Modeling surface runoff and subsurface tile drainage under drainage and controlled drainage with sub-irrigation in southern Ontario

by

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A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Science

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Abstract

Controlled drainage with subirrigation has been applied as a strategy in southern Ontario to mitigate nutrient loss from subsurface drained cropland to surface water bodies. The Root Zone Water Quality Model (RZWQM2) has been widely used for simulating management effects on crop production and soil and water quality, and a subirrigation component was recently developed. The objective of this study is to model surface runoff, subsurface tile drainage, and crop yield under two water management practices: regular drainage (DR) and controlled drainage with subirrigation (CDS) in southern Ontario. Field observed hydrological and yield data under those two water management practices near Harrow, ON from June 2008 to December 2011 were used to evaluate RZWQM2. The measured surface and subsurface water discharges were monitored continuously year round in a corn-soybean rotation field. Subirrigation was not measured but was estimated assuming it met the daily crop ET computed by the model. RZWQM2 was calibrated and validated against tile drainage and yield data from regular drainage and controlled drainage with subirrigation, respectively. For the calibration against runoff and tile drainage data under regular drainage, percent bias (*PBIAS)* was within ±15%, Nash-Sutcliffe efficiency (*NSE*) > 0.50, and index of agreement (*IoA*) > 0.80; however, for the validation under the controlled drainage with subirrigation, *PBIAS* >±15%, *NSE* < 0.22, and *IoA* < 0.78. This RZWQM2 was capable of predicting tile drainage and surface runoff under the regular drainage, but was not as precise for the controlled drainage with subirrigation treatment. This may be attributable to a poor estimation of subirrigation amount as model input.

Résumé

Le drainage contrôlé avec sous-irrigation a été appliqué en tant qu'une stratégie au sud d'Ontario afin de mitiger la perde des éléments nutritifs, des terres agricoles avec un système drainage souterrain aux eaux pluviales. Le modèle de qualité de l'eau de la zone de racine (RZWQM2) a été utilisé à grand échelle pour simuler les effets de la gestion sur la production de culture ainsi que la qualité de l'eau et le sol, et un composant de sous-irrigation a été récemment développé. L'objectif de cette étude est de modeler le ruissellement, le drainage souterrain et le rendement de culture sous l'effet de deux pratiques de gestion d'eau tel que le drainage régulier et le drainage contrôlé avec sous-irrigation au sud d'Ontario. Les données hydrologiques et de rendement observées et ramassées sur le terrain du Juin 2008 au Décembre 2011 pour un champ du maïs-soja sous ceux deux pratiques de gestion d'eau à proximité de Harrow, ON, ont été utilisées afin d'évaluer le RZWQM2. Les débits mesurés de l'eau en surface et de l'eau souterraine, ont été surveillés en continu toute au longe de l'année. La sous-irrigation n'était pas mesurée mais elle était estimée en supposant que l'évapotranspiration journalière estimée a été atteint par le modèle. Le RZWQM2 a été calibré and validé contre les données du drainage et du rendement respectivement par le drainage régulier et le drainage contrôlé avec sous-irrigation. Pour le calibrage contre les données du ruissellement et drainage sous le drainage régulier, le pourcentage de biais (PBIAS) était entre ±15%, le rendement de Nash-Sutcliffe (NSE) était plus de 0.5 et l'indice d'accordance (IOA) était plus de 0.80. Cependant, pour la validation sous le drainage contrôlé avec sous-irrigation, le PBIAS était au-delà de ±15%, NSE < 0.22, et IOA < 0.78. Cette étude de modélisation a fait prouve que le RZWQM2 est capable de prédire le drainage et le ruissellement sous le drainage régulier, mais ce n'est pas aussi précise pour le

drainage contrôlé avec sous-irrigation. La raison pourrait être une estimation incorrecte du teneur de sous-irrigation comme la donnée du modèle.

Acknowledgements

I would like to thank my supervisor Dr. Zhiming Qi for his constant guidance, and his understanding and encouragement throughout my research. I would like to thank Dr. Chin Tan and Dr. Tiequan Zhang of Agriculture and Agri-Food Canada in Harrow, Ontario for generously providing valuable field data and answering many of my questions. I would like to thank Dr. Shiv Prasher. I would also like to thank Ms. Eslamian Faezeh for helping me with the French translation of my abstract.

I would like to thank all my friends and my fellow graduate students for their friendship and support, especially Qianjing Jiang, Sunli Chen, Hongkai Qi and Zhangzhao Liu. Your make graduate life wonderful and give me strength. Finally I thank my mother and father for their unconditional support of my studies and for bearing with all the ups and downs of my life but always believing in me. Thank you.

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List of Abbreviations and Symbols

Units are listed in brackets where applicable, and unit-less parameters are indicated by (-)

C	Carbon
P	Phosphorus
N	Nitrogen
RZWQM2	Root Zone Water Quality Model
DRAINMOD	software for simulating hydrology of poorly drained, high water table soils
DSSAT	Decision Support System for Agrotechnology Transfer software
Hydrus-1D	software package for simulating water flow, heat, and solute transport in variable saturated porous media
LEACHM	Leaching Estimation and Chemistry Model
NSE	Nash-Sutcliffe model efficiency (-)
PBIAS	Percent of Bias
IoA	Index of Agreement

Chapter 1 Introduction

1.1 Background of Computer simulation

Computer models have been widely applied to predict the effect of different climate and management practices on agricultural production. It is a very useful tool to inform the decision making process of agricultural activities such as fertilization and evaluate the effects of agricultural activities on the environment (Ahuja *et al.*, 2002). Each computer model has its own strengths, weaknesses, and assumptions. It requires model users to be capable of recognizing the valuable of each model, because different model exists many gaps of the function (Sinclair and Seligman, 1996).

Process-based modeling is an excellent approach for simulating and evaluating medium-term and long-term effect of agricultural management practices. Compared to field experiments that may take decades and vast resources to complete, the modeling approach is faster and more efficiency when the model can be calibrated and validated using short-term site-specific data (Liu *et al.*, 2011). As a consequence, modeling represents an important approach to study the effect of the potential implementation of agricultural management practices on surface and groundwater quality. There are many studies as the examples of applying computer simulation model. For example, Chen et al. (2010) applied the Agricultural Production System Simulator (APSIM) model to simulate crop yield and water balance under different water management regimes on the North China Plain. Similarly, Patel and Rajput (2008) used the Hydrus-2D model to simulate subsurface drip irrigation in an onion (Allium cepa L.) crop.

Once model has been verified and tested adequately, the model can be applied to predict the impacts of various agricultural management practices on hydrologic cycle, environment, and crop production (Tan and Reynolds, 2003). The Root Zone Water Quality Model (RZWQM2), described in Ahuja et al. (2000), contains plant growth, water movement, nitrogen/carbon dynamic, and chemical transport components. RZWQM2 has to be thoroughly tested before use as a management tool. It has been tested for different conditions, such as soil water transport under tile drainage by Singh and Kanwar (1995a) in Nashua, Iowa. Ma et al. (1998b) tested this model's evapotranspiration component. RZWQM2 also was used to evaluate nitrogen cycling (Tan and Fulton, 1980), and pesticide processes (Ma *et al.*, 2004). However, the subirrigation component of RZWQM2 has not been tested.

1.2 RZWQM2 and RZ-SHAW

Ahmed et al. (2007) used RZWQM2 model to simulate tile flow, soil NO3-N, crop yields, and NO_3-N concentration in tile flow in Ontario. The early version of RZWQM2 used by Ahmed et al. (2007) had simplified snowmelt routines, rendering it unable to handle frozen soil which was one of the factors which affected infiltration, drainage, runoff and erosion and was not including snow components. Moreover, due to lack of winter data at data the experiment sites, winter and early spring drainage were not investigated in that study. Ahmed et al. (2007) suggested that improving the snow algorithm in RZWQM2 might provide better simulated results for northern climes (Ahmed *et al.*, 2007b). In order to strengthen the capability of RZWQM2 in addressing freeze-thaw processes, one of the most detailed snow and freezing soil models 'Simultaneous Heat and Water' (SHAW; Flerchinger and Saxton, 1989a) was incorporated into RZWQM2 (Flerchinger *et al.*, 2000). A widely used model to simulate freezing-thaw procedure, SHAW addresses residue and tillage effects on the water cycle under the freeze-thaw process. Flerchinger et al. (2000) reported that RZ-SHAW outperformed SHAW in simulating soil temperature. The hybrid RZ-SHAW model had been used to simulate soil temperature and evaporation under different tillage systems (Kozak *et al*., 2007). These studies showed better performance of hybrid RZ-SHAW model than the original RZWQM2 and SHAW models individually.

1.3 Objectives

The objective of this study was to explore the ability of RZWQM2 to model surface runoff, subsurface tile drainage, and crop yields under regular drainage and controlled drainage with subirrigation at a site near Harrow, ON, in a region with cold winter. The novel features of this study are that in evaluating the model:

1. RZWQM2's subirrigation component is tested for the first time;
2. Surface runoff and subsurface tile drainage are modelled over the full year, in particular during winter.

