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

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## Abstract

Systematic tile drainage is used extensively in poorly drained 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. Thus, there is a need to simulate the hydrological behaviour of tile drains to understand the impacts of climate or land management change on agricultural surface and subsurface runoff. The Cold Regions Hydrological Model (CRHM) is a physically based, modular modeling system developed for cold regions. Here, a tile drainage module is developed for CRHM. A multi-variable, multi-criteria model performance evaluation strategy was deployed to examine the ability of the module to capture tile discharge under both winter and summer conditions (NSE>0.29, RSR<0.84 and PBias <20 for tile flow and saturated storage ~~water table~~ simulations). Initial model simulations run at a

15-min interval did not satisfactorily represent tile discharge; however, model simulations improved when the time step was lengthened to hourly but also with the explicit representation of capillary rise for moisture interactions between the rooting zone and groundwater, demonstrating the significance of capillary rise above the saturated storage layer ~~water table~~ in the hydrology of tile drains in loam soils. Novel aspects of this module include the sub-daily time step, which is ~~shorted~~ shorter than most existing models, ~~and which may enable future water quality modules to be added,~~ and the use of field capacity and its corresponding pressure head to provide estimates of drainable water and the thickness of the capillary fringe, rather ~~using~~ than using detailed soil retention curves that may not always be available. An additional novel aspect is the demonstration that flows in some tile drain systems can be better represented and simulated when related to shallow saturated storage~~water table~~ dynamics.

Keywords: tile drainage, cold regions, hydrological model, capillary fringe, drainable water, saturated storage~~water table~~ 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~~surface water is an important contributor to the increased frequency of algal blooms being experienced in North America and elsewhere (Sharpley et al., 1995; Correll, 1998; Filippelli, 2002;

Ruttenberg, 2005; Schindler, 2006; Quinton et al., 2010; Costa et al., 2022). Although n~~N~~utrient 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 lower ~~the~~ seasonally ~~high water~~high-water tables in poorly drained fields, reduce the retention time of soil water, lesseningg 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 nutrients and particulate ~~nutrients~~ material (Kladivko et al., 1999; Tomer et al., ~~2015~~2003). In Alberta, tile drains have also been used to address salinity issues (Broughton and Jutras, 2013). 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, controlled tile drainage and surface runoff in different soil types at the small basin scale, which ~~mainly~~typically calculate the amount of gravitational drainage from the soil, 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, and~~but~~ ~~research shows 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 also 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~~increasing in many cold regions (Kokulan et al., 2019a; OMAFRA, 2023), it has become important to integrate such human-induced processes in the specialized hydrological modelling tools that have been developed 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~~ events ~~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) 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 water table 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 soil hydrological storage (typically represented as water table). In cases where there is a need for more focus on soil matrix hydrology and less need for understanding hydrological processes at the catchment scale and the relative contribution of tiles (and its interplay), 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, hydraulic gradients and the positioning of the saturated storage layer~~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 hydrological 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 loss from farmland via surface runoff and tile flow, models must be able to predict soil moisture and saturated layer storage ~~and the water table elevation accurately~~ (Brockley, 1976; Rozemeijer et al., 2016; Javani-Jouni et al., 2018). Early ~~Many S~~s~~ome s~~tudies have shown that in some soil types, including silty loam and clay loam soils, the drainable water is less than expected based on the effective porosity (*e.g.*, ~~Skeggs~~ Skaggs et al., 1978; Raats and Gardner, 1974). Raats and Gardner (1974) have argued that the calculation of drainable porosity requires knowledge of water table elevation and the distribution of soil moisture above the saturated storage layer ~~water table~~. Skaggs et al. (1978) added that the calculation of drainable porosity should consider “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 depth of saturated water (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 soil was 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~~ did not always drain all the gravitational water following a rainfall/snowmelt event and the soil may remain at or above field capacity (Skaggs et al., 1978; Lam et al., 2016a). ~~Therefore~~This means that ~~,~~ 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 (represented as a "water yield") (Skaggs, 1980b), and is calculated for layered soil profiles (Badr,1978), it requires detailed information surrounding the soil water characteristic curve (Skaggs, 1980b). Although it is indeed optimal to use soil-specific water characteristic curves, ~~Twarakawi~~ Twarakavi et al. (2009) found that it ~~was~~ is possible to employ average representative values from the soil water characteristic curve to represent soil drainable water where ~~a~~ soil-specific curves are ~~was~~ not available, with some reduction in~~.~~ ~~and They~~ ~~they~~ ~~found in this case that the~~ model performance ~~was reduced~~.

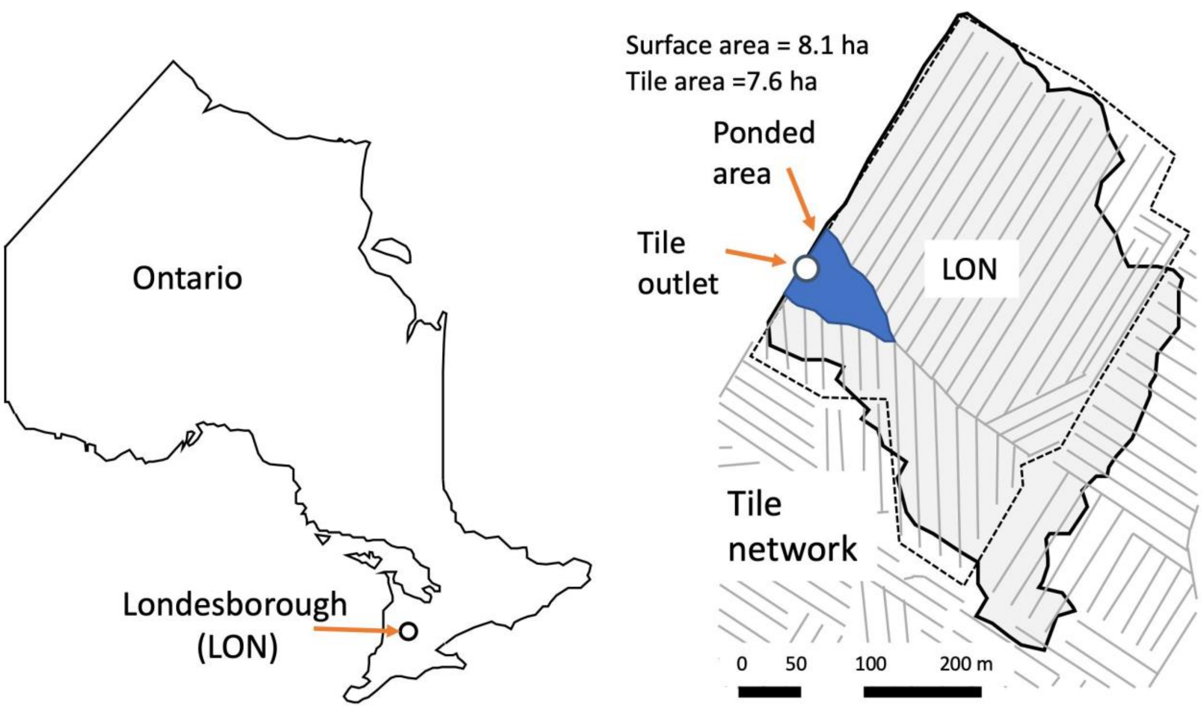
In this study, a new Tile Drainage Module (TDM) was developed and incorporated within the physically based, modular Cold Regions Hydrological Modelling (CRHM) platform (Pomeroy et al., 2022) to enable hydrological simulations in tile-drained farm fields in cold agricultural regions. As a first iteration, the new module was developed for a field with sloping ground and loam soil with imperfect drainage. Such landscapes are common in the Great Lakes Region (e.g., Michigan and Vermont, USA and Ontario, Canada) and tile drainage in such landscapes has not been as widely studied as it has been in clay-dominated soil. In this module, considerations were explicitly included for the effects of capillary rise and annual fluctuations in saturated storage ~~groundwater water table fluctuations~~ on drainable soil water storage. The use of field capacity and groundwater/soil saturated storage ~~water elevation head~~ (~~Twarakawi~~ Twarakavi 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 circumvent the need for water characteristic curves. The development of this physically based module provides insight into hydrological processes in tile drainage from sloping landscapes with imperfect drainage, which are increasingly being artificially drained (Cordeiro and Ranjan, 2012; Kokulan et al., 2019a; OMAFRA, 2023).

## 2. Materials and Methods

### *2.1 Study area*

The study site is a ~10 ha farm field located near Londesborough, Ontario at UTM 17T 466689m E, 4832203m N, shown as LON in 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~~ type 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) but may also receive lateral groundwater flow from neighbouring fields. Water yields from the tile drain laterals (10 cm diameter) are discharged via a common tile outlet (main, 15 cm diameter) below ground. Surface runoff from the field is directed toward a common outlet on the surface using plywood berms installed along the field edge (see van Esbroeck et al., 2016). The tile and surface runoff outlets do not join into a common outlet and are fully separated from one another, even during surface ponding events. The 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), soil characteristics are provided in Plach et al. (2018a) and Plach et al. (2018b) and equipment and monitoring are provided in van Esbroeck et al., (2016). The outlets for both surface and tile flow 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, presumably due to either surface runoff or return flow (see ponded area, Fig. 1b). However, surface water or elevated soil moisture conditions are not observed in this topographic low during smaller events or dry periods of the year, suggesting that this saturated ponding is not in a perennial groundwater discharge zone. Although surface ponding is observed in the topographic depression within the field, water discharges freely at the opposite end of the culvert, facilitating the measurement of flow.




