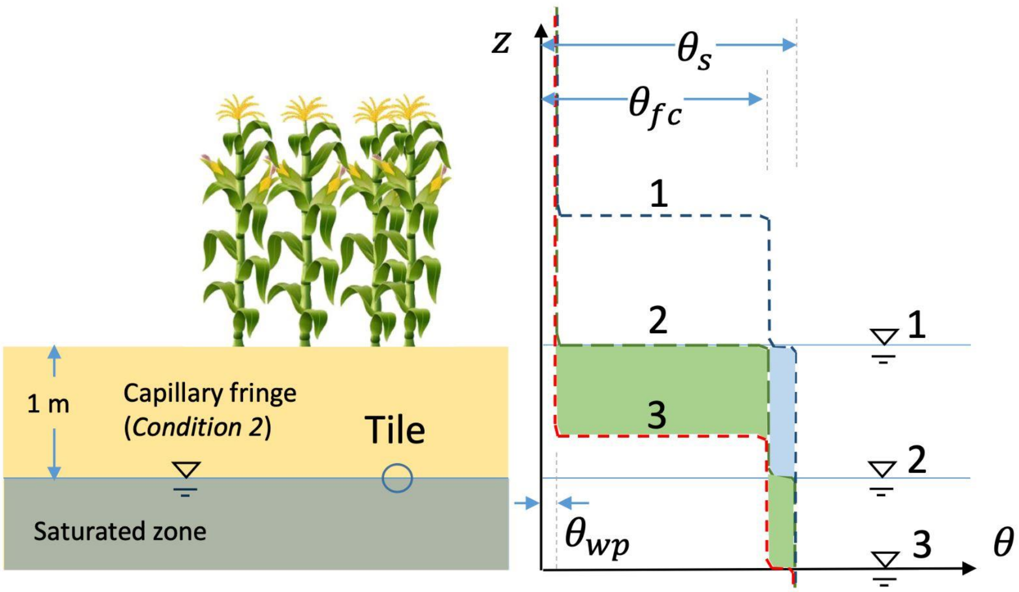

Figure 2. Schematic representation of the capillary fringe above the soil water level assuming a 1-m thickness (for demonstration purposes). The soil characteristic curves are shown for the three water level conditions considered: water level at the (1) surface, (2) intermediate depth, and (3) deeper depth. Two transitional drops can be seen in the characteristic curves, one from saturation (θ_s) to field capacity (θ_{fc}) (between *Conditions 1* and *2*) and one from field capacity to wilting point (θ_{wp}) (between *Conditions 2* and *3*). The colored areas (green and blue) of the right panel correspond to the amount of water that can be released between *Conditions 1* and *2* (blue) and between *Conditions 2* and *3* (green).

2.4.3 Tile flow calculation

A modified version of the Hooghoudt equation was used to calculate tile flow (Smedema et al., 2004), which presumes no surface ponding, an assumption that generally holds at the study site (Eq. 1), where water ponds only during very wet periods and on a small portion of the study site

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(see Fig. 1b). Hooghoudt's equation (Hooghoudt, 1940) is a steady state, physically based equation for saturated flow toward the tile drain. Flow estimates are provided based on the hydraulic conductivity of the soil and matric potential. It allows different saturated hydraulic conductivities for the layers above (AL) and below (BL) the tile (Fig. S1). In the particular case of the case study site, soil surveys have reported almost the same soil type (Loam) down to the depth of 90 cm (*e.g.* Van Esbroeck et al., 2016; Plach et al., 2018b), which was parameterized in the model set up as,

$$q = \frac{8 \times K_2 \times d \times h}{L^2} + \frac{4 \times K_1 \times h^2}{L^2}, \qquad (1)$$

where K_1 and K_2 are respectively the saturated hydraulic conductivity in the upper and lower layers in mm h^{-1}; L is the tile spacing in mm; h is the soil water level elevation above the tile in mm, d is the lower layer thickness in mm (Fig. S1), and q is the predicted tile flow in mm h^{-1}. The only variable that is dynamically updated by CRHM is h. Equation (1) is used to estimate the tile flow.

2.4.4 Calculation of the effect of tile flow on soil moisture and water levels

The simulated tile flows (see Sect. 2.3.3) are subtracted from the soil moisture. To calculate a water level from soil moisture, a threshold soil moisture content (sm_t) is defined, which consists of drainable water in the soil when the upper boundary of the capillary fringe is at the surface (*Condition 2*, Fig. 2) and can be calculated as:

$$sm_t = sm_{max} - (C_t \times \varphi_c), \qquad (2)$$

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where sm_{max} is the maximum soil moisture and C_t is the capillary fringe thickness in mm. However, since the hydrological conditions of the soil are markedly different between the two transitional situations described in Sect. 2.3.2 and Fig. 2 (*Condition 1* to *2* and *Condition 2* to *3*), a step function had to be considered for determination of the matric potential:

$$SWL = \begin{cases} \frac{sm_t - \left(C_t \times \left((\varphi_s - \varphi_c) + \theta_{wp}\right)\right)}{\varphi_s + \theta_{wp}} + \frac{sm - sm_t}{\varphi_c} & , if\ between\ Conditions\ 1\ and\ 2 \\ \frac{sm_{max}}{\varphi_s + \theta_{wp}} - \left(\left(\frac{sm_t - sm}{\varphi_s}\right) + C_t\right) & , if\ between\ Conditions\ 2\ and\ 3 \end{cases}, \quad (3)$$

where SWL is soil water level elevation in mm from the bottom of the soil, and sm is soil moisture in the given time step in mm. Equation (3) is determined based on soil moisture curves in Fig. 2 and water level *Conditions 1-3* discussed in Sect. 2.3.2. In Fig. 2, the first and second parts of Eq. (3), which refer to *Conditions 1* to *2* and *2* to *3*, respectively, correspond to the volumes of soil water highlighted in "blue" and "green."