1.4 Scope

In this study, the RZWQM2 model was evaluated for tile drainage, surface runoff and crop yield in a clay loam soil in southern Ontario by graphical comparison and statistical analyses. The model was calibrated with observed field data from June 1, 2008 to December 22, 2011 under regular drainage treatment, and validated with field data from June 1, 2008 to December 22, 2011 under control drainage with subirrigation treatment. While the model simulated tile drainage and runoff in DR treatment relatively well, it should be tested for other treatment about its validity. The model was unable to simulate P transport.

1.5 Thesis Outline

Chapter 2 is a review of literature on overview of the other models. Chapter 3 is the methods section, which explains RZWQM2 model, site description, field experimental design, data collection, model input parameters, and the statistical methods used to for model evaluation. Chapter 4 presents and discusses the results of model calibration and validation for crop yield, subsurface tile drainage and surface runoff. Chapter 5 is the summary and conclusion of the thesis and provides recommendations for future studies.

Chapter 2. Literature Review

2.1 Phosphorus movement in tile drainage

While phosphorus (P) is essential to agriculture crop production, the application of excessive inorganic fertilizer and animal manures results in P build-up in soils, which can, in turn, contribute to P loss to waterways and eutrophication. Tile drainage system is designed to remove excess soil water for optimum crop performance and transport P in dissolved and particular forms. It increases non-point source pollution by enhancing the movement of agricultural nutrients, sediments and pesticides to shallow groundwater and surface water resources (Tan *et al.*, 1993, Rudolpy and Gross, 1993, Gaynor and Findlay, 1995, Gaynor *et al.*, 1995). Therefore, excess P loading from non-point sources is the primary causes of freshwater eutrophication.

Tile drainage often increases proportion of annual precipitation which distributes the water to surface water via subsurface flow. Therefore, tile drainage increased the total water yield between 10% and 25% (Serrano *et al.*, 1985, Magner *et al.*, 2004, Tomer *et al.*, 2005). Over the past two decades, tile drainage has been defined as a significant source of P in agricultural filed. It was found that up to 73% of soil P loss in tile drainage especially during the fall and early spring (Zhang *et al.,* 2004). Ruark et al. (2012) estimated that tile drainage contributed 17% to 41% of cumulative total P loss in Wisconsin.

Moreover, several studies informed that the tile drainage is the majority of stream flow in may agricultural watershed across the Midwestern United States and Canada. For example, Macrae et al., (2007) found that tile drainage contributed 42% of annual watershed discharge in a watershed in Ontario, Canada. An estimated 51% of annual stream flow originated from tile drainage in a headwater watershed in Ohio (King *et al.,* 2014). Although subsurface drainage trends to increase total water yield from a field, it often significantly decreases sediment yield (Robinson *et al.*, 1999, Skaggs *et al.*, 1994, Dolezal *et al.*, 2001).

P loss through the tile drainage affected the Lake Erie basin in southern Ontario in Canada (Chambers *et al.*, 2001). Therefore, water management practices which involve installing drainage control structure have been developed to reduce the negative water quality in agricultural filed. In controlled drainage system, P leaching losses would be reduced by slowing the tile drainage rates through the control structure, raise the water table, and may increase vertical seepage and surface runoff (Gilliam *et al.*, 1979, Tan *et al.*, 1993, Tan and Zhang, 2011, Skaggs Breve and Gilliam, 1994).

2.2 Models overview

Some models have been designed to simulate subsurface water flow: DRAIMOD (Skaggs, 1980), the Leaching Estimation and Chemistry Model (LEACHM) (Huston and Wagenet, 1992), Hydrus-1D (Simunek *et al.*, 2009) and Hydrus (2D/3D). The advantages and weaknesses of several field scale models are listed in Table 1. DRAIMOD is a 1-dimensional and field-scale model that simulates hydrology of agricultural fields, including surface runoff, subsurface tile drainage, infiltration, water flux, lateral water movement and evapotranspiration. Based on soil water conditions, DRAINMOD is able to simulate crop yields. The main limitation of DRAIMOD is that it is not equipped with pesticide and phosphorus transport components. However once linked with an N model, the combination model (DRAINMOD-N) was able to simulate N processes in the soil. Moreover, DRAINMOD-S is able to consider the effect of irrigation management and drainage design on soil salinity and its effect on yield (Kandil *et al.*, 1995).

LEACHM is a process-based model which simulates vertical water movement, plant uptake of tracer ions, solute transport and solute distribution in the soil profile (Jemison *et al.*, 1994) LEACHM consists of four simulation models which differ in their description of chemical equilibrium, transformation and degradation pathways: LEACHW describes the water regime only, LEACHP describes pesticides, LEACHN describes nitrogen and phosphorus, and LEACHC describes salinity in calcareous soils. This model considers a large number of input parameters such as organic matter decomposition, manure fertilizer as well as interactions between C, P and N pools. All of these input parameters are drawn from realistic experimental field conditions. However, LEACHN lacks ability to simulate subsurface tile drainage.

Hydrus-1D is a one-dimensional model for simulating solute transport which includes ions' (e.g., $CO_3^{2-}, Mg^{2+}, Ca^{2+}$etc.) adsorption, transportation and reactions. The model used Hooghoudt's equation or Ernest equations to simulate subsurface tile drainage (Simunek *et al.*, 2009). The model is able to consider weather condition, soil properties, root depth, crop parameters, and solute transport (Simunek *et al.*, 2009). However, this model lacks ability of addressing controlled drainage, controlled drainage with sub-irrigation and agriculture management such as solid fertilizer, manure, cropping and tillage. HYDRUS (2D/3D), the HYDRUS-1D model's commercial version, is a 2 or 3 dimensional model for simulating solute flow and water flow. While retaining the same functions as HYDRUS-1D, HYDRUS (2D/3D) was improved to include macro-pore flow. This model simulates macro-pore flow using an add-on dual permeability module which allows water and solute to flow between macro-pores and the soil matrix. However, the HYDRUS-2D/3D model one, is unable to implement agricultural management practices such as fertilization, cropping, or tillage.

Table 1. The advantages and weaknesses of several field scale models.

Model	Type	Input	Advantages	Weaknesses
RZWQM	1-D	Weather data; soil information; agricultural management	Simulate water flow, snow accumulation, melting and 23 crop species	Cannot simulate Phosphorous
DRAINMOD	1-D	Weather data; soil properties; crop parameters; drainage parameters	Simulate hydrology, sanity, crop yield, wetland and wastewater	Unable to simulate solute transport
LEACHM	Process-based	Weather data, soil information	Simulate vertical water flow, solute transport, and reactions	Unable to simulate subsurface tile drainage
HYDRUS-1D	1-D	Weather data; soil information; crop properties; root depth	Simulate water flow; solute transport;	No agricultural practices; cannot address sub-irrigation
HYDRUS2D/3D	2-D/3-D	Weather data; Soil information; crop properties; root depth	Simulate water flow; solute transport; allow irregular tile drain	No agricultural management

As a 1-dimensional process-based model, the Root Zone Water Quality Model (RZWQM2) simulates water flow, biological processes and solute transport in agricultural systems. The hydrological processes represented in RZWQM2 included drainage, surface runoff, evapotranspiration, infiltration, water redistribution and water uptake by roots. Soil hydrological processes are handled in sub-daily time steps (from 5-60 min), overcoming many difficulties encountered with daily time step models. Although predicting surface runoff volume is a difficult task for any model, it is very important because surface runoff correlated with loss of pesticides, sediments and other agricultural chemicals into ground water. Unlike other runoff models, when hydrologic events occur, RZWQM2 calculates runoff in “real time” (Ahuja *et al.* 2000). During a rainfall event, RZWQM2 applies the Green and Ampt model to calculate water which has infiltrated into the soil profile (Ahuja and Hebson, 1992). The excess water flows into macropores, if present, when rainfall intensity exceeds the simulated infiltration rate. In the absence of macropores or if they are filled, the excess water leaves as runoff (Ahuja *et al.,* 2000). RZWQM2 also can be used to simulate various agricultural management practices, including tillage, harvesting, and crop planting, manure application, inorganic fertilizers, irrigation, and residual decomposition. Moreover, McLaughlin (2001) ranked the RZWQM2 model at the top of nine agricultural non-point source pollution models for simulating hydrologic and nutrient processes (Ahmed *et al.*, 2007a).