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.

*2.2 CRHM: The modelling platform*

CRHM is a modular hydrological process modelling platform that allows users to select relevant process ~~sub~~modules and apply them as needed to their study. For example, ~~The~~ ~~modular~~ the 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 is able to calculate~~s~~ 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 (Pomeroy et al., 2007; 2022). ~~Water quality nNutrients losses in water can also be simulated in CRHM (Costa et al., 2021), although this was not done in the current study.~~ Modules of a CRHM model can be customized 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 modules ~~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. The size of ~~TDM~~ HRUs is flexible and can be as small as the size of a single tile pipe (e.g., 1 m) times the pipe spacing (which was 14 m in our case study region), and as large as entire tile networks within a given farm or study area. CRHM does not require a stream within a modelled basin. The feature allows CRHM to model the hydrology of cold regions dominated by storage and episodic runoff, such as agricultural fields.

Although CRHM has the capability to represent many hydrological and thermodynamic processes, not all processes need/must be represented in all situations. The modular design of the CRHM platform enables the user to activate or ~~inactive~~ inactivate specific processes to optimize the model for a particular situation. This is a modelling approach that enables testing different modelling hypotheses and has been pioneered by CRHM and other models, which has inspired a range of hydrological (e.g., SUMMA, Clark et al., 2015a, 2015b), hydrodynamic (e.g., mizuRoute, Mizukami et al., ~~2015~~2016) and biogeochemical (e.g., OpenWQ, Costa et al., 2023~~a, 2023b~~) modelling tools. For example, in the current study, blowing snow was not employed in CRHM as it does not appear to be significant at the study site (periodic snow surveys showed relatively uniform snow cover). Similarly, ~~P~~preferential flow into tile drains was not included in ~~developed for~~ the current simulation. ~~as a~~Although it ~~it~~ can be ~~is~~ a key process in some clay loam soils, previous studies at the study site have shown that it is not ~~as it does not appear to be a significant~~the case here ~~driver of preferential flow into tile drains~~ ~~at the study site~~, which is a combination of clay-loam and silt-loam soils ~~in coarse textured soil~~ (Pluer et al., 2020; Macrae et al., 2019)~~, and was consequently it was not included in our model at this stage~~. ~~We used h~~Hydrograph analysis (Macrae et al., 2019) and conservative tracer (electrical conductivity and major ions, as well as temperature) over multiple years (Pluer et al., 2020) showed that ~~and found minimal~~ preferential flow was minimal at this site as well as other similar sites. ~~For this reason, preferential flow was not included in this study. However, we will certainly continue exploring this transport mechanism in future studies.~~ ~~We did not model preferential flow in this study, and it will be assessed in future~~

~~studies.~~ Freeze-thaw of soil can occur in the study region, leading to partially frozen soils. However, the extent of freezing varies~~can differ~~ with snowpack development, winter temperatures and ~~other~~ radiation~~tive factors~~. Data collected over an 8-year period at this site found soil freezing was restricted to brief periods and such freezing never extended below 10 cm depth (Macrae, unpublished data) which is insufficient for soils to behave as frozen ground for infiltration calculations. Consequently, freeze-thaw processes were ~~also~~ not deployed in the CRHM model of this site~~employed in the current study. As the model is improved further in the future,~~ S~~these and other model simplifications should be addressed~~~~uch processes can be included in future studies to further develop the model.~~~~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, water table elevation (saturated storage ~~water table~~ elevation head) 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 for water table elevation and soil moisture at the site due to farming activity; consequently, water table elevation head and soil moisture were measured at the approximate midpoint of the field at the edge-of-field. Both tile flow rates and surface runoff were determined using simultaneous measurements of flow velocity and water depths in each of the pipes at the edge-of-field using Hach Flo-tote sensors and an FL900 data logger (Onset Ltd.) (Table A1, Appendix A). Continuous measurements of velocity were included due to the potential for impeded drainage under very wet conditions or caused by the accumulation of snow and ice around the surface culvert in winter. An additional barometrically-corrected pressure transducer (U20, Onset Ltd.) (Table A1) was also used for periods when the flow sensors did not function using a rating curve developed from the depth-velocity sensors; however, it should be noted that these were for brief periods and the depth-velocity sensor functioned for the majority of the study. The water table elevation was measured using a barometric pressure-corrected pressure transducer (U20, Onset Ltd.).

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~~were implemented in 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 an RH Smart Sensor (Table A1). These observations were continuously recorded throughout the study period, except for 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~~2020), located 31.7 km from the field site. Periodic snow surveys done at the site throughout the study period found that data from the nearby stations was a close approximation of snow at the field site (Plach et al., 2019). Hourly snowfall observations from Wroxeter-Geonor were used for the period between 2015 and 2018, whereas daily data from the Wroxeter-Geonor were used for the 2011 to 2014 period, reconstructed to 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 (Figures 2, 3) with the goal of adding the ability to simulate tile flow and the resulting saturated storage ~~(water table)~~ at an hourly time step. CRHM was forced with hourly precipitation, air temperature, solar radiation, wind speed and relative 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.

Using the simulation of soil moisture (including both saturated and unsaturated 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 site-specific information regarding the tile network, such as tile depth, diameter and spacing. Information regarding site-specific details regarding tile depth, diameter and spacing may be obtained directly from landowners or can be estimated based on standard design and installation guidelines for the region. This information was used to set up the model together with parameterization to translate the hydrological effects of the soil capillary fringe (CF), if present, through two variables, CF thickness and CF drainable water (discussed in Section 2.5, Figures 2, 3). These two variables are used to limit the fraction of the soil moisture that can freely drain to the tiles.

### *2.4.1 Soil moisture and saturated storage~~water table elevation~~*

The TDM uses the water quality soil module or soil module (*WQ_soil* or *Soil*), which divides the soil column into three~~wo~~ layers: a recharge layer where evapotranspiration and root uptake generally take place, ~~and~~ a deeper layer that connects to the groundwater system and a deeper groundwater layer that is always saturated. ~~Since~~ CRHM's state variable for soil moisture in the upper two layers is soil water storage volume (Fig. 2), the model results were converted into water table elevation above the semi-permeable layer (Table B1, Appendix B; ~~see~~ Fig. 2b) for comparison with water table observations, ~~)~~ by dividing volumetric soil moisture content (Table B1) by soil porosity (Table B1) for the cases with no capillary fringe above the water table. 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 average volumetric water content at capillary fringe ($\theta_C$) which is usually greater than the field capacity ($\theta_{fc}$) (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~~ Twarakavi et al. (2009). Therefore, the drainable water in the capillary fringe becomes the difference between saturation ($\theta_s$), computed dynamically in CRHM, and $\theta_C$, which corresponds to the water held by capillary forces at the capillary fringe moisture content (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 water table is at the surface and the soil is completely saturated (matric potential = 0);
2. *Condition 2* is when the water table drops but the upper boundary of the capillary fringe is at the soil surface; and
3. *Condition 3* is when the water table drops further, and the upper boundary of the capillary fringe drops beneath the surface.

In essence, the soil is completely saturated ($\theta_s$) 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 $\theta_s$-$\theta_C$ or $\varphi_c$ (dimensionless). Between *Conditions 2* and *3*, two layers with distinct hydraulic characteristics develop: (1) the top one at $\theta_{fc}$ that releases water up to $\theta_C$-$\theta_{fc}$, and (2) the lower one that corresponds to the capillary fringe and can release up to the volume of water corresponding to $\theta_s$-$\theta_C$ or $\varphi_c$.

