Development and Evaluation of SWATDRAIN, A New Model to Simulate the Hydrology of Agricultural Tile-Drained Watersheds

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ABSTRACT

Doctor of Philosophy **Bioresources Engineering**

It is important for watershed models to realistically simulate tile drainage flow and water table dynamics. Therefore, a new model, SWATDRAIN, was developed in this study by incorporating the DRAINMOD model into the Soil and Water Assessment Tool (SWAT) to better simulate surface and subsurface flow in tile-drained watersheds and also to improve the prediction of water table depth. This was accomplished by fully integrating the DRAINMOD model, which has been tested and widely used to simulate the performance of drainage and water table control systems on a continuous basis at field scale, into the SWAT model.

The SWATDRAIN model was evaluated for a fully tile-drained watershed in eastern Ontario, Canada. The measured tile drainage outflow and water table depth data for the Green Belt watershed were used to evaluate the capability of the new model to simulate water balance for this fully tile drained agricultural watershed. Together with hydrographs, the Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS) and coefficient of determination (R^2) statistics were used in evaluating the accuracy of SWATDRAIN to predict tile flow and water table depth in light of the measured values. Simulations were carried out over the period of 1991 to 1993; 1991 and 1992 data served as model calibration and 1993 data were used to validate the process. Model accuracy statistics for the monthly and daily water table depth over the validation period were, respectively, 0.86 and 0.70 for R^2, 0.11 and 2.90 for PBIAS, and 0.80 and 0.67 for the NSE. Model accuracy statistics for events, monthly and daily tile drainage over the validation period were, respectively, 0.86, 0.88 and 0.70 for R^2, 11.7, 17.26 and 23.85 for PBIAS, and 0.84, 0.86 and 0.62 for the NSE.

The SWATDRAIN model was also applied to a partially tile-drained watershed in southern Ontario. Simulations were carried out from 1975 to 1983;

data from 1975 to 1978 were used for model calibration and data from 1980 to 1983 were used for validation. The new model was able to adequately simulate the hydrologic response at the outlet of the watershed. Comparing the observed monthly and daily tile drainage with the model's output over the validation period returned R^2 values of 0.75 and 0.62, PBIAS of 13.96 and 17.99 and modeling efficiency of 0.71 and 0.62.

In this study, the effects of a drainage water management operational strategy on hydrology were simulated using SWATDRAIN in the Green Belt watershed in Ontario. The effects of drainage water management on subsurface drainage and surface runoff were predicted for a period of four years from 2004 to 2007. Implementing the controlled drainage strategy from June 15 to August 15 during the cropping season and also from November 1 to May 1 in the non-growing season resulted in a reduction of the average annual drain flow by 18%, while it increased the surface runoff in the order of 30%. The results showed that the surface runoff increase mostly happened during the snowmelt period in April and also it was slightly increased during the month of November. However, higher amount of surface runoff in flat watersheds during the snowmelt period may not cause a serious problem.

RÉSUMÉ

Doctorat en Philosophie **Génie des Bioressources**

Une bonne modélisation de bassin versant se doit de simuler correctement l'écoulement par drains souterrains ainsi que la dynamique des fluctuations de la nappe phréatique. Un nouveau modèle, SWATDRAIN, fut créé afin de mieux simuler à la fois l'écoulement en surface et souterrain, et le niveau de la nappe phréatique dans les bassins versants équipés d'un réseau de drainage souterrain. Ce modèle représente une intégration complète du modèle hydrologique DRAINMOD, bien éprouvé et largement utilisé pour simuler la performance de systèmes de drainage et de contrôle de la nappe phréatique en mode continue à l'échelle du champ, dans SWAT, un outil de prédiction des effets à l'échelle du bassin versant du mode de gestion agricole sur la quantité et qualité des eaux, ainsi que leur teneur en sédiments, éléments nutritifs et pesticides.

La performance du modèle SWATDRAIN fut évaluée pour un bassin versant agricole de l'est ontarien, entièrement soumis au drainage souterrain. Les données d'écoulement souterrain et de profondeur de la nappe phréatique mesurées dans le bassin versant Green Belt servirent à évaluer la capacité du nouveau modèle à simuler avec précision l'équilibre hydrique de ce bassin versant. Conjointement avec la comparaison d'hydrographes, les statistiques du coefficient d'efficacité Nash-Sutcliffe (NSE), du pourcentage de biais (PBIAS) et de la valeur de R^2 servirent à évaluer la précision de SWATDRAIN dans sa prédiction de l'écoulement souterrain et de la profondeur de la nappe phréatique. Les simulations furent entreprises pour une période s'étendant de 1991 à 1993, avec les années 1991 et 1992 servant à la calibration du modèle, et l'année 1993 à sa validation.. La précision du modèle en phase de validation pour les moyennes mensuelle et quotidiennes de profondeur de la nappe phréatique fut confirmée par des valeurs respectives de 0.86 et 0.70 pour R^2, 0.11 et 2.90 pour le PBIAS, et 0.80 et 0.67 pour le NSE. La précision du modèle en phase de validation pour les

moyennes mensuelle et quotidiennes d'écoulement souterrain fut confirmée par des valeurs respectives de 0.86 et 0.70 pour R^2, 11.7 et 23.85 pour le PBIAS, et 0.84 et 0.62 pour le NSE.

Le modèle SWATDRAIN fut également mis à l'œuvre dans un bassin versant agricole sud-ontarien, partiellement soumis au drainage souterrain. Les simulations furent entreprises pour une période s'étendant de 1975 à 1983, avec les années 1975 and 1978 servant à la calibration du modèle, et les années 1980 à 1983 à sa validation. SWATDRAIN simula adéquatement la réaction hydrologique à l'exutoire du bassin. La précision du modèle en phase de validation pour les moyennes mensuelles et quotidiennes d'écoulement souterrain fut confirmée par des valeurs respectives de 0.75 et 0.62 pour R^2, 13.96 et 17.99 pour le PBIAS, et 0.71 et 0.62 pour le NSE.

Dans une étude additionnelle, les effets potentiels d'une stratégie de gestion des eaux d'écoulement souterraines sur les paramètres hydrologiques du bassin versant ontarien Green Belt furent simulés avec la version de SWATDRAIN validée pour ce bassin versant. Les effets d'une gestion des eaux de drainage sur l'écoulement souterrain et de surface furent prédits pour les quatre années de 2004 à 2007. Mettant en œuvre d'une stratégie de drainage contrôlé durant la saison de culture (15 juin au 15 août), et hors-saison (1 novembre au 1 mai) donna lieu à une réduction de l'écoulement souterrain annuel moyen de 18%, tout en augmentant l'écoulement en surface annuel moyen de près de 30%. Ces résultats indiquèrent que la majorité de l'écoulement en surface eut lieu durant la fonte des neiges d'avril et que celle-ci était quelque peu élevée durant le mois de novembre. Cependant, un niveau élevé d'écoulement en surface dans un bassin relativement plat lors de la fonte ne risque pas de causer de problèmes majeurs.

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I would like to dedicate this thesis to the loving memory of my sister, who is a constant source of inspiration

FORMAT OF THE THESIS

This thesis is submitted in the format of papers suitable for journal publication. This thesis format has been approved by the Faculty of Graduate and Postdoctoral Studies, McGill University, and follows the conditions outlined in the Guidelines Concerning Thesis Preparation, which are as follows:

"As an alternative to the traditional thesis format, the dissertation can consist of a collection of papers of which the student is an author or co-author. These papers must have a cohesive, unitary character making them a report of a single program of research. The structure for the manuscript-based thesis must conform to the following:

1. Candidates have the option of including, as part of the thesis, the text of one or more papers submitted, or to be submitted, for publication, or the clearly-duplicated text (not the reprints) of one or more published papers. These texts must conform to the "Guidelines for Thesis Preparation" with respect to font size, line spacing and margin sizes and must be bound together as an integral part of the thesis. (Reprints of published papers can be included in the appendices at the end of the thesis.)

2. The thesis must be more than a collection of manuscripts. All components must be integrated into a cohesive unit with a logical progression from one chapter to the next. In order to ensure that the thesis has continuity, connecting texts that provide logical bridges between the different papers are mandatory.

3. The thesis must conform to all other requirements of the "Guidelines for Thesis Preparation" in addition to the manuscripts.

The thesis must include the following:

(a) A table of contents;

(b) An abstract in English and French;

(c) An introduction which clearly states the rational and objectives of the research;

(d) A comprehensive review of the literature (in addition to that covered in the introduction to each paper);

(e) A final conclusion and summary;

4. As manuscripts for publication are frequently very concise documents, where appropriate, additional material must be provided (e.g., in appendices) in sufficient detail to allow a clear and precise judgment to be made of the importance and originality of the research reported in the thesis.

5. In general, when co-authored papers are included in a thesis the candidate must have made a substantial contribution to all papers included in the thesis. In addition, the candidate is required to make an explicit statement in the thesis as to who contributed to such work and to what extent. This statement should appear in a single section entitled "Contributions of Authors" as a preface to the thesis. The supervisor must attest to the accuracy of this statement at the doctoral oral defense. Since the task of the examiners is made more difficult in these cases, it is in the candidate's interest to clearly specify the responsibilities of all the authors of the "co-authored papers".

CONTRIBUTIONS OF AUTHORS

The chapters of this thesis have been presented at scientific conferences and are in process of publication in peer reviewed journals. The author of this thesis was responsible for the model development, calibration and validation, and analysis of the data, and preparation of manuscripts for publication. Dr. Shiv Prasher is the thesis supervisor and gave such advice on model conceptualized development and evaluation. He was also involved in editing and reviewing the manuscripts. Dr. Ali Madani is the thesis co-supervisor, and provided advice, and available datasets. He was also involved in editing and reviewing the manuscripts.

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List of publications and scientific presentations related to the thesis:

A. Part of this thesis has been submitted as follows;

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Golmohammadi, G., S. O. Prasher, A. Madani, M. Youssef, and R. Rudra (2013). “SWATDRAIN, a New Model to Simulate Hydrology of Agricultural Farmlands, PartII: Model Evaluation for a Fully Tile-Drained Agricultural Watershed" Transactions of the American Society of Agricultural and Biological Engineers, ASABE (To be submitted).

Golmohammadi, G., S. O. Prasher, A. Madani, M. Youssef, and R. Rudra (2013). “Evaluation of SWATDRAIN Model for a Partially Tile Drained Watershed in Ontario, Canada" Journal of Agricultural Water Management (To be submitted).

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B. Part of this thesis has been presented at scientific conferences;

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LIST OF ABBREVIATIONS

SWAT	Soil and Water Assessment Tool
WARMF	Watershed Analysis Risk Management Framework
AnnAGNPS	Annualized Agricultural Non-Point Source
AGNPS	Agricultural Non-Point Source
ANSWERS	Areal Non-point Source Watershed Environment Response Simulation
HSPF	Hydrological Simulation Program-Fortran
RZWQM	Root Zone Water Quality Model
SWAP	Soil-Water-Atmosphere-Plant
APEX	Agricultural Policy/environmental eXtender
GIS	Geographic Information Systems
DEM	Digital Elevation Model
Obs.	Observed
Sim.	Simulated
R^2	Coefficient of Determination
RMSE	Root Mean Square Error
NSE	Nash Sutcliffe Modeling Efficiency
PBIAS	Percent Bias
RSR	Standardized RMSE
RO	Runoff
SRO	Surface Runoff
Tflow	Tile Flow
Latflow	Lateral Flow
Sflow	Streamflow
Gflow	Groundwater Flow
ET	Evapotranspiration
PET	Potential Evapotranspiration
WTD	Water Table Depth
WTM	Water Table Management
BMP	Best Management Practices
LAI	Leaf Area Index

NPS	Non-Point Source Pollution
IWRM	integrated water resources management
USEPA	US Environmental Protection Agency
DHI	Danish Hydraulic Institute
MSEA	Management System Evaluation Areas
SAW	Soil Available Water
SCS	Soil Conservation
CN	Curve Number
DDRAIN	Drain Depth
SDRAIN	Drain Spacing
AET	Actual Evapotranspiration on any current day in HRU
HRU	Hydrologic Response Unit
ARS	Agricultural Research Service
MSEA	Management System Evaluation Areas
SHAW	Simultaneous Heat and Water
NPS	Non-Point Source Pollution
GUI	Graphical User Interface
BMP	Best Management Practices
NAM	Nedbor-Afstromnings
XAJ	Xinanjiang
MSEA	Management System Evaluation Areas
EPRI	Electric Power Research Institute
DSS	Decision Support System
USEPA	US Environmental Protection Agency
MENV	Ministry of Environment
ITDRN	Tile Drainage Routine Flag
IWTDN	Water Table Depth Routine Flag
WSSD	World Summit on Sustainable Development
DSSAT	Decision Support System for Agro Technology Transfer
DWSM	Dynamic Watershed Simulation Model
ETDAY	Amount of Actual Evapotranspiration on any Current Day in HRU

CNVL	Conventional Drainage
CTRL	Controlled Drainage
SurQ	Surface Runoff
TileQ	Tile Drainage
PCP	Precipitation
SW	Amount of Water Available in the Soil Profile
ARS	Agricultural Research Service
USDA	U.S. Department of Agriculture
EPIC	Environmental Policy Impact Climate

CHAPTER 1: Introduction

"A water secure world is one in which it is possible to harness its productive power and minimize the destructive force of water in order to have enough water for social and economic development and ecosystems. Water security also means addressing the issues of sustainable development, environmental protection and the negative effects of poor management of water resources." (Global Water Partnership, 2008).

In 2002, the World Summit on Sustainable Development (WSSD) in Johannesburg, South Africa, called for all countries to draw up national integrated water resources management (IWRM) plans as a means of moving towards worldwide water security (Global Water Partnership, 2008). Planning and managing water resources at a watershed scale are the basis for this IWRM, and both surface water and ground water should be considered in order to achieve sustainable development (Global Water Partnership, 2008).

Increasing yield on currently productive land and transforming idle land into productive land are the two main targets of the agricultural producers due to the ever increasing need for food, fuel, and fiber to drive the world's economies (Frana, 2012). Different approaches can be implemented including transforming plant phenotypes for plants to thrive in previously inhospitable land (Reynolds and Borlaug, 2006), improving the nutritional value of plant varieties (Borlaug, 2000), improving irrigation techniques and efficiencies in arid lands (Fereres and Soriano, 2007), and applying subsurface drainage to increase yield (Skaggs et al., 1994).

These improvements to land use management practices must also be in balance with the natural cycles of the planet, such as seasonal changes or drought-monsoon cycles, in order to provide a sustainable future; this must be achieved at both the field, and watershed levels (Frana, 2012).

In humid regions, with poorly drained soils, subsurface drainage systems are installed to enhance crop production by protecting crops from the waterlogging resulting from shallow water tables (Dayyani, et al., 2010b).

Not only does subsurface drainage allow for greater soil aeration, earlier planting dates, and overall better field conditions (Zhou et al., 2011), but also it has the potential to reduce surface runoff and pollutants associated with surface runoff (Bengston et al., 1995). However, subsurface drainage systems are also known to be major sources of nutrients and other pollutants exported to the water bodies (Dinnes et al., 2002; Moriasi et al., 2012).

In Canadian provinces of Ontario and Quebec, approximately two million hectares of croplands, used mostly for corn and soybean production, are subsurface-drained (Helwig et al., 2002). In Ontario, more than 50% of the arable land is artificially drained (O'Neill, 2008). In the Grand River Basin in Ontario, approximately 90% of the watershed is agricultural land and tile drains cover approximately 100,000 ha of agricultural land in the basin (O'Neill, 2008).

Research of water resources systems at the watershed level can be conducted by either field experiments or using watershed computer simulation models. Field research in agriculture has been conducted without the active help of agricultural system models and it has been largely empirical and site-specific (Ma et al., 2000a). Collecting long-term hydrologic and water quality data for a range of agro-climatic conditions is an expensive, difficult and time-consuming process (Dayyani et al., 2010a). On the other hand, watershed models can be used to simulate the natural hydrologic cycle or hydraulic processes with lower costs and are less time consuming when compared to field experiments (Rong, 2009). Use of computer models has greatly increased our ability to simulate the impacts of hydrologic effects at the field level and on the watershed scale (Dayyani, et al., 2009). In many humid areas, drainage, either natural or artificial, is part of the water system and cannot be ignored. Therefore, it is important that hydrologic models realistically simulate tile drainage flow.

There are several hydrologic models developed to simulate subsurface hydrology (Soil Water Atmosphere Plant or SWAP (Van Dam et al., 1994); Root Zone Water Quality Model or RZWQM (Ahuja et al., 2000); and DRAINMOD (Skaggs, 1980)). However, DRAINMOD (Skaggs, 1978) was the first comprehensive model developed to simulate the water balance and the impact of subsurface water management of tile-drained fields. The first version of DRAINMOD was developed in the 1970s, with numerous modifications and additions continuing until the present (Skaggs, 2012). DRAINMOD includes freezing, thawing, and snowmelt components and it is capable of simulating drainage phenomena in cold regions (Luo et al., 2000, 2001). DRAINMOD has been used and tested worldwide and it is proven to be an efficient model in simulating flows from poorly drained high water table soils experiencing freeze-thaw cycles (Skaggs, 1982; Singh et al., 1994; Luo et al., 2000, 2001; Youssef et al., 2006; Yang et al., 2007; Wang et al., 2006; Dayyani et al., 2009, 2010a).

Numerous hydrologic models can be used to simulate the hydrology of a watershed (Hydrological Simulation Program-Fortran or HSPF (Bicknell et al., 1996); the European Hydrological System Model or MIKE SHE (Refsgaard and Storm, 1995); Areal Non-point Source Watershed Environment Response Simulation or ANSWERS (Dillaha, 2004); Annualized Agricultural Non-Point Source model or AnnAGNPS (Bingner et al., 1998); Watershed Analysis Risk Management Framework or WARMF (Chen et al., 1998); The Agricultural Policy/environmental eXtender (APEX) model (Williams and Izaurralde, 2006; Williams et al., 2006; Williams et al., 2008; Gassman et al., 2009); Soil and Water Assessment Tool or SWAT (Arnold et al., 1998)). Each model has its own strengths and weaknesses. Hydrologic model is one of the key tools in recent research activities for watershed management; however, most of these models are focused on surface water systems. The lack of a good, integrated, watershed management model with a subsurface drainage simulation tool has been noted in the literature.

One of the watershed-scale models that contains a tile drainage component is the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Arnold and Fohrer, 2005). SWAT is a conceptual, continuous-time model developed to help water resource managers in assessing the impact of management and climate on water supplies and nonpoint-source pollution in watersheds and large river basins (Arnold et al., 1998). SWAT has been widely applied in various scenarios and watersheds (Hanratty and Stefan, 1998). SWAT has also been proven to be an effective tool for assessing water resource and nonpoint-source pollution problems for a wide range of scales and environmental conditions across the globe (Gassman et al., 2007).

SWAT2000 was enhanced with a subsurface tile flow component and satisfactorily tested with measured field data (Arnold et al., 1999). However, it was found that SWAT2000 was not able to accurately simulate subsurface flow and stream discharge when applied on a watershed-scale because the incorporated tile drainage algorithms did not accurately represent the water table dynamics at the watershed scale (Arnold et al., 1999). Furthermore, these modifications do not allow for scenario simulations, such as different tile spacing, drain size, drainage intensity, and water table management to aid in designing cost-effective water management systems (Moriasi et al., 2007a).

Moriasi et al. (2007a) incorporated the Hooghoudt's (1940) steady-state and Kirkham's (1957) tile drain equations into SWAT, which have been successfully used in the DRAINMOD model (Skaggs, 1978); these alternative tile flow simulation methods take into account tile spacing and drain tube size, in addition to the depth of the tile drain. This version of SWAT was tested at the watershed scale with satisfactory results for simulating water balance components of the tile drained South Fork Watershed (Moriasi et al., 2012). The rate of subsurface water movement into drain tubes, or ditches, depends on the lateral saturated hydraulic conductivity (K) of the soil as well as the drain spacing, size, and depth, the depth of the soil profile and the water table elevation (Skaggs, 1980). Therefore, it can be said that the tile drain equation used to compute tile flow, at any given time, is determined by proximity of the water table to the ground surface. Therefore, in addition to tile drainage, it is also important that a hydrologic model realistically simulates water table depth.