Chapter 3 Materials and Methods

3.1 RZWQM2 Overview

Developed by the USDA-ARS scientists, the RZWQM2 model simulates crop production, hydrologic cycle, fate and transport of nutrients and pesticides under different climate patterns and agronomic management practices. For soil heat transfer, soil water and surface energy balance, it runs on a sub-hourly time step and on a daily time step for plant growth, pesticides and N balance (Ma *et al.*, 2012). The model can discriminate up to ten layers of soil and devotes 200 event slots for management practices such as planting dates, manure and pesticide applications, and tillage. Soil water retention is described using the Brooks-Corey equation (Brooks and Corey, 1964). The Green-Ampt approach is used to compute the water infiltration from rainfall, snow melt and irrigation. The model employs Richard's equation to simulate water redistribution in the soil profile. The SHAW model was recently linked to RZWQM2 to simulate ice in soil, snow accumulation, snow melting, as well as soil freeze-thaw cycles. The SHAW model enables the RZWQM2 to simulate varying management scenarios, long-term crop rotations, surface conditions, and management for multiple seasons (Flerchinger *et al.*, 2000b) Hybridized with DSSAT 4.0 crop models, it can simulate 23 crop species and their varietal characteristics as well as turf and trees (Ahuja *et al.*, 2000, Ma *et al.*, 2005, Ma *et al.*, 2006).

3.2 Field Site and Experiments

The experimental site was located on a Brookston clay loam soil at the Eugene F. Whalen experimental Farm in southwestern Ontario (42°13′ N, 82°44′ W). The soil contained 28% sand, 35% silt and 37% clay. The average soil bulk density (ρ) was 1.34 Mg cm^{-3}, the average porosity was 52.4% and the soil hydraulic conductivity (Ks) was between 1.7 and 11.9 mm d^{-1}, with a mean average saturated hydraulic conductivity (k_{sat}) of 5.0 mm d^{-1} (Qiao, 2013).

The site consisted of 16 uniform 67.1m long by 15.2m wide plots with a 0.05% to 0.1% slope. Impermeable double layer 4-mm thick plastic barriers were installed vertically from the surface to a depth of 1.2m to prevent subsurface water from infiltrating into adjacent plots. Buffer zones consisted of plots 7.5 m wide by 67 m long with a single drain to further prevent cross contamination between plots. The drainage system consisted of three 10.2 cm diameter corrugated and perforated tile drains pipes, which were located at a 0.80 m depth in the soil and ran parallel to the length of the plot. The spacing between each tile drains was 3.8 m, which was the same as the spacing between the edge of the plot and the tile drain. Collection basins were set up at the end of the downslope to collect surface runoff. Both the tile drainage and surface runoff were then individually transported to an instrumentation building via subsurface tubes, and their flow rates were continuously monitored and recorded by 32 automatic gauges (Tan *et al.*, 2009). The field experiment began on June 1, 2008, and was continuously monitored through December 22, 2011. The daily runoff and drainage data were cleaned, corrected, and split up into 17 periods showing in Table 2.

Table 2. Summary period for tile drainage and surface runoff

Period	Specific duration		Period	Specific duration	
	From	To		From	To
1	June 1, 2008	June 16, 2008	10	Apr 21, 2010	June 11, 2010
2	June 17, 2008	Jul 17, 2008	11	June 12, 2010	Aug 5, 2010
3	Jul 18, 2008	Oct 22, 2008	12	Aug 6, 2010	Dec 21, 2010
4	Oct 23, 2008	Feb 11, 2009	13	Dec 22, 2010	Mar 23, 2011
5	Feb 12, 2009	Mar 27, 2009	14	Mar 24, 2011	June 22, 2011
6	Mar 28, 2009	May 26, 2009	15	June 23, 2011	Set 7, 2011
7	May 27, 2009	Jul 17,2009	16	Sep 8, 2011	Nov 9, 2011
8	Jul 18, 2009	Oct 23, 2009	17	Nov 10, 2011	Dec 22, 2011
9	Oct 24, 2009	Apr 20, 2010			

The cropping systems used in this study were a corn-soybean rotation with corn grown in 2008 and 2010 and soybean [*Glycine max* (L.) Merr.] alone grown in 2009 and 2011. There were duplicated plots with 8 treatment combinations. These combinations consisted of 4 fertilization treatments and 2 water management treatments. Figure 1 is a diagrammatical site plan showing the site layout and the assigned treatment combinations as well.

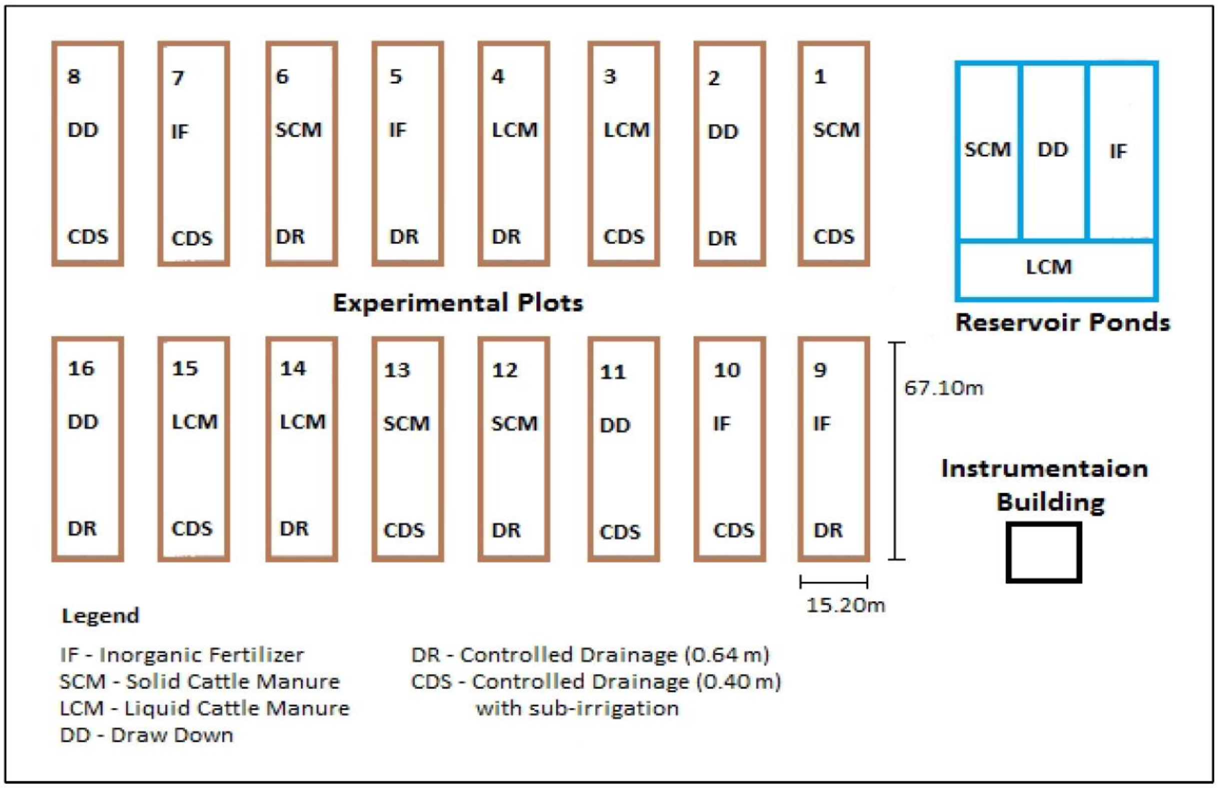

Figure 1.Site-plan of the AAFC-Harrow research site. Not drawn to scale (Tan *et al.*, 2009).

The regular drainage system (DR), without an outlet riser, mimicked the typical subsurface drainage employed in that region of Ontario. The controlled drainage with subirrigation system (CDS) used an outlet riser to control water table and to allow subirrigation during cropping season. The riser under CDS system was set at 0.2 m depth from the soil surface during the growing season, and 0.36 m depth from soil surface during the non-growing season. The CDS system was temporary set to the regular drainage (DR) mode during planting and harvesting field operation. Under CDS system, the water would be pumped into drain pipe during the growing season to increase the water level in the field and provided the irrigation water directly to the crop root zone (Madramootoo *et al.*, 1993, Tan *et al.*, 2007). Subirrigation systems are considered to present great benefits in terms of water management development (Tan *et al.*, 2011).

Surface runoff, subsurface tile drainage, and crop yield from DR treatment and "Draw Down" fertilization treatment (plots 2 and 16) were used to calibrate the model, and subsequently the model was calibrated using data from the CDS treatment under the same fertilization treatment (plots 8 and 11).

3.3 Data Collection

3.3.1 Weather data

Rainfall, air temperature, solar radiation, relative humidity, and wind speed are required for the RZWQM2 model. The hourly input values of such weather components were recorded at the nearby Whelan weather station, located less than 0.5 km from the experiment site. Rain gauge problems leading to inaccurate measurement during the winter period of October 1, 2008 to April 30, 2009, led to the use of precipitation data from the Harrow weather station (station ID 6133362, latitude 42.03 N, longitude 82.9 W), located 16.6 km away for that period (Environment Canada, 2008). Hourly weather information from 2008 to 2011, including hourly precipitation, air temperature, solar radiation, wind speed and relative humidity were drawn from Tan et al. (2009). The hourly precipitation was converted to breakpoint rainfall data in the

RZWQM2 model. The annual rainfall for 2008 was 896.2 mm, 2009 was 742.6 mm, 2010 was 774.3 mm, and 2011 was 1341.9 mm.