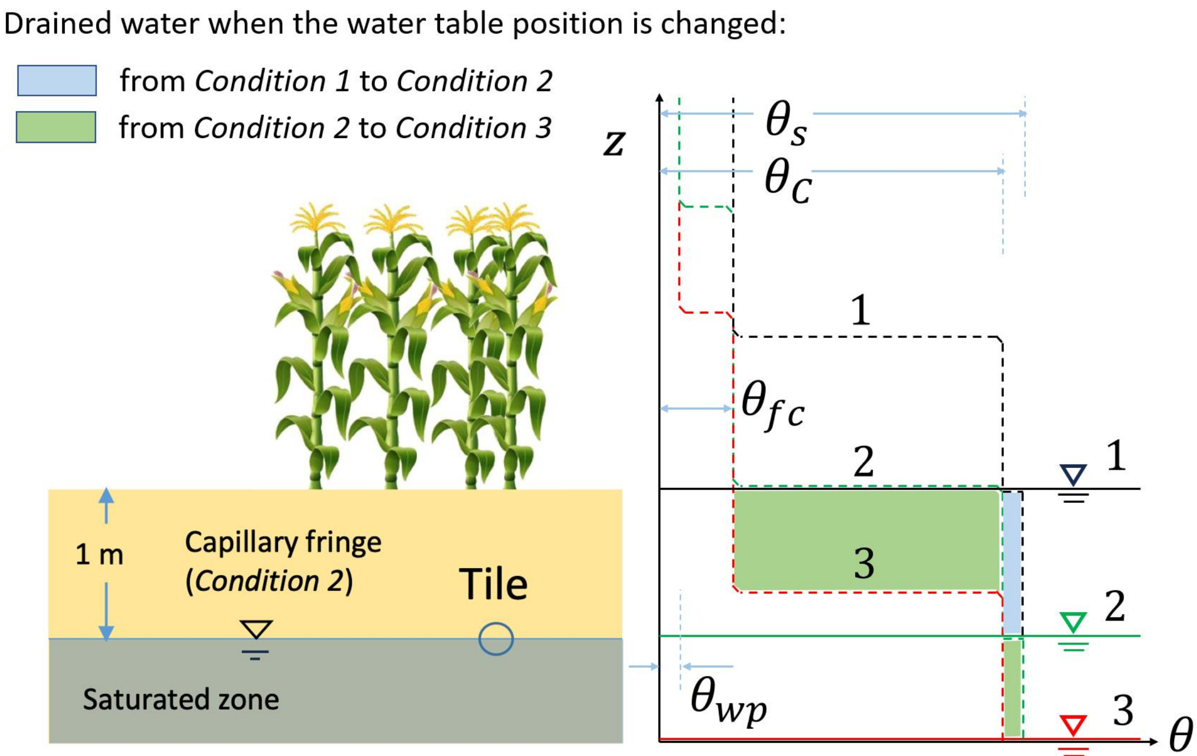



Figure 2. Schematic representation of the capillary fringe above the water table assuming a 1-m thickness (for demonstration purposes). The soil characteristic curves are shown for the three water level conditions considered: water level at the (1) surface, (2) intermediate depth, and (3) deeper depth. Two transitional drops can be seen in the characteristic curves, one from saturation ($\theta_s$) to capillary fringe water content ($\theta_C$) (between *Conditions 1* and *2*) and one from $\theta_C$ to field capacity ($\theta_{fc}$) (between *Conditions 2* and *3*). The coloured 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 in the TDM (Smedema et al., 2004). This~~, 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 (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 water table elevation above the tile pipe. It allows different saturated hydraulic conductivities for the layers above (AL) and below (BL) the tile (Fig. S1). At the 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 water table 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~~ was used to estimate ~~the~~ tile flow rates in TDM, using saturated storage to estimate *h*.

*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) we~~a~~re subtracted from the soil moisture. To calculate saturated storage (water table or groundwater elevation head level) from soil moisture calculated by the model, a threshold soil moisture content ($sm_t$) is defined, which consists of drainable water in the soil ($\varphi_c$) when the upper boundary of the capillary fringe is at the surface (*Condition 2*, Fig. 2) and was calculated as:

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

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 was deployed for determination of saturated storage ~~the water table elevation~~:

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

where ~~*WT* is water table elevation (or soil~~ SS is saturated storage~~, SSS)~~ in mm from the bottom of the soil, and *sm* is soil moisture (both saturated and unsaturated storage) in the given time step in mm. Water table observations were used to estimate SS from the field. 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~~fields. 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 table 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 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, using the sine function, was used in this application to simulate annual fluctuations in saturated storagegroundwater water table, in Eq. (4), over a period of 1 year, with minimums around the middle of the growing season (mid-July), and maximums in the cold season (early February). This translates into the lower highergreater matric potential, with soil moisture depletion, during the growing season, coinciding with soil moisture depletion, and lower matric potential, with soil moisture increases, then during the non-growing season, an elevated matric potential coinciding with an increase in the soil moisture, consistent with field observations. Thus, a sine function representing the annual fluctuations in percolation rate from soil to groundwater ($G_{y,i}$) layers in CRHM, through the lower soil semi-permeable layer (in mm hr$^{-1}$) is defined as:

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

where $T_s$ is the time step number, $D_d$ is a time delay in days, $A$ is the amplitude of the water tablesaturated storage (WTSS) 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). Although this is a simplification of the entire groundwater system dynamics, it was needed here to provide a more controlled basis for testing the new module at the field scale before expanding it to larger areas in future work.

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

The study site is a relatively small field, and 2 HRUs were sufficient to capture its hydrological dynamics 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., 2016, 2020b). The CRHM model with its new TDM module w~~ere~~as set up using the information described in Table 1. Soil textures at the LON site measured in a 25 m 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~~ 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 0.04 (volumetric water content) and $h_{fc}$ of ~0.8 m (~~Twarskawi~~ Twarskavi 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 outflows examined were tile flow, surface flow, and saturated storage~~water table depth~~. The multi-metric approach contemplated five different methods, namely the Nash-Sutcliffe efficiency ($NSE$), Root-

Mean-Square Error (RMSE), Model Bias (Bias), Percentage Bias (Pbias), and RMSE-observation standard deviation ratio (RSR). These methods were used to assess model accuracy. See Appendix C 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). Five different metrics were used to evaluate model accuracy in order to describe different aspects of the discrepancies between simulated and observed values. For example, Bias reveals the positive or negative general deviations of simulated values from the observed values, while RMSE shows the average absolute differences between them (Moriasi et al., 2007). Hourly values were used in these calculations, which departs from the daily and monthly analyses typically reported for these types of models. Although the hourly timestep is challenging for this sort of simulation, it is an important advance forward toward more detailed, accurate, and advanced models for ~~tile-~~ tile-drained agricultural fields. 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 or Soil thickness, $T_{SL}$ | 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) $\varphi_s$ | 0.045 | | Yes | Adjusted |
| Saturated Hydraulic conductivity, $K_s$~~K~~ in lower soil layer | 5 | mm h$^{-1}$ | Yes | Adjusted |
| $K_s$~~K~~ in upper soil layer | 5 | mm h$^{-1}$ | Yes | Adjusted |
| Capillary fringe thickness, $T_{CF}$ | 0.8 | m | Yes | Adjusted |
| Capillary fringe drainable water, $\varphi_c$ | 0.03 | | Yes | Adjusted |
| Surface depression close to farm surface flow outlet (HRU2) | 35 | mm | Yes | Calculated |
| Surface depression in rest of the field (HRU1) | 0 | mm | No | Calculated |
| Surface area of HRU1 | 79000 | m$^2$ | No | Field observations and DEM |
| Surface area of HRU2 | 1000 | 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 $i = 1, 2$ |

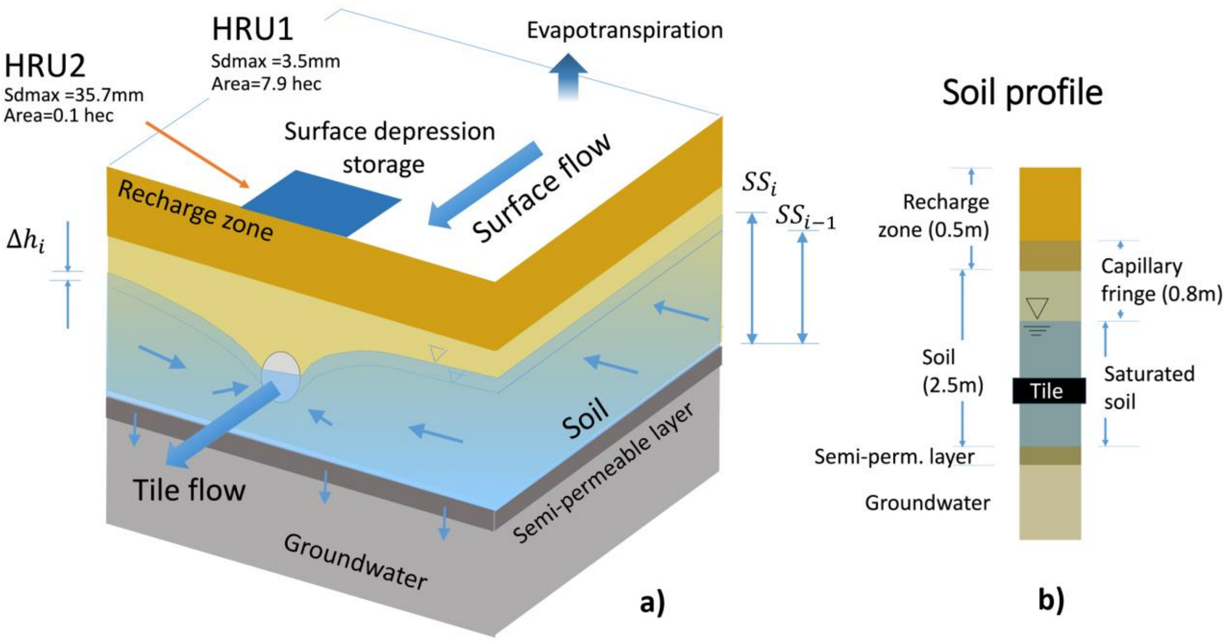



Figure 3. a) Schematic conceptual view of the CRHM model configuration, including soil layers, ~~water table~~saturated storage (~~WT~~SS), groundwater, and tile flow.; and b) soil profile, including the capillary fringe and its location relative to the soil and tile.