DRAINMOD, which is a model designed to compute fluctuations in shallow water table depth and the effect of tile drainage systems on the soil water balance, computes water table depth based on drainage volume versus water table depth relationship, where drainage volume is the effective air volume above the water table, defined as the void space that holds water between field capacity and saturation. This relationship is used to determine the distance that the water table falls or rises when a given amount of water is removed or added. The drained water volume at various water table depths can be measured directly from large undistributed soil cores or it can be estimated from the soil water characteristics or from the drainable porosities of each layer (Skaggs, 1980).

The shallow water table depth simulation methods available in the current or previous versions of SWAT model are the SWAT-M (Du, et al., 2005), SWAT2005 (Neitsch et al., 2002a), revised modified DRAINMOD (Moriasi et al., 2011). In the SWAT-M model approach (Du, et al., 2005), a restrictive layer is set at the bottom of the soil profile which simulates a confining layer and is used as the maximum water table depth (WTD). The soil profile above the restrictive layer is allowed to fill to field capacity; additional water is allowed to fill the profile from the bottom soil layer upward, from which the height of the water table above the restrictive layers is computed. The SWAT2005 (Neitsch et al., 2002a) routine computes WTD using 30-day moving summations of precipitation, surface runoff and ET.

The modified DRAINMOD algorithm relates drainage volume with WTD (Moriasi et al., 2009). Water table depth is computed as a function of drainage volume and a calibration factor which converts drainage volume into water table depth for hydrologic response units (Moriasi et al., 2009). In this modified approach, the water table depth is computed as a function of volume drainage using a simple linear water table depth prediction equation that closely matches the measured water table depth values. In the revised, modified DRAINMOD approach (Moriasi et al., 2011), the calibration factor is automatically computed as a function of soil physical properties. This modified DRAINMOD approach of water table depth calculation differs from the DRAINMOD approach in the way in which the drainage volume is determined and how drainage volume relates to water table depth.

However, in revised modified DRAINMOD version of SWAT, DRAINMOD was not fully integrated into SWAT and the water table calculation is different from that in DRAINMOD. Although, it calculates tile drainage using Hooghoudt's (1940) and Kirkham's (1957) tile drain equations, this approach is different from DRAINMOD in terms of the way in which the water table depth affects tile drainage on a daily basis. Since the water table has a considerable effect on tile drainage on a daily basis, the developed approach in SWAT could not fully integrate the advantages of the DRAINMOD model into the subsurface drainage calculation.

Furthermore, the most recent version of SWAT model, which includes the Hooghoudt's (1940) steady-state and Kirkham's (1957) tile drain equations and the revised modified DRAINMOD approach to water table depth, is unable to perform multiple scenario simulations such as controlled drainage and the wastewater application to determine cost effective water management systems at the watershed scale. On the other hand, DRAINMOD is a well-known drainage model, which has been successfully tested and applied for subsurface simulation at the field scale, is capable of simulating the different water management scenarios (Singh et al., 2007; Ale et al., 2009).

In this present study, a new computer watershed scale model was developed by combining the surface hydrology simulation model, SWAT, and the subsurface water table management model, DRAINMOD. The fully integrated model, SWATDRAIN is an effective decision-making system for predominantly subsurface-drained agricultural watersheds. The model is also capable of evaluating different management scenarios such as controlled drainage and subirrigation on a watershed scale.

1.1. Objectives

The primary goal of the research was to develop a new comprehensive and user-friendly model, SWATDRAIN by fully incorporating DRAINMOD into SWAT in order to improve water flow estimation from fully drained/partially-drained watersheds. Surface flow in the new model is simulated using SWAT model and subsurface flow in unsaturated zone is simulated by the DRAINMOD model.

By fully integrating the SWAT and DRAINMOD models, the strong surface flow modeling capabilities of the former is combined with the powerful subsurface modeling abilities of the latter, resulting in a final model which is expected to be superior to both component models. Moreover, while using the new integrated model, several scenario analyses and water management practices can be carried out on a watershed scale, which were not previously possible.

Specific objectives are:

1. To evaluate the SWAT model for surface flow simulations and to compare it with two other watershed models, MIKE SHE and APEX in order to assess the pros and cons of SWAT model, compared to other watershed scale models;

2. To develop a new model, SWATDRAIN by integrating SWAT and DRAINMOD, in order to simulate the total stream flow transport on an agricultural watershed;

3. To evaluate the SWATDRAIN model for a fully tile-drained agricultural watershed in eastern Ontario;

4. To evaluate the model on a predominantly agricultural, partially tile-drained watershed in southern Ontario;

5. To use the model for assessing potential impacts of drainage water management scenarios such as controlled drainage on watershed scale and the consequent impact on watershed hydrology.

This study was conducted in two watersheds located in southern and eastern Ontario, Canada. A first test of the model was conducted on the 14-ha Green Belt Watershed, located at Agriculture and Agri-Food Canada Centre Experimental Farm, near Ottawa, Ontario. This watershed lies in a cold and humid region of eastern Canada. This watershed is fully tile drained and the model was evaluated for tile drainage discharge and water table depth.

The second application of the model was conducted on the 18 km^2 Canagagigue Creek West Watershed, located in the Grand River Basin in southern Ontario. This watershed is partially tile drained. The streamflow data collected were used in calibrating and validating SWATDRAIN. The climate of the area, according to the Koppen-Geiger climatic classification system, is characterized as humid continental, with warm summers and moderate winters.

1.2. Thesis Outline

This thesis has been written as a series of manuscripts, each of which contributes to the objectives stated above.

A review of the existing literature on watershed hydrology, and watershed modeling is presented in Chapter 2.

This chapter is followed by five sequentially connected manuscripts: the first manuscript (Chapter 3) presents the evaluation of three watershed scale models including; MIKE SHE, APEX and SWAT and compares the simulated hydrology.

The second manuscript (Chapter 4) discusses the development of SWATDRAIN, developed by incorporating DRAINMOD into SWAT.

Chapter 5 presents the evaluation of the SWATDRAIN model for simulating tile flow and water table depth in a small, fully tile drained agricultural watershed in eastern Ontario. The 6th chapter of the thesis presents an application of the newly developed model for a predominantly agricultural watershed located in southern Ontario.

Chapter 7 presents the application of the SWATDRAIN model in simulating the potential effect of controlled drainage on hydrology of a watershed in eastern Ontario. The 8^{th} chapter summarizes the important results of the study and Chapter 9 lists the major contributions to knowledge and provides recommendations for future research.

CHAPTER 2: Literature Review

2.1. Hydrologic Cycle

The schematic diagram of hydrologic processes is presented in Figure 2.1. The hydrologic cycle is usually described in terms of 6 major components : precipitation (P), evaporation (E), infiltration (I), transpiration (T), surface runoff (R), and groundwater flow (G) (Warren and Gary, 2003). For computational purposes, evaporation and transpiration are usually combined as evapotranspiration (ET). The principles of the hydrologic cycle and water balance are the same regardless of the scale of the study (Gollamudi, 2006). Moisture content in the air increases through evaporation from water bodies and the transpiration of plants. This water vapor condenses on suspended particles to form clouds, which finally reach the ground as precipitation - in the form of snow or rain.

At the ground level, this precipitation is intercepted by the plant canopy, infiltrates through the soil profile, appears as surface runoff, subsurface lateral flow or percolates into deep aquifer storage (Linsley et al., 1982).

When the amount of precipitation falling on the ground is greater than the infiltration rate, surface runoff occurs. Subsurface flow may be through natural lateral flow or artificial tile drains installed to maintain the water table depth at a desirable level for crops. Along with significant rainstorms, spring snowmelt has been identified as a major nutrient transport event from agricultural fields (Jamieson, 2001). Since the hydrological cycle plays a dominant role in the movement of flow and pollutants, the accurate estimation and prediction of flows are necessary to quantify the magnitude of the pollutant loads from different sources.

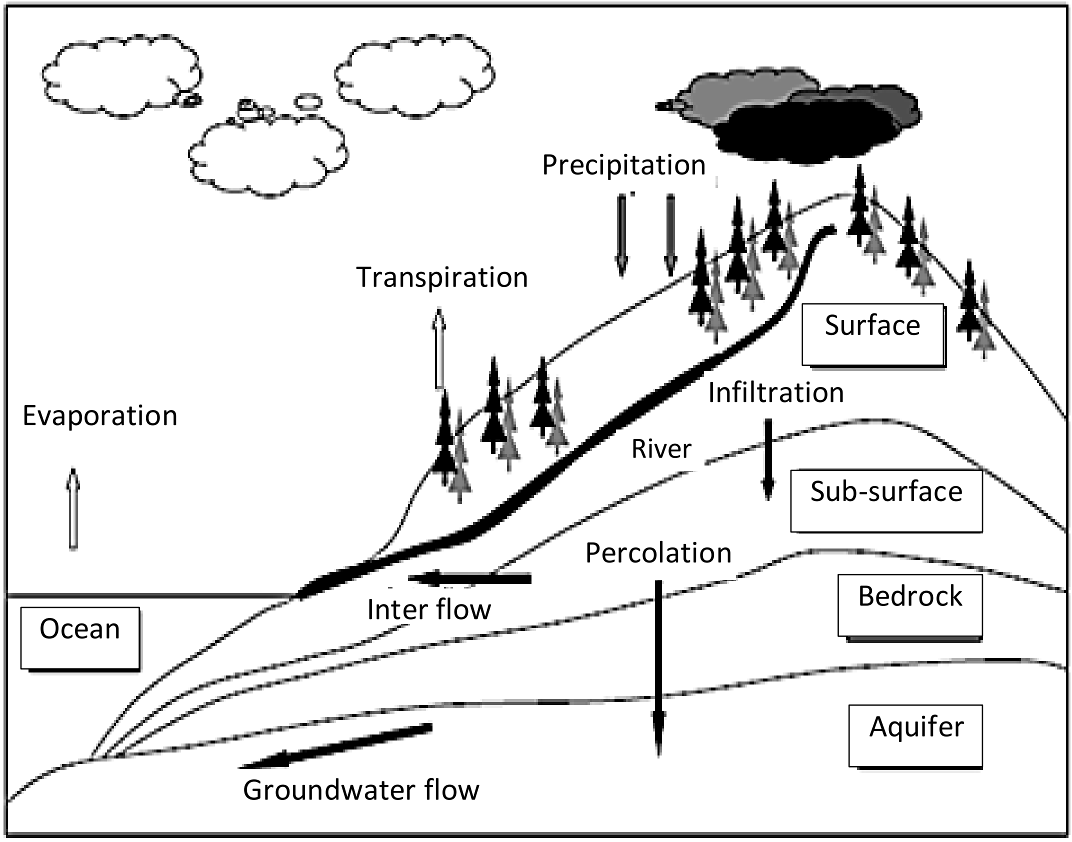

Figure 2.1: Schematic representation of the hydrologic cycle (Adopted from Ward and Trimble, 1995)

2.2. Watershed Hydrology

A watershed (Figure 2.2), delineated by a topographic or groundwater divide, is defined as the land area contributing surface runoff into a stream or to any point of interest (Warren and Gary, 2003).

Usually, one watershed consists of several sub-watersheds or may be part of a larger watershed or river basin. The characteristics of a watershed (topography, geology, and land cover) play an important role in determining the quantity, quality, and timing of stream flow as well as groundwater outflow at its outlet. The components of water balance in a watershed are shown in Figure 2.2.

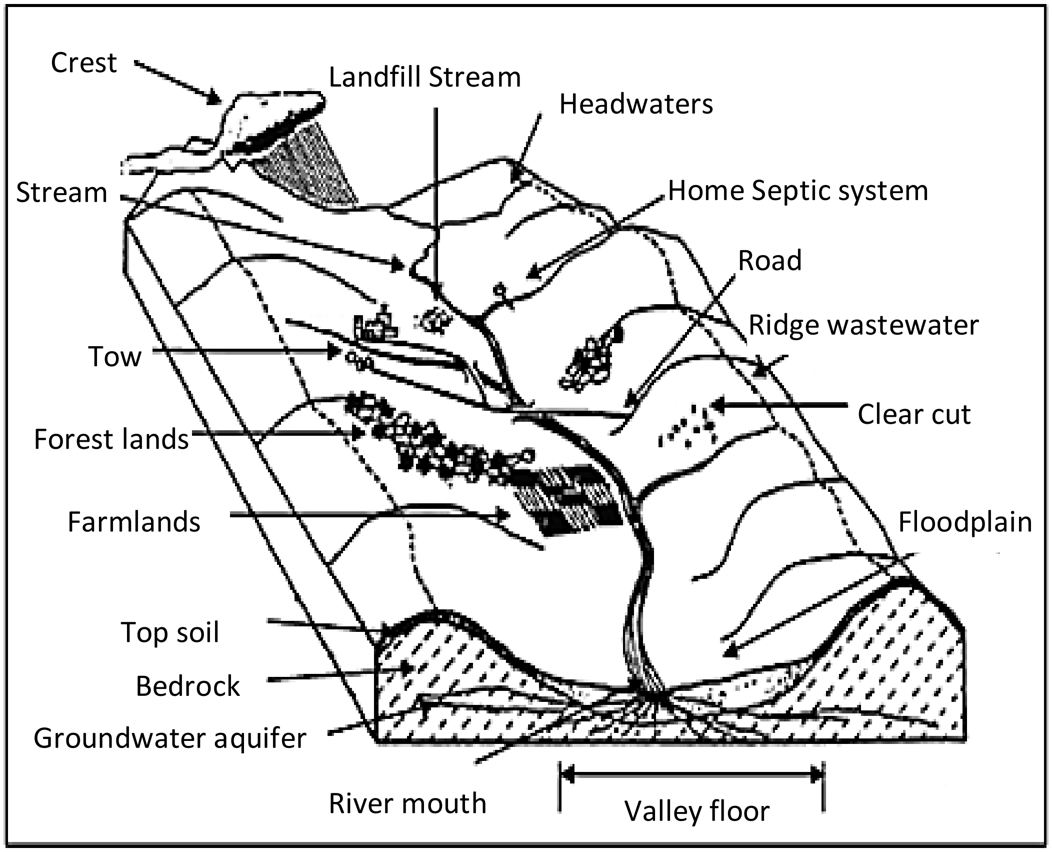

Figure 2.2: Schematic representation of a watershed system (Adopted from AGWA, 2004)

2.3. Tile Drainage and Water Table Depth in Eastern Canada

Though artificial drainage improves the structure, infiltration, and aeration characteristics of soil, it also affects the route of water transport from field to the nearby stream (Thooko et al., 1991). Tile drainage, an essential water management practice in humid regions for the improvement of soil productivity, adds another dimension to non-point source pollution.

Approximately two million ha of cropland, used mostly for corn and soybean production, in the Canadian provinces of Ontario and Quebec, are subsurface-drained (Helwig et al., 2002). Subsurface drainage ensures trafficable and workable soil conditions in early spring and late fall; plus it provides a suitable environment for plant growth for most productive soils in southern Ontario (Thooko et al., 1991). Therefore, there is a need for the design, installation, and efficient operation of cost-effective agricultural water table management systems in southern Ontario (Singh et al., 1994). Artificial tile drainage systems are installed in many agricultural fields in Ontario. In the province of Ontario, subsurface drainage is necessary for several reasons. First, intensive cropping of cereals, forage and vegetables is practiced on heavy soils which consist mainly of clays and clay loams, with some fine sands and silts, which are of lower hydraulic conductivity. Secondly, the cropland is quite flat and absorbs large amounts of precipitation. The region also experiences a short growing season.

Therefore, the installation of artificial drainage systems is necessary for crop production. Artificial drainage also reduces surface runoff, and subsequently, soil erosion and particulate pollutant transport. In Ontario, more than 50% of the arable land is artificially drained. In the Grand River Basin in Ontario, approximately 90% of the watershed is agricultural land. Tile drains cover approximately 100,000 ha of agricultural land in the basin (O'Neill, 2008).

2.4. Hydrological Models

Understanding the natural processes which occur in watersheds is a challenge for both scientists and engineers (Wu and Chen, 2009). Over the past few decades, great strides have been made in technology and modeling techniques that allow users to make informed and relatively accurate representations of ungauged watersheds that previously would have been impractical (Frana, 2012).

Hydrologic and water quality models are useful tools to understand the problems and to find solutions through best management practices (Borah and

Bera, 2003). A model used in hydrology to understand why a flow system is behaving in a particular observed manner and to predict how a flow system will behave in the future (Fetter, 2001). These two uses, understanding observed flow and predicting future behavior, are integral in creating real world infrastructure that will be able to sustainably exist within the hydrologic and hydraulic systems (Frana, 2012).

Hydrologic models, simplified representations of actual hydrologic systems, simulate hydrologic responses and allow one to study the functions and interactions of various inputs, and gain a better understanding of hydrologic events (Brooks et al., 1991). With proper calibration, physically based models can be applied to widely varying landscapes with useful results. The goal of hydrologic modeling is to estimate the distribution and movement of water over land, underground, and in-stream, as well as the quantity of water stored in the soil and/or in natural bodies of water and their exchange rate; they can also estimate changes in rates and quantities over time (Oogathoo, 2006). Currently, several hydrologic models exist, which were developed for specific tasks.

Hydrologic models are categorized into continuous simulation models or event based models (Singh, 1995). They can also be based on distribution parameters or lumped parameter concepts (Singh, 1995). In scope, they range from small field size application models to large watershed models (Singh, 1995). Continuous simulation models are used for analyzing the long-term effects of hydrological changes and agricultural management practices. While, event-based models are useful for analyzing severe actual, storm events, they may also be used to evaluate structural management practices (Borah et al., 2003).

A clear understanding of a model is important in order to use it appropriately and to avoid any misuse (Borah and Bera, 2003). In order to select the best model to meet our needs, it is important to know what the purpose of the model is, under what conditions it will perform accurately, what accuracy can be expected, and what the limitations are (Parsons et al., 2004). It is essential to bear in mind the needs of the water resource problem before developing, choosing, or applying a model (Parsons et al., 2004).

A literature review of several widely used hydrologic models was completed. This included surface flow models, such as Hydrological Simulation Program-Fortran or HSPF (Bicknell et al., 1996); the European Hydrological System Model or MIKE SHE (Refsgaard and Storm, 1995); Areal Non-point Source Watershed Environment Response Simulation or ANSWERS (Dillaha, 2001); Annualized Agricultural Non-Point Source model or AnnAGNPS (Bingner et al., 1998); Watershed Analysis Risk Management Framework or WARMF (Chen et al., 1998); The Agricultural Policy/environmental eXtender (APEX) model (Williams and Izaurralde, 2006; Williams et al., 2006; Williams et al., 2008; Gassman et al., 2009); Soil and Water Assessment Tool or SWAT (Arnold et al., 1998). It also included and subsurface flow models such as Soil Water Atmosphere Plant or SWAP (Van Dam et al., 1994); Root Zone Water Quality Model or RZWQM (Ahuja et al., 2000a); and DRAINMOD (Skaggs, 1980).

2.4.1. Surface Flow Models

2.4.1.1. AnnAGNPS

The Annualized Agricultural Non-Point Source Model (Bingner et al, 1998) was developed at the USDA-ARS North Central Soil Conservation Research Laboratory in Morris, Minnesota. This model was developed to simulate surface runoff as well as sediment, nutrient and pesticide movement within an agricultural watershed. It can simulate the impact on the environment of nonpoint-source pollutants from predominantly agricultural watersheds.