The RZWQM2 model accesses daily weather data (from 2008 to 2011) and converts it to the appropriate meteorology file in RZWQM2 model. Further input parameters of the RZWQM2 model include cultivar file (Table 8) and soil profile file (Table 3, 4) were inputs of the RZWQM2 model. Crop yield, tile drainage flow rates, as well as surface runoff flow rates were included in the field measurements and some observations were drawn from Tan and Zhang (2011).

3.4 Model Initialization

The soil profiles were represented as six layers (0-0.25, 0.25-0.45, 0.45-0.80, 0.80-1.20, 1.20-3.00, 3.00-3.09 m), each described in terms of mean bulk density (ρ, measured 2010), particle density, porosity, and fraction of sand, clay, slit (Table 3). Soil physical properties were measured to a maximum depth of 1.2 m; therefore, the soil physical properties assigned to the 1.20-3.00 m and 3.00 to 2.09 m layers were those measured for the 0.80-1.20 m. The local soil is Brookston clay loam, consisting, on average of 28% sand, 37% silt, and 35% clay. For the calibration treatment, the model used the average soil fraction from soil fraction in plots 2 and 16. The calculated average soil fraction in plot 8 and 11 were shown in Table 3 as well.

Table 3. Observed soil horizon description in plot 2&16, plot 8&11. [a]

Soil type	Depth (m)	PD (cm)	BD (gcm^{-3})	Plot 2 and Plot 16			Plot 8 and Plot 11		
				Clay	Silt	Sand	Clay	Silt	Sand
Clay loam	0-0.25	2.65	1.33	26.4	34.2	39.4	30.3	43.2	26.5
Clay	0.25-0.45	2.65	1.39	34.3	38.7	27.0	37.0	40.6	22.4
Clay loam	0.45-0.80	2.65	1.39	31.9	47.7	20.4	36.2	37.2	26.6
Clay loam	0.80-1.20	2.65	1.39	34.3	43.0	22.7	36.5	37.2	29.8
Clay loam	1.20-3.00	2.65	1.39	34.3	43.0	22.7	36.5	37.2	29.8
Clay loam	3.00-3.09	2.65	1.39	34.3	43.0	22.7	36.5	37.2	29.8

[a] PD = Particle Density; ρ = Bulk Density.

The saturated hydraulic conductivity (k_{sat}) measurements were distributed among the layers in selected plots: 2&16 (DR) and plot 8&11 (CDS) and ranged from 1.7 to 11.9 cm d^{-1}. The calibrated soil hydraulic parameters (Table 4) and soil horizon description (Table 3) were used as input parameters in the RZWQM2 model. Calibrated k_{sat} was based on the soil hydraulic parameters default value table from Rawls et al. (1982), namely k_{sat}= 0.23 for clay loam soil. This k_{sat} value resulted in simulated water flow underestimating observed water flow; therefore, k_{sat} was adjusted to a higher value was aiming to increase the simulated water flow. The saturated water content (θ_{sat}) was assumed equal to the porosity. For bubbling pressure, the value was adjusted slightly to reduce error between simulated tile drainage and observed tile drainage. Lateral saturated conductivity k_{sat}^{L} a major parameter to calculate subsurface tile drainage flow in Hooghoudt's equation (Ma *et al.*, 2012), was adjusted to 2×k_{sat}. Other parameters such as albedo (Table 5) of dry soil and albedo of wet soil were 0.55 and 0.5 respectively. The crop albedo at maturity and the albedo of fresh residue were set to 0.55 and 0.8 respectively, thereby adjusting simulated evapotranspiration (ET) into a comparable range as wad measured. The surface soil resistance for the S-W PET (s m^{-1}) was adjusted to 200, to reduce ET so that the simulated tile drainage and runoff were well matched with observed tile drainage and surface runoff. The lateral hydraulic gradient parameter was adjusted to zero for controlling lateral flow losses, and for a better match of simulated subsurface tile drainage and observed subsurface tile drainage

Table 4.Calibrated soil hydraulic properties in selected plots (2&16, 8&11). [a]

Depth (cm)	Pb	K_{SAT} (cm h^{-1})	LK_{SAT} (cm h^{-1})	Water Content (cm3 cm-3)[b]				
				θ_r	θ_s	θ_{33}	θ_{10}	θ_{1500}
0-25	-15.00	0.85	1.70	0.040	0.500	0.325	0.383	0.198
25-45	-11.00	3.40	6.80	0.090	0.475	0.329	0.370	0.236
45-80	-9.00	3.00	6.00	0.090	0.475	0.329	0.370	0.236
80-120	-15.00	2.00	4.00	0.090	0.475	0.347	0.390	0.246
120-300	-15.00	1.00	2.00	0.090	0.475	0.347	0.390	0.246
300-309	-15.00	1.00	2.00	0.090	0.475	0.347	0.390	0.246

[a] k_{sat} = saturated conductivity, L_{Ksat} = lateral saturated conductivity.

[b] θ_r = residual water content, θ_s = saturated water content, θ_{33} = soil water content at pressure of 33 kPa, θ_{10} = soil water content at pressure of 10 kPa, and θ_{1500} = soil water content at pressure of 1500 kPa.

Table 5. Calibrated albedo for RZWQM2.

Parameter	Calibrated	Default
Albedo of dry soil	0.55	0.2
Albedo of wet soil	0.5	0.2
Albedo of crop at maturity	0.55	0.38
Albedo of fresh residue	0.8	0.4

The initial nutrient conditions were set using the model's initialization wizard, which also set organic matter fraction values (Table 6) for the different soil layers, based on values from a site with similar soil type located in the same region in southern Ontario (Ahmed *et al.*, 2007b). Twenty percent of total organic carbon (TOC) was partitioned in the fast and intermediate humus pool in each layer, and 80% in the slow humus pool. Because the fast and intermediate pool did not partition with respect to recent management history in the field, TOC was set at 10% in the fast humus pool between fast and intermediate pool in the RZWQM2. The model was then able to calculate and display the N profile automatically. Other parameters including C: N ratio and chemical parameters for all nutrient components in RZWQM2 were set to default values except for the parameters are given in Table 6 and Table 7. The initial water profile and temperature profile are shown in the Table 7. The calibrated initial conditions of water profile and temperature was determined by making sure that simulated subsurface drain flow began approximately when the subsurface drain flow actually began in the field.

Table 6. Initial nutrient and soil parameters used for simulations.

Layer	Depth (cm)	Residue pool ($ug\ C\ g^{-1}$)		Organic Matter Pools ($ug\ C\ g^{-1}$)			Microorganism Pools ($ug\ C\ g^{-1}$)			NO3-N ($ug\ C\ g^{-1}$)	NH4-N ($ug\ C\ g^{-1}$)
		Fast	Slow	Fast	Inter.	Slow	Aerobes	Autotrophs	Anaerobes		
1	0-25	74.1	14.5	427.1	3843.8	17083.6	100000	1000.0	10000.0	0.50	0.10
2	25-45	13.7	42.4	346.3	3116.6	13851.6	81081.0	810.0	8108.0	0.50	0.10
3	45-80	9.5	23.7	80.8	727.2	3232.0	18918.0	189.00	1891.0	0.50	0.10
4	80-120	5.8	24.8	57.7	519.4	2308.6	13513.0	135.0	1351.0	0.50	0.10
5	120-300	3.1	11.9	46.2	415.5	1846.9	10810.0	108.0	1081.0	0.50	0.10
6	300-309	1.6	3.8	23.1	207.8	923.4	5405.0	54.0	540.0	0.50	0.10

Table 7. Soil organic matter and initial state of water profile and temperature profile.

Layer	Depth (cm)	Organic matter (%)	Tensiometric potential (cm)	Temperature (℃)
1	0-25	3.7	-85.00	15.000
2	25-45	2	-100.00	15.000
3	45-80	0.7	-200.00	15.000
4	80-120	0.5	-200.00	15.000
5	120-300	0.4	-10.00	15.000
6	300-309	0.2	0.00	15.000

Two water table management treatments, regular drainage (DR) and controlled drainage with subirrigation (CDS), were set up through the hydraulic control tab of RZWQM2 (Table 8). In the DR system, the water table depth was fixed at 0.64 m from 2006 to 2011. For the CDS system, water table depth was controlled at two depths (0.36 m and 0.20 m below soil surface) throughout the 4-year experimental period. In 2008, there was no subirrigation and the water table depth was fixed at 36 cm for the entire season. The water table depth for control drainage mode was controlled at 36 cm from January 1, 2009 to June 18, 2009 and September 15, 2009 to the end of year. However, during the sub-irrigation time which from June 19, 2009 to September 14, 2009, the water table depth was controlled at 20 cm. In the 2010, the head gate depth for CDS plots were 20 cm between July 14 and September 8. And in the rest of season, the head gate depth were 36 cm. During the 2011, the water table depth were controlled for CDS plots were 20 cm from July 19 to September 16. Moreover, the water table depth were controlled at 36 cm for the rest of season.