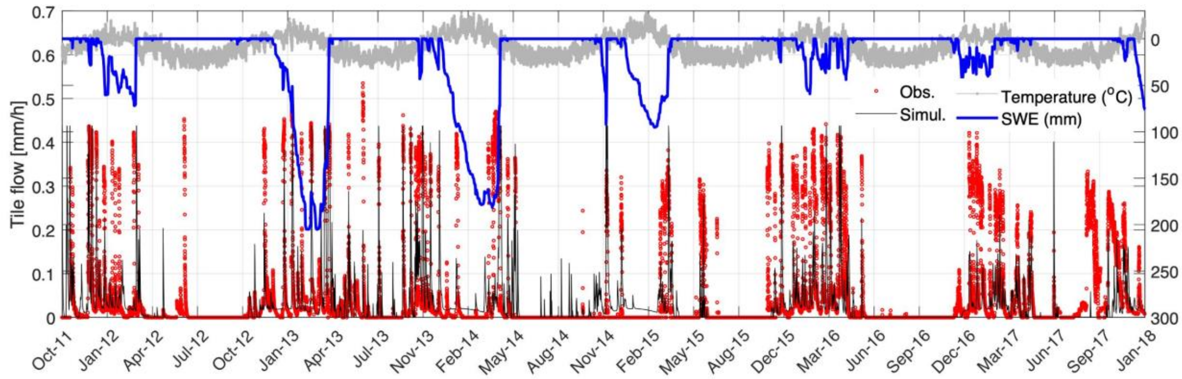
# 3. Results

A multi-variable, multi-metric model evaluation approach was deployed to verify the capacity of the model to predict not only tile flow but also the effects it has on the local hydrology, from surface to sub-surface processes. The outflows examined were tile flow (Section 3.1), saturated storage~~water table depth~~ (Section 3.2), and surface flow (Section 3.3). The multi-metric approach contemplated five different methods, namely the Nash-Sutcliffe efficiency (NSE), Root-Mean-Square Error (RMSE), Model Bias (Bias), Percentage Bias (Pbias), and RMSE-observation standard deviation ratio (RSR).

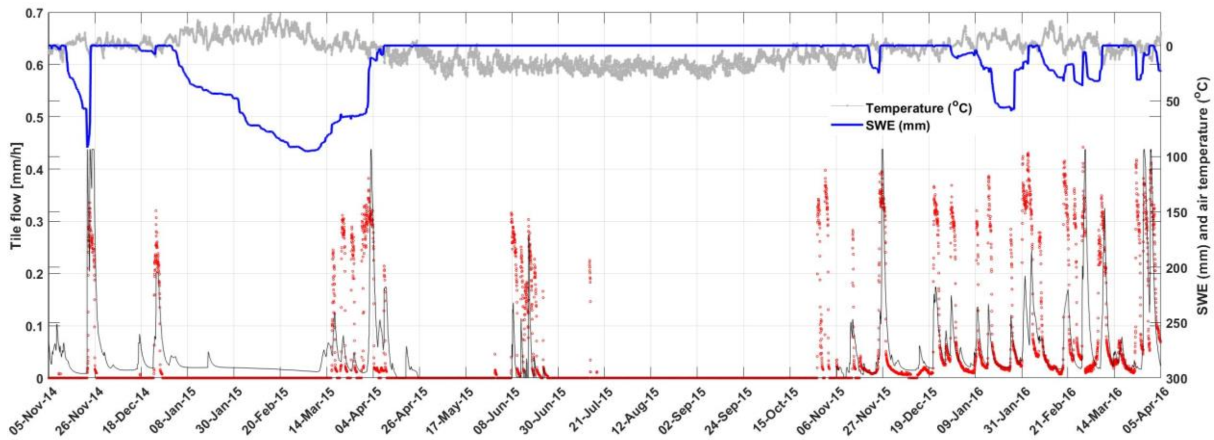
*3.1 Tile flow*

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~~near absence of flow during the growing season (May to September) was captured. The simulated flow peaks generally had 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 were also adequately predicted.

Results show that tile flows generally occurred during snowmelt events, as indicated by the synchrony between snow water equivalent (SWE) depletion and tile flow. The maximum 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. Although ~~the magnitude of~~peak tile drainage flow ~~peaks~~ was not always predicted accurately, the model was able to capture the annual trends of both an absence of tile flow during the summer months (growing season) and the ascending and descending limbs of the tile hydrograph during events (Figure 4).




a)




b)

Figure 4. Comparison between observed and simulated tile flows, simulated SWE (snow water equivalent), and observed air temperature in the LON site, between October 2011 to January 2018 (a) and between November 2014 to April 2016 (b).

### *3.2 ~~Water table or s~~Soil saturated storage*

Simulated and observed soil saturated storage ~~and the observed water table~~ are compared in Fig. 5, alongside air temperature and precipitation observations. Despite the gaps in the observational record during two periodic equipment failures, the model agrees well with observations. Above tile drains, ~~water table~~ fluctuations in saturated storage were controlled by infiltration/recharge, tile flow, groundwater flow, and matric potential that affect the drainable water from the capillary fringe. This caused flashier storage responses above the tile that were captured well by the model. In contrast, tiles did not withdraw water from the soil layer below the tile pipe and thus did not control ~~water table~~ fluctuations in saturated storage when levels were below the drain pipe, and tile drains did not flow during such periods. During the growing season, both the observed and simulated ~~water table (or~~ saturated storage~~)~~ dropped 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 declines in ~~the water table and~~ saturated storage were observed, whereas in wetter years such as 2013 and 2014, seasonal saturated storage ~~water level~~ declines were smaller. The seasonal declines in saturated storage ~~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 event (~35 mm) in the growing season of 2016 that did not produce tile flow (apparent in both model and observations).

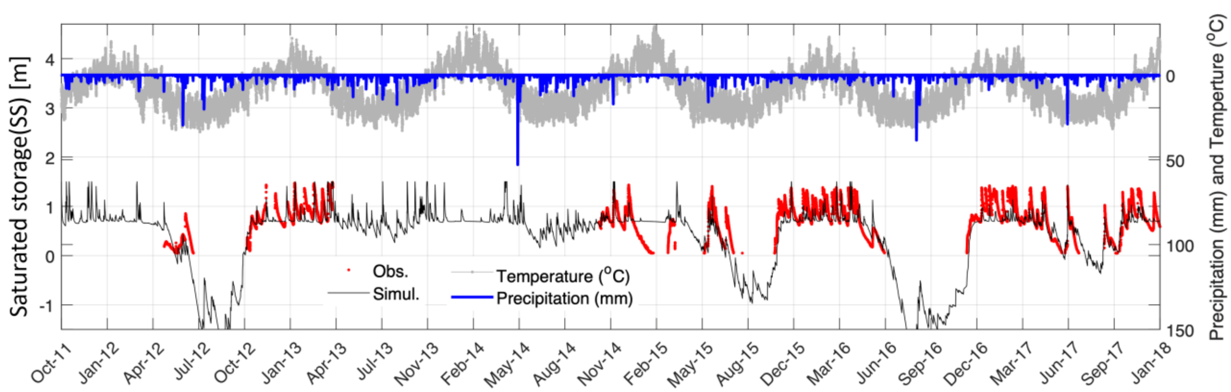
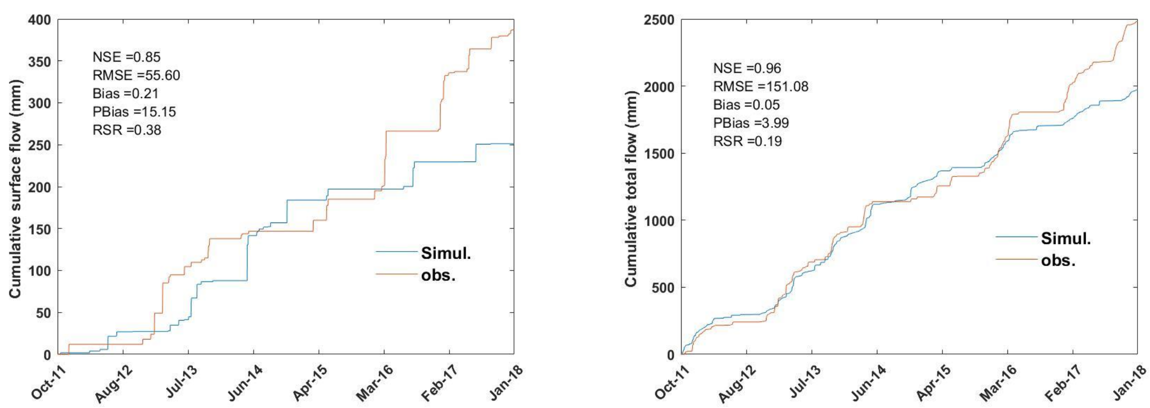



Figure 5. Time series of the simulated and observed saturated storage ~~and (or observed water table)~~ in the soil or groundwater layers of the model along with the observed temperature and precipitation. ~~Given that tiles do not flow when the WT is below them, the WT = 0 when the water table elevation is at the depth of the tile drainpipe. In the figure, the water table is measured as the elevation above (+) or below (-) the tile pipe.~~

*3.3 Surface flow and total flow*

The model was not always able to capture the observed surface flow as satisfactorily as it captured tile drainage (Fig. 6a). Some 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 prior to when it exitinged the field through the culvert (see Fig. 1), or uncertainty in field estimates of SWE. However, the model performance improvesd considerably when both runoff and tile flow weare 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 the tile pipe in early 2017, which may have affected both surface and tile flow. The differences in timing of the simulated and observed surface flow for many of the main events (Figure 6) shows that there remain systematic issues in simulation of surface flow by CRHM which should be addressed in future research.




(a) (b)

Figure 6. Observed and simulated cumulative surface flow (a) and total flow (b).