The runoff volume and rate are calculated using the SCS-Curve number method and TR-55 method, respectively, where the simulated direct runoff is due to storm events only. The input data are on a daily basis, while the model output is on an event, monthly, or annual basis (Young et al., 1995; Bosch et al., 2001). The major components of AnnAGNPS include hydrology, and transport of sediments, nutrients, and pesticides resulting from snowmelt, precipitation and irrigation. Kliment et al. (2008) compared AnnAGNPS with SWAT, and concluded that AnnAGNPS may not be suitable for areas with a high base flow. This model was also tested by Yuan et al. (2001) and Suttles et al. (2003) who reported that AnnAGNPS was able to adequately predict long-term monthly and annual runoff, but the model's overland flow did not properly represent the riparian areas and over-estimated the nutrient and sediment loads.

AnnAGNPS was used in Australia and showed satisfactory results for event flow predictions (Baginska et al., 2003). Das et al., (2004) demonstrated that AnnAGNPS was able to simulate runoff with acceptable accuracy in a watershed in south-western Ontario. However, a study in Nepal (Shrestha et al., 2005) indicated that event-based peak flows were over-predicted. AnnAGNPS was applied to a watershed on an island in the Caribbean (Sarangi et al., 2007). The model estimated runoff volume reasonably well for days with high precipitation, but was less accurate in estimating runoff for days with lower precipitation amounts. Das et al. (2007) used AnnAGNPS for Canagagigue Creek watershed in southern Ontario, which was the same watershed used in the research in this study, and obtained acceptable flow simulation.

The major limitation of the AnnAGNPS model is that runoff and associated sediment, nutrient, and pesticide loads for a single day are routed to the watershed outlet before the next day's simulation.

2.4.1.2. ANSWERS

ANSWERS-2000 (Dillaha et al., 2001), the current version of the ANSWERS model (Areal Non-point Source Watershed Environment Response Simulation), was developed at Purdue University to study the impact of the management practices on sediment and nutrient transport. The hydrology component of ANSWERS-2000 addresses interception, surface retention/detention, infiltration, evapotranspiration percolation and surface runoff (overland and channel flow).

The ANSWERS model has been applied to different watersheds to assess surface runoff, nitrate pollution risks, and sediment loads. Connolly et al., (1997) reported that ANSWERS was able to accurately simulate different surface cover conditions; however, runoff prediction for low intensity rainfall events was less accurate than for high intensity events. Bai et al. (2004) applied ANSWERS-2000 to the Canagagigue Creek Watershed for assessment of runoff and sediment, and they concluded that ANSWERS-2000 performed satisfactory for no-snow periods, but further improvements should be provided for winter seasonal simulation. The model is limited to medium-size watersheds (500 to 3000 ha) where surface hydrologic processes dominate. Other limitations associated with the model are: the absence of proper fertilization inputs, poor snowmelt simulations and non-significant base flow simulations (Dillaha et al., 2001).

2.4.1.3. MIKE SHE

MIKE SHE (Refsgaard and Storm, 1995) is one of the few hydrologic models that were initially developed to integrate surface water and groundwater (DHI, 2004). MIKE SHE is a physically based, distributed, integrated hydrological and water quality modeling tool which consists of a water movement and several water quality modules.

The water movement module simulates the hydrological components including evapotranspiration, soil water movement, overland flow, channel flow (MIKE 11), and groundwater flow. The water movement module uses a finite difference approach to solve the partial differential equations describing the processes of interception; evapotranspiration (Rutter model/Penman-Monteith Model or Kristensen-Jensen model); overland flow (two-dimensional, kinematic wave, Saint-Venant equation) and channel flow (one-dimensional, diffusive wave, Saint-Venant equation); flow in the saturated (two- or three- dimensional, Boussinesq equation) and unsaturated (one-dimensional, Richards' equation) zones; and exchange between aquifers and rivers (DHI, 2004).

MIKE SHE is capable of simulating flow and transport of solutes and sediments in both surface water and groundwater, and has both continuous long-term and single-event simulation capabilities. The model does not have limitations regarding watershed size. Watershed is horizontally divided into an orthogonal network of grid squares; hence, the spatial variability in parameters such as elevation, soil type, land cover, and precipitation, can be represented. Lateral flow between grid squares occurs as either overland flow or subsurface, saturated zone flow. The one-dimensional Richards' equation employed for the unsaturated zone assumes that horizontal flow is negligible compared to vertical flow (Refsgaard et al., 1995).

Oogathoo (2006) used MIKE SHE for runoff simulation at the Canagagigue Creek Watershed for different land management scenarios concluding that MIKE SHE could be used to simulate various management scenarios to solve hydrologic problems under the southern Ontario climatic conditions.

The MIKE SHE model was used to evaluate a watershed in northwestern China (Zhang, et al., 2009), using the streamflow data measured from this overland flow dominant watershed. Model calibration and validation suggested that the model could capture the dominant runoff process of the small watershed. It was also concluded that the model was useful for understanding the rainfall-runoff mechanisms. However, more measured data with higher temporal resolution are needed to further test the model for regional applications (Zhang, et al., 2009).

MIKE SHE model makes predictions that are distributed in space, with state variables that represent local averages of storage, flow depths or hydraulic potential. Because of the distributed nature of the model, the amount of input data required to run the model is rather large and it is rare to find watershed where all input data required to run the model has been measured (Abu El-Nasr et al., 2005).

The model assumes that flow in the unsaturated zone is one-dimensional and vertical. In addition, the codes are not available and this is the main limitation for its lack of common use. It also needs significant data which are not available in most watersheds.

2.4.1.4. HSPF

The Hydrological Simulation Program-Fortran HSPF (Bicknell et al., 1996), is a continuous watershed simulation model that produces the time history of water quantity and quality at any point in a watershed (ASCE, 2007). It was specifically developed to evaluate the impact of land use changes on water, sediment and pollutant movement. This mathematical, continuous-simulation, lumped-catchments, conceptual model is used to simulate water movement as overland flow, interflow, and groundwater flow. The model employs hydrological response units (HRUs) based on uniform climate and storage capacity factors. The flow from each HRU is routed downstream using the storage routing kinematic wave method (Johnson et al., 2003). The model provides a water budget and considers snow accumulation and melt.

Johnson et al. (2003), comparing the performance of the HSPF and Soil Moisture Routing (SMR) models on a watershed in the United States, found that they both simulate stream flow with almost equal accuracy. The HSPF model provided better simulation of winter stream flow than SMR as the former includes a complex snowmelt routine with rigorous energy-balance equations. Albek et al. (2004) conducted a study on a Turkish watershed, where they examined the effects of land use and climate change on watershed response. They demonstrated that the model is in agreement with the observed data. Singh et al. (2004) evaluated HSPF and SWAT for stream flow simulation of the Iroquois River

Watershed in east central Illinois and found the two models provided accurate predictions of the daily, average monthly, and annual stream flows.

The limitation of the HSPF model is that it is not fully distributed, and it lumps the watershed characteristics and climatic parameters into several units. Also, HSPF has many parameters to calibrate and therefore, it is cumbersome to use.

2.4.1.5. WARMF

The Watershed Analysis Risk Management Framework (WARMF) (Chen et al., 1998) is classified as a watershed decision support system (DSS); it provides information and tools that facilitate collaborative decision making among interested stakeholders (EPRI, 2001). WARMF is a user-friendly tool, organized into five linked modules, with a GIS-based graphical user interface (GUI). It was developed under the sponsorship of the Electric Power Research Institute (EPRI) as a decision support system for watershed management (EPRI, 2001). The scientific basis of the model has undergone several peer reviews by independent experts under US EPA guidelines (EPRI, 2000).

The model can simulate surface flow and also parameters such as pH, temperature, dissolved oxygen, ammonia, nitrate, phosphate, suspended sediments, *E.coli*, major cations and anions, pesticides (up to three), and three algal types. The spatial distributions of point and non-point loadings can be displayed in a graphical manner. Furthermore, the water quality status of a river or lake in terms of its suitability for water supply, swimming, fish habitat, recreation or other uses (based on users' or stakeholders' water quality criteria) can be presented (EPRI, 2000).

WARMF has been applied to over 15 watersheds in the United States and internationally (Chen et al., 2001a; Weintraub et al., 2001b, 2004,; Herr et al., 2002; Keller et al., 2004; Geza and McCray, 2007; Rambow et al., 2008). The focus of these studies has varied from TMDL calculation (nutrients, sediment, fecal coliform, metals) to more research-oriented applications such as modeling the fate and transport of mercury in a watershed and the impact of onsite wastewater systems on a watershed scale. There is no limit on the size or scale of a potential WARMF application as long as adequate topography data are available (USEPA, 2009b).

Although WARMF can simulate subsurface flow/chemical transport, tile drainage systems are not taken into consideration by the model. For example, if the moisture content of a soil layer is below field capacity, the hydraulic conductivity of the said layer is set at zero. Also if the soil moisture is at saturation, the infiltration rate is equal to the hydraulic conductivity. In between, WARMF interpolates the infiltration rate. In addition, the codes are not available and this is the main limitation that hinders its common use.

2.4.1.6. APEX

The Agricultural Policy/environmental eXtender (APEX) model (Williams and Izaurralde, 2006; Williams et al., 2006; Williams et al., 2008; Gassman et al., 2009) is a flexible and dynamic tool that is capable of simulating management and land use impacts for whole farms and small watersheds. APEX is essentially a multi-field version of the predecessor Environmental Policy Impact Climate (EPIC) model (Williams, 1995), which has been extensively tested and applied for a wide variety conditions in the U.S. and other regions (Gassman et al., 2005).

APEX has been tested and applied at the field or watershed level in several different cropland, pasture, or forest based studies, primarily in the U.S., as chronicled by Gassman et al. (2010). Wang et al. (2006) also conducted an extensive sensitivity test of 15 APEX parameters for 159 sites representative of agricultural conditions across the U.S.

However, ongoing testing of APEX is needed to further improve its accuracy and to expand the overall climatic, management, landscape, and vegetation conditions that the model can be applied to in both the U.S. and other regions (Gassman et al., 2010). In China, APEX erosion tests were reported for the Loess Plateau region (Wang et al., 2006), which is characterized by much different conditions as compared to the Huaihe River Watershed.

The percent errors of mean (PE) were within 20%, with Nash Sutcliffe efficiency (NSE) and R^2 values all above 0.45 and 0.55 for both daily runoff and sediment yield for the three plots during the calibration period, respectively. For the validation period, the PE values were within 25%, and the EF and R^2 values ranged from 0.41 to 0.84 and from 0.55 to 0.85, respectively.

2.4.1.7. SWAT

The Soil and Water Assessment Tool, SWAT, is a conceptual, physically-based, continuous simulation, watershed model, developed by Arnold et al., (1998); and improved by Arnold and Fohrer, (2005) for the USDA Agricultural Research Service (ARS).

The SWAT model operates on a daily time step. The objective in model development was to predict the impact of management practices on water, sediment and agricultural chemical yields in large un-gauged watersheds.

SWAT requires specific information on weather, soil properties, topography, vegetation, ponds or reservoirs, groundwater, the main channel, and land management practices to simulate water quality and quantity (Neitsch et al., 2005). The model has eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. SWAT model allows a number of different physical processes to be simulated in a watershed. These processes will be briefly summarized in this section. For modeling purposes, a watershed may be divided into a number of subwatersheds or subbasins.

The use of subbasins in a simulation is particularly important when different areas of the watershed are dominated by different land uses or soils. Input information for each subbasin are: climate; hydrologic response units or HRUs; pond/wetlands; groundwater; and the main channel or reach, draining the subbasin.

Water balance is the driving force behind all the process in the watershed (Neitsch et al., 2009). Simulation of the hydrology of a watershed can be separated into two major parts: Landing phase and routing phase. The first division which is the land phase of the hydrologic cycle, presented in Figure 2.3.

The land phase of hydrologic cycle includes the amount of water, sediment, nutrient and pesticide loading to the main channel in each subbasin. The second phase which is the water or routing phase of the hydrologic cycle is the movement of water, and chemicals, etc. through the channel network of the watershed to the outlet of the watershed. Since the present study was modifying the SWAT model for subsurface drained watersheds, this model is described in greater detail in the following pages.

2.4.1.7.1. Land Phase of the Hydrologic Cycle

The hydrology model of SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{t=1}^{t} \left(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw} \right) \tag{2.1}$$

Where SW_t is the final soil water content (mm), SW_0 is the initial soil water content on day *i* (mm), *t* is time (days), R_{day} is the amount of precipitation on day *i* (mm), Q_{surf} is the amount of surface runoff in day *i* (mm), E_a is the amount of evapotranspiration on day *i* (mm), W_{seep} is the amount of water entering the vadose zone from the soil profile on day *i* (mm), and Q_{gw} is the amount of return flow on day *i* (mm).

Since the model maintains a continuous water balance, complex basins are subdivided to reflect differences in ET for various crops and soils. Thus, runoff is predicted separately for each HRU and routed to obtain the total runoff for the basins. This increases the accuracy and gives a better physical description of the water balance.

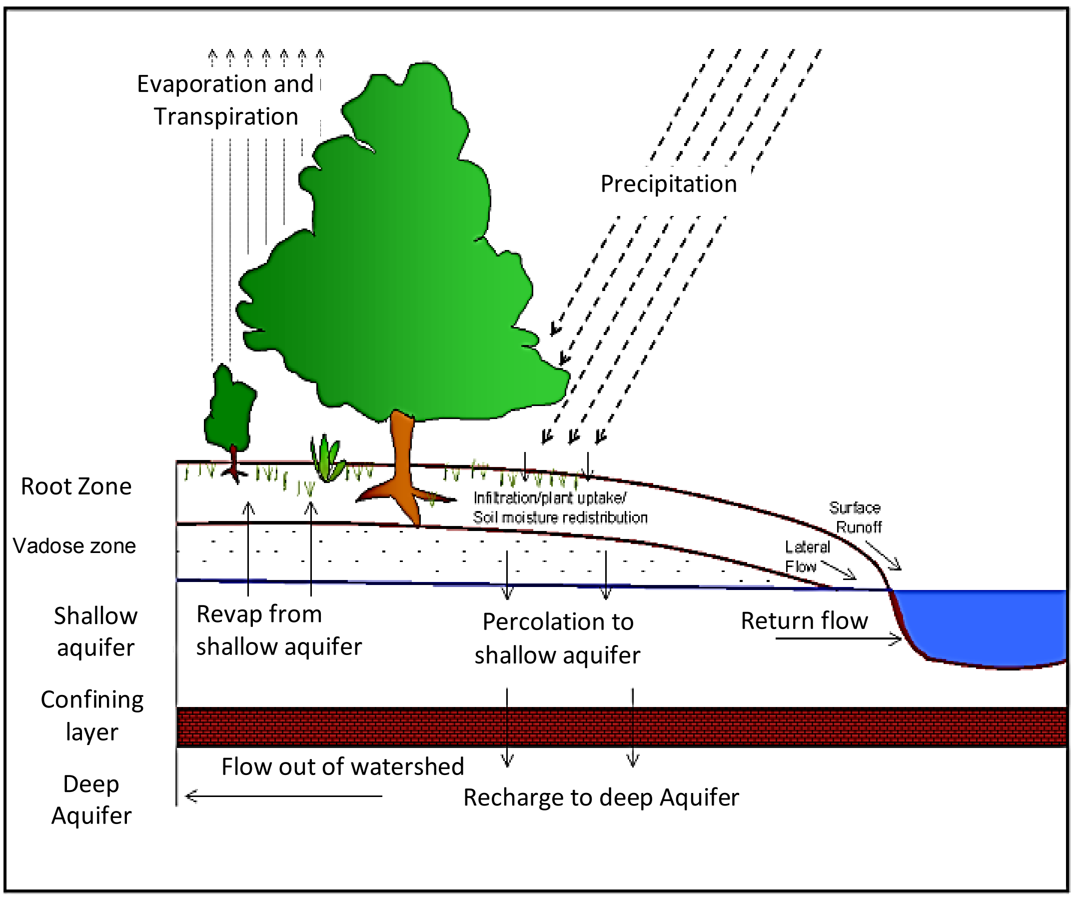

Figure 2.3. Schematic representation of the landphase of hydrologic cycle (adopted from Neitsch et al., 2005)

2.4.1.7.2. Climate

Daily precipitation, maximum/minimum air temperature, solar radiation, wind speed, and relative humidity are the climatic variables required by SWAT model. These variables can be incorporated into input files from records of observed data from the climate stations. They also, can be generated during the simulation process.

A simple, uniform snow cover model which has been updated to a more complex model allows non-uniform cover due to shading, topography and land cover (Neitsch et al., 2009) is used for snow cover component of the SWAT model(Neitsch et al., 2009). Snow melt is calculated by the air and snow pack temperature, the melting rate, and the areal coverage of snow. Snow is melted when the maximum temperature exceeds $0^{o}C$ using a linear function of the difference between the average snow pack maximum air temperature and the threshold temperature for snow melt.

2.4.1.7.3. Canopy Interception

Canopy interception is calculated as a variable if surface runoff is computed by Green and Ampt method. If surface runoff is computed by SCS runoff curve number method it contained in surface runoff (Neitsch et al., 2009). Both the maximum water storage within canopy and Leaf Area Index (LAI) are necessary for solution of canopy interception.

2.4.1.7.4. Surface Runoff and Infiltration

Surface runoff or overland flow volume is computed either from the modified SCS curve number method (Soil Conservation Service, 1972) or the Green and Ampt infiltration method (Green and Ampt, 1911). The SCS method is computed from:

$$Q_{surf} = \frac{\left(R_{day} - 0.2S\right)^2}{\left(R_{day} + 0.8S\right)} \tag{2.2}$$

Where Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), and S is the retention parameter (mm).

The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content and estimated from:

$$S = 25.4 \left(\frac{1000}{CN} - 10\right) \tag{2.3}$$

Where CN is the curve number for the day.

Users are allowed to select between two methods for calculating the retention parameter. The traditional method is to allow the retention parameter to vary with soil profile water content. An alternative is added to the model to allow the retention parameter to vary with accumulated plant evapotranspiration. Calculation of the daily CN value as a function of plant evapotranspiration was added because the soil moisture method was over-predicting runoff in shallow soil (Neitsch et al., 2009). By calculating daily CN as a function of plant evapotranspiration, the value is less dependent on soil storage and more dependent on antecedent climate.

The Green and Ampt (Green and Ampt, 1911) infiltration method which requires precipitation data in smaller time steps, directly estimate infiltration,

The Green and Ampt method was modified by Mein-Larson (1973) to develop the excess rainfall method and it was incorporated into SWAT which provide an alternative option for determining surface runoff (Neitsch et al., 2009). The Green and Ampt method requires sub-daily precipitation data and calculates infiltration as a function of the wetting front matric potential and effective hydraulic conductivity. The Green and Ampt Mein-Larson infiltration rate is defined as:

$$f_{inf,t} = K_e\left[1 + \frac{\Psi_{wf}.\Delta\theta_v}{F_{inf,t}}\right] \tag{2.4}$$

Where f_{inf} is the infiltration rate at time t (mm/hr), K_e is the effective hydraulic conductivity (mm/hr), Ψ_{wf} is the wetting front matric potential (mm), $\Delta\theta_v$ is the change in volumetric moisture content across the wetting front (mm/mm) and F_{inf} is the cumulative infiltration at time t (mm).

For each time step, SWAT calculates the amount of water entering the soil. The water that does not infiltrate into the soil becomes surface runoff.

2.4.1.7.5. Redistribution

Redistribution refers to the continued movement of water through a soil profile after input of water such as precipitation and irrigation at the soil surface has been stopped. Redistribution is occurred due to differences in water content in the profile. Once the water content through the entire profile is uniform, redistribution will stop. The redistribution component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone (Neitsch et al., 2009).

Redistribution also is affected by soil temperature. If the temperature in a particular layer is below the 0^{o}C, no redistribution is allowed from that layer (Neitsch et al., 2009). Percolation happens if the field capacity of a soil layer is exceeded and the layer below is not saturated. The flow rate is governed by the saturated conductivity of the soil layer.