2.4.5 Lower semi-permeable soil layer and periodicity in annual groundwater levels

This model application focused on the study site field without including other adjacent areas. This was possible because years of field monitoring at this site have demonstrated that there is no observable surface flow into the site from adjacent farms. The tile network is restricted to the field and is not connected to tile drains or surface inlets in adjacent fields. However, field soil water level observations show evidence of annual groundwater level periodicity/fluctuation (Rust et al., 2019) that are sinusoidal in nature and cannot be neglected. Some studies predict the

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annual groundwater oscillations or the annual responses of groundwater to precipitation by using sine and cosine functions (De Ridder et al., 1974; Malzone et al., 2016; Qi et al., 2018). De Ridder et al. (1974) studied the design of the drainage systems and described the seasonal groundwater fluctuations observed in wells using sinusoidal curves. Malzone et al. (2016) used a sine function to predict annual groundwater fluctuations in the hyporheic zone. Qi et al. (2018) and Rust et al (2019) used a cross-wavelet transform, consisting of the superposition of sine and cosine curves, to predict shallow groundwater response to precipitation at the basin scale. This approach was used in this application to simulate annual fluctuations in groundwater water tables, in Eq. (4), with a period of 1 year, minimums around the middle of the growing season (mid-July), and maximums in the cold season (early February). This translates into the lowering of the matric potential during the growing season, causing soil water seepage, and an elevated matric potential during the non-growing season, causing an increase in the soil moisture consistent with field observations.

$$G_{y,i} = \left[A \times sin\left(\frac{(T_s - D_d \times 24) \times 360}{24 \times 365.25}\right) - B\right] \times f_{y,i} \quad (4)$$

where T_s is the time step number, D_d is a time delay in days, A is the amplitude of the soil water level fluctuation, and B is an intercept factor. $f_{y,i}$ is a seasonal factor. The sine function coefficient (D_d, A, and B) and seasonal factor were adjusted for the whole period and for each year through model verification and shown in Table 1. Appendix C provides more details on the implementation of Eq. (4).

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2.5 *Model application and multi-variable, multi-metric validation*

The study site is a relatively small field, and 2 HRUs revealed sufficient to capture its hydrological dynamic in CRHM. The HRUs represent (1) the area immediately upstream of the outlet where surface ponding occurs (depression storage); and (2) the remaining field (Fig. 3). The maximum ponding capacity of HRU 1 was estimated using the spatially distributed hydrodynamic model FLUXOS-OVERFLOW (Costa et al., 2020b). The CRHM model and new TDM module were set up using the information described in Table 1. Soil textures at the LON site measured in a 25m grid across three soil depths (0-25 cm, 25-50 cm, and 50-100 cm) averaged 29% sand, 48% silt, and 23% clay (Ontario Ministry of Agriculture, Food and Rural Affairs Soil Team, unpublished data). This soil grain size distribution corresponds with a soil-saturated hydraulic conductivity of ~ 0.56 cm h^{-1} (~$10^{-2.5}$) (Garcia-Gutierrez et al., 2018), which was implemented in CRHM (0.5 cm h^{-1}), corresponding to a field capacity of 0.03 and h_{fc} of ~0.8 m (Twarskawi et al., 2009, based on a drainage flux of 0.1 cm d^{-1}).

A robust multi-variable, multi-metric model evaluation strategy was deployed to verify the capacity of the model to predict tile flow and its impact on the local hydrology. The state variables examined were tile flow, surface flow, and matric potential. The multi-metric approach contemplated four different metods, namely the Nash-Sutcliffe efficiency (NSE), Root-Mean-Square Error (RMSE), Model Bias (Bias), Percentage Bias (PBias), and RMSE-observation standard deviation ratio (RSR). See Appendix A for more details about the methodology used. It is generally assumed that NSE>0.50, $RSR \leq 0.70$, and $PBias$ in the range of $\pm$25% are satisfactory for hydrological applications (Moriasi et al., 2007). Hourly values were used in these

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calculations, which departs from the daily and monthly analyses typically reported for these types of models. Although this is a challenging proposition, it is an important one as it constitutes a necessary step forward toward more detailed, accurate, and advanced models for these regions. For example, Costa et al., 2021 noted that the successful extension of hydrological models to water quality studies relies on their ability to operate at small time scales in order to capture intense, short-duration storms that may have a disproportional impact on the runoff transport of some chemical species such as phosphorus – in essence to capture hot spots and hot moments for flux generation.

Table 1. Key model parameters in CRHM for representation of the LON site.

Model Parameter	Value	Unit	Source	Adjusted/Calibrated	Comment
Soil depth	2	m		No	Assumed
Semipermeable layer depth	3	m		No	Assumed
Tile depth	0.9	m		No	Farmer/Blueprints of the field
Corn root depth	0.5	m		No	Online sources
Soil recharge zone thickness	0.5	m		No	Based on the root depth
Tile spacing	14	m		No	Farmer/Blueprints of the field
Soil porosity (soil drainable water) φ_s	0.045			Yes	Adjusted
K in below layer	5	mm h^{-1}		Yes	Adjusted
K in above layer	5	mm h^{-1}		Yes	Adjusted
Capillary fringe thickness	0.8	m		Yes	Adjusted

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Capillary fringe drainable water φ_c	0.03		Yes	Adjusted
Surface depression in small area close to farm surface flow outlet (HRU2)	35	mm	Yes	Calculated
Surface depression in rest of the area (HRU1)		mm	No	Calculated
Surface area of HRU1		m^2	No	Field observations and DEM
Surface area of HRU2		m^2	No	Field observation and DEM
Soil module name in CRHM	WQ_soil		No	
Infiltration module name in CRHM	GreenAmpt		No	
Soil type in GreenAmpt module	5		Yes	Adjusted
Saturated K in GreenAmpt module	6	mm h^{-1}	Yes	Adjusted
Soil wilting point	0.025		Yes	Adjusted
A, in sine function	0.025	mm h^{-1}	Yes	Adjusted
B, in sine function	-0.005	mm h^{-1}	Yes	Adjusted
D_d, in sine function	15	d	Yes	Adjusted
$f_{2012,2}$ (Seasonal factor, sine function)	2.0		Yes	Adjusted
$f_{2015,2}$ (Seasonal factor, sine function)	1.8		Yes	Adjusted
$f_{2016,2}$ (Seasonal factor, sine function)	2		Yes	Adjusted
$f_{2017,2}$ (Seasonal factor, sine function)	1.4		Yes	Adjusted
$f_{y,i}$	1		No	By default for $y = 2012\ to\ 2017$ and $i = 1, 2$