### 3.4 *Overall model performance*

The model performance was calculated based on hourly data for various model outputs (Table 2). To compare the performance of the model in different seasons we calculated the coefficient for ~~whole~~entire year as well as separately for the growing and non-growing seasons~~ separately~~. The results confirm that ~~for the whole year~~ the model is robust over an annual cycle in the sense that it can capture the main patterns of tile flow, surface flow, and saturated storage~~water table elevation~~. The Pbias values are below 25% for most of the fluxes and cumulative fluxes. The RSR values are also generally below 1.0. The NSE values are positive and above 0.3 for most fluxes, except for surface flow, where the model exhibited some difficulties. The weaker performance of the model in the simulation of surface flow, which is illustrated by the NSE coefficient, can be partly related to difficulties in measurement of surface flow during flooding, ponding, and freeze~~- and~~ thaw on the surface. The performance coefficients were calculated for~~,~~ the growing season, May-September (Table 2b) and non-growing season, October-April (Table 2c). The results shows that surface flow biases are significantly larger and negative in May-September and are smaller and positive during October-April. For tile flow the ~~Biases~~ biases are ~~a bit~~slightly higher in May-September ~~while~~ whereas for saturated storage~~oil water table~~ and total flow the biases are ~~a bit~~slightly lower in May-September. The NSEs are more acceptable in October to April for surface flow, tile flow and total flow, but the NSE for ~~WT~~ SS is more acceptable in May-September. The overall performance of the model for both tile and surface flow is more reliable in the non-growing season, when the regional water table was above the tile and saturated storage ~~the water level~~ fluctuations ~~was~~were mainly controlled by tile flow rather than regional groundwater oscillations.

Table 2. Performance coefficients for surface flow, tile flow and ~~water table~~saturated storage (~~WT~~SS/~~SSS~~), as well as total (tile + surface) flow, for the simulation period of October 2011 to January 2018. The coefficients were calculated for both hourly and

daily flow rates, for the whole year (a) for May to September (b) and for October to April (c). (Green and red color show the seasonal coefficients improved and worsened, respectively, -compared to their seasonal values).

a) Coefficients for whole year

| **Performance coefficients** | **Surface flow** | **Tile flow** | **~~WT (m)~~SS** | **Total flow** | |
|---|---|---|---|---|---|
| NSE* | -2.29 | 0.31 | 0.49 | -1.38 | Coefficients calculated for hourly flow rates (mm $h^{-1}$) |
| RMSE^ | 0.27 | 0.08 | 0.26 | 0.30 | |
| Bias# | 0.54 | 0.24 | 0.14 | 0.28 | |
| Pbias$ | 21.77 | 17.91 | 10.46 | 18.63 | |
| RSR& | 1.82 | 0.83 | 0.71 | 1.54 | |
| NSE | -0.73 | 0.29 | 0.50 | 0.01 | Coefficients calculated for daily flow rates (mm $d^{-1}$) |
| RMSE | 2.04 | 1.72 | 0.24 | 2.92 | |
| Bias | 0.35 | 0.20 | 0.09 | 0.22 | |
| Pbias | 35.11 | 19.63 | 9.33 | 21.73 | |
| RSR | 1.31 | 0.84 | 0.70 | 0.99 | |

b) coefficients for May to September

| **Performance coefficients** | **Surface flow** | **Tile flow** | **~~WT (m)~~SS** | **Total flow** | |
|---|---|---|---|---|---|
| NSE* | -18.98 | 0.19 | 0.40 | -11.76 | Coefficients calculated for hourly flow rates (mm $h^{-1}$) |
| RMSE^ | 0.26 | 0.03 | 0.12 | 0.26 | |
| Bias# | -1.43 | 0.49 | 0.03 | 0.11 | |
| Pbias$ | -142.79 | 48.88 | 3.44 | 10.96 | |
| RSR& | 2.85 | 0.57 | 0.39 | 2.27 | |
| NSE | -3.89 | 0.21 | 0.41 | -1.08 | Coefficients calculated for daily flow rates (mm $d^{-1}$) |
| RMSE | 1.39 | 0.73 | 0.11 | 1.66 | |
| Bias | -1.43 | 0.49 | 0.02 | 0.11 | |
| Pbias | -142.79 | 48.88 | 2.07 | 10.96 | |
| RSR | 1.41 | 0.56 | 0.39 | 0.92 | |

c) coefficients for October to April

| **Performance coefficients** | **Surface flow** | **Tile flow** | **~~WT (m)~~SS** | **Total flow** | |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| NSE* | -0.37 | 0.24 | 0.20 | -0.04 | Coefficients calculated for hourly flow rates (mm $h^{-1}$) |
| RMSE^ | 0.11 | 0.07 | 0.21 | 0.14 | |
| Bias# | 0.87 | 0.14 | 0.11 | 0.24 | |
| Pbias$ | 86.59 | 13.56 | 11.00 | 24.11 | |
| RSR& | 0.90 | 0.67 | 0.77 | 0.79 | |
| NSE | -0.11 | 0.26 | 0.24 | 0.18 | Coefficients calculated for daily flow rates (mm $d^{-1}$) |
| RMSE | 1.50 | 1.56 | 0.21 | 2.40 | |
| Bias | 0.87 | 0.14 | 0.11 | 0.24 | |
| Pbias | 86.59 | 13.56 | 10.58 | 24.11 | |
| RSR | 0.81 | 0.67 | 0.75 | 0.70 | |

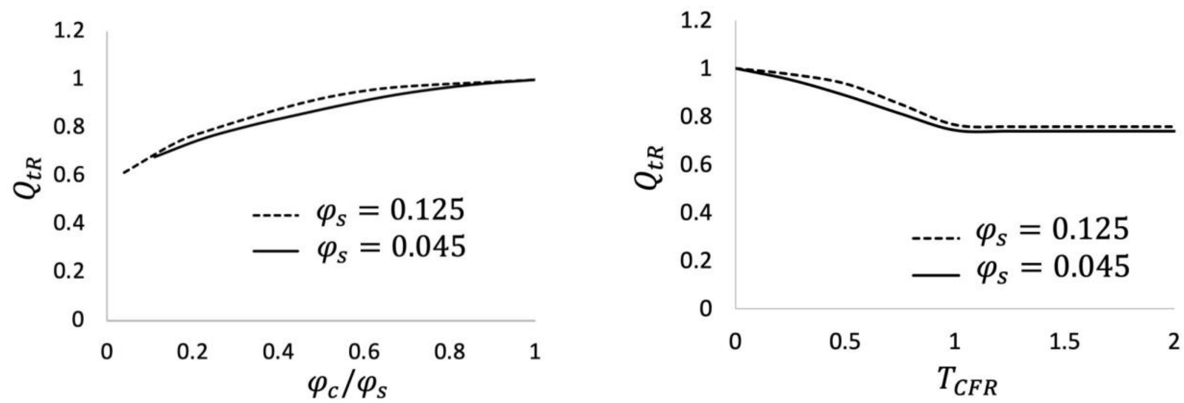
* Nash-Sutcliffe efficiency, ^Root-Mean-Square Error, #Model Bias, $Percentage Bias, &RMSE-observation standard deviation ratio

### *3.5 Presence of capillary fringe: effects and hypotheses*

Results show that the thickness and vertical positioning of the capillary fringe ~~have~~ had a strong impact on the amount of drainable soil water that ~~can~~ flowed into the tiles. To investigate this effect further, the response of tile flow and soil moisture to changes in the capillary fringe was examined. It should be noted that although this thickness may change slightly depending on the soil type and water retention curves (Skaggs et al., 1978), the model assumed a constant value given the field-scale nature of the simulations and myriad of processes contemplated. However, despite the simplification, the vertical positioning of the capillary fringe was still calculated and enabled a dynamic (time-dependent) calculation of the drainable soil water that was 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 $\varphi_s$ values (0.045 and 0.125). The values were normalized (0 – 1 scale) 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 $\varphi_s$ (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 fringe thickness divided by tile depth), but only while the $T_{CFR}$ is less than 1 that is when the capillary fringe position is above the tile but has not reached the soil surface. Beyond this point, increments in the capillary fringe thickness have no impact on tile flow because *Condition 1* has been reached (see Fig. 2), which essentially means that the capillary fringe has reached the soil surface. The match between the curves for two different $\varphi_s$ values shows that the changes in $\varphi_s$ does not influence the effect of normalized capillary fringe thickness and drainable water on normalized tile flow. In Appendix D the sensitivity of cumulative tile flow and mean saturated storage ~~soil water table elevation~~ to different parameters are shown along with general approaches for evaluation of the model parameters for new sites, the site with no tile flow and water table observations.




a) b)

Figure 7. Comparison between normalized tile flow ($Q_{tR}$) and (a) normalized drainable soil water ($\varphi_c/\varphi_s$) and (b) capillary fringe thickness ($T_{CFR}$) for different maximum soil saturation values ($\varphi_s$), by drawing the model prediction lines.

*Effect of capillary fringe on soil moisture*

Observations and simulations of saturated storage ~~model results of WT~~ 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 influence~~depth~~ of the tile pipe and the second peak reflecting that from the capillary fringe ~~thickness~~. ~~In~~ I simulated soil saturated storage ~~(SSS as a measure of WT)~~ frequency distributions (Fig. 9), show a ~~the~~ first peak that 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 fringe thickness. It shows that when there is near-constant percolation 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 saturated storage~~water table~~ fluctuates faster and is more unstable within this range, it also remains there for shorter periods. This bimodal response tends to push the saturated storage layer ~~water table depth~~ below the tile. In Figure 9, ~~we can see that~~ the first peak happens at 0.9 m depth where the tile pipe is located, and the second peak happens at the depth equal to capillary fringe thickness. In Figure 9 the second peak is ~~more~~ clearer for the capillary fringe thickness of more than 1000 mm. The first peak in the observed water table saturated storage frequency plot (Figure 8) happened around 0.8 m which almost matches with the tile depth. And the second peak happened at the depth of ~1.2 m which shows that the capillary fringe thickness should be around 1.2 m. But, to have a more reliable estimate for the capillary fringe, based on Figure 8, data is needed at depths greater than 1.5 m.