Table 8. Tile head gate (from soil surface to water table) for the controlled drainage with subirrigation field.

No.	Date	Depth (cm)
1	01/Jan/2008	36
2	19/Jun/2009	20
3	14/Sep/2009	36
4	14/Jul/2010	20
5	08/Sep/2010	36
6	19/Jul/2011	20
7	16/Sep/2011	36

Note: for the regular drainage (DR) water table was consistently controlled at 64 cm.

For management practices, corn and soybean were planted in year-to-year rotation, a common practice in the region corn (cv. IOB0033 PIO 3780) planted on June 18, 2008 and June 26, 2010 at a density of 79,800 seeds ha^{-1} was harvested on October 21, 2008 and October 25, 2010, respectively. On May 22, 2009 and June 15, 2011, soybean variety Pioneer 990002 M Group 2 with a density of 486,700 seeds ha^{-1} were planted and harvested on October 20, 2009 and December 13, 2011. Crop yields, tile drainage flow rates, as well as surface runoff flow rates were included in field measurements and observations which were provided by Tan and Zhang (2011).

Table 9. Agronomic management for all the treatments.

Activity	Type	2008	2009	2010	2011
Maize Planting	IBO 0033 PIO 3780	18 June	--	26 June	--
Maize Harvesting	IBO 0033 PIO 3780	5 Nov.	--	8 Nov.	--
Soybean Planting	990002 M Group 2	--	22 May	--	15 June
Soybean Harvesting	990002 M Group 2	--	20 Oct.	--	13 Dec.

The corn crop received 200kg N ha^{-1} of N fertilization on June 25, 2008 and June 23, 2010.As regards fertilization treatments, same amount of N was applied to corn planting years. Those treatments were fertilized during June 4-17 2008 and June 11-25, 2010. Four fertilizer treatments providing equal quantities of N and K Inorganic fertilizer (IF), solid dairy cattle manure (SCM), liquid dairy cattle manure (LCM), and P "draw down" (DD) were 4 tested fertilizer treatments which provided the equal amount of N, P and K. The fields were provided inorganic fertilizers with K and N to achieve 100kg K ha^{-1} of KCI and 200kg N ha^{-1} of NH_4NO_3. The plots were fertilized with only inorganic N and K fertilizer as "draw down" treatment, which were designed to investigate the effect of absence of P fertilization on patterns of crop yields and water quality over time (Tan and Zhang, 2011). Applied "draw down" fertilizer which had 200kg N of NH_4NO_3 (155kg NO_3-N and 45kg N of NH_4-N) to plot 2&16 and plot 8&11 in 2008 and 2010. Soybean received on N fertilization. After harvest, November 1 of 2008, 209 and 2010, soil was tilled using a chisel-plow, while in the very wet fall of 2011, tillage was postponed until the following spring.

Table 10. Agricultural management practices used in initializing nutrient component.

Crop	Year	Tillage	Fertilizer Application			
			Date	Type	NO_3-N(kg)	NH_4-N (kg)
Maize	2008	Chisel-plow	June 25	Injected	155	45
Soybean	2009	Chisel-plow	--	--	--	--
Maize	2010	Chisel-plow	June 23	Injected	155	45
Soybean	2011	Chisel-plow	--	--	--	--

Subirrigation was not applied in 2008. The total quantities of subirrigation water applied in 2009, 2010, and 2011 were 116 mm (May 22 to October 20), 134 mm (June 26 to November 8), and 37 mm (June 26 to November 8), respectively (Tan *et al.*, 2011; Figure 1). Since no specific irrigation dates or amounts were mentioned for the experiment site in Tan et al. (2011), subirrigation timing and quantity on a day to day basis was estimated according to irrigation requirements (daily precipitation minus simulated daily ET) on specific day during the growing season. Days of low precipitation required more, irrigation water. The irrigation application rate was 10 mm h^{-1} in the RZWQM2 model.

Table 11. Irrigation timing and amount (mm) for sub-irrigation system from 2009 to 2011.

Year	Date	Amount	Date	Amount	Date	Amount
2009	10/Jul/2009	10	21/Jul/2009	10	28/Jul/2009	10
	31/Jul/2009	10	02/Aug/2009	5	04/Aug/2009	5
	7/Aug/2009	10	14/Aug/2009	5	16/Aug/2009	5
	22/Aug/2009	5	25/Aug/2009	10	01/Sep/2009	5
	04/Sep/2009	6	06/Sep/2009	10	14/Sep/2009	10
2010	17/Jul/2010	10	22/Jul/2010	10	04/Aug/2010	15
	09/Aug/2010	5	14/Aug/2010	5	17/Aug/2010	10
	19/Aug/2010	10	21/Aug/2010	10	25/Aug/2010	4
	27/Aug/2010	10	30/Aug/2010	10	31/Aug/2010	10
	01/Sep/2010	10	05/Sep/2010	5	08/Sep/2010	10
2011	19/Jul/2011	4	23/Jul/2011	10	26/Jul/2011	10
	02/Aug/2011	3	30/Aug/2011	3	30/Aug/2011	5
	02/Sep/2011	5				

3.5 Model calibration and validation

3.5.1 Model Calibration

Since both drain spacing and k_{sat} are input parameters for Hooghoudt's equation, they figure as the major parameters influencing subsurface tile flow (Walker *et al.*, 2000). In order to calibrate the subsurface tile drainage and surface runoff from 2008 through 2011, the soil hydraulic parameters (Table 4) were adjusted to reduce the error between observed and simulated data. Increasing lateral k_{sat} increased tile drainage. Runoff occurred when the precipitation rate exceeded the infiltration rate which was itself related to (vertical) k_{sat} hydraulic conductivity. The other water-related outputs such as infiltration and runoff were responded to k_{sat} as well. The bubbling pressure was calibrated within a reasonable range based on the default values for each soil type (Rawls *et al.,* 1982). A similar bubbling pressure value (-15) was reported in Thorp et al. (2007). In calibrating monthly subsurface tile flow, decreasing bubbling pressure of the second and third layers of soil would increase tile drainage. In contrast, high bubbling pressure indicated that the soil retained more water, making it difficult for water to move down through the soil profile, thereby decreasing tile drainage, but increasing surface runoff. Surface residues affected ET: when surface residues increased, more water was allowed reach the drains, thereby decreasing ET(Walker *et al.,* 1994). Using the default value for surface residue resulted in overestimating ET and underestimating tile drainage; therefore, to adjust ET, to a reasonable level the surface residue value was increased to 0.8. Moreover, increased surface residue would increase tile drainage and runoff (Walker *et al.*, 2000).

In-soil denitrification rate was adjusted to reduce the discrepancy between observed crop yield and simulated crop yield. Ellis et al. (1998) reported that the application of N fertilizers had a significant effect on denitrification. Elmi *et al.* (2005) who found elevated denitrification rates under corn fertilized at a rate of 200 kg N ha^{-1}, showed this microbial process to decrease NO_3^--N in the soil solution (Elmi *et al.*, 2003). In the present study the denitrification rate was adjusted because the model's default rate resulted in a denitrification loss of roughly 200 kg N ha^{-1} y^{-1}, indicating that nearly all the applied N fertilizer (200 kg ha^{-1}) was denitrified. This further resulted in low corn yield. Having adjusted the denitrification rate to 1E-14, in the calibrated model, N losses through denitrification were between 7 g ha^{-1} d^{-1} and 40 g ha^{-1} d^{-1} under the DR treatment, and between 5 g ha^{-1} d^{-1} and 109 g ha^{-1} d^{-1} under the CDS treatment. These range concur with losses reported by Elmi et al. (2005), who for the same fertilization rate of 200 kg ha^{-1}, found growing season (May to October) denitrification rates of between 2 g ha^{-1} d^{-1} and 33 g ha^{-1} d^{-1} under free drainage treatment and between 4 g ha^{-1} d^{-1} and 105 g ha^{-1} d^{-1} under CDS.