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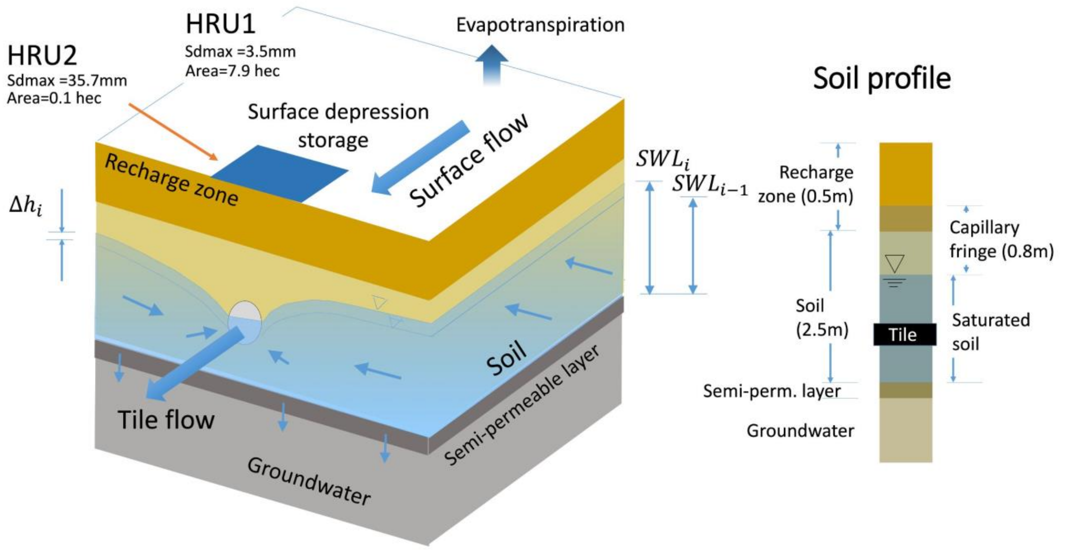

Figure 3 a) Schematic conceptual view of the CRHM model configuration, including soil layers, soil water level, groundwater, and tile flow.; and b) soil profile, including the capillary fringe and its location relative to the soil and tile.

3. Results

3.1 Tile flow

The model was able to capture most tile flow events, both in terms of the timing and magnitude of peak flows and the most important seasonal patterns (Fig. 4). For example, the almost complete absence of tile flow during the growing season (May to September) was captured. The simulated flow peaks generally have a good agreement with observations, as well as the low flow or base flows during cold periods (December-March). The ascending and descending limbs of the response signal are also adequately predicted.

Results show that tile flows generally occur during snowmelt events, as indicated by the synchrony between snow water equivalent (SWE) depletion and tile flow. The maximum

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snowpacks (or snow water equivalent, SWE) were markedly smaller during the winters of 2016 and 2017 when compared with those of 2013 to 2015. However, this did not necessarily translate into lower tile flows as precipitation also occurred as rain during these seasons.

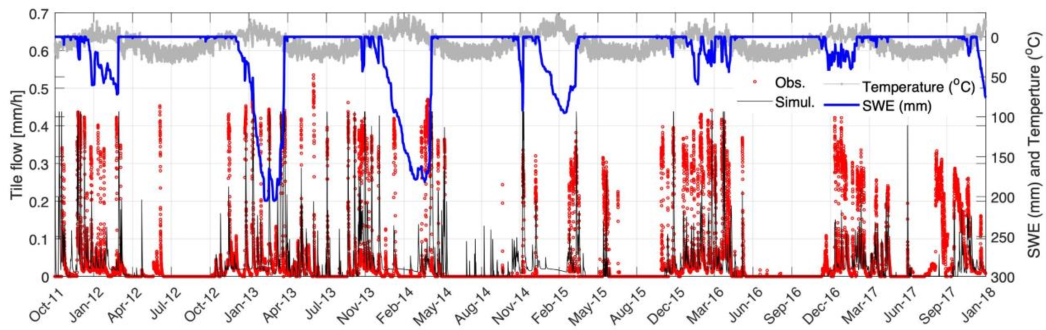

Figure 4 Comparison between observed and simulated tile flows, simulated SWE, and observed air temperature in the LON site.

3.2 Soil water levels

Simulated and observed soil water levels (m) are compared in Fig. 5, alongside air temperature and precipitation observations. Despite the observation gaps, the model agrees well with observations. Above tile drains, water fluctuations are controlled by infiltration/recharge, tile flow, groundwater flow, and matric potential that affects the drainable water from the capillary fringe. In contrast, tiles do not withdraw water from the soil layer below the tile pipe. This causes flashier soil moisture responses above the tile that are captured well by the model. During the growing season, both the observed and simulated soil water levels drop abruptly because of the seasonal lowering of the regional groundwater water table. In the growing seasons of 2012, 2015 and 2016, which were dry years, large drops in the soil water level were observed, whereas in other more wet years such as 2013 and 2014, seasonal water level declines were smaller. The seasonal declines in water level during the growing season led to a cessation in tile flow in most years (Fig. 4, 5), even following rainfall events. For example, there was a large precipitation

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event (~35 mm) in the growing season of 2016 that did not produce tile flow (apparent in both model and observations).

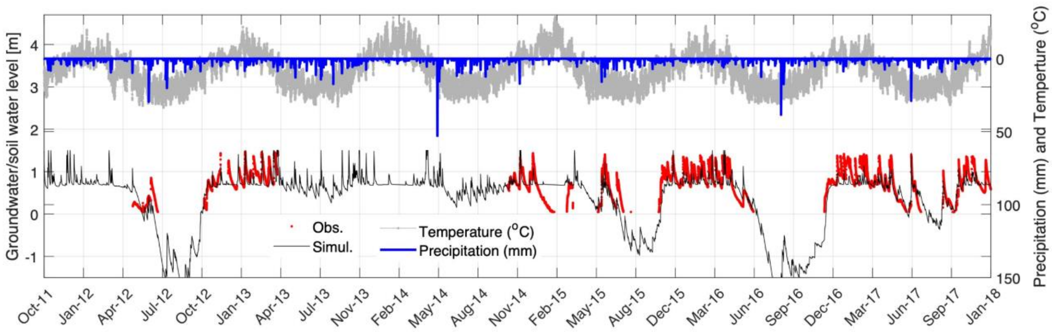

Figure 5 Time series of the simulated and observed water level in soil along with the observed temperature and precipitation. The horizontal line shows the depth of the tile pipe.