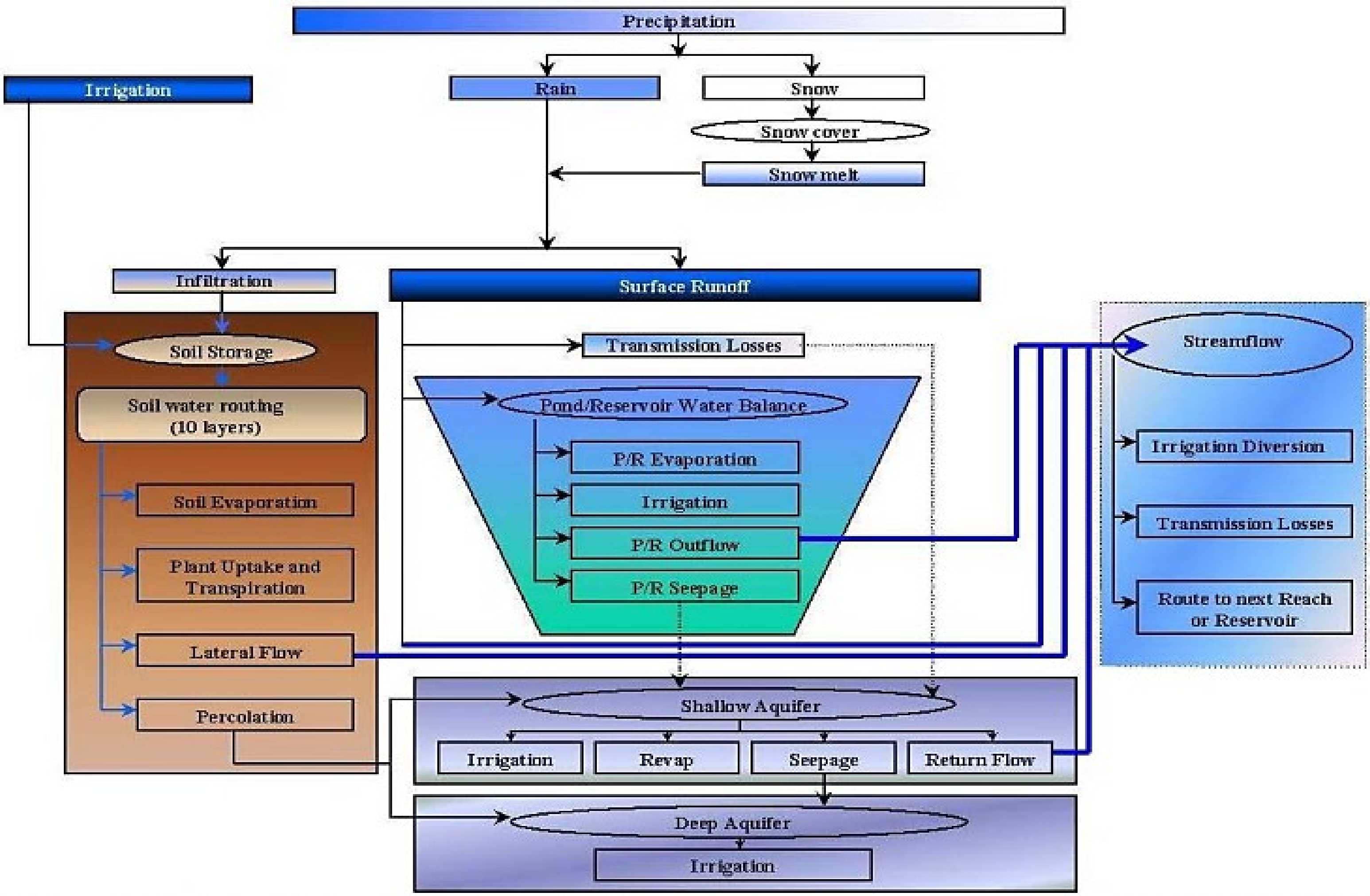

Figure 2.4. Schematic pathways available for water movement in SWAT (adopted from Neitsch et al., 2005)

2.4.1.7.6. Percolation

A storage routing technique combined with a crack-flow model to predict flow through each layer is used to calculate the percolation component uses a (Neitsch et al., 2009).

Once water percolates below the root zone, becomes return flow or appears as return flow in downstream basins, so it is lost from the watershed. When a lower layer exceeds field capacity then upward flow may occur. If the temperature in a particular layer is below 0^{o} C , no percolation is allowed from that layer (Neitsch et al., 2009).

2.4.1.7.7. Lateral Subsurface Flow

Lateral subsurface is the streamflow which happens below the surface but above the zone where rocks are saturated with water (Neitsch et al., 2009). In SWAT model, the lateral subsurface flow in the soil profile is calculated simultaneously with redistribution. Lateral flow in each soil layer is calculated using a kinematic storage model which accounts for variation in conductivity, slope, and soil water content (Neitsch et al., 2009).

2.4.1.7.8. Interflow

Interflow in each soil layer is calculated by the kinematic storage model with the calculation of the redistribution (Neitsch et al., 2009). The kinematic storage model considers the influence of the slope, different conductivities, and soil moisture content on interflow (Neitsch et al., 2009).

2.4.1.7.9. Groundwater

In SWAT, groundwater is refered to the water stored in shallow aquifer and also in deep aquifer (Neitsch et al., 2009). Water in shallow aquifer enters the streams within the watershed or or transmitted to the unsaturated soil layers. The deep aquifer water flows into streams somewhere out of the watershed (Neitsch et al., 2009).

2.4.1.7.10. Evapotranspiration

Evapotranspiration is referred to all processes by which water in the liquid or solid phase at or near the earth's surface become atmospheric water vapor. The SWAT model computes evaporation from soils and plants separately as described by Ritchie (1972). Potential soil water evaporation is estimated as a function of potential evapotranspiration and leaf area index.

The model offers three options for estimating potential evapotranspiration: Hargreaves (Hargreaves et al., 1985), Priestley-Taylor (Priestley and Taylor, 1972) and Penman-Monteith (Montheith, 1965). The Actual soil evaporation is estimated by exponential functions of soil depth and water content. Plant transpiration is simulated as a linear function of potential evapotranspiration and leaf area index.

2.4.1.7.11. Ponds

The water storage structures located within a subbasin which intercepts surface runoff called ponds. It is assumed that the ponds never receive water from upstream subbasins. Water storage of a pond is a function of pond capacity, daily inflows and outflows, seepage and evaporation. Required inputs are the storage capacity and surface area of the pond when filled to capacity.

2.4.1.7.12. Tile Drainage

In order to simulate the tile drainage outflow in an HRU, the depth from the soil surface to the drains, the amount of time required to drain the soil to field capacity, and the amount of lag between the time water enters the tile until it exits the tile and enters the main channel (Neitsch et al., 2009). It is assumed that the tile drainage occurs when the purched water table rises above the drain tube depth. The amount of tile drainage is calculated from:

$$tile_{wtr} = \frac{h_{wtbl} - h_{drain}}{h_{wtbl}} \; (SW - FC) \left(1 - exp\left[\frac{-24}{t_{drain}}\right]\right) \qquad (2.5)$$

$$if \; h_{wtbl} > h_{drain}$$

Where $tile_{wtr}$ is the amount of water removed from the layer on a given day by tile drainage (mm), h_{wtbl} is the height of the water table above the impervious zone (mm), h_{drain} is the height of the tile drain above the impervious zone (mm), SW is the water content of the profile (mm), FC is the field capacity water content of the profile, and t_{drain} is the time required to drain the soil to field capacity (hrs).

In the modified SWAT approach (Moriasi, 2007a), tile flow is calculated using Hooghoudt's (1940) steady-state and Kirkham (1957) tile drain equations that have been successfully used in DRAINMOD model (Skaggs 1978). Water moves toward drains in both saturated and unsaturated zones. The drainage rates are computed by assuming the lateral water movement occurs mainly in the saturated zone. Effective horizontal saturated hydraulic conductivity is used by Hooghoudt and Kirkham equations to evaluate flux in terms of the water table elevation midway between the drains and the water level or hydraulic head in the drains (Figure 2.5).

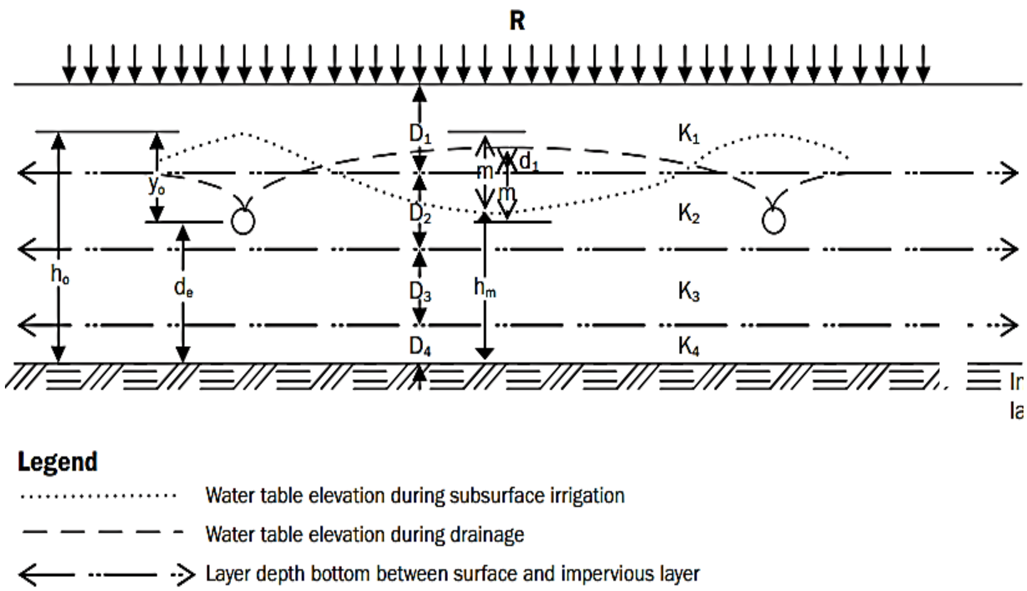

Figure 2.5. Water table drawdown to and subirrigation from drain tubes (adopted from Moriasi et al., 2012)

The tile drainage outflow is calculated using a three-step approach as follows. First, for the situations of water table below the ground surface and for ponded surface depressional depths less than S1 which is a depressional storage (Figure 2.8), the Hooghoudt (1940) steady state equation is used:

$$q = \frac{8K_e d_e m + 4K_e m^2}{CL^2} \tag{2.6}$$

Where q is the drainage rate (cm h^{-1}), m is the midpoint water table elevation above the drain, K_e is the equivalent lateral hydraulic conductivity of the profile (cm h^{-1}), d_e is the equivalent depth from the drain to the restrictive layer (cm), and L is the drain spacing (cm).

Second, for ponded depth greater than Sl, when water table rises to the ground surface and the ponded water table remains at the surface for relatively long periods of time, flux drainage is computed using the Kirkham (1975) equation:

$$q = \frac{4\pi K_e (t + b - r)}{gL} \tag{2.7}$$

Where t, b, and r, are as shown in Figure 2.6 and g is a dimensionless factor which is determined using an equation developed by Kirkham (1957).

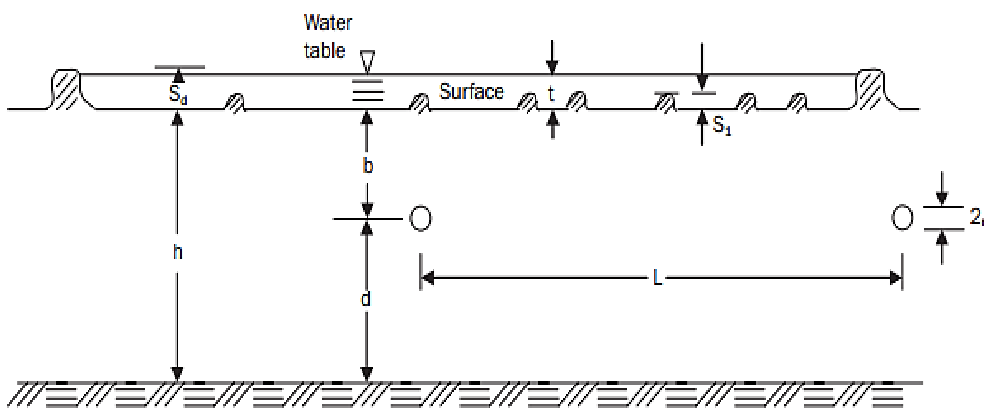

Figure 2.6. Drainage from a ponded surface (adopted from Moriasi et al., 2012)

Third, when the tile drainage outflow predicted by the appropriate equation is greater than the amount of drainage coefficient (DC). In this case the drainage flux is equal to the DC.

Therefore, the rate of subsurface drainage depends on hydraulic conductivity of the soil (K); drain spacing, size, and depth; soil profile depth; and water table elevation (Skaggs, 1980). In addition to tile drainage, it is also important that SWAT realistically simulates water table depth

2.4.1.7.13. Water Table Depth

The shallow water table depth simulation methods which have been associated in SWAT are the SWAT-M (Du, et al., 2005), SWAT2005, revised modified DRAINMOD (Moriasi et al., 2011).

In the SWAT-M model approach, a restrictive layer, is set at the bottom of the soil profile which simulates a confining layer and is used as the maximum water table depth (WTD) and the soil profile above the restrictive layer is allowed to fill to field capacity, additional water is allowed to fill the profile from the bottom soil layer upward and from which the height of the water table above the restrictive layers computed (Du et al., 2005). The SWAT2005 routine computes WTD using 30-day moving summations of precipitation, surface runoff and ET (Neitsch et al., 2002a).

The modified DRAINMOD algorithm relates drainage volume with WTD (Moriasi et al., 2009). In this approach, the water table depth is computed as a function of drainage volume using a simple linear water table depth prediction equation that closely matches the measured water table depth values (Moriasi et al., 2009).

$$sw_{del_{cj}} = sol_{sw_{pj}} - sol_{sw_{cj}} \tag{2.8}$$

Where $sw_{del_{cj}}$, $sol_{sw_{pj}}$, and $sol_{sw_{cj}}$ are the change in the soil water in the current day, the amount of water stored in the soil profile in the previous day, and the amount of water stored in the soil profile in the current day.

In the revised modified DRAINMOD approach (Moriasi et al., 2011), wt_fctrj is automatically computed for each soil layer as a function of soil physical properties.

$$drpor_{i,j} = sol_{por_{i,j}} - sol_{up_{i,j}} \tag{2.9}$$

Where $drpor_{i,j}$, $sol\_por_{i,j}$, and $sol\_up_{i,j}$ are the effective porosity, the total porosity of the soil layer expressed as a fraction of the total volume, and water table content of the soil at -0.33 MPa (field capacity) expressed as mm per unit mm of soil, respectively, for soil layer I in HRU.

The water table depth is computed as a function of sw_del_{cj} using the following equations.

$$wtd\_del_{cj} = wt\_fct_j \times sw\_del_{cj} \tag{2.10}$$

$$wtd_{cj} = wtd_{pj} + wt\_del_{pcj} \quad if\ wtd_{cj} \leq dep_{imp_j} \tag{2.11}$$

$$wtd_{cj} = dep\_imp_j \quad if\ wtd_{cj} > dep_{imp_j} \tag{2.12}$$

$$wtd_{cj} = 0.0 \quad if\ wtd_{cj} \leq 0.0 \tag{2.13}$$

Where wtd_del_{cj} is the change in water table depth on the current day (mm), wtd_{cj} and wtd_{pj} are the current and previous day water table depth measured from the ground surface to the water table depth (mm), and dep_imp_j is the depth from the ground surface to the impervious layer (mm) for HRU j.

2.4.1.7.14. Routing Phase of the Hydrologic Cycle

SWAT determines the loadings of water, sediment, nutrients and pesticides to the main channel (Neitsch et al., 2009), and then, the loadings are routed through the stream network of the watershed using a command structure similar to that of HYMO (Williams and Hann, 1972). In addition to keeping track of mass flow in the channel, SWAT simulates the transformation of chemicals in the stream and streambed (Neitsch et al., 2009). Figure 2.7 illustrates the different in-stream processes modeled by SWAT.

Due to evaporation and transmission through the bed of the channel, a portion of water may be lost as it flows downstream. Another potential loss of water is its removal of from the channel for agricultural or human use. Flow may be supplemented by the rainfall directly on the channel and/or the addition of water from point source discharges. Flow routing through the channel can be calculated using a variable storage coefficient method developed by Williams (1969) or the Muskingum routing method. Geographic Information System (GIS) and other interface tools to support the input (topographic, land use, soil, and other digital data) into SWAT are important trends that have paralleled the historical development of SWAT.

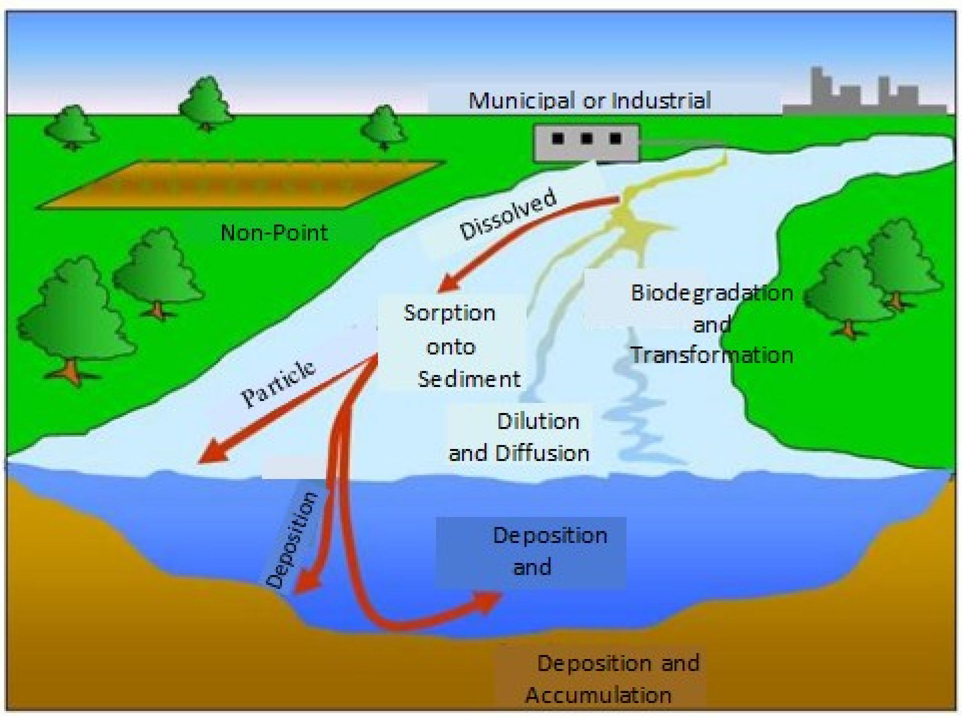

Figure 2.7. In-stream process modeled by SWAT (adopted from Neitsch et al., 2005)

Various statistical indices have been used to evaluate SWAT hydrologic simulations. Moriasi et al., (2007b) provided guidelines for statistical evaluation methods. It has been recommended that three quantitative statistical parameters, which is Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR), in addition to the graphical techniques, be used in model evaluation. In general, model simulation can be judged as satisfactory if NSE > 0.50 and RSR ≤ 0.70, and if PBIAS ± 25% for streamflow, PBIAS ± 55% for sediment, and PBIAS 70% for N and P.

Bingner (1996) applied SWAT to the Goodwin Creek Watershed in northern Mississippi and reported an NSE value of 0.80 for monthly stream flow. SWAT was also successfully validated for streamflow for the Mill Creek Watershed in Texas (Srinivasan et al., 1998). Monthly streamflows were well simulated (NSE = 0.77 and R^2 = 0.87 for calibration period; NSE = 0.52 and R^2 = 0.65 for validation period) but the model over-estimated streamflows in a few years during the spring/summer months. The over-estimation may be accounted for by variable rainfall during those months.