Calibrated crop parameters for corn and soybean are given in Table 13. Degree days (base temperature of 8 °C) from seedling emergence to end of juvenile phase (P1) was adjusted to 190 °C day, well within the range of 100 to 450 recommended by Ma et al., (2011). A value of 685 °C day was chosen for the thermal time (base temperature of 8°C) from silking to physiological maturity (P5). Both P1 and P5 values were adjusted in order to match the physiological maturity of corn over its growth period. The maturity dates of corn under the DR treatment were October 14 in 2008 and October 18 in 2010, while for the CDS treatment, the maturity dates were October 12 in 2009 and October 20 in 2011. For soybean, time between first seed and physiological maturity (SD-PM) was adjusted to 38 days, the maximum value for the SD-PM stage, in order to best match the maturity date. However, the modelled crop's maturity was still not reached, so critical short day length (CDSL) and slope of the relative response of development to photoperiod with time (PPSEN) were set as 13.4 and 0.285, respectively, to match the soybean maturity date seen in the field. The modified CDSL value was within the range of 11 and 15, and adjusted PPSEN value was within the range of 0.129 and 0.349, as recommended by Ma et al., (2011). Time between plant emergence and flower appearance (EM-FL) was selected as 19 days so as to adjust the date and obtain a good simulation of yield. Similarly, the time between first flower and first seed (FL-SD) was adjusted to 12 for the model output to match observed yield.

Table 12. Calibrated crop parameters for corn and soybean. Values not listed in this table are default numbers.

Crop		Parameter	Value
Corn[a]	P1	Thermal time form seeding emergence to the end of the juvenile phase (°C day)	190
	P5	Thermal time from silking to physiological maturity (°C day)	480
Soybean[b]	CSDL	Critical Short Day Length below which reproductive development progress with no day length effect (for short day plants) (hour)	13.4
	PPSEN	Slope of the relative response of development to photoperiod with time (positive of short day plants) (1/hour)	0.285
	EM-FL	Time between plant emergence and flower appearance (R1)	19
	FL-SD	Time between first flower and first pod (R3)	12
	SD-PM	Time between first seed (R5) and physiological maturity (R7)	38

[a] Cultivar Maize IBO0033 PIO 3780.

[b] Cultivar Soybean 99002 M Group 2.

In the present study, measured soil physical data, hydraulic properties and observed data for crop yield, subsurface tile drainage and surface runoff were mainly drawn from Tan et al. (2009). For calibration, subsurface tile drainage and surface runoff data from June 1, 2008 to December 22, 2011 was drawn from phosphorus draw down plots under conventional drainage (plots 2 and 16; Figure 2), while for validation data from the same period, but from phosphorus draw down plots under controlled drainage-subirrigation (plots 8 and11; Figure 2) was used.

3.5.2 Model Validation

In this study, we compared the simulated surface runoff and subsurface tile drainage to observed surface runoff and subsurface tile drainage in plot 8&11 which were under CDS system with "Draw Down" fertilizer from June 1, 2008 to December 22, 2011 as validation in the RZWQM model. All of the input parameters were kept the same as the calibration (DR) except for water table control.

Three quantitative statistics used to evaluate the RZWQM2 model, percent of bias (*PBIAS*), Nash-Sutcliffe efficiency coefficient (*NSE*), and Index of Agreement (*IoA*), were defined by:

$$PBIAS = 100 \cdot \frac{\sum_{i=1}^{i=n}[O_i - S_i]}{\sum_{i=1}^{i=n} O_i} \qquad (1)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Oi - Si)^2}{\sum_{i=1}^{n}(Oi - \bar{O})^2} \qquad (2)$$

$$IoA = 1 - \frac{\sum_{i=1}^{n}|Si - Oi|}{2\sum_{i=1}^{n}|Oi - \bar{O}|} \qquad (3)$$

Where

n = number of data points

Si = simulated data (cm)

Oi = Observed data (cm)

$\bar{O}$ = mean of observed data (cm)

For surface runoff and subsurface tile drainage, according to the Moriasi et al. (2007), when *PBIAS* is within ±15%, *NSE* > 0.50, and *IoA* closer to 1, model performance is considered acceptable. Model performance in predicting crop yield was evaluated using *PBIAS*, and when within ±15% the model performance is considered acceptable.

Chapter 4 Results and Discussion

4.1 Crop growth

The observed crop yield and simulated crop yields are shown in Table 13, as well as the statistical analysis of the closeness of match between observed and simulated crop yield for the calibration period (2008-2011) under the DR treatment and validation period (2008-2011) under the CDS treatment, show the simulated yield to remain within ±15% of the observed yield for both corn and soybean. In general, the model performed acceptable in predicting crop yield. While Tan et al. (1980) reported irrigation to be necessary for the achievement of maximum crop productivity in the study region, observed corn and soybean yields in the DR and CDS treatments were similar and good. Presumably, the study site received sufficient rainfall and nutrients for the crops grown in these years.

Table 13. Observed and simulated crop grain yields (kg ha^{-1}) under drainage (DR) in plots 2&16 and controlled drainage with subirrigation (CDS) in plots 8&11. [a]

		Crop Yields (kg ha^{-1})			
		Calibration (DR)		Validation (CDS)	
Year	Main crop	Obs.	Sim.	Obs.	Sim.
2008	Corn	7660	8089	7864	7998
2009	Soybean	4083	4007	3999	3724
2010	Corn	7468	8318	7486	8702
2011	Soybean	3839	3543	3680	3439
PBIAS	2008	5%		2%	
PBIAS	2009	-2%		-7%	
PBIAS	2010	10%		14%	
PBIAS	2011	-8%		-7%	

[a] Obs. = observed; Sim. = simulated.

[b] PBIAS = Percent of Bias.

4.2 Hydrology Calibration

4.2.1 Tile drainage

The model was performed well in the calibration treatment of DR for subsurface tile drainage and surface runoff, from June 1, 2008 to December 22, 2011. Figure 2 depicts the simulated and observed subsurface drainage and surface runoff under the DR treatment during the period in Table 2, and the statistics were shown in Table 17. Total simulated subsurface drainage was 133.30 cm, within -15% bias of the observed value of 155.86 cm. The *NSE* of subsurface tile drainage was higher than 0.5, and *IoA* was no less than 0.84 which implied that the performance of the model in predicting surface runoff and subsurface drainage under the DR treatment was acceptable.

The simulated partition of rainfall to drainage, runoff, and ET was in general comparable to observed percentage in Tan et al. (2001). In our simulation, of the total annual water input (precipitation) to the field site, 7% was partitioned to the surface runoff, 39% to tile drainage, and 47% to ET. In Tan et al. (2001) of the total annual water input, 8% was partitioned to surface runoff, 30% to the tile drainage, and 55% removed by ET. Our simulated tile drainage as a percent of total precipitation (39%) was slightly higher than 30% in Tan et al. (2001) while the simulated ET percentage was lower than observed. This might because of adequate rainfall which resulted in no significant higher ET under the CDS treatment in comparison to DR. The average precipitation in this study (2008-2011, 98.8 cm) was about 25% higher than 1992-1994 (78.6 cm). Our simulated partition of ET, tile drainage, and runoff were closer to the observed percentage in a wet year of 1992 with an annual precipitation of 96.8 cm in Tan et al. (2001). According to Tan et al. (2001), in the wet year of 1992 in DR system, 45% of total annual precipitation (96.7cm) was removed by evapotranspiration, 38% was partitioned to subsurface tile drainage, and 8% was removed from field by surface runoff.

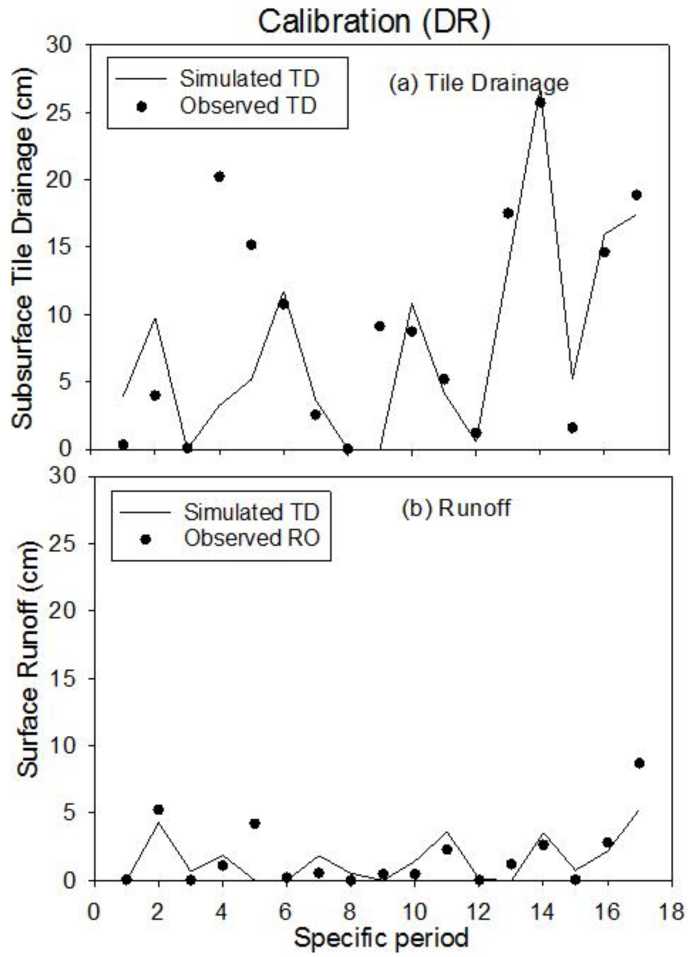

Figure 2.Observed and simulated (a) subsurface tile drainage and (b) surface runoff under DR treatment (calibration phase) from June 1, 2008 to December 22, 2011.