3.3 Surface flow and total flow

The model was not able to capture the observed surface flow as satisfactorily as it captured tile drainage (Fig. 6a). Some of the possible reasons are uncertainties in the measurements of surface flow due to ponding in surface depressions on the field, which impeded the drainage of some of the surface runoff (see Fig. 1). However, the model performance improves considerably when both runoff and tile flow are combined (referred to as total flow, Fig. 6b). Indeed, most of the flow from the field was through tile drains (80% in 5-year average) rather than surface runoff (20% in 5-year average, Plach et al., 2019). The underestimation of both cumulative total and surface flows during 2017 and 2018 is possibly due to the removal of the blockage in tile pipes in early 2017 that may have affected both surface and tile flows.

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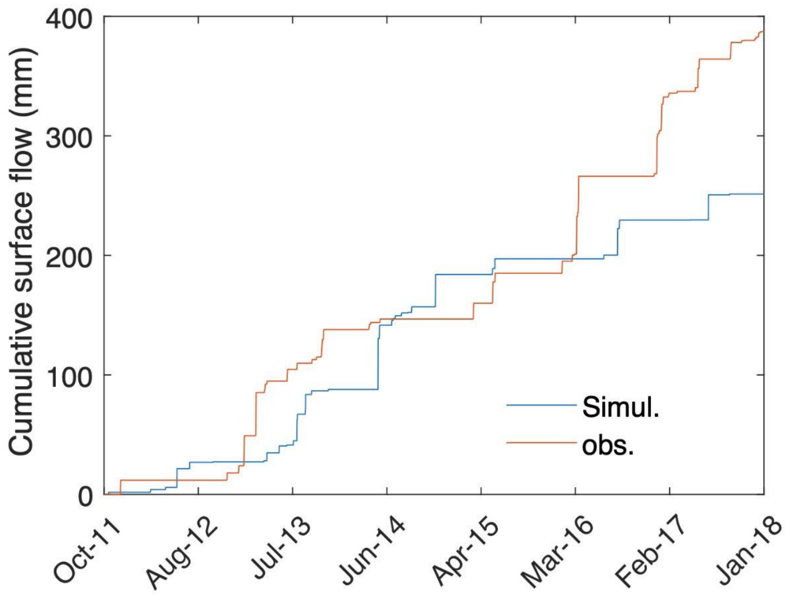
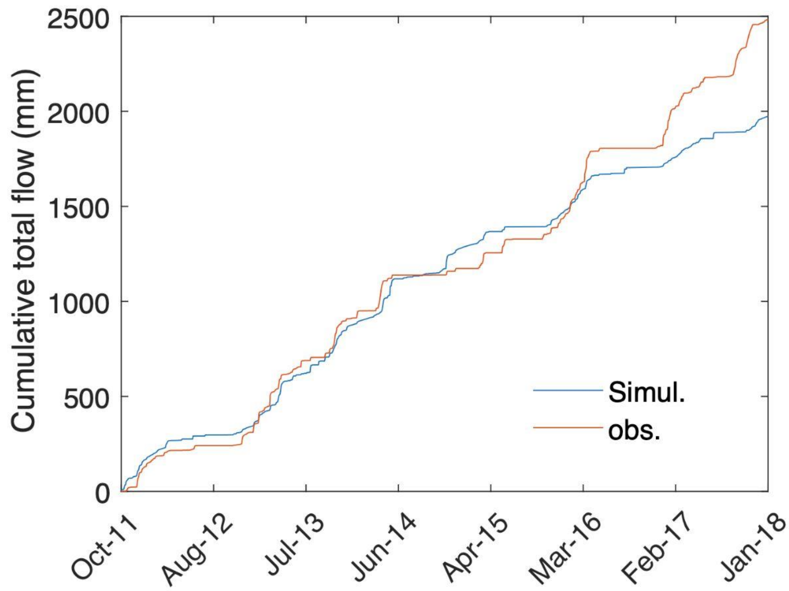


a)



b)

Figure 6 Observed and simulated cumulative surface flow (a) and total flow (b) with their performance coefficients.

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3.4 Overall model performance

The model performance was calculated based on hourly data for various model outputs (Table 2). The results confirm that the model is robust in the sense that it can captures the main patterns of tile flow, surface flow, and matric potential levels. The PBias values are below 25% for most of the fluxes and cumulative fluxes. The RSR values are also generally below 0.82. The NSE values are positive and above 0.3 for most fluxes, except for surface flow, where the model exhibited some difficulties.

Table 2 Performance coefficients for surface flow, tile flow and soil water level as well as total (tile+surface) flow and the cumulative surface, tile and tile+surface flows.

Performance coefficients	**Surface flow ($mm\ h^{-1}$)**	**Tile flow ($mm\ h^{-1}$)**	**SWL (m)**	**Total flow ($mm\ h^{-1}$)**	**Cumulative Tile flow (mm)**	**Cumulative Surface flow (mm)**	**Cumulative Total Flow (mm)**
NSE	-2.29	0.31	0.49	-1.38	0.98	0.85	0.96
RMSE	0.27	0.08	0.26	0.30	111.13	55.61	151.08
Bias	0.54	0.24	0.14	0.28	0.026	0.22	0.047
PBias	21.77	17.91	10.46	18.63	2.05	15.15	3.99
RSR	1.82	0.83	0.71	1.54	0.16	0.39	0.20

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3.5 *Presence of capillary fringe: effects and hypotheses*

Results show that the thickness and vertical positioning of the capillary fringe have a strong impact on the amount of drainable soil water that can flow into tiles. To investigate this effect further, we examined the response of the tile flow and soil moisture to changes in the capillary fringe. It should be noted that although this thickness may slightly change depending on the soil type and water retention curves (Skaggs et al., 1978), the model assumed a constant value given the catchment-scale nature of the simulations and myriad of processes contemplated. However, despite the simplification, the vertical positioning of the capillary fringe was still computed and enabled a dynamic (time-dependent) calculation of the drainable soil water that is available for tile drainage over time.