Arnold et al. (2000) applied SWAT for regional estimation of base flow and groundwater recharge in the Upper Mississippi River Basin. The report revealed a general tendency for SWAT to under-estimate spring peaks and to over-estimate fall monthly stream flow. Annual simulated base flow suggested that SWAT tends to over-estimate base flow in high runoff regions with deep soils. Still the Nash-Sutcliffe coefficient (E) value of 0.65 was reported for monthly stream flow simulations during the validation period (Arnold et al., 2000).

Spruill et al. (2000) used the SWAT model to simulate daily stream flow in a small central Kentucky watershed for a two-year period. Results showed that SWAT adequately predicted the trends in daily stream flow.

Eckhardt and Arnold (2001) used a stochastic global optimization algorithm to perform the automatic calibration of SWAT simulation on a low mountain range catchment in central Germany. Results showed a good correlation between measured and simulated daily stream flow with E of 0.70 and a correlation coefficient of 0.84. They concluded that the mean annual stream flow was under-estimated by 4%. Van Liew et al. , (2003) evaluated SWAT's ability to predict streamflow under varying climatic conditions for three nested watersheds in the 610 km^2 Little Washita River Watershed in south western Oklahoma. They found that SWAT could adequately simulate runoff for dry, average and wet climatic conditions in one sub-watershed, following calibration for relatively wet years in two of the sub-watersheds.

Govender and Everson (2005) reported daily streamflow simulation results (R^2 = 0.86 for the calibration period; and R^2 = 0.65 for the validation period) for a small (0.68 km^2) research watershed in South Africa; However, they found that SWAT performed better in drier years than in wet years.

SWAT2000 was enhanced by Arnold et al. (1999) with a subsurface drainage systems component with equations that assume that these systems have already been designed to specific spacing and pipe size. This enhanced version of SWAT was evaluated at the field scale with measured field data and yielded satisfactory results. However, it was found that SWAT2000 was not able to accurately simulate subsurface flow and stream discharge when applied to at the watershed-scale because the incorporated tile drainage algorithms did not accurately represent the water table dynamics at the watershed scale (Arnold et al., 1999). The modifications which applied to the model do not allow for simulations of systems with varying tile spacing, size, drainage intensity, and water table management in order to aid in designing cost-effective water management systems (Moriasi et al., 2009).

Moriasi et al. (2007a) incorporated the steady-state Hooghoudt's (1940) and Kirkham (1957) tile drain equations into SWAT; these alternative tile flow simulation methods take into account tile spacing and drain tube size in addition to the depth to the tile drain. This version of SWAT was tested at the watershed scale with satisfactory results for simulating water balance components of the tile drained South Fork Watershed (Moriasi et al., 2012).

The rate of subsurface water movement into drain tubes, or ditches, depends on the lateral saturated hydraulic conductivity (K) of the soil as well as the drain spacing, size, and depth, the depth of the soil profile and the water table elevation (Skaggs, 1980). Therefore, it can be said that the tile drain equation used to compute tile flow, at any given time, is determined by proximity of the water table to the ground surface. Therefore, in addition to tile drainage, it is also important that a hydrologic model realistically simulates water table depth.

SWAT was modified (SWAT-M) to simulate water table dynamics and it was linked with a simple tile flow equation in addition to including pothole algorithms, which improved the predicted pattern and amount of monthly flow and subsurface drainage on a watershed-scale (Du et al., 2005). The modified model was referred to as SWAT-M and resulted in clearly improved tile drainage and streamflow predictions for the relatively flat and intensively cropped watershed in central Iowa (Du et al., 2005). A code modification was performed by Vazquez-Amabile and Engel (2005) that allowed the reporting of soil moisture for each soil layer. The soil moisture values were then converted into groundwater table levels based on the approach used in DRAINMOD (Skaggs, 1982). It was concluded that predictions of water table levels would be useful to include in SWAT. While incorporating the Hooghoudt (1940) steady-state and Kirkham (1957) tile equations into SWAT2005, Moriasi et al., (2007a) noted that the SWAT-M and SWAT2005 methods exhibited some weaknesses in simulating water table depths. The water table depth approach used in SWAT does not accurately simulate water table depth fluctuation profiles, especially during relatively short dry periods, followed by short wet periods (Moriasi et al., 2009).

The modified DRAINMOD algorithm relates drainage volume with WTD (Moriasi et al., 2009). Water table depth is computed as a function of drainage volume and a calibration factor converts drainage volume into water table depth for hydrologic response units (Moriasi et al., 2009). In the revised, modified DRAINMOD approach (Moriasi et al., 2011), the calibration factor is automatically computed as a function of soil physical properties. This modified DRAINMOD approach of water table depth calculation differs from the DRAINMOD approach in the way in which the drainage volume is determined and how drainage volume relates to water table depth.

However, in this version of SWAT, DRAINMOD was not fully integrated into SWAT and the water table calculation is different from that in DRAINMOD. Although, it calculates tile drainage using Hooghoudt's (1940) and Kirkham's (1957) tile drain equations, this approach is different from DRAINMOD in terms of the way in which the water table depth affects tile drainage on a daily basis. Since the water table has a considerable effect on tile drainage on a daily basis, the developed approach in SWAT could not fully integrate the advantages of the DRAINMOD model into the subsurface drainage calculation. The soil water content distribution in the unsaturated zone does not follow the soil water retention relationship when there is tile drainage in the watershed. This can cause an error in computing evapotranspiration, drainage flux, and the water table elevation.

Furthermore, the revised modified DRAINMOD approach to water table depth is unable to perform multiple scenario simulations such as controlled drainage and the wastewater application to determine cost effective water management systems at the watershed scale. On the other hand, DRAINMOD is a well-known drainage model, which has been successfully tested and applied for subsurface simulation at the field scale, is capable of simulating the different water management scenarios (Ale et al., 2009; Singh et al., 2007).

2.4.2. Subsurface Flow Models

2.4.2.1. **RZWQM**

Root Zone Water Quality Model (RZWQM) (Ahuja, et al., 2000) is a comprehensive simulation model designed to predict the hydrologic response, including surface and groundwater contamination of alternative crop-management systems. The RZWQM simulates the major physical, chemical and biological processes in an agricultural crop production system. It is a one-dimensional (vertical in the soil profile) process-based model that simulates the growth of plants and the movement of water, nutrients, and pesticides over under a range of common management practices. The model includes the simulation of a tile drainage system. RZWQM consists of six major scientific sub-modules or processes that define the simulation program, a Numerical Grid Generator, and an Output Report Generator (Ahuja, et al., 1999). The first version of RZWQM was released in 1992 and was adopted as the model for the Management System Evaluation Areas (MSEA) project (Watts et al., 1999). In 2007, an updated version of RZWQM was released as RZWQM2, which contains surface energy balance from the SHAW (Simultaneous Heat and Water) model (Flerchinger and Saxton, 1989; Flerchinger and Pierson, 1991) and the crop growth modules from Decision Support System for Agrotechnology Transfer (DSSAT) (Jones et al., 2003). Recently, the Parameter Estimation

Singh et al. (2001) compared the RZWQM and DRAINMOD for annual NO_3-N losses to tile outflows, and found that both models have the capability to simulate the effect of crop rotation under different climatic conditions.

Results indicated that both models simulated tile flow within an acceptable range. However, DRAINMOD simulated results were closer to the actual observed values. Detailed results are presented in this paper.

The limitations of this model are that the crops parameterizations are limited to corn, soybean, and wheat. Frozen soil dynamics are not considered. Rainfall is entered as break point increments, and fairly detailed descriptions of the soil profile and initial state have to be known to give a good simulation response to the system. In general, RZWQM is a complex model and needs data which are not normally available. Overland flow and sediment routing are not available in the currently released version, but are available in a test version. Pesticide uptake by plants is not simulated in the currently released version, but is available in a test version.

2.4.2.2. **SWAP**

Soil-Water-Atmosphere-Plant, or SWAP, model (Van Dam et al., 1997) is the successor of the agro hydrological model SWATR (Feddes et al., 1978) and some of its numerous derivatives. SWAP simulates the transport of water, solutes and heat in unsaturated/saturated soils. The model is designed to simulate flow and transport processes at the field scale during seasons and for long term time series. The model employs Richard's equation and includes root water extraction to simulate soil moisture movement in variably saturated zones (Kroes et al., 2008).

The SWAP model has been applied to compute the effects of land drainage (12 combinations of drain depth and spacing) on soil moisture conditions in the root zone and their effect on crop yield and soil salinization in Pakistan, (Sarwar and Feddes, 2000). The optimum drain depth for the multiple cropping systems of the FDP-area was found to be 2.2 m. The main limitation of the SWAP model is that, at low values of saturated hydraulic conductivity, the model did not succeed in completing the simulations.

2.4.2.3. **DRAINMOD**

DRAINMOD (Skaggs, 1980) is a field-scale, hydrologic model that was developed to describe the hydrology of poorly, or artificially, drained lands. Figure 2.8 presents the schematic diagram of drainage and related drainage water management systems simulated by the model. DRAINMOD is the hydrology component of the soil carbon and nitrogen dynamics model DRAINMOD-N II (Youssef et al., 2005), the soil salinity model DRAINMOD-S (Kandil et al., 1995), the recent whole-system models DRAINMOD-Forest (Tian et al., 2012), and DRAINMOD-DSSAT (Negm, 2011), which simulates the hydrology, biogeochemistry, and plant growth for drained forested and agricultural lands. This model is described in following pages since this model has been combined with the SWAT model in this study.

DRAINMOD is a computer simulation program that characterizes the response of the soil water regime to various combinations of the surface and subsurface water management. DRAINMOD simulates the response of the water table and the soil water above the water table to the other hydrologic components, such as infiltration and evapotranspiration (ET), as well as to surface and subsurface drainage. . Surface irrigation can also be considered. Climatological data are used in the model to simulate the performance of a given water management system across several years.

The rates of infiltration, ET, drainage, and distribution of soil water in the profile are calculated by various methods, (Skaggs, 1980). The Green and Ampt (Green and Ampt, 1911) equation is used to describe the infiltration component in DRAINMOD. The model calculates daily potential ET using the Thornthwaite method, although ET can be computed by the method of the user's choice (e.g., Penman–Monteith or Hargreaves).

Surface runoff is characterized by the average depth of surface depression storage and begins when surface depressions are filled out (Skaggs, 1999). The Hooghoudt's steady state equation, with a correction for convergence near the drains (Schilfgaarde, 1974), is used to calculate drain outflow, according to the Dupuit–Forchheimer (D–F) assumptions and flow is considered in the saturated zone only.

The model also calculates the subsurface drainage flux from a pond surface using Kirkham's steady state flow equation. Deep seepage rates are calculated with an application of Darcy's Law. Approximate methods were used to characterize the water movement processes in DRAINMOD. A summary outputs are available on a daily, monthly, yearly, and ranked bases, at the option of the user (Skaggs et al., 2012).

2.4.2.3.1. **Water Balance**

DRAINMOD model is based on water balance for a section of soil of unit surface area that extends from the impermeable layer to the ground surface which is located midway between parallel drains (Skaggs, 1980). The water balance for a time increment may be expressed as:

$$\Delta Va_a = D + ET + DS - F \tag{2.14}$$

Where ΔV_a is the change in the air volume (cm), D is the lateral drainage (cm) from (or subirrigation) ET is the evapotranspiration (cm), DS is the deep seepage (cm), and F is the infiltration (cm) during the time increment Δt.

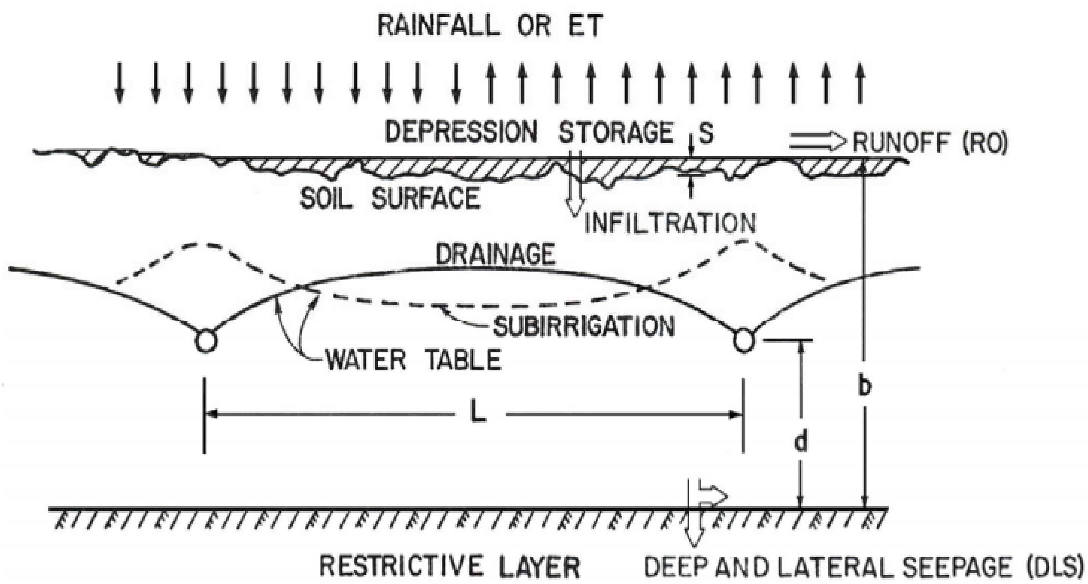

Figure 2.8. Schematic diagram of hydrologic processes simulated by DRAINMOD (Adapted from Skaggs, 1980)

The water table depth is actually relatively flat in the broad center portion of the field, even during wet periods. During dry periods, when the water table is close to, or below the drain, it becomes essentially flat (Skaggs, 1980). Thus, equation 2.14 approximates a relatively wide area in the center of the field. The water balance can be conducted for the cross-section, from drain to drain, by expressing the drainage and seepage rates in terms of the average water table depth, rather than the depth at the midpoint (McCarthy et al., 1992), but the standard version conducts the water balance at the midpoint between drains. A water balance is also computed at the soil surface for each time increment Δt and may be written as:

$$P = F + \Delta S - RO \quad (2.15)$$

Where P is precipitation (cm), ΔS is change in the volume of water stored on the surface (cm), and RO is runoff (cm) during Δt.

2.4.2.3.2. **Infiltration**

The Green and Ampt (1911) equation is used to predict infiltration in DRAINMOD model:

$$f = K + KM_d \frac{S_f}{F} \tag{2.16}$$

Where f is the infiltration rate (cm h^{-1}), F is cumulative infiltration (cm), K is the vertical hydraulic conductivity of the transmission zone (cm h^{-1}), M_d is the difference between final and initial water contents (cm3 cm^{-3}), and S_f if the effective suction at the wetting front (cm).

For a specific soil with a given initial condition, equation 2.16 may be written as:

$$f = \frac{A}{F} + B \tag{2.17}$$

Where A (cm^2 h^{-1}) and B (cm h^{-1}) are parameters that depend on soil properties and plant factors, such as extent of cover, depth of root zone, and soil water content when rainfall begins. Infiltration parameters are entered in DRAINMOD as a table of A and B versus initial water table depth.

2.4.2.3.3. **Surface Drainage**

The average depth of depression storage defined as the intensity of surface storage (Figure 2.9) that must be satisfied before runoff can begin. It is assumed that depression storage is evenly distributed over the field, in most cases.

In DRAINMOD model surface storage is further divided to difference between water that can move freely over the surface to the vicinity of the drains versus that in local depressions remote from a drain or where flow is blocked, by secondary roughness, furrows, or beds (Skaggs, 1980) (Figure 2.9).

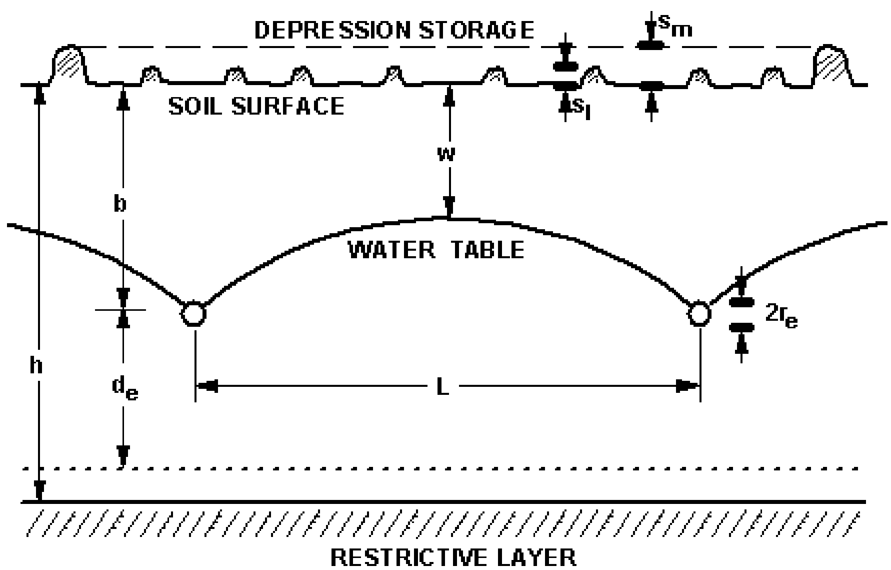

Figure 2.9. Surface drainage (Adapted from Skaggs, 1980)

2.4.2.3.4. **Subsurface Drainage**

The rate of the subsurface water moving into the drain tubes depends on the hydraulic conductivity of the soil, drain spacing, and drain depth, profile depth and water elevation (Skaggs, 1980). DRAINMOD calculates drainage rates based on the assumption that lateral water movement happens mainly in the saturated region.

When the soil profile is saturated and water is ponded on the ground surface, the drainage rate is calculated by equations developed by Kirkham (1957). Streamlines are concentrated near the drains with most of the water entering the soil surface in that vicinity. After the depth of the surface water fell from depth S_m to depth S_1 due to drainage and evaporation, water is not able to move across the surface to the vicinity of the drains anymore. So, the water table near the drain is drawn down, and the Kirkham equation is no longer valid. At the time which the water table midway between the drains is just coincident with the surface and attains an approximately elliptical shape the drainage rate can be estimated with the steady state Hooghoudt equation.

$$q = 4K_e m \frac{2d_e + m}{L^2} \tag{2.18}$$

Where q is the drainage rate (cm h^{-1}), m is the midpoint water table elevation above the drain, K_e is the equivalent lateral hydraulic conductivity of the profile (cm h^{-1}), d_e is the equivalent depth from the drain to the restrictive layer (cm), and L is the drain spacing (cm).

Although the drawdown process at the water table to drain depth, is not steady-state, but because in most cases proceeds slowly, the drainage rate can be adequately estimated by the Hooghoudt equation (Skaggs and Tang, 1976). The water table may continue to recede due to ET and seepage, but the drainage rate would be zero at the time it falls below drain depth. Drainage intensity (DI) may be defined as the drainage rate when the midpoint water table is at the ground surface. DI is a function of the drain spacing and depth and the hydraulic conductivity of the profile. DRAINMOD assumes that the tile flux is equal to DI for that condition (m=c). The values calculated by the Kirkham and Hooghoudt equations quantify the rate of water movement through the soil to the drain tubes for given water table elevations.

In some cases the drainage rate may be limited by the hydraulic capacity of the drainage system which is an input called the drainage coefficient (DC) in DRAINMOD. The DC depends on the size of the area being drained and the parameters defining the outlet, such as the size, slope, and hydraulic roughness of the main drain, or the pumping capacity in the case of pumped outlets (Skaggs, 1980). In DRAINMOD the calculated drainage flux is limited to values less than or equal to the DC, regardless of the water table position (Skaggs, 1980).

2.4.2.3.5. **Drainage Water Management**

DRAINMOD model can simulate different water management practices such as controlled drainage and subirrigation, either separately or in sequence with conventional drainage (Skaggs, 1980). The rate of water movement back into the profile when the water level in the outlet is higher than the water table in the field is calculated by an equation presented by Ernst (1975). A separate water balance is used for the controlled drainage mode, which considers storage in the outlet structure and associated main and lateral drains (Skaggs et al., 2012).