The model generally performed well in simulating drainage and runoff during the calibration phase. The peak simulated subsurface tile drainage was observed for Period 14 (March 24, 2001 to June 22, 2011; Figure1). However, the model underestimated tile drainage and runoff for the DR treatment during the winter month (e.g. Period 4, October 23, 2008 to February 11, 2009; Period 5, February 12, 2009 to March 27, 2009; and Period 9, October 24, 2009 to April 20, 2010). In these periods subsurface drainage was underestimated, and the observed *vs.* simulated discrepancy was greatest, largely due to underestimated infiltration through frozen soil and underestimated snow melt. Snow melting simulation in RZWQM2 is based on air temperature, soil surface temperature, wetness of soil, wind transport, etc. However, while soil surface temperature are different from the air temperature, the RZWQM2 model assumes the soil surface temperature to be equal to the mean daily air temperature, possibly contributing to simulation error. The work of Sogbedji and McIsaac (2002) found that deep seepage reduced soil moisture and led to low tile drainage. Deep seepage was 43.8 mm and 68.0 m in the 5th and 9th periods, respectively. Although simulated winter season tile drainage generally underestimated measured winter drainage, tile drainage was usually over-predicted after in the spring (Periods 6 and 10), possibly as the result of snow sublimation. The RZWQM2 does not include a snow sublimation component, whereas in reality snow sublimation might occur under high temperatures.

Although most of simulated tile drainage was underestimation in winter term, tile drainage usually was over-predicted after the winter time (sixth and tenth period). This might because of the snow sublimation. The RZWQM2 does not include a snow sublimation component, whereas in reality snow sublimation might occur when the temperature increased drastically.

4.2.2 Surface runoff

Surface runoff occurs when rainfall intensity exceeds infiltration capacity (Taylor and Blake, 1981) and soil crusting occurs (Ma *et al.*, 1998). Although the calibration phase model generally performed satisfactorily in predicting surface runoff for the DR plots over the period of 2008-

2011 (Figure 2b; Table 14) as with tile drainage, runoff was somewhat underestimated in the winter and overestimated in the summer. Because RZWQM2 is very sensitive to rainfall intensity (Schwartz and Shuman, 2005), when faced with high precipitation, the model tens to over-predict surface runoff (Table 15). In contrast, on low rainfall days, simulated runoff was generally nil. In reality, the fully developed plant canopy intercepted rainfall, decreasing the intensity and amount of rainfall reaching the soil surface. The intercepted rainfall was carried to rhizosphere, where the soil was generally looser than other areas, affording the rainfall a better chance to infiltrate deeper, rather than participating to surface runoff. Therefore, since the model did not consider this situation, simulated surface runoff would exceed observe runoff (Ma *et al.*, 1998).

The RZWQM2 simulated daily runoff based on constant initial ρ, however, in reality ρ kept changing during years, leading to uncertainties in simulated infiltration and surface runoff. An increase in ρ results in less infiltration and more runoff (Ma *et al.*, 1997). Some processes (reconsolidation) are affected by rainfall. Leading to changes in soil properties such as ρ, soil porosity and k_{sat}. This, in turn, results in differences between observed and model-simulated surface runoff. In our study, a chisel plow was applied after the crop was harvested in November; therefore, ρat the field scale was lower in the winter than in summer, after soil reconsolidation. This may explain the underestimated runoff in the winter while overestimated runoff in summer.

The simulated partition of rainfall to drainage, runoff, and ET was in general comparable to the proportions observed by Tan et al. (2002). In our simulation, of total annual precipitation at the field site, was partitioned 8%, 38% and 47% to surface runoff, tile drainage, and ET, respectively, similar to the equivalent values obtained by Tan et al. (2002): 8%, 30%, and 55%. Our simulated tile drainage as a percent of total precipitation (38%) was slightly higher than the

30% reported in Tan et al. (2002) while our simulated ET percentage was lower than observed. The mean precipitation in this study (2008-2011, 988 mm y^{-1}) was about 25% higher than that recorded in 1992-1994 (786 mm y^{-1}). Our simulated partition of surface runoff, tile drainage, and ET was closer to that observed for the wet (967 mm y^{-1}) year of 1992 (8%, 38%, 45%, respectively), in which precipitation totaled 968 mm y^{-1} (Tan *et al.*, 2002).

Table 14. Total observed and simulated subsurface drainage (TD) and surface runoff (RO) in calibration period of DR system, and validation period of CDS system from June 1st 2008 to December 22nd 2011 in plot 2&16 and plot 8&11. [a]

	Calibration (DR)		Validation(CDS)	
	TD	RO	TD	RO
Observed (cm)	155.86	30.04	63.57	89.56
Simulated (cm)	133.24	26.85	79.55	91.85
PBIAS	-15%	-11%	25%	3%
NSE	0.51	0.56	-0.57	0.22
IoA	0.86	0.84	0.73	0.78

[a] NSE = Nash-Sutcliffe modeling efficiency; IoA = Index of Agreement.

Table 15. Rainfall intensity (mm h^{-1}) and daily runoff (mm).

Date	Time	Rainfall intensity **(**mm h^{-1}**)**	Simulated Surface Runoff (mm)
Period 7			
20 VI 2009	0:00-0:00	12.8	
	1:00-2:00	2	
	4:00-5:00	6.6	
	5:00-6:00	9.4	
	6:00-7:00	4.4	
	Daily Total	38.5	3.1
24 VI 2009	15:00-16:00	16.2	1.1
11 VII 2009	8:00-9:00	2.2	
	9:00-10:00	31.6	
	10:00-11:00	0.2	
	Daily Total	34	14.2
Period 11			
27 VI 2010	15:00-16:00	22.2	
	17:00-18:00	0.6	
	Daily Total	22.8	2.7
24 VII 2010	2:00-3:00	0.2	
	3:00-4:00	0.8	
	14:00-15:00	20.4	
	15:00-16:00	0.4	
	18:00-19:00	20.8	
	19:00-20:00	29.6	
	20:00-21:00	1.2	
	22:00-23:00	0.4	
	DailyTotal	73.8	32.6

4.3 Hydrology Validation

In this study, the calibrated model was validated against subsurface tile drainage and surface runoff data from the CDS treatment plots (Plots 8 and 11). Under the CDS treatment, the total simulated subsurface drainage volume did not match well with the observed drainage (Table 14). The total simulated subsurface drainage of 734.7 mm overestimated the observed value 635.7 mm beyond 25% bias of the observed value of 635.7 mm by over 15% bias. The *NSE* and *IoA* values of subsurface tile drainage were -0.87 (<0.50, very poor) and 0.72 (<0.84, poor), respectively, suggesting an unacceptable RZWQM2 performance for the CDS treatment. The *PBIAS* for total simulated surface runoff over the validation period was within 15%, suggesting that the surface runoff estimation fell into an acceptable range; however, the *NSE* was 0.22, indicating that the model performed poorly in simulating surface runoff under the CDS treatment.

The total subsurface tile drainage was generally overestimated (Figure 3a) for the CDS treatment. While the subsurface tile drainage was generally underestimated during winter time (e.g., Period 4, 23 X 2008 - 11 II 2009; Period 5, 12 II 2009 – 27 III 2009; and Period 13, 22 XII 2010 – 23 III 2011), but overestimated the remainder of the time. The surface runoff under CDS treatment followed tile drainage trends: overestimation during the summer months, but underestimated during the winter/spring time (e.g., Period 4, 23 X 2008 – 11 II 2009; Period 5, 12 II 2009 – 27 III 2009; Period 6, 28 III 2009 – 26 V 2009; Period 9, 24 X 2009 – 20 IV 2010; Period 13, 22 XII 2010 – 23 III 2011; and Period 17, 10 XI 2010 – 22 XII 2010). The total simulated surface runoff was higher than the total observed surface runoff as well.

These discrepancies between simulated and observed data sets could be explained by a number of reasons: (i) subirrigation (Table 11) was estimated by calculation, leading to inaccuracies in amount and date, (ii) plot to plot variation – though plots 8 and 11 received identical treatments, observed tile drainage were 60.20 cm and 66.95 cm, respectively, while and surface runoff were 96.75 cm and 82.37 cm, (iii) gaps in measured data could lead to deviations in the simulated data sets and observed data sets. Overall, model validation showed poorer accuracy statistics than for calibration.