The bimodal behaviour of the observed water table and and simulated saturated storage (observed saturated storage is the observed water table ) demonstrated here provides the opportunity to quantify the thickness of the capillary fringe using continuously monitored saturated storagewater table elevations. The capillary fringe thickness determined using this method can then be used as an input to the TDM module.

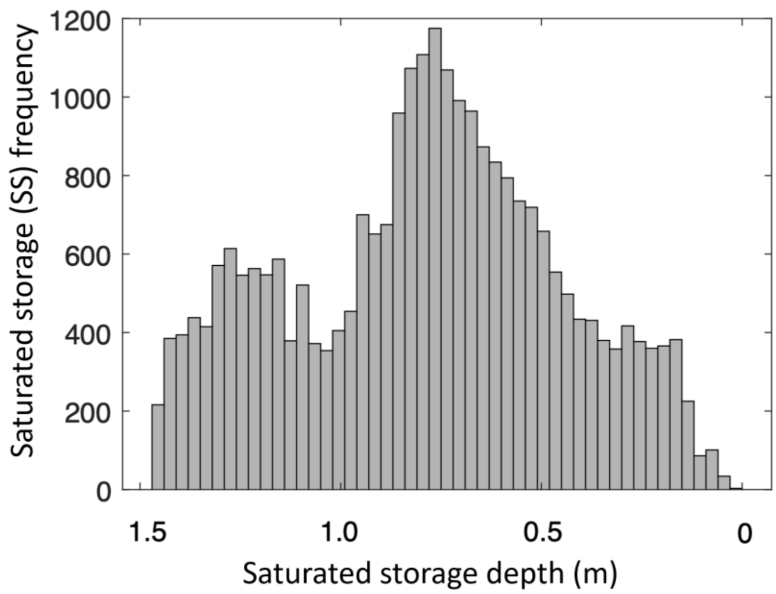



Figure 8. Histogram of the observed saturated storage (or observed water table) distribution for the period pf 2011 to 2018 in LON (Londesborough).

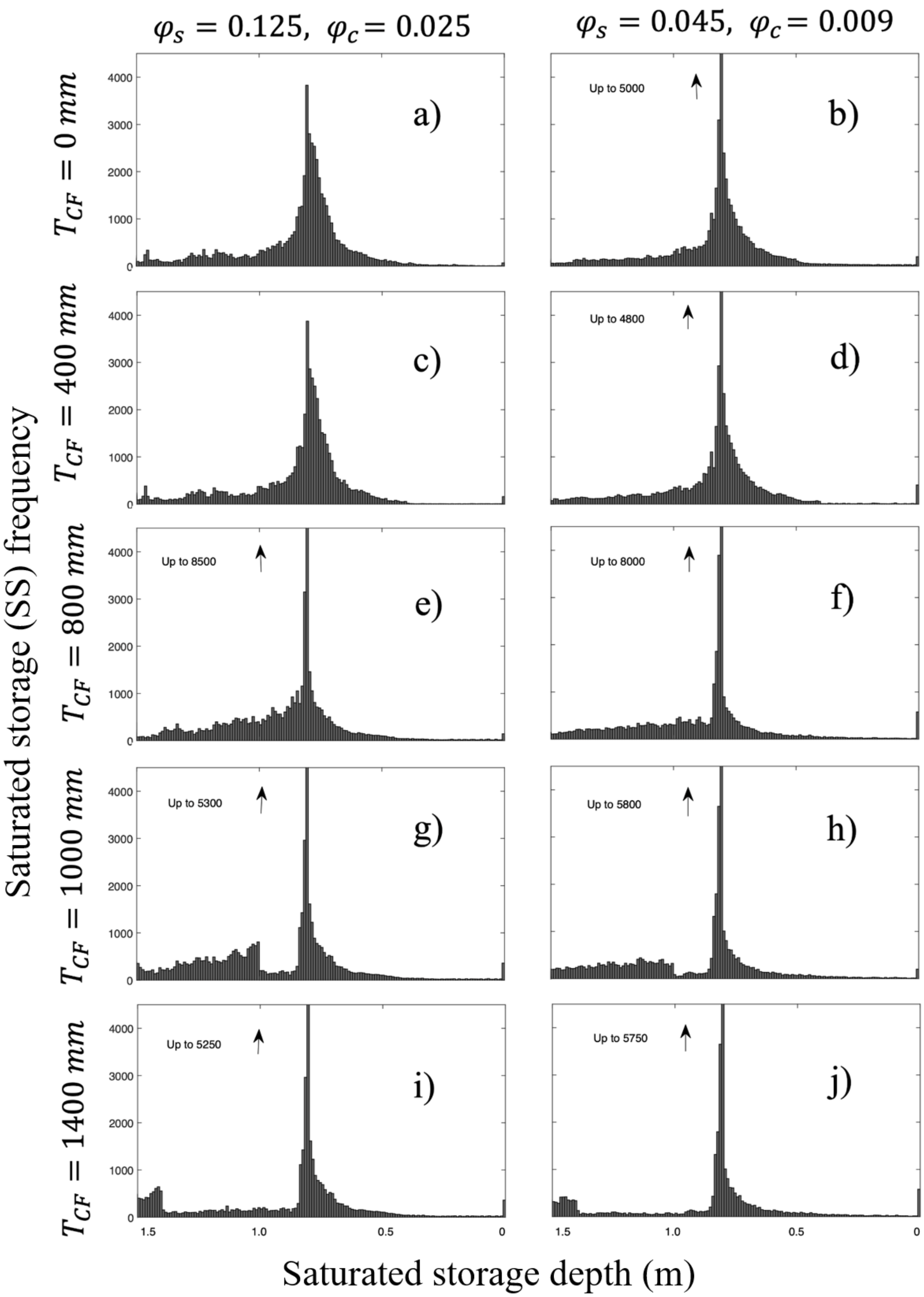



Figure 9. Histograms of the simulated soil saturated storages versus saturated storage depth ~~(SSS or WT)~~ for the capillary fringe thicknesses of 0 (a,b), 400 (c,d), 800 (e,f), 1000 (g,h) and 1400 (I, j) mm and for the $\varphi_s$ and $\varphi_c$ of 0.125 and 0.025 (left column)as well as 0.045 and 0.009 (right column).

# 4. Discussion

### *4.1 Insights into key control mechanisms of tile flow ~~for catchment-scale~~for model simulations*

The model suggests that tile flow may not be accurately predicted exclusively based on the soil's saturated storage ~~the water table depth~~ and ~~soil~~ saturated hydraulic conductivity as suggested by the steady-state flow assumptions of the Hooghoudt's equation (Hooghoudt, 1940). These 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 saturated storage ~~the groundwater table (GWRD)~~ are 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 residence time for groundwater seepage and evapotranspiration increases when the hydraulic tile carrying capacity is exceeded. Comparatively, the effect of soil drainable water, $\varphi_s$ (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 saturated storage ~~WT~~ were very sensitive to (1) the ratio between $K_s$~~K~~ and drainable soil water; and (2) the net outflow in the soil through tile flow and ~~groundwater level~~ fluctuations in saturated storage ~~(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 non-drainable water.

Results show that large fluctuations in saturated storage ~~WT SS (or SSSWT)~~ and tile flow during the cold season, when the water table tends to be above the tile, are primarily triggered by the development of a 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 ~~water table (~~saturated storage~~)~~ 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 reduced capillary forces, lower field capacities (but correspondingly larger drainable water) and higher hydraulic conductivity. Notably, both model and observations of saturated storage ~~WT SS (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 saturated storage ~~WT or SSS 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 table 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 water table 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 saturated storage frequency ~~WT~~ distribution and tile flow differently over time (*Conditions 1* to *3*, see Fig. 2). Herein, while a capillary fringe with a fixed thickness that is generally related to the soil properties was assumed, 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 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 (soil unsaturated storage) 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. This~~It~~ suggests that the saturated storage ~~water table~~ and capillary fringe can reach an equilibrium condition within one hour at this field site, enabling the ~~us to~~ use of a steady state equation (Hooghoudt, 1940) to predict the dynamic behaviour of the water table fluctuations.

### *4.2 Importance of capturing seasonal patterns in saturated storage ~~groundwater~~ to improve tile flow predictions*

The saturated storage ~~GWRD~~ changed dramatically between seasons affecting soil moisture (both saturated and unsaturated storage in~~of~~ the soil) 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 (both unsaturated ~~storage~~ and saturated ~~storage~~) that leads to a substantial storage capacity in fields. Even following moderate and high-intensity storms during the growing season, rapid soil moisture increases ~~a~~were observed (both saturated and unsaturated soil storage); however, tile flow rarely developed~~s~~ due to higher evapotranspiration and a seasonal decrease in the saturated storage ~~GWRD~~, suggesting that the soil is able to hold the water (Lam et al., 2016a; Van Esbroeck et al., 2016). In contrast, tile flow wa~~i~~s often observed during the cold season, with significantly smaller evapotranspiration fluxes, even during smaller rainfall-runoff and snowmelt events because of reduced soil storage but also a seasonal increase in regional groundwater table~~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).