2.4.2.3.6. **Evapotranspiration**

The determination of the ET rate is a two-step process in DRAINMOD. First, the daily potential ET (PET) is determined and distributed on an hourly basis. After PET is calculated, it is been checked if ET is limited by soil water availability.

If ET is not limited by available soil water, it is set equal to the PET; otherwise, ET is set to the smaller amount that can be supplied from the soil system. Daily PET may be determined by the method of the user’s choice or it can be read into the model as input an input file. PET in DRAINMOD may be calculated by Thornthwaite (1948) method. Inputs used to determine whether soil water conditions limit ET are the soil water characteristic, the relationship of maximum steady upward flux and water table depth, effective depth of the root zone, and soil water content at the lower limit (Skaggs, 1980).

2.4.2.3.7. **Seepage**

In DRAINMOD, simple methods based on Darcy's Law and the Dupuit-Forchheimer assumptions are used to calculate vertical and lateral seepage (Skaggs, 1980). The rate of the vertical seepage (q_v) is calculated as:

$$q_v = \frac{k_v\,(h_1 + d_v - h_v)}{d_v} \qquad (2.19)$$

Where h_1 is the water table elevation above the restrictive layer, d is the thickness and k_v is the vertical hydraulic conductivity of the restrictive layer, and h_v is the hydraulic head in the aquifer, referenced to a datum at the bottom of the restrictive layer. Lateral seepage from the field under controlled drainage is calculated as:

$$q_L = \frac{k_L(h_1^2 - h_2^2)}{2xa} \qquad (2.20)$$

Where q_L is the lateral seepage loss per unit area (cm d^{-1}) from the field with controlled drainage, h_2 is the water table or water level elevation in the sink, x is the distance between the boundary drains in the two fields, a is the effective width of the controlled field, and k_L is the effective lateral hydraulic conductivity of the profile.

2.4.2.3.8. **Soil Water Distribution**

The methods used to calculate the different components of the water balance equation, depend on the depth of water table and the soil water distribution in the unsaturated zone. The water table depth is one of the key variables in DRAINMOD calculations (Skaggs, 1980).

In DRAINMOD, it is assumed that the soil water is distributed in two zones; a wet zone extending from the water table up to the root zone and possibly through the root zone to the surface, and a dry zone. The water content distribution in the wet zone is assumed to be a drained to equilibrium profile (Skaggs, 1980). When the maximum rate of the upward flux, is not sufficient to supply ET demand, then the water is removed from the root zone storage, led to create a dry zone (Skaggs, 1991). The soil water distribution and volume of water free pore space (cm^3cm^{-2}) in the profile above the water table is calculated at each time step. Required Inputs for these calculations include the soil water characteristic for each soil layer and the volumetric water content at the lower limit available to the crop.

2.4.2.3.9. **Soil Temperature, Freezing, Thawing and Snowmelt**

The DRAINMOD model includes freezing, thawing, and snowmelt components, which allows, DRAINMOD to simulate the drainage phenomena in cold regions.

DRAINMOD solves the water flow and heat flow equations simultaneously based on the principles of mass and energy conservation. It uses soil temperature to simulate processes controlling field hydrology under cold conditions such as freezing, thawing, and snowmelt (Luo et al., 2000). During the freezing conditions, the model modifies soil properties, infiltration and drainage rates according to the ice content in the profile and (Skaggs et al, 2012).

Over the past three decades, DRAINMOD has been extensively tested for a wide range of soils, crops, and climatological conditions and proven to be a reliable model for simulating water table fluctuations and drainage volumes in artificially drained, high water table soils (Skaggs, 1982; Gayle et al., 1985; Fouss et al., 1987; Sanoja et al., 1990; Cox et al., 1994; Singh et al., 1994; Madramootoo et al., 1999; Luo et al., 2000; Luo et al., 2001; Helwig et al., 2002; Zwierschke et al., 2002; Youssef et al., 2003; Wang et al., 2006; Youssef et al., 2006; Yang et al., 2007; Dayyani et al., 2009, 2010a, Skaggs et al., 2012).

2.5. Model Selection

A good approach to modeling the hydrology of agricultural watersheds is to use a model that can adequately address the hydrology of both un-drained and tile-drained areas. SWAT and DRAINMOD models are selected because together, they meet these requirements very well.

SWAT is a continuous, semi-distributed, physically-based hydrological model for natural water resources simulation (Neitsch et al., 2005). Extensive research has been implemented on SWAT applications under the worldwide conditions (Gupta et al., 1999; Das et al., 2007;; Moriasi et al., 2007a; Santhi et al., 2001; Wang and Melesse, 2005). It appears that SWAT is a good candidate as the analysis tool for this research because of the continuous development of its user-friendly interface from GIS, complete documentation support in its theoretical interpretation, a user manual and tutorial explanations, and even open source code is available with a free download, physically based analysis functions, flexible input modifications and extensive applications around the world. Moreover, it can be applied to small and large watersheds. Although SWAT excels as a surface flow and transport model, subsurface flow is handled in the model in a rather simplistic way. Furthermore, the model does not account for managing subsurface drainage, controlled drainage or subirrigation systems.

DRAINMOD (Skaggs 1980) was the first comprehensive computer model developed to aid in the design and evaluation of agricultural drainage and water table management systems for poorly drained, high water table soils. The model includes freezing, thawing, and snowmelt components and thus, it is capable of simulating drainage phenomenon in cold regions. Agricultural tile drainage is a common water management practice in agricultural regions with high water tables, such as Ontario. Artificial tile drainage systems are installed in many agricultural fields in humid regions, such as eastern Canada, for crop production. Ontario has a cool and wet spring and fall seasons, and a cold winter, and thus experiences freezing, thawing, and snowmelt. DRAINMOD has been used and tested worldwide and it is proven to be an efficient model in simulating flows from poorly drained high water table soils experiencing freeze-thaw cycles (Skaggs, 1982; Singh et al., 1994; Lou et al., 2000, 2001; Youssef et al., 2006; Yang et al., 2007; Wang et al., 2006; Dayyani et al., 2009, 2010a; Skaggs, 2012). In this respect, DRAINMOD appears to be a good candidate for subsurface flow simulation.

As it was mentioned in the literature review, the previous attempts tried to improve subsurface hydrology and tile drainage and shallow water table depth simulation methods in SWAT model (Arnold et al., 1999; Moriasi et al., 2007a; Moriasi 2012; Du et al., 2005; Neitsch et al., 2002a; Moriasi et al., 2011), but several simplified assumptions have been considered and more research needs to be performed in order to improve the subsurface hydrology. The latest version of SWAT calculates the tile drainage flow using Kirkham/Hooghoudt equations and estimates water table depth as a function of volume drainage using a simple linear water table depth prediction equation that closely matches the measured water table depth values. In the revised, modified DRAINMOD approach (Moriasi et al., 2011), the calibration factor is automatically computed as a function of soil physical properties. This modified DRAINMOD approach of water table depth calculation differs from the DRAINMOD approach in the way in which the drainage volume is determined and how drainage volume relates to water table depth.

However, in the revised modified DRAINMOD version of SWAT, DRAINMOD was not fully integrated into SWAT and the water table calculation is different from that in DRAINMOD. Although, it calculates tile drainage using Hooghoudt's (1940) and Kirkham's (1957) tile drain equations, this approach is different from DRAINMOD in terms of the way in which the water table depth affects tile drainage on a daily basis. Since the water table has a considerable effect on tile drainage on a daily basis, the developed approach in SWAT could not fully integrate the advantages of the DRAINMOD model into the subsurface drainage calculation. Furthermore, this version is unable to perform multiple scenario simulations such as controlled drainage to determine cost effective water management systems at the watershed scale.

The full integration of DRAINMOD and SWAT is anticipated to enable scenario simulations, which will aid in designing more efficient water management systems in agricultural regions with shallow water tables. Therefore, in this study, the DRAINMOD model will be incorporated into SWAT to develop a new model and further improve the existing subsurface hydrology and tile flow component. It is expected that the new model, SWATDRAIN, can effectively simulate both surface and subsurface flow processes in a rational way on a watershed-scale in humid regions.

CONNECTING TEXT TO CHAPTER 3

This chapter has been submitted to the Hydrology Journal. The format has been changed to be consistent within this thesis. All literature cited in this chapter is listed in the reference section at the end of this thesis. Chapter 3 covers the comparison of three watershed scale models: SWAT, APEX, and MIKE SHE. A description of the site instrumentation and data collection methodology is provided along with calibration procedures and statistical analyses. Simulation results for streamflow at the watershed scale for three models are presented.

CHAPTER 3: Evaluating Three Hydrological Distributed Watershed Models: MIKE-SHE, APEX, SWAT

Golmar Golmohammadi, Shiv O. Prasher, Ali Madani, Mohamed Youssef, and Ramesh Rudra

Abstract

Selecting the right model to simulate a specific watershed has always been a challenge and field testing of watersheds could help researchers to use the proper model for their purposes. The performance of three popular GIS based watershed simulation models (MIKE SHE, APEX and SWAT) were evaluated for their ability to simulate the hydrology of the 52.6 km^2 Canagagigue Watershed located in the Grand River Basin in southern Ontario, Canada. All three models were calibrated for a 4-year period and then validated using an independent 4-year period by comparing simulated and observed daily, monthly and annual streamflows. Simulated flows generated by the three models are quite similar, and closely match observed flow, particularly for the calibration results. The mean daily/monthly flow at the outlet of the Canagagigue watershed simulated by MIKE SHE and SWAT were more accurate than that simulated by APEX model, during both calibration and validation periods. Moreover, for the validation period, MIKE SHE and SWAT predicted the overall variation of streamflow slightly better than APEX.

Key Terms: Hydrology; MIKE SHE; APEX, SWAT; Canagagigue

3.1. Introduction

Many computer simulation models have been developed to simulate watershed-scale processes and the hydrologic effects of different management scenarios. Watershed models are effective tools for investigating the complex nature of those processes that affect surface and subsurface hydrology, soil erosion, and the transport and fate of chemical constituents in watersheds (Singh et al., 2005). A watershed model can be used to achieve a better understanding of the impact of land use activities and different management practices on these hydrologic processes. Due to increased spatial data availability more and more distributed hydrological models are used. For example, from 2004 to 2011, as part of the overall Conservation Effects Assessment Project, thirteen projects on agricultural watersheds, situated in the United States, were funded jointly by the USDA, National Institute of Food and Agriculture, and the Natural Resources Conservation Services, (Arabi et al., 2012). Geographic information system (GIS) has provided another useful base for spatially distributed physical processes including watershed models. Selecting the proper model to simulate hydrologic processes of a specific watershed has always been a challenge and field testing of the hydrologic components of watersheds could help researchers to use the proper model for their purposes.

In recent years, distributed watershed models have increasingly been used to implement alternative management strategies in the areas of water resources allocation, flood control, land use, and climate change impact assessments as well as pollution control (Shi, et al., 2011). Some authors tend to criticize the use of distributed models; their main concern is that many parameters can be altered during the calibration phase (Abu El-Nasr et al., 2005). According to Beven (1996), a key characteristic of distributed models is the same problem of over parameterization. In response, Refsgaard and Storm (1995) emphasize that a rigorous parameterization procedure might help overcome the problems faced in calibrating and validating fully distributed physically-based models.

In this study, three GIS based distributed continuous simulation models, commonly used for watershed management assessment, are evaluated and field verified. These models include the Agricultural Policy/Environmental eXtender (APEX) (Williams, 1995), MIKE SHE (Refsgaard and Storm, 1995) and the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998). There have been several applications of these models either individually or in comparison with another model. Some of these applications are described below:

Borah and Bera (2003), reviewed eleven watershed-scale hydrological models and concluded that AGNPS, AnnAGNPS, DWSM, HSPF, MIKE-SHE and SWAT were able to simulate all major components (hydrology, sediment, and chemical) applicable to watershed-scale catchments. SWAT was considered a promising model for continuous simulations in predominantly agricultural watersheds. In general MIKE SHE and SWAT showed better performances when compared with other models. All of these studies indicated that further investigation was needed in all these studies to reach a solid conclusion about the superiority of one model over the others. APEX was not included in this study.

Borah et al. (2007) evaluated and compared SWAT and DWSM results for the 620 km^2 Upper Little Wabash River watershed (Effingham, IL) using a visual comparison of hydrographs. These results showed SWAT's weakness in predicting monthly peak flows (mostly under predictions). Shi et al. (2011) compared the performance of the SWAT and Xinanjiang (XAJ) models, the latter widely used in China, and showed that both models performed well in the Xixian River Basin, with a percentage of bias (PBIAS) of less than 15%, Nash-Sutcliffe Efficiency (NSE) > 0.69 and coefficient of determination (R^2) > 0.72 for both calibration and validation periods. Two popular watershed scale models, SWAT and HSPF, were used to simulate streamflow, sediment and nutrients loading from the Polecat Creek Watershed in Virginia and the results indicated that both models were generally able to simulate effectively streamflow, sediment and nutrient loading. However, HSPF simulated hydrology and water quality components were more accurate than those of the SWAT model at all monitoring sites within the watershed (Im et al., 2003). HSPF and SWAT were also evaluated for simulating the hydrology of watersheds in Illinois and Indiana. As a rule, the characteristics of simulated flows from both models were similar to each other and to observed flows, particularly for the calibration results. However, SWAT predicted flows slightly better than HSPF for the verification period, with the primary advantage being a better simulation of low flows (Singh et al., 2005).

Refsgaard and Knudsen (1996) validated and compared three different models in three catchments namely, the Nedbor-Afstromnings (NAM) lumped conceptual modeling system (Nielsen and Hansen, 1973), the MIKE SHE distributed, physically-based system (Abbot et al., 1986a,b) and the Hybrid WATBAL approach (Knudsen et al.,1986). The study was applied on two large catchments and a medium sized one (1090, 1040 and 254 km^2). The authors concluded that all models performed equally well when at least 1 year of data was available for calibration, while the distributed models performed marginally better for cases where no calibration was performed.

The performance of the fully distributed MIKE SHE model and that of the semi-distributed SWAT model were compared for the 465 km^2 Jeker River Basin, situated in the loamy belt region of Belgium (Abu El-Nasr et al., 2005). The two models differed in conceptualization and spatial distribution, but gave similar results during calibration. However, MIKE SHE provided slightly better overall predictions of river flow.

All of these studies concluded that the models performances are site specific and because no one model is superior under all conditions; a complete understanding of comparative model performance requires applications under different hydrologic conditions and watershed scales. Since APEX is able to be used for small scale watersheds and farms, and also to evaluate a wide range of alternative management scenarios, it will be important to evaluate the hydrological component of this model.

Therefore, the objective of the present study is to compare and assess the suitability of three widely used watershed simulation models, namely APEX, MIKE SHE, and SWAT for simulating the hydrology of a major tributary of the upper Grand River Basin, the Canagagigue Watershed, Ontario, Canada. This watershed is representative of the land use and soils throughout much of the Grand River Basin. The performance of the three models was assessed with respect to their capacity to generate the daily flow rate at the catchment outlet of the Canagagigue Watershed, a small sized watershed situated in a loamy region of the Grand River Basin. This paper presents the overall performances of the three models in this Ontario watershed where there is significant snowfall and snowmelt influence runoff.

3.2. Materials and Methods

3.2.1. Site Description

With almost 7,000 km^2 in drainage area, southwestern Ontario's Grand River Basin contributes about 10% of the water received by Lake Erie. A minor tributary of the Grand River, the Canagagigue Creek, has a drainage area which extends over 143 km^2 (43.60-43.70°N, 80.55-80.63°W) and covers the Peel and Pilkington townships of Wellington County and Woolwich township of Waterloo County, ON (Figure 3.1).

A gauging station situated near Floradle, Ontario (approx. 100 km west of Toronto), provided hourly stream flow observations for the period of 1989-2000, monitored at the southerly outlet of a 53 km^2 subwatershed housing the upper reaches of the Canagagigue Creek. With a mean elevation of 417 m above mean sea level, this roughly triangular and southerly down sloping subwatershed shows a flat to gently undulating topography (mean slope <1.5%). The main soil types in the watershed are presented in Figure 3.2. Soil surveys of Waterloo County (Presant and Wicklund, 1971). Hoffman et al., (1963) indicate that most of the watershed bears 0.2 to 0.6 m of loam or silty loam of the Huron and Harriston series over a loam till.

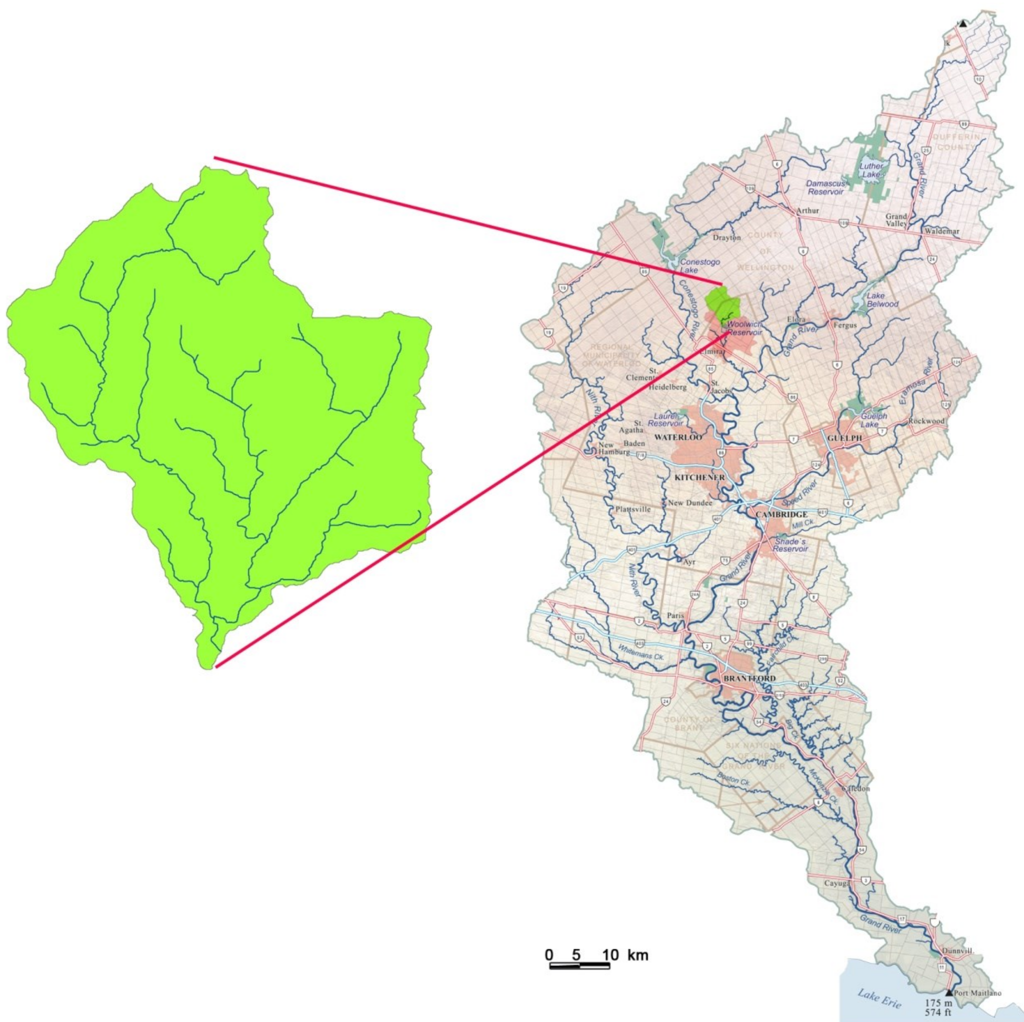

Figure 3.1. Location of the study area in Grand River Basin and the river network