Effect of capillary fringe on tile flow

Figure 7a relates the simulated normalized total cumulative tile flow (Q_{tR} , total tile flow divided by the total tile flow when there is no influence of capillary fringe) to capillary fringe drainable water ($\varphi_{cR} = \varphi_c/\varphi_s$) for two different φ_s values (0.045 and 0.125). The values were normalized for comparison purposes. As expected, the model indicates that tile flow increases with drainable water, but the relationship is non-linear, likely because as tile carrying capacity is exceeded more frequently, there is more opportunity for groundwater seepage and evapotranspiration. The direct effect of φ_s (comparing the solid and dashed lines) on tile flow is small because the amount of water that can effectively drain to the tile is controlled by the capillary fringe and the associated drainable soil water. Figure 7b looks at the impact of the capillary fringe thickness on tile flow. Here, the values are also normalized. Results show that Q_{tR} decreases with increasing normalized thickness of the capillary fringe, T_{CFR} ($\frac{T_{CF}}{D_t}$, capillary

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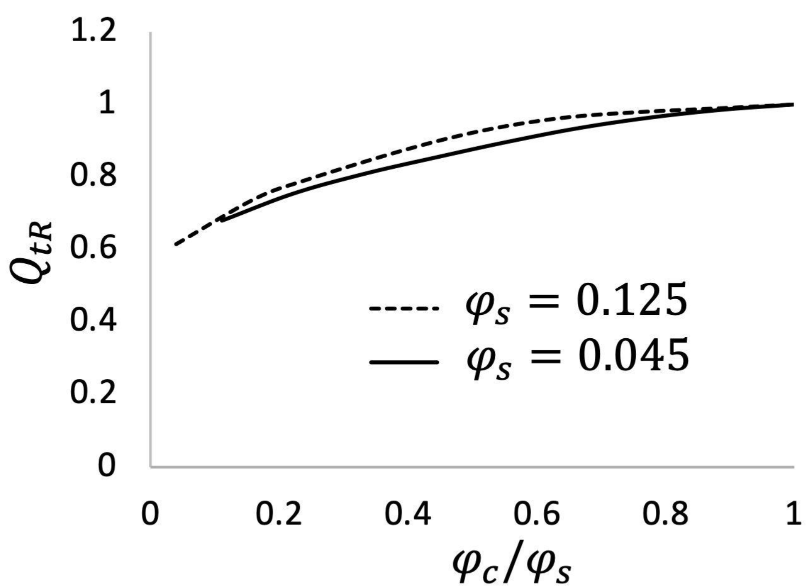
499 fringe thickness divided by tile depth), but only while the T_{CFR} is less than 1 that is when the
500 capillary fringe position is above the tile but has not reached the soil surface. Beyond this point,
501 increments in the capillary fringe thickness have no impact on tile flow because *Condition 1* has
502 been reached (see Fig. 2), which essentially means that the capillary fringe has reached the soil
503 surface.



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505 a)

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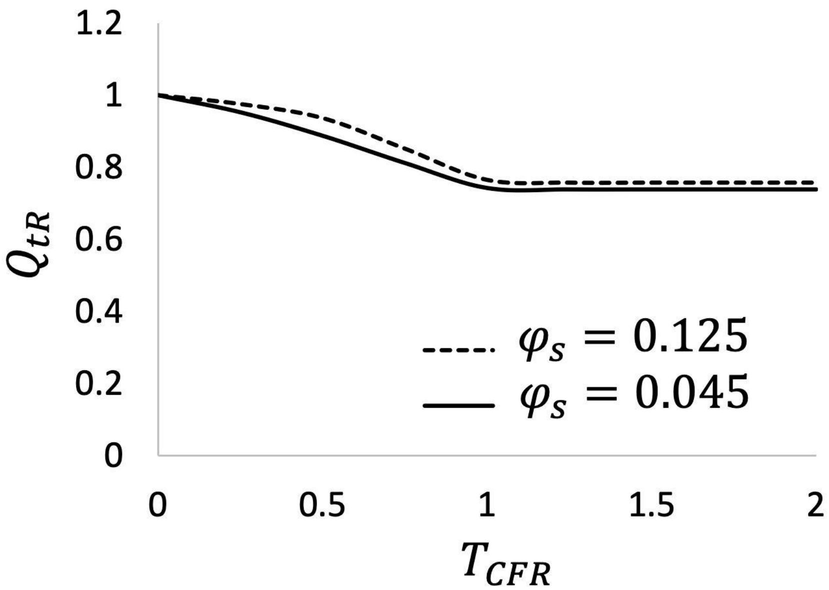

b)

Figure 7 Comparison between normalized tile flow (Q_{tR}) and (a) normalized drainable soil water (φ_c/φ_s) and capillary fringe thickness (T_{CFR}) for different maximum soil saturation values (φ_s).

Effect of capillary fringe on soil moisture

Observations and model results of SWL (as an indicator of soil moisture) reveal a bimodal frequency distribution (Fig. 8 and 9, respectively) with peaks at 0.85 m and 1.25 m depth, with the former corresponding to the depth of the tile pipe and the second peak reflecting capillary fringe thickness. In the simulated SWL frequency distributions (Fig. 9), the first peak highlights again the efficiency of the tile in removing soil moisture. In contrast, the second peak indicates a strong model response to differences in the capillary fridge thickness. It shows that when there is an almost constant discharge from the bottom of the soil layer, the matric potential varies the greatest while it remains between the tile depth and the soil surface. While the matric potential

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fluctuates faster and is more unstable within this range, it also remains there for shorter periods. This bimodal response tends to push the matric potential below the tile.

The bimodal behavior of the soil water levels demonstrated here provides the opportunity to quantify the thickness of the capillary fringe using continuously monitored soil water levels. The capillary fringe thickness determined using this method can then be used as an input to the TDM module.