These results (the controlling effect of soil drainable water and saturated storage ~~groundwater level~~ fluctuations on tile flow) suggest that while soil moisture (both saturated and unsaturated storage) is largely controlled by tile flow rather than saturated storage ~~GWRD~~ in the cold season, this reverses in the growing season (*i.e.*, soil moisture controls tile flow), with soil moisture (both saturated and unsaturated storage) being also impacted by evapotranspiration. The controlling effect of groundwater fluctuations in the growing season has also been studied by Hansen et al., (2019). The model indicated that the rapid drops in observed saturated storage ~~WT~~ during the growing season could not be explained by evapotranspiration alone~~ as well as the crop root depths~~, thus pointing to the role of saturated storage~~ GWRD.~~. Johnsen et al. (1995) and Akis (2016) also showed that the effect of groundwater accretion was more effective on tile flows than surface runoff. Also, Vaughan et al. (1999) found that tile drain flows in their study site in San Joaquin Valley of California were better explained and related to nonlocal groundwater appearance than to local variations in irrigation amount, evapotranspiration, variation in water storage or tile drain blockage. Thus, it was determined ~~that in~~that in addition to soil saturated hydraulic conductivity and soil thickness, the seasonal ~~groundwater~~ fluctuations in saturated storage and capillary fringe drainable water are other important controlling factors on tile flow rates.

# 5. Conclusions

A new tile drain module within the modular Cold Regions Hydrological Modelling (CRHM) platform has been created and tested at the field scale to support the management of agricultural basins with 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 saturated storage~~the groundwater water table~~, in addition to (3) the typical saturated storage near the tile pipe depth, ~~(3)~~ ~~water table elevation above the tile pipe~~ and (4) the soil saturated hydraulic conductivity considered by the steady-state flow Hooghoudt's equation. The saturated storage ~~groundwater table~~ and matric potential changed dramatically between seasons, affecting patterns of overall 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-saturated storage.

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~~ saturated storage response in the presence of tiles, which is controlled by the relative positioning of the capillary fringe in relation to the soil surface and the depth of tile drains below the soil surface. Capturing these dynamics is a critical advance enabling the accurate prediction of the swift hydrological changes caused by the presence of tiles in models.

The TDM was developed as a first approximation from a single field site with the goal of providing insight into control mechanisms of tile flow. Given this limitation, it is not yet widely applicable across multiple field sites and for larger areas. ~~However~~Yet, the development of this module provides critical insights into its potential and performance for hourly time-step simulations, as well as the importance of saturated storage ~~regional groundwater table~~ fluctuations and simplifying the capillary fringe parameters within models in some landscape type~~s~~. Future work ~~will~~ should ~~include~~ build~~ing~~ on the current model ~~and~~ adapting it to ~~for~~ different soil textures, such as those in clay loam soils, where preferential flow can have a strong impact on ~~soil~~-~~s~~saturated storage and tile flow. Also, explicit representation of unsaturated flow ~~will~~ may be needed to enable the use of the model in regions where groundwater is disconnected from surface water, as commonly happens in arid and semi-arid regions. Subsequent steps should include also the integration of the new TDM model with CRHM's frozen soil and water quality modules.

## Code/Data availability

The tile flow and soil water table data are not publicly available and will be provided upon request to the data owner, Merrin Macrae. TDM code is not completely implemented in the main version of the Cold Regions Hydrological Model platform and is provided ~~only u~~upon request to the corresponding author.

## Author contribution

MK and DC developed the new model code and performed the simulations. MM prepared the data and supported the field work. JP developed CRHM. MK, DC and MM prepared the manuscript with contributions from JP and RP. All authors edited the manuscript.

## Competing interests

The contact author has declared that none of the authors has any competing interests.

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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 |

| | |
|---|---|
| Wspeed | Wind speed |
| RH | Relative Humidity |
| Qsi | Incoming solar irradiance |
| R | Rainfall |
| WQ_soil | Water Quality soil module |
| WT | Water table elevation above the semipermeable layer |
| SS~~S~~ | Soil saturated storage or the saturated part of the soil moisture |
| soil_moist | Soil moisture |
| Poro_soil | Soil porosity |
| AL | Above layer |
| BL | Below layer |
| ~~GWRD~~$K_s$ | ~~Groundwater level fluctuations, groundwater recharge and discharge~~Saturated hydraulic conductivity |

**Appendix C**

Here, it was shown how seasonal factors ($f_{y,i}$) is assessed for different years. Equation (4) can be written as:

$$G_{y,i} = G \times f_{y,i} \quad \text{(C1)}$$

For each year $(y)$, $f_{y,i}$ for the first $(f_{y,1})$ and second $(f_{y,2})$ part of the sine function $(G)$ were assessed individually. It should be note that in first and second part of the sine function for each year G is larger than zero $(G \geq 0)$ and smaller than zero $(G < 0)$, respectively. $G$ can be defined for the two parts as:

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

$G$ is the sine function representing the annual fluctuations in ~~water table~~saturated storage (~~WT/S~~SS) or it can be simply defined as the percolation rate (in mm $hr^{-1}$) of soil water to groundwater through lower semi-permeable layer. 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 its sign. The $f_{y,i}$ values for the sine function parameters are presented 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 happened more in the warm seasons (growing seasons). Also, the seasonal oscillation in sine function is very similar to the temperature general oscillations.

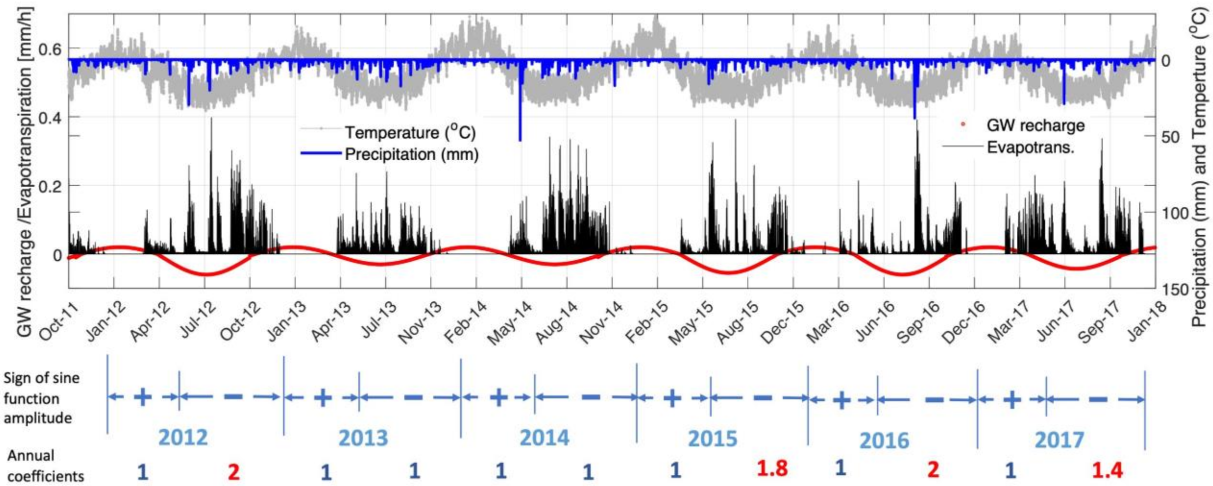


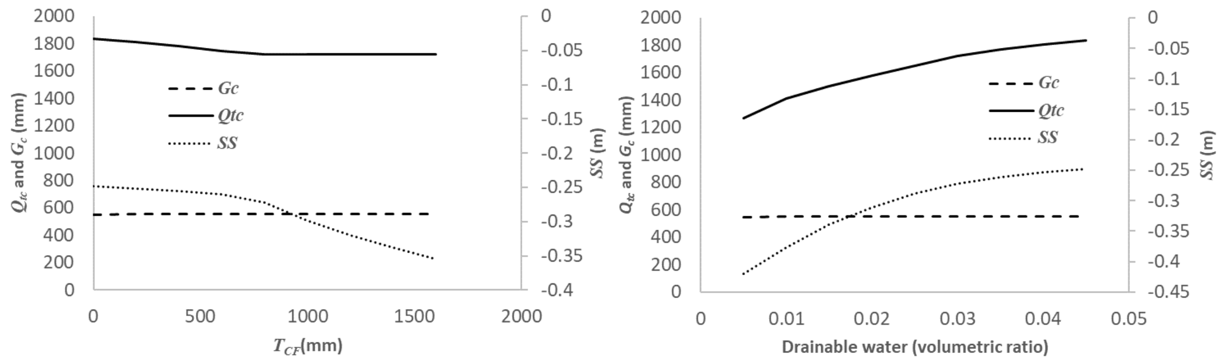

Figure C1. Time series of the adjustable sine function along with the time serioes of calculated evapotranspiration, temperature and precipitation during the study period from Oct 2011 to Sept 2018.