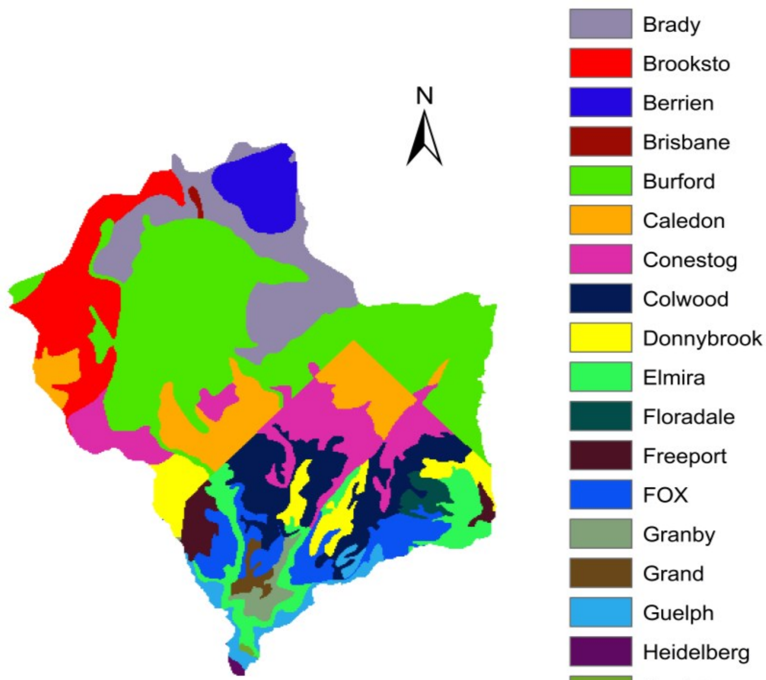

Figure 3.2. Soil classifications in Canagagigue Creek watershed

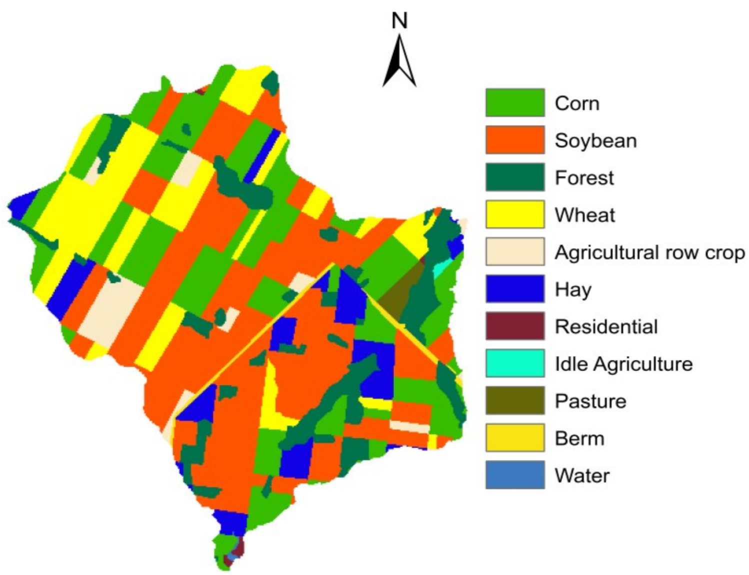

Figure 3.3. Soil and land use classifications in Canagagigue Creek watershed

In the northern part of the watershed, clay loam is predominant, while loam is the main soil type in the central portion of the watershed. In the south and southeastern sections, the soil types can be characterized as moraine deposits of very fine sand and fine sandy loam with occasional layers of other material. A map of land use characteristics (Figure 3.3) shows 80% of the area is devoted to agriculture and another 10% to woodlots (Carey et al., 1983). The remaining watershed is occupied by urban areas, fallow land, and rivers, and lakes.

3.2.2. SWAT

SWAT is a conceptual, physically-based, continuous model. It operates on a daily time step and is designed to predict the impacts of watershed management practices on hydrology, sediment, and water quality on a gauged or an un-gauged watersheds. The major model components include weather generation, hydrology, sediment, crop growth, nutrient, and pesticide subroutines (Arnold et al., 1998). To accurately simulate water quality and quantity, SWAT requires specific information about topography, weather (precipitation, temperature), hydrography (groundwater reserves, channel routing, ponds or reservoirs, sedimentation patterns), soil properties (composition, moisture and nutrient content, temperature, erosion potential), crops and vegetation, and agronomic practices (tillage, fertilisation, pest control) (Neitsch et al., 2002a, 2002b).

The model simulates a watershed by dividing it into subbasins, which are further subdivided into hydrologic response units (HRUs), a compartmentational unit which is determined by finding small scale regions of similarity by overlaying digitized soil, slope, and land use maps. For each HRU in every subbasin, SWAT simulates the soil water balance, groundwater flow, lateral flow, channel routing (main and tributary), evapotranspiration, crop growth and nutrient uptake, pond and wetland balances, soil pesticide degradation, and in stream transformation nutrients and pesticides (Vazquaz-Amabile and Engel, 2005). The hydrologic components in SWAT include surface runoff, infiltration, evapotranspiration, lateral flow, tile drainage, percolation/deep seepage, consumptive use through pumping (if any), shallow aquifer contribution to streamflow for a nearby stream (baseflow), and recharge by seepage from surface water bodies (Neitsch et al., 2002a, 2002b). More detailed descriptions of the model are given by Arnold *et al.* (1992) and/or in the SWAT theoretical documentation (Neitsch et al., 2002a).

3.2.3. APEX

The APEX model was developed to extend the EPIC model's (Williams, 1995) capabilities to whole farms and small watersheds. The model consists of 12 major components: climate, hydrology, crop growth, pesticide fate, nutrient cycling, erosion-sedimentation, carbon cycling, management practices, soil temperature, plant environment control, economic budgets, and subarea/routing. Management capabilities include sprinkler, drip or furrow irrigation, and drainage; furrow diking, buffer strips, terraces, waterways, fertilization, manure management, lagoons, reservoirs, crop rotation and selection, cover crops, biomass removal, pesticide application, grazing, and tillage.

The simulation of liquid waste applications from concentrated animal feeding operation (CAFO) waste storage ponds, or from lagoons, is a key component of the model. Stockpiling and subsequent land application of solid manure in feedlots or other animal feeding areas can also be simulated in APEX. In addition to routing algorithms, groundwater and reservoir components have been incorporated into APEX. The routing mechanisms provide for the evaluation of interactions between subareas involving surface run-off, return flow, sediment deposition and degradation, nutrient transport, and groundwater flow. Water quality in terms of soluble and organic N and P and pesticide losses may be estimated for each subarea and at the watershed outlet.Williams (1995) provided the first qualitative description of the APEX model, which included a description of the major components of the model, including the manure management component. Williams et al. (2006), expanded qualitative descriptions of the modelwhich provided an overview of the manure erosion and routing components, including some mathematical description. Williams and Izaurralde (2006) provide an exhaustive qualitative description of the model coupled with the mathematical theory for several of the components. Complete theoretical descriptions of APEX were initially compiled by Williams et al. (2000) and Williams and Izaurralde (2006); Williams et al. (2008) provide an updated, in-depth theoretical manual for the latest APEX model (version 0604).

3.2.4. MIKE SHE

The MIKE SHE (Refsgaard and Storm, 1995) is a deterministic physically-based distributed model for the simulation of different processes of the land phase in the hydrologic cycle. The hydrological processes are modeled by finite difference representations of the partial differential equations for the conservation of mass, momentum and energy, in addition to some empirical equations (Abu El-Nasr et al., 2005). The MIKE SHE modeling system simulates hydrological components, including the movement of surface water, unsaturated subsurface water, evapotranspiration, overland channel flow, saturated ground water, and exchanges between surface water and ground water. With regard to water quality, the system simulates sediment, nutrient, and pesticide transport in the model area.

The model also simulates water use and management operations, including irrigation systems, pumping wells, and various water control structures. A variety of agricultural practices and environmental protection alternatives may be evaluated using the many add-on modules developed at the Danish Hydraulic Institute (DHI). Model components describing the different parts of the hydrologic cycle can be used individually or in combination depending on the scope of the study (DHI, 1999). To account for the spatial variations in catchment properties, MIKE SHE represents the basin horizontally by an orthogonal grid network, and uses a vertical column at each horizontal grid square to describe the variation in the vertical direction. This is achieved by dividing the catchment into a large number of discrete elements or grid squares then and solving the equations for the state variables for every grid into which the study area was divided. To run the model for each cell, several parameters and variables have to be given as input parameters (Refsgaard, 1997).

The system has no limitations in terms of watershed size. The modeling area is divided into polygons based on land use, soil type, and precipitation region. Most data preparation and model set-up can be completed using GIS, ArcView, or MIKE SHE's built-in graphic pre-processor. The system has a built-in graphics and digital post-processor for model calibration and evaluation of both current conditions and management alternatives. Animation of model scenarios is another useful tool for analyzing and presenting results. The MIKE SHE model makes predictions that are distributed in space, with state variables that represent local averages of storage, flow depths or hydraulic potential. Because of the distributed nature of the model, the amount of input data required to run the model is rather large and it is rare to find a watershed, where all input data required to run the model, has been measured (Abu EL-Naser et al., 2005)..

3.2.5. Performance Evaluation

In order to calibrate and validate the models and for comparison purposes, some quantitative information is required to measure model performance. In this study, the streamflow data measured at the outlet of the watershed was used to assess the model performance. The performance assessment was based on the water balance closure of the watershed, agreement of overall shape of the time series of discharge together with the total accumulated volumes, and value of statistical performance indices such as: Root Mean Square Error (RMSE), the Modeling Efficiency (EF) and the goodness of fit (R^2), (Nash and Sutcliffe, 1970; Legates and McCabe, 1999; Singh et al., 2004).

The RMSE, (Equation 3.1) indicates a perfect match between observed and predicted values when it equals 0 (zero), with increasing RMSE values indicate an increasingly poor match. Singh et al. (2004) stated that RMSE values, less than half the standard deviation of the observed (measured) data, might be considered low and is indicative of good model prediction.

The Nash-Sutcliffe efficiency coefficient (NSE), ranges between -∞ and 1. It indicates a perfect match between observed and predicted values when NSE = 1Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values less than 0.0 indicate that the mean observed value is better than the simulated value, which indicates unacceptable performance.

The coefficient of determination, R^2, (Equation 3.3), which ranges from 0 to 1, describes the proportion of the variance in the measured data, which is explained by the model, with higher values indicating less error variance. Typically $R^2 > 0.5$ is considered acceptable (Santhi et al., 2001, Van Liew et al., 2003).

The percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). The optimal value of PBIAS is 0.0, with low magnitude values indicating an accurate model simulation. Positive values indicate under-estimation bias, and negative values indicate over-estimation bias (Gupta et al., 1999).

RMSE-observations standard deviation ratio (RSR) is calculated as the ratio of the RMSE and standard deviation of measured data. RSR varies from the optimal value of 0, to a large positive value. The lower RSR, the lower the RMSE, and the better the model simulation performance.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \quad (3.1)$$

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}\right] \quad (3.2)$$

$$R^2 = \left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{n}(P_i - \bar{P})^2}}\right]^2 \quad 0 \leq R^2 \leq 1 \quad (3.3)$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(O_i - P_i) * 100}{\sum_{i=1}^{n}(O_i)}\right] \quad (3.4)$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}}\right] \quad (3.5)$$

where, n is the number of observations in the period under consideration, O_i is the i^{th} observed value, $\bar{O}$ is the mean observed value, P_i is the i_{th} model-predicted value, and is the mean model-predicted value.

3.2.6. Calibration and Validation

In order to evaluate the model, the first year of the data (1989) served to initialize the model, and the following two times four years of data were divided into two parts of four years each to validate and calibrate the model. Calibration of SWAT was performed in two steps by first calibrating the average annual water balance and then the calibration of the hydrograph shapes for the daily streamflow graphs. This was carried out in a logical order according to the most sensitive parameters, based on the sensitivity analysis.

In order to obtain more realistic and physically meaningful results, the observed total flow was separated into two components, surface runoff and baseflow, using an automated baseflow digital filter separation technique (Arnold and Allen., 1995). The Base Flow Index (BFI) is then defined as the observed ratio of the baseflow, which contributed to the total water yield. The baseflow from total streamflow is estimated to be 40% annually for this watershed. Surface runoff was calibrated, by adjusting the curve numbers for the different soils in watershed under the conditions prevailing in the region, and then, using the soil available water (SAW) and soil evaporation compensation factor. In the next step, the baseflow component was calibrated by changing the 'revap' coefficient which controls the water movement from shallow aquifer into the unsaturated zone. The temporal flow was then calibrated by changing the transmission losses for the channel hydraulic conductivity and the baseflow alpha factor which is a direct index of groundwater flow response to changes in recharge.

Since the Canagagigue Creek Watershed is subject to significant snowfall and snowmelt during the winter and early spring, certain parameters important to the snow water mass balance were investigated with regard to their sensitivity to surface runoff, base flow, and actual evapotranspiration and streamflow, through a review of pertinent literature.

For SWAT these parameters were ESCO (soil evaporation compensation factor), SMTMP (snow fall temperature), TIMP (snow pack temperature lag factor), SMFMN (melt factor for snow on December 21), and SMFMX (melt factor for snow on June 21). The range of values for calibration of the SWAT model is listed in Table 3.1. All applied calibration steps applied to the SWAT model were in line with the recommended calibration steps listed in the SWAT User Manual 2000 (Neitsch et al., 2000).

Table 3.1. Calibrated values of adjusted parameters for streamflow calibration of the SWAT model for the Canagagigue Creek Watershed

Description	Default values	Calibrated values
SWAT		
Soil evaporation compensation factor	0.01 - 1.00	1.00
Initial soil water storage expressed as a fraction of field capacity water content	0.01 - 1.00	0.95
Snowfall temperature (°C)	1.00	-2.00
Melt factor for sow on June 21 (mm H_2O / °C-day)	4.5	6.90
Melt factor for snow on December 21(mm H_2O / °C-day)	4.5	1.40
Snow pack temperature lag factor	1.0	0.20
Minimum snow water content that corresponds to 100% snow cover	1.00	10.00
Snowmelt base temperature (°C)	0.5	0.00
Surface runoff lag coefficient (d)	0.00 - 4.00	0.20
Curve Number method flag	0 or 1	1.0
Curve Number coefficient	0.00 - 2.00	1.5
Manning's "n" value for overland flow	0.014	0.15- 0.5
Manning's "n" value for main channel	0.014	0.014
MIKE SHE		
Degree-day factor (mm snow/day/°C)	2.0	3.5
Threshold melting temperature (°C)	0	0
Manning's n		
- Urban area	90.9	109.1
- Agricultural crops	5.9	7.1
- Hay/Pasture	4.2	5.0
- Fallow land	20	24
- Water	25	30
- Woodlot	1.25	1.5
APEX		
Soil evaporation coefficient	1.50 – 2.00	1.50
Soil evaporation-plant cover factor	0.01 – 0.50	0.10
Runoff curve number initial abstraction	0.05 – 0.40	0.20
Groundwater storage threshold	0.001 – 0.10	0.01
SCS curve number index coefficient	0.20 – 2.50	2.50
Peak runoff rate-rainfall energy adjustment factor	0.00 – 1.00	1.00

In order to calibrate the MIKE SHE model, the snowmelt constants (degree-day factor and threshold melting temperature) as well as Manning's n were adjusted to match the simulated and observed runoff. An adjustment in the timing of peaks was attempted by increasing the Manning's n parameter by 20% over the entire watershed and thus reducing the surface roughness and increasing the surface runoff velocity. Table 3.1 shows the MIKE SHE model parameters subjected to calibration.

To calibrate the APEX model, a sensitivity analysis on flow parameters in the model showed that certain parameters which are presented in Table 3.1 are more sensitive parameters. Adjusting these parameters resulted in a better match between observed and simulated flow data in the Canagagigue Watershed. Among these parameters, the curve number for moisture condition 2 or average curve number (CN2) are the most influential for runoff. Evapotranspiration was estimated using Penman-Monteith method. Other parameters in Table 1 were also fine-tuned within the recommended range that resulted in a better match between observed and simulated flow data in Canagagigue watershed. In addition, parameters affecting CN, such as soil hydrological class and land use, were modified in some of the HRUs during the calibration.

3.3. Results and Discussion

Daily streamflow data from October 1, 1994 to September 30, 1998 were used for calibration and the remaining data from October 1, 1990 to September 30, 1994 were used to validate the model performance. The calibration years were chosen for the completeness of their observed data and the inclusion of representative years (normal, wet and dry).

The watershed water balance for the calibration and the validation period is presented in Table 3.2. On average, SWAT over-estimated and MIKE SHE under-estimated the mean annual flow rate. APEX under-estimated river flow rate in the calibration period but overestimated it during the validation period.

Table 3.2. Watershed water balance during calibration period for MIKE SHE, APEX and SWAT

	Indicator	Calibration Period				Validation Period			
	Hydrologic year	94-95	95-96	96-97	97-98	90-91	91-92	92-93	93-94
Measured	Precipitation (mm)	814	1136	906	677	1032	932	925	835
	$Flow_{obs}$ (mm)	281	440	489	254	474	311	323	300
	Surface runoff (mm)	169	264	294	152	284	187	194	180
MIKE SHE	ET (mm)	618	560	545	599	620	580	559	593
	$Flow_{sim}$ (mm)	244	444	414	265	442	202	429	300
	Surface runoff $_{sim}$(mm)	146	227	248	159	146	227	248	159
APEX	ET (mm)	632	614	589	476	655	656	605	601
	$Flow_{sim}$ (mm)	202	404	319	146	513	160	450	330
	Surface runoff $_{sim}$(mm)	121	243	192	88	308	96	270	198
SWAT	ET (mm)	563	500	506	459	566	520	519	454
	$Flow_{sim}$ (mm)	272	514	448	173	506	325	482	365
	Surface runoff $_{sim}$(mm)	163	308	269	164	304	195	289	219

Note: $Flow_{obs}$: observed flow; Surface runoff: basesflow separation obtained surface runoff; Et: Evapotranspiration; $Flow_{sim}$: simulated flow by the models; Surface runoff $_{sim}$: simulated surface runoff by the models

Observed and simulated daily and monthly average streamflow using SWAT, MIKE SHE and APEX for the calibration and validation periods are presented in Figures 3.6 to 3.9.

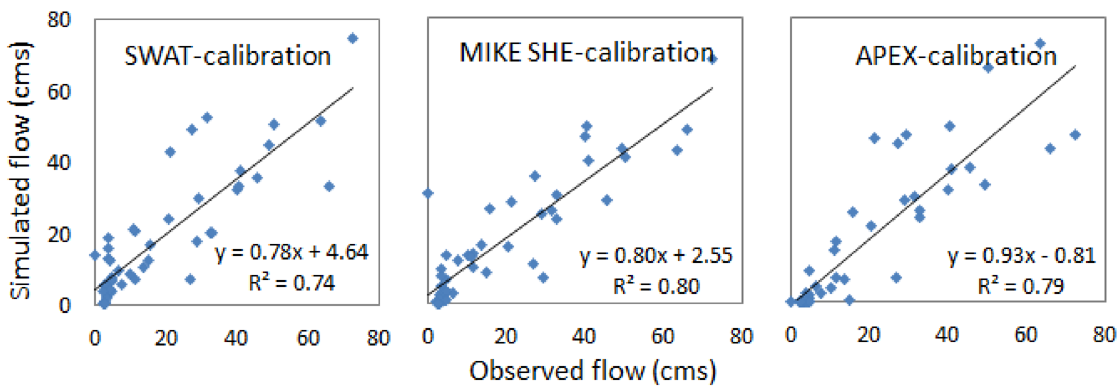

Figure 3.4. Observed and simulated monthly average streamflow for the calibration period (1994-1998)

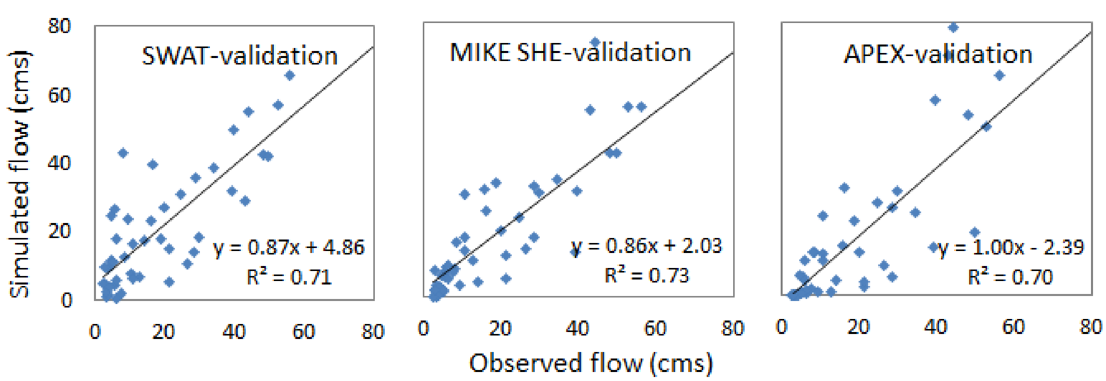

Figure 3.5. Observed and simulated monthly average streamflow for the validation period (1990-1994)

The scatter plots of observed and simulated monthly discharges (mm) for the three models are plotted in Figures 3.4 and 3.5 for the calibration and the validation periods, respectively. On the basis of the visual analysis of the observed and predicted runoff (Figure3.4 and 3.5), the overall simulation appears to be reasonably good.