Nonetheless, the simulated annual tile drainage under CDS was comparable that observed in 1992-1994 by Tan et al. (2001). Although, in the present study 21% (vs. 30% reported in Tan et al. 2002) of total annual water inputs (precipitation plus subirrigation) were partitioned into simulated, mean simulated subsurface tile drainage (209.9 mm) was similar to an observed value of 275 mm in a wet year (1992) under the same CDS treatment (Tan *et al.,* 2002). Moreover, the simulated drainage under CDS was 40% less than the DR treatment in our study, which was similar to 48% observed by Tan et al. (2010). The simulated surface runoff was not predicted well in the RZWQM2 model. Compared to DR treatment (287.9 mm), CDS treatment (89.56 cm) produced significantly greater surface runoff. The CDS treatment produced higher surface runoff than DR treatment might because that the CDS treatment had wetter soil profile. The CDS system produced 206% more surface runoff relative to the DR system which lower than 406% in Tan et al. (2012). The annual simulated surface runoff was 254.6 mm in CDS system which was greater than 17.5 cm during the wet year of 1992 in Tan et al. (2002). Even if the simulated surface runoff was higher than Tan's reported, the total simulated surface runoff (891.4 mm) still close to the observed surface runoff (895.6 mm). Fourteen percent of total water input was contributed to the ET. Although they reported that 55% (477 mm) of total water inputs were removed by ET, compared to 47% in the present case, our simulated mean ET was comparable to their field observations.

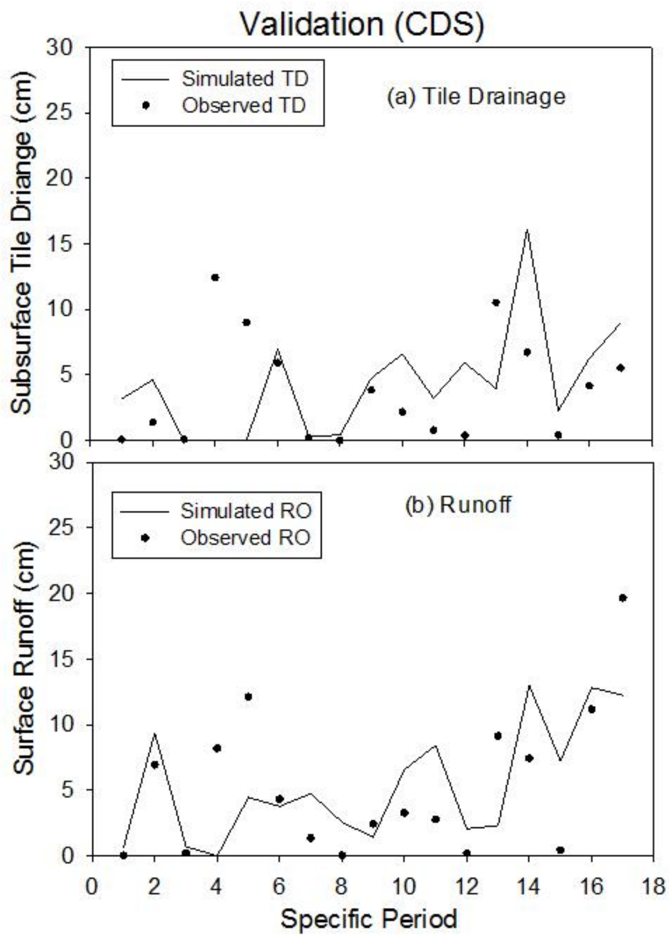

Figure 3. Observed and simulated (a) subsurface tile drainage and (b) surface runoff under CDS treatments from June 1, 2008 to December 22, 2011.

4.3 Evapotranspiration

In this study, the simulated ET was in a comparable range. When estimating ET through subtracting observed drainage and runoff by precipitation, in our study, the estimated ET was 460 mm for DR and 551.5 mm for CDS through the experimental periods. The simulated ET were 474.7 mm and 480.5 mm for DR and CDS, respectively, which were comparable to estimated ET through water balance method. In a field study conducted at the same site in 1992-1994 (Tan *et al.*, 2002), observed average ET under DR and CDS was 55% of the total water input, which were 43.2 cm and 47.7 cm, respectively. Our simulated ET was comparable to this field observation. Our simulated ET was comparable to the simulated value average of 46.8 cm in tile drained sites in southern Ontario (Ahmed *et al.,* 2007) though they believed that it was underestimated.

Although subirrigation in CDS may result in higher ET, in this study our simulation did not demonstrate a higher ET under the CDS than DR. The simulated ET under CDS was only 0.58 cm (1%) higher than DR. This is supported by similar observed yield under CDS and DR (Table 15). The average observed yield for corn under CDS was 7675 kg ha^{-1}, 1% higher than observed yield of 7564 kg ha^{-1} under DR; soybean yield under CDS was 3% less than DR. It might because the rainfall was adequate for crop growth during the experimental period.

Chapter 5 Summary and conclusions

5.1 Summary and Conclusions

The main objective of this study was to simulate subsurface tile drainage, surface runoff and crop yield under regular drainage (DR) and controlled drainage with subirrigation (CDS) in southern Ontario using the RZWQM2 model. Soil hydraulic, crop, and ET parameters were calibrated against observed tile drainage, surface runoff, and crop yield data for the DR treatment. The model was subsequently validated under controlled drainage with sub-irrigation system (CDS).

The RZWQM2 model performed generally well in simulating corn and soybean yield under both DR and CDS treatments. Simulated crop yield under the CDS system was not significantly higher compared to the DR system, suggesting that there was adequate rainfall for crop growth in those 4 years. The simulation also showed no water stress and similar actual ET under both water table management treatments. The simulated ET were reasonable as under both treatments they were similar to ET values observed by Tan et al. (2002) at the same site.

The RZWQM2 model showed a good performance on simulating subsurface drainage and surface runoff under the DR treatment (calibration), with *PBIAS* within ±15%, *NSE* > 0.50, and *IoA* > 0.80. Both subsurface tile drainage and surface runoff under calibration (DR system) were slightly underestimation in winter periods which suggested that more information is needed during the winter period to further test and improve the model.

The RZWQM2 was evaluated against tile drainage and runoff data collected from the CDS system using the same parameters calibrated using DR data. The statistical analysis suggested that the model performance was not satisfactory in simulating subsurface drainage and surface runoff under the CDS treatment. The relevant *PBIAS* values exceeded ±15%, while *NSE* < 0.22, and *IoA* < 0.79. Simulation accuracy followed similar trends to that of the calibration (DR treatment): subsurface tile drainage and surface runoff was usually under-predicted during the winter time when the freeze-thaw process complicates the hydrologic cycle. Therefore, more information, such as snow depth, melting, and hydrologic conductivity as affected by frost, is needed in the winter period to better test and to improve the model. Moreover, predicting surface runoff was a difficult task because t the model needed accurate measurement of soil physical properties and the fact was some of these were changing with time and management practices.

5.2 Recommendations for Future Research

The model being developed for this study serves as a starting point for the simulation of tile drainage and runoff under DR and CDS treatment. Improvements can be made to the current model in following ways.

1. The current simulation of tile drainage and runoff during fall to winter has the greatest errors. Therefore, the recommendation is that optimizing the snow accumulation and snow melting as well as the frozen soil conditions.
2. The current model only simulated tile drainage and runoff from June 1, 2008 to December 22, 2011 which compared with the observed data. The other data such as observed evapotranspiration was not available. As additional data becomes available in the future, they should be used to re-evaluate this model to establish its validity for the tile drainage and runoff under DR and CDS treatment at the AAFC experimental site.

3. The current model simulated tile drainage and runoff under CDS treatment not very well. If detailed irrigation schedule presents, the input parameter is more reliable and it results in a precise simulation.
4. There is great opportunity to model the rest of the field experiment. The current model only simulated two duplicate plots with controlled drainage and controlled drainage with subirrigation under "Draw Down" (no P) fertilizer. There are four other experimental plots with inorganic P fertilizer, which can be simulated using the current model but requires current model has P simulation component in order to make reliable input parameters.
5. The model need more work to test the capabilities by using field data from different soil types, weather data, crops, and drainage settings in other areas.

For model developers, there are a number of features that would greatly enhance the modeling of hydrology in the RZWQM2. An ideal model that encompasses all the needs should have a strong water quality component which is capable of simulating N and P losses in tile drainage and runoff. There needs to be a good chemistry component that allows for multiple solute pools, connected by chemical interactions that can be user-defined based on pH, soil moisture, temperature, soil fertility, etc. A microbial module may help administering the biological degradation processes for P simulation as well as for N and other chemicals. Finally, it would also be meaningful to incorporate phosphorus and carbon components into a nitrogen model as these factors are closely related to each other through soil fertility.

All of the model functions described here can already be found in existing models, although each existing model usually only hosts one or few of these functions and lacks in other areas.

Recommendation for future developers is thus to combine existing models into hybrids to offer greater model capabilities to simulate field conditions as realistically as possible.

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