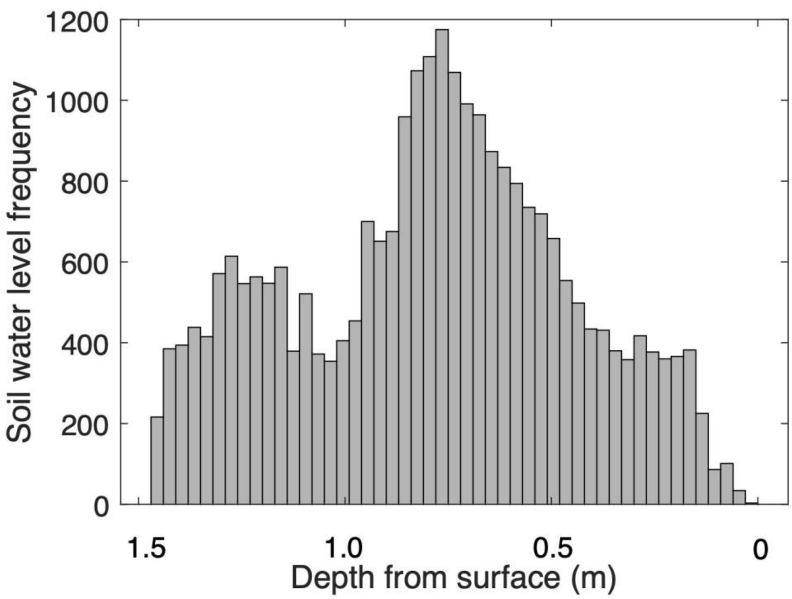

Figure 8 Histogram of the observed soil water level distribution for the period pf 2011 to 2018 in LON.

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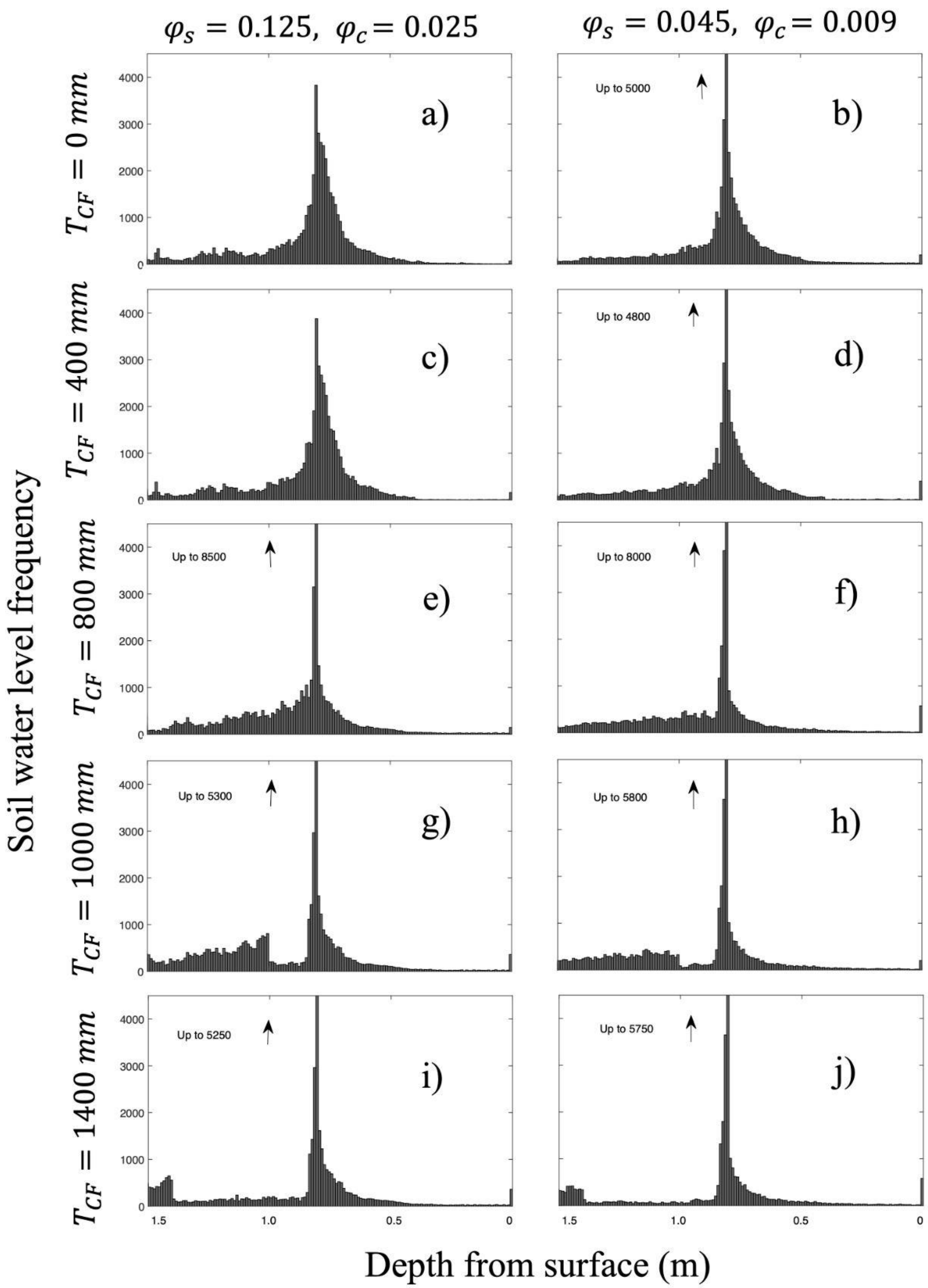

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Figure 9 Histograms of the soil water levels for the capillary fringe thicknesses of 0 (a,b), 400 (c,d), 800 (e,f), 1000 (g,h) and 1400 (i, j) mm and for the φ_s and φ_c of 0.125 and 0.025 (left column)as well as 0.045 and 0.009 (right column).

4. Discussion

The new TDM module developed for CRHM was able to capture tile drainage flow and its effect on the hydrological patterns of a farm field in southern Ontario. This module can help extend the use of the CRHM platform from agricultural basins in the colder Canadian Prairies to the more temperate Great Lakes region. Tile drainage is prevalent across much of the cultivated lands in the Great Lakes basin and adjacent regions from southern Canada to the upper US Midwest. It is expanding in the eastern Canadian Prairies as well. The new TDM module will also permit simulating the impacts of a changing climate on runoff processes in these landscapes. In addition to this potential, the development of the TDM has also provided insights into hydrological processes in tile-drained landscapes. These are discussed in more detail below.