Model predictions were compared with observed data on a daily and monthly basis. All three modelling approaches and observed data are compared, on a monthly basis, in Figures 3.6 and 3.7, respectively, for the calibration and validation years. Similar comparisons, but on a daily basis are presented in Figures 3.8 and 3.9, respectively.

Based on Figures 3.4 to 3.9, one can conclude that with respect to the mean observed discharge assessed under calibration conditions, the models yielded comparable results. The performance of the models with respect to simulated river discharge was further examined using statistical criteria, applied to the calibration and validation periods. Model calibration and validation statistics, comparing observed and simulated flows for monthly and daily time intervals, are presented in Table 3.3 and Table 3.4. Better model performances are realized if the values of RMSE are closer to zero, and R^2 and EF are close to unity and smaller PBIAS and RSR have small values. According to Moriasi et al. (2007b), a model is considered calibrated for flow if monthly NSE $\geq$ 0.65 and PBIAS $\leq \pm 10\%$ and RSR $\leq$ 0.60. Therefore, all three MIKE SHE, SWAT and APEX models were well calibrated as shown by the statistics in Table 3.3.

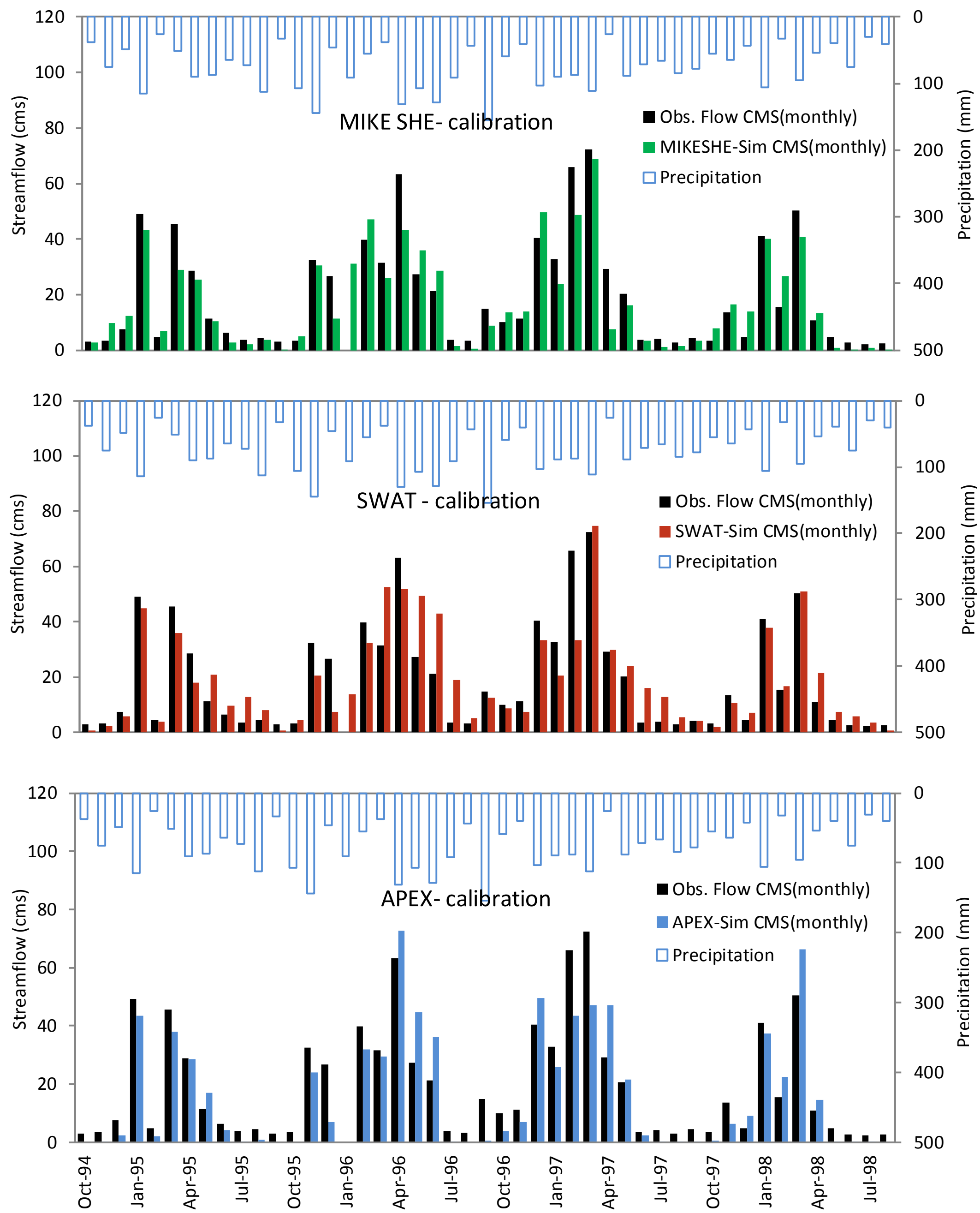

Figure 3.6. Observed and simulated monthly average streamflow using SWAT, MIKE SHE and APEX for the calibration period (1994-1998)

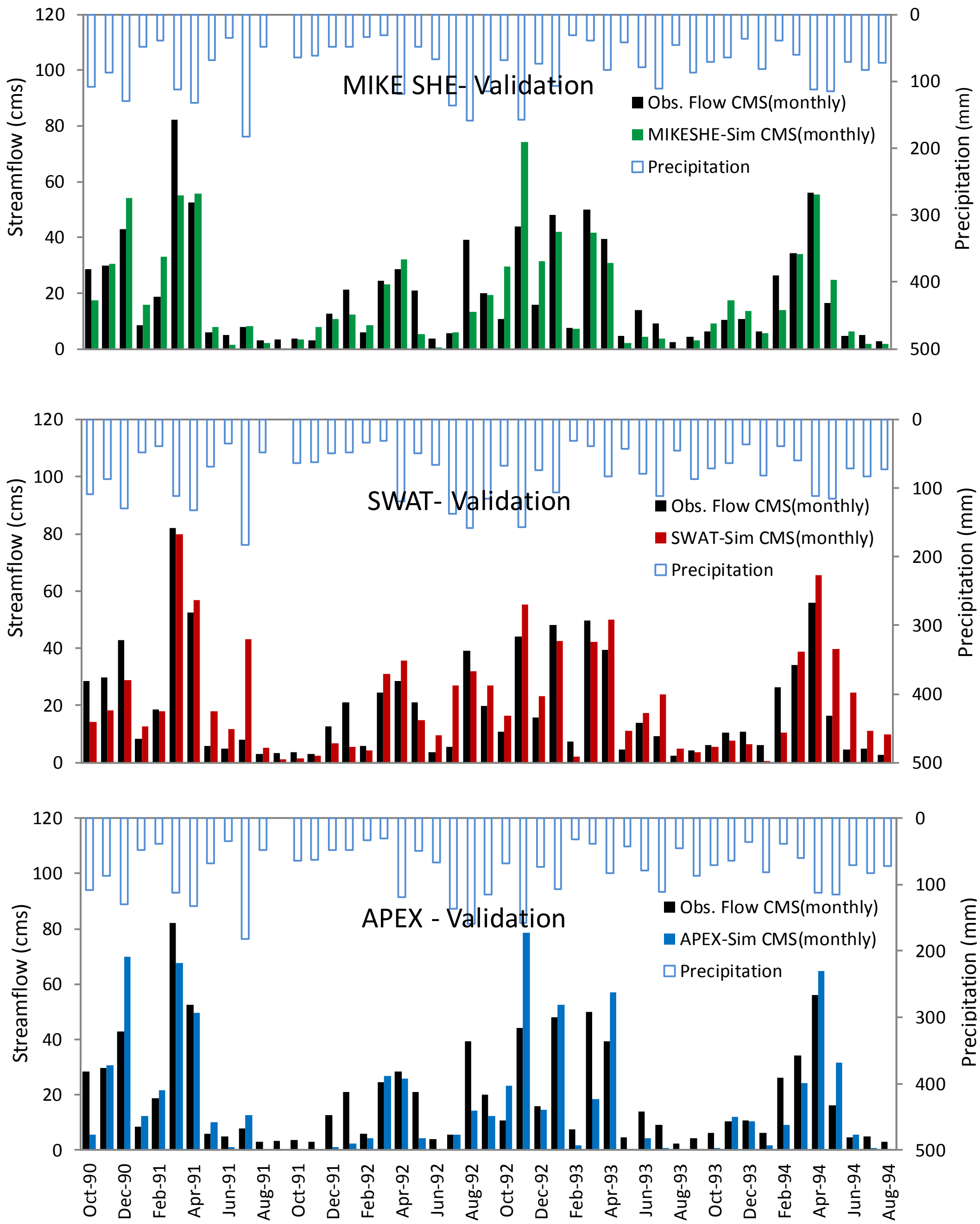

Figure 3.7. Observed and simulated monthly average streamflow using SWAT, MIKE SHE and APEX for the validation period (1990-1994)

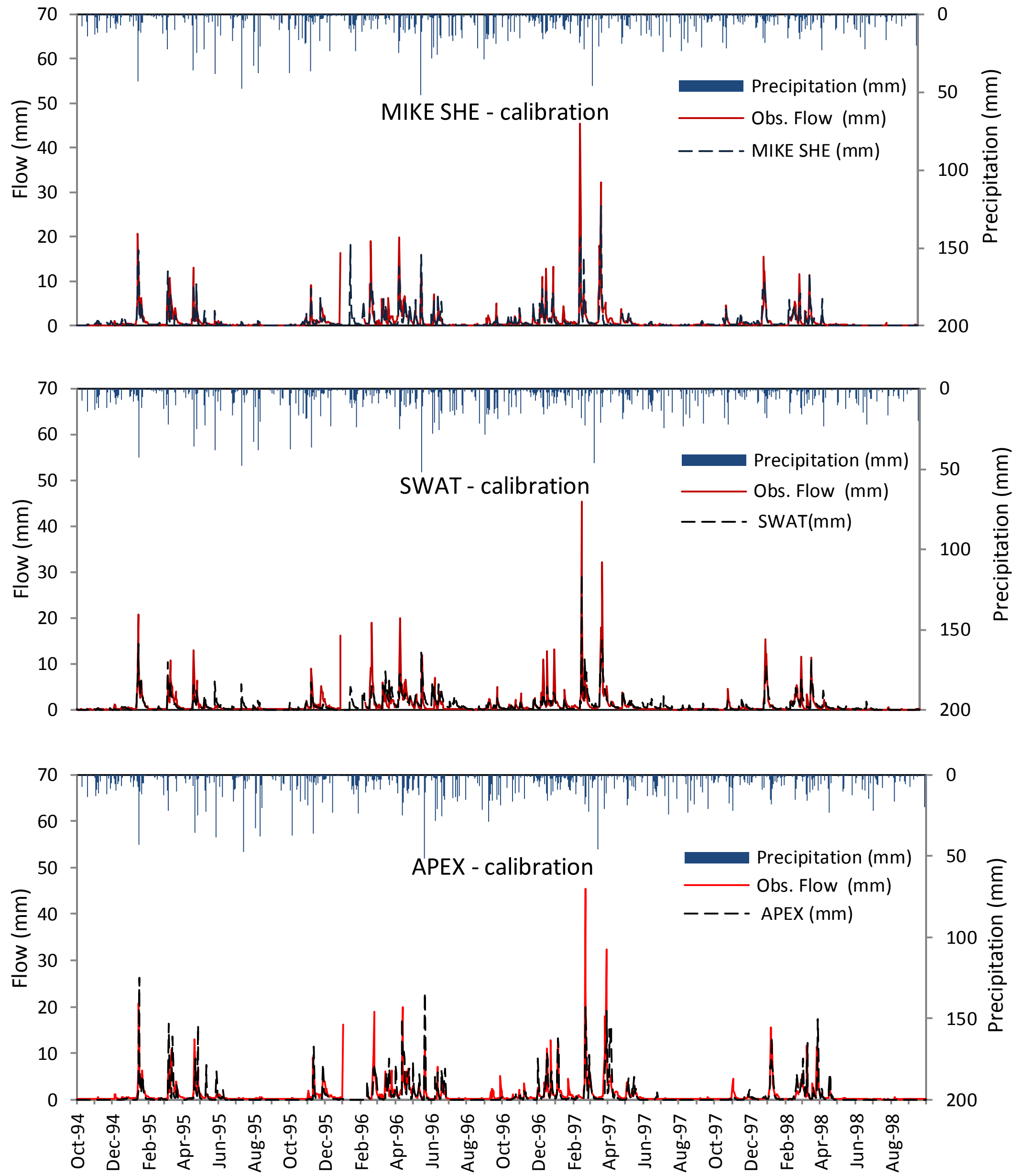

Figure 3.8. Observed and simulated daily streamflow using SWAT, MIKE SHE and APEX for the calibration period (1994-1998)

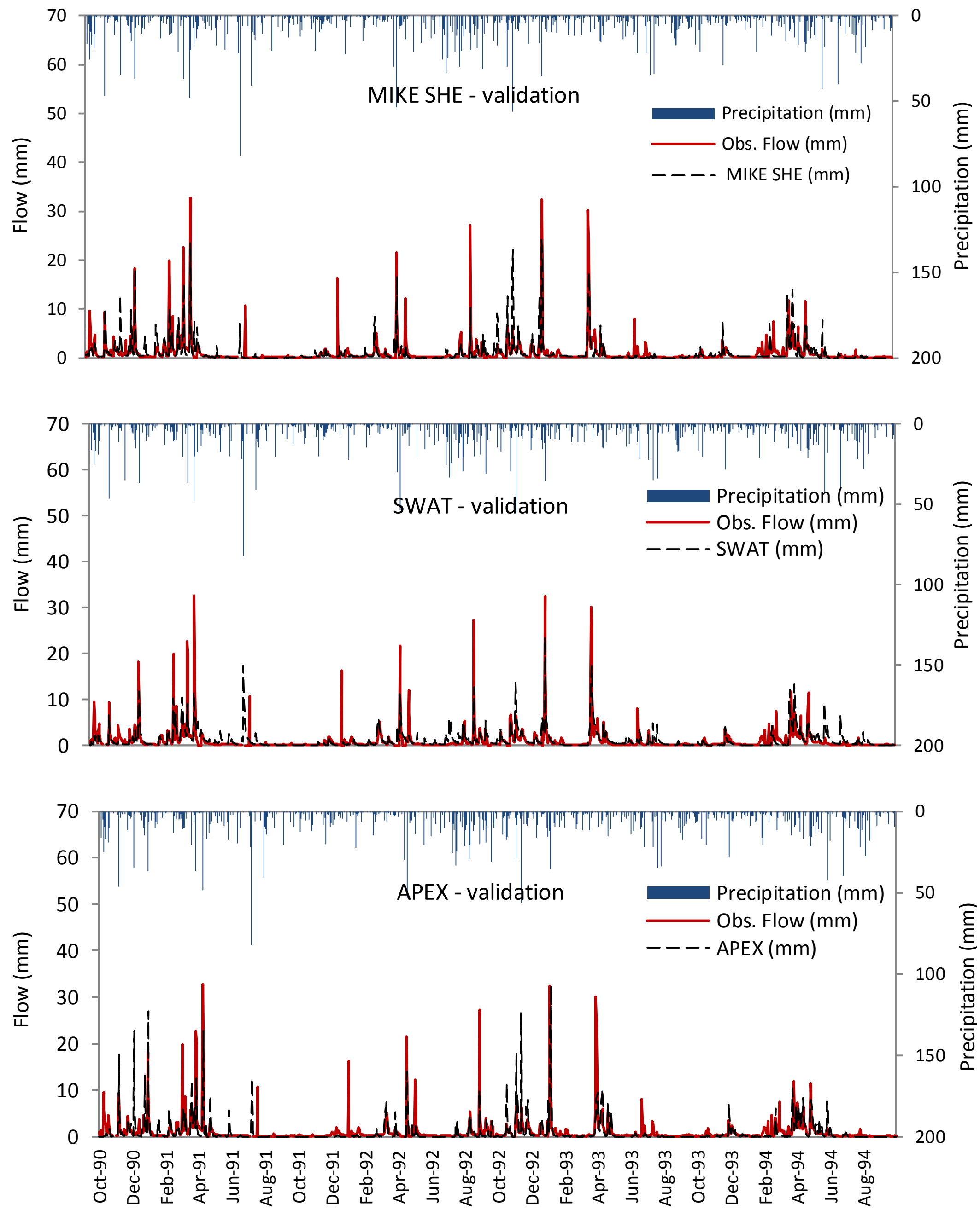

Figure 3.9. Observed and simulated daily streamflow using SWAT, MIKE SHE and APEX for the validation period (1990-1994)

Table 3.3. Monthly calibration and validation statistics for MIKE SHE, APEX and SWAT

Statistical Index	SWAT		MIKE SHE		APEX	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
R^2	0.74	0.64	0.80	0.64	0.81	0.65
RMSE	9.89	12.04	8.70	11.42	9.43	14.75
RSR	0.27	0.34	0.21	0.29	0.32	0.44
NSE	0.73	0.73	0.79	0.71	0.76	0.70
PBIAS	-3.14	-12.5	6.67	3.57	11.71	13.07

Table 3.4. Daily calibration and validation statistics for MIKE SHE, APEX and SWAT

Statistical Index	SWAT		MIKE SHE		APEX	
	Calibration	Validation	Calibration	Validation	Calibration	Validation
R^2	0.57	0.41	0.59	0.44	0.51	0.29
RMSE	1.03	2.00	0.95	2.00	1.26	2.19
RSR	0.47	0.61	0.40	0.60	0.60	0.72
NSE	0.53	0.39	0.59	0.40	0.30	0.31
PBIAS	-1.52	-7.8	10.29	8.30	10.69	27.20

These statistical coefficients (Tables 3.3 and 3.4) show that the fully-distributed physically-based MIKE SHE model performed better than the semi-distributed SWAT and APEX models during both calibration and validation. As might be expected, all three models performed slightly better in the calibration period than in the validation period.

Based on RMSE and R^2 values all three models performed better for monthly comparisons than daily ones. On a monthly basis, the R^2 for APEX was slightly better than that for SWAT or MIKE SHE; however, the converse was the case for the RMSE and NSE. This shows that although the APEX prediction follows trends in the observed data, the deviation of the results from the average is high. For daily predictions, all statistical parameters show better performances with the MIKE SHE results.

3.4. Conclusions

The observed mean daily discharge was used to examine the performance of the fully distributed MIKE SHE model and the semi-distributed SWAT and APEX models. All three models require a fair amount of input and model parameters. In order to understand their limitations and advantages, these widely used watershed management models were tested using the same flow data drawn from a gauging station at