## Appendix D

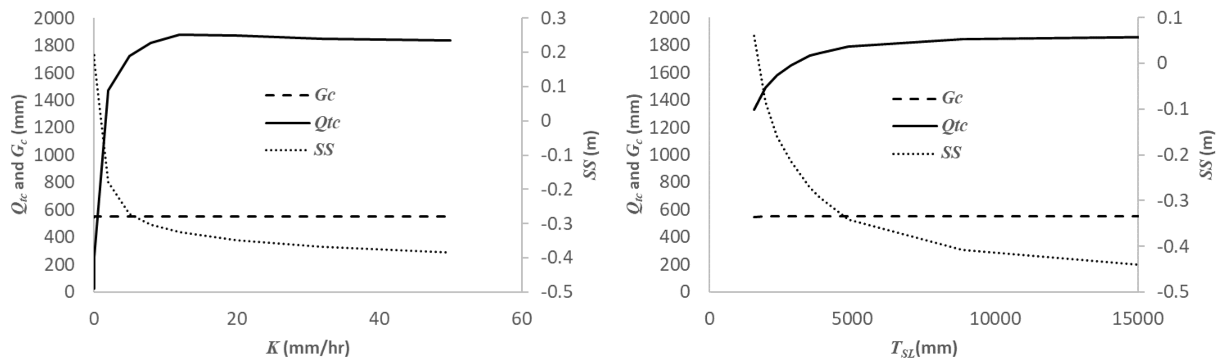
A sensitivity analysis was conducted for the cumulative tile flow ($Q_{tc}$), mean soil saturated storage ($SS$) (it is equal to water table elevation, ($WT_m$, as it is mentioned in Eq. 3) and cumulative outflow rate from the semi-permeable layer at the bottom of the soil to groundwater ($G_c$) (see section 2.4.5, Eq. 4) with respect to six module parameters. Additionally, an approach for assessing model parameters at a new sites, potentially lacking water table elevation and tile flow observations is proposed.

### D.1 Sensitivity analysis

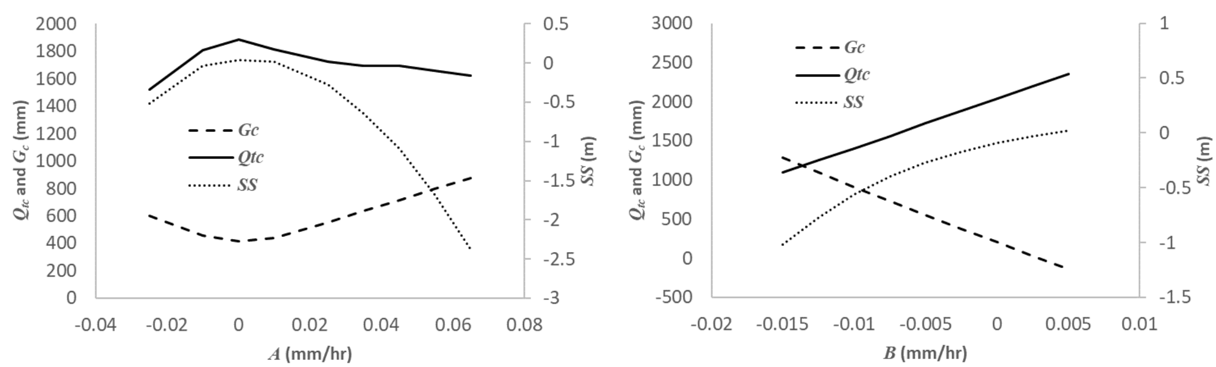
In this section, the sensitivity of $Q_{tc}$, $SS$ and $G_c$ to six distinct module parameters, namely capillary fringe thickness ($T_{CF}$), capillary fringe drainable water ($\varphi_c$), soil saturated hydraulic conductivity ($K$), soil thickness ($T_{SL}$), sine function amplitude ($A$) and sine function ($B$) was examined. $Q_{tc}$, $G_c$ and $SS$ were computed over the entire simulation period, expressed in units of mm, mm and m, respectively. Figures D-1a to f illustrate these sensitivities, with each parameter's impact discussed in dedicated sections.




a) b)




c) d)




e) f)

Figure D-1 Sensitivity of cumulative tile flow, $Q_{tc}$, cumulative soil to groundwater percolation rate, $G_c$, and mean soil ~~water table~~saturated storage elevation, $SS$, to capillary fringe thickness, $T_{CF}$ (a) capillary fringe drainable water, $\varphi_c$ (b), soil hydraulic conductivity, $K$ (c), soil thickness, $T_{SL}$ (d), sine function amplitude, $A$ (e ) and sine function intercept, $B$ (f).

*D.1.1 Sensitivity to capillary fringe thickness*

To gauge sensitivity to capillary fringe thickness $T_{CF}$, flow rates and the *SS* were analyzed for $T_{CF}$ ranging 0 to 1600 mm. Figure D-1a indicates that as $T_{CF}$ increases, both cumulative tile flow ($Q_{tc}$) and mean soil ~~water table~~saturated storage (*SS*) decline. The *SS* drop is sharper for $T_{CF}$ beyond 900 mm. Beyond this thickness, $Q_{tc}$ stabilizes at a minimal value. A negative *SS* indicates its position below the tile pipe. $G_c$ remains consistent despite $T_{CF}$ variations.

*D.1.2 Sensitivity to capillary fringe drainable water*

With rising $\varphi_c$ both $Q_{tc}$ and *SS* surge (Figure D-1b). As $\varphi_c$ ascends from 0.005 to 0.45, $Q_{tc}$ jumps from 1300 mm to 1900 mm and *SS* from -0.45 m to -0.25 m (Figure D-1b). $G_c$ stays constant, irrespective of $\varphi_c$ fluctuations.

*D.1.3 Sensitivity to soil hydraulic conductivity*

Increasing soil hydraulic conductivity ($K$) from 0 to 10 mm $hr^{-1}$leads to a surge in $Q_{tc}$ and a drop in *SS* (Figure D-1c). However, adjusting $K$ from 10 to 50 mm $hr^{-1}$ results in leveling off slopes for $Q_{tc}$ and *SS*, especially when $K$> 20mm $hr^{-1}$. Both metrics are acutely responsive to $K$ when $K$ is below 10 mm $hr^{-1}$ but become non-responsive beyond 20mm $hr^{-1}$. $G_c$'s response to $K$ remains neutral.

*D.1.4 Sensitivity to soil thickness*

Similar to $K$, a rise in $T_{SL}$ from 1500mm to 15000 mm cause $Q_{tc}$ to rise and $SS$ to decline (Figure D-1d). The most significant rate of change for both metrics occurs between 1500 to 5000 mm $T_{SL}$. Beyond 5000 mm, changes flatten. $G_c$ shows no response to $T_{SL}$ variations.

*D.1.5 Sensitivity to sine function amplitude*

Increasing the sine function amplitude, $A$, from -0.03 to 0 mm hr$^{-1}$ pushes both $Q_{tc}$ and $SS$ increase and reach to their maximum at $A$=0 (Figure D-1e). But as $A$ rises from 0 to 0.06 mm hr$^{-1}$, they both decline. In contrast, $G_c$ descends to its lowest (400 mm) when $A$ shifts from -0.03 to 0 and then increases to 900 mm as $A$ hits 0.063.

*D.1.6 Sensitivity to sine function intercept*

Both $Q_{tc}$ and $SS$ ascend with the growth in sine function's intercept, $B$. Increasing $B$ from -0.015 to 0.005 mm hr$^{-1}$sees $G_c$ descend. During this $B$ increase, $Q_{tc}$ expands from 1100 to 2400 mm, while $G_c$ shrinks from 1400 to 0 mm. It seems the sum of $Q_{tc}$ and $G_c$ might be constant. This suggests that water either drains through the tile pipe or percolates through the soil bottom.

$Q_{tc}$, and $SS$ appear sensitive to all six module parameters, but $G_c$ only to $A$ and $B$.

**D.2 Module parameter evaluation for new sites**

As discussed in section 2.5, initial values for $K$, $T_{CF}$ and $\varphi_c$ can be determined by soil grain-size distribution. Parameters less explored in past research for new sites include the sine function's amplitude ($A$), intercept ($B$), and time delay ($D_d$).

*D.2.1 Evaluating sine function's A and B*

If no percolation exists from the soil's bottom to groundwater and $G_{y,i}$ is zero, both $A$ and $B$ should be zero. However, if percolation or interactions between soil and groundwater occurs, $A$ and $B$ need calibration assessment. Before this, reasonable initial values and bounds must be set. From this study's findings, $A$ and $B$ should fall between the mean hourly difference of infiltration and observed tile flow rates. For instance, observed hourly rates for infiltration and tile flow at our site are 0.07 and 0.03 mm $hr^{-1}$. Thus, $A$'s and $B$'s initial values should range from -0.04 to 0.04 mm $hr^{-1}$. Negative $A$ and $B$ values indicate outflow from soil to groundwater and vice versa. Initial values were set at 10% of the range limits: -0.004 for $B$ and 0.004 for $A$. Eventually, $B$ and $A$ were adjusted to -0.005 and 0.025 mm $hr^{-1}$.

*D.2.2 Assessment of sine function's time delay*

The sine function begins on the first Julian day. If its peak occurs around 91st Julian day ( three months later), its minimum should be on the 274th day. If the peak comes later, say the 111th day, a 20-day delay is present. This delay should mirror in both function's minima and maxima. In this case the minimum would be on day 294. This delay aligns with the soil water table's peak annual fluctuations. When no observed fluctuations exist, the delay can be calibrated. A sensible initial delay can be ascertained by examining the study site's water table elevations, fitting a sine function, and noting the peak's Julian day annually.