4.1 Insights into key control mechanisms of tile flow for catchment-scale simulations

The model suggests that tile flow may not be accurately simulated exclusively based on the matric potential and soil saturated hydraulic conductivity as suggested by the steady-state flow assumptions of the Hooghoudt's equation (Hooghoudt, 1940). Our results indicate two additional controls: (1) the amount of drainable soil water in the soil, which has also been identified in some field studies (*e.g.*, Skaggs et al., 1978; Moriasi et al., 2013) and (2) fluctuations in the groundwater table (GWRD) are equally important to account for in catchment-scale simulations. However, the relationship between drainable water and tile flow rates is non-linear, as demonstrated in Fig. 7a. This is because the opportunity time for groundwater seepage and

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evapotranspiration increases when the hydraulic tile carrying capacity is exceeded. Comparatively, the effect of soil drainable water, φ_s (see also Fig. 7a) on tile flow is small because the capillary fringe and associated drainable soil water control the amount of water that can effectively flow to the tile.

The verification of the model also indicated that the slopes of the rising and falling limbs of tile flow hydrographs and SWL were very sensitive to (1) the ratio between K and drainable soil water; and (2) the net outflow in the soil through tile flow and groundwater level fluctuations (GWRD). This is supported by previous studies showing rapid responses of tile flow to precipitation events (Gentry et al., 2007; Smith et al., 2015) and others that have related rapid responses in tile discharge to antecedent moisture conditions (Macrae et al., 2007; Vidon and Cuadra, 2010; Lam et al., 2016a; Macrae et al., 2019), which can be affected by the development of a capillary fringe and its holding capacity.

Results show that large fluctuations in SWL and tile flow during the cold season, when the soil water level tends to be above the tile, are primarily triggered by the development of the capillary fringe that reduces the amount of drainable soil water. Model sensitivity tests showed that a small amount of drainable soil water produces steeper rising and falling responses (and with larger fluctuation amplitudes) in both the soil water level and the tile flow. Indeed, this pattern can be observed by exploring differences in tile drain responses in clay loam soils with larger field capacities (and correspondingly smaller drainable water) and smaller hydraulic conductivity which are more likely to experience pronounced oscillations (*e.g.*, steeper rising and falling response curves) compared to tile drain responses of sandy soil, which is characterized by

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reduced capillary forces, lower field capacities (but correspondingly larger drainable water) and higher hydraulic conductivity. Notably, both model and observations of SWL (as a proxy for soil moisture) reveal a bimodal (*i.e.*, two peaks) frequency distribution when examined in relation to the tile depth and capillary fringe thickness (Fig. 8 and 9, respectively). The two peaks (*i.e.* most frequently observed SWL conditions) correspond with the (1) depth of the tile pipe (0.75 m), which demonstrates the efficacy of the tile at rapidly removing excess soil water, and the (2) the capillary fringe thickness (for the depths of 1.0 and 1.4 m, Figs. g, h, i and j) beyond which the amount of drainable water above the water level significantly increases.

These findings align well with studies such as Lam et al. (2016a) that recorded soil moisture near saturation after tile flow had ceased, suggesting the development of a capillary fringe. Combined experimental and modeling works, such as in Moriasi et al. (2013) and Logsdon et al. (2010), also discuss the impact of drainable soil water ("drainable porosity" or "specific water yield") on tile flow and note that the drainable water is, in turn, dependent on the soil type, soil-water dynamic and soil water level depth. However, these studies did not explore the dynamic nature of the capillary fringe and its thickness relative to the soil column above in determining the transient amount of drainage soil water that will impact the SWL distribution and tile flow differently over time (*Conditions 1* to *3*, see Fig. 2). Herein, while we assumed a capillary fringe with a fixed thickness that is generally related to the soil properties, its vertical positioning was simulated dynamically, which allowed determining the drainable soil water based on the evolution of pressure head corresponding to field capacity. Thus, the development of the TDM has provided a step forward in the modeling of tile drainage at catchment scale and suggests that in loam soils such as those at the study site, the effects of a capillary fringe on tile flow should be included. Soil moisture measurements from the study site by Van Esbroeck et al., (2017) between November 2011 and May 2014 from depths of 10, 30, and 50 cm (using EC-5 Soil Moisture Smart Sensor) showed that almost 90% of the gravitational soil moisture drains out with 0.5 to 2.5 h.

4.2 Importance of capturing seasonal patterns in groundwater to improve tile flow predictions

The GWRD changed dramatically between seasons affecting soil moisture and tile flow patterns. Both observations and model results show that low precipitation and higher evapotranspiration rates tend to produce little tile flow during the growing season. These seasonal patterns in precipitation and evapotranspiration are accompanied by a reduction in soil moisture (soil water level) that leads to a substantial storage capacity in fields. Even following moderate and high-intensity storms during the growing season, rapid soil moisture increases are observed; however, tile flow rarely develops, suggesting that the soil is able to hold the water (Lam et al., 2016a; Van Esbroeck et al., 2016). In contrast, tile flow is often observed during the cold season, even during smaller rainfall-runoff and snowmelt events because of reduced soil storage but also a seasonal increase in GWRD (Lam et al., 2016a; Macrae et al., 2007, 2019; Van Esbroeck et al., 2016). This concurs with several studies throughout the Great Lakes and St. Lawrence region that have reported stronger tile responses during the non-growing season, with the summer months often showing little to no tile flow (Lam et al., 2016a, 2016b; Jamieson et al., 2003; Macrae et al., 2007; Hirt et al., 2011; King et al., 2016; Van Esbroeck et al., 2016; Plach et al., 2019).

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These results (the controlling effect of soil drainable water and groundwater level fluctuations on tile flow) suggest that while soil moisture is largely controlled by tile flow rather than GWRD in the cold season, this reverses in the growing season (*i.e.* soil moisture controls tile flow), and, soil moisture is also impacted by evapotranspiration. The model indicated that the rapid drops the observed in SWL during the growing season could not be explained by evapotranspiration alone as well as the crop root depths, thus pointing at the role of GWRD.

5. Conclusion

A new tile drain module has been created and tested for catchment-scale simulations within the modular Cold Regions Hydrological Modelling platform to support management in agricultural basins that have seasonal snow covers. The model was tested and validated for a small working farm in southern Ontario, Canada, and presents a step forward in the dynamic simulation of tile flow and its effects on the hydrological cycle in cold climates. Observations and model results showed that the dynamic prediction of tile flow and soil moisture at catchment scales needs to account for (1) the amount of drainable soil water that can be affected by the development of a capillary fringe and (2) fluctuations in the groundwater water table, in addition to the typical (3) matric potential above the tile pipe and (4) the soil saturated hydraulic conductivity considered by the steady-state flow Hooghoudt's equation.

The groundwater table and matric potential changed dramatically between seasons, affecting patterns of soil moisture and tile flow. Observations and model results showed that low precipitation and higher evapotranspiration rates caused minimal tile flows during the crop-growing season. Conversely, tile flow was often observed during the cold season, even during small rainfall-runoff and snowmelt events due to a seasonal increase in the groundwater table and soil water level.

Model sensitivity tests showed that the capillary fringe strongly affected the amount of drainable soil water flowing into the tile. Tile flow increased with drainable water, but the relationship is highly non-linear likely because, as the tile carrying capacity is exceeded more frequently, there is more opportunity time for groundwater seepage and evapotranspiration. Finally, observations and model results reveal a bimodal soil moisture response in the presence of tiles, which is controlled by the relative positioning of the capillary fringe in relation to the soil surface and tile pipe. Capturing these dynamics is a critical advance enabling the accurate prediction of the swift hydrological changes caused by the presence of tiles in catchment-scale models.

Author contribution

MK and DC developed the model code and performed the simulations. MM prepared the data and supported the field work. MK and DC prepared the manuscript with contribution of MM, JP and RP.

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Appendix A

Table A1 Instrument names and descriptions

Instrument name	**Description**
Hach Flo-tote and FL900 logger	Flow velocity and water level measurement
U20, Onset Ltd.	Barometrically-corrected pressure transducer
Temperature Smart Sensor S-THB-M002	Air temperature measurement
Wind Smart Sensor S-WSET-M002	Wind speed measurement
(Silicon Pyranometer)-S-LIB-M003	Solar radiation sensor
Tipping bucketrain gauge, 0.2 mm Rainfall Smart Sensor – SRGB-M002	Rainfall measurement
RH Smart Sensor(S-THB-M002)	Relative Humidity measurement

Appendix B

Table B1 Parameter names and their symbols in CRHM platform

Parameter symbol	**Parameter name**
Tair	Air temperature

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Wspeed	Wind speed
RH	Relative Humidity
Qsi	Incoming solar irradiance
R	Rainfall
WQ_soil	Water Quality soil module
soil_WL/SWL	Soil water level elevation above the semipermeable layer
soil_moist	Soil moisture
Poro_soil	Soil porosity
AL	Above layer
BL	Below layer
GWRD	Groundwater level fluctuations, groundwater recharge and discharge

Appendix C

We show how we assess seasonal factors ($f_{y,i}$) for different years in this study. Equation (4) can be written as:

$$G_{y,i} = G \times f_{y,i} \tag{C1}$$

For each year (y), $f_{y,i}$ for the first ($f_{y,1}$) and second ($f_{y,2}$) part of the sine function (G), where $G \geq 0$ and $G < 0$ respectively, were defined as:

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$$\begin{cases} if\ G \geq 0\ \ [i = 1\ ]then\ f_{y,1} = x \\ if\ G < 0\ \ [i = 2\ ]then\ f_{y,2} = y \end{cases} \quad \text{(C-2)}$$

G is the sine function representing the annual fluctuations in soil water level. So, for n years there are $n \times 2$ $f_{y,i}$ values. The default values for $f_{y,i}$ are 1 and the default values can be changed for each year and for first and second parts in each year independently. Calculated $G_{y,i}$ in each time step add or subtracted to or from the total soil moisture depend on the its sign. The values for the sine function parameters are in Fig. C1. The verified sine function time series along with time series of temperature, precipitation and calculated evapotranspiration are shown in Fig. C1. In this figure it is obvious that in years 2012 and 2015 to 2017 the warm season amplitudes are larger. The ET values are happen more in the warm seasons (growing seasons). Also it can be seen that the seasonal oscillation in sine function is very similar to the temperature general oscillations.

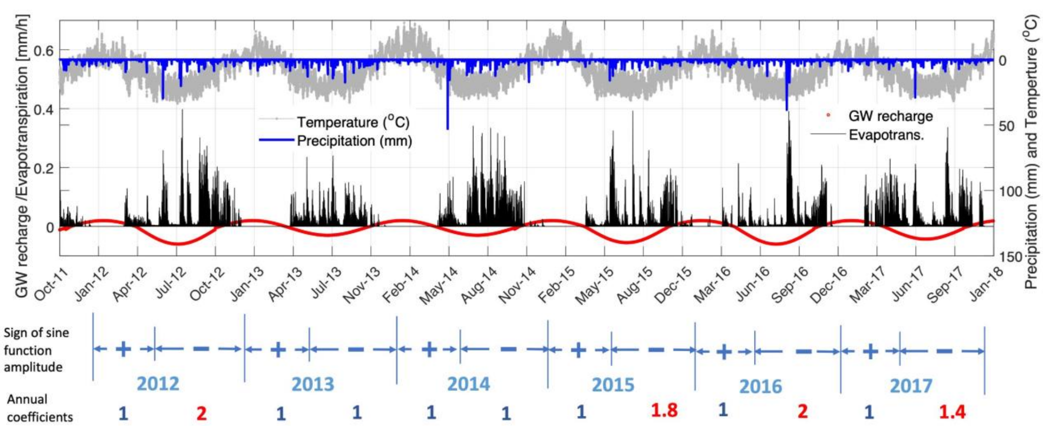

Figure C1 Time series of the adjustable sine function along with the time serioes of calculated evapotranspiration, temperature and precipitation during the study period from Oct 2011 to Sept 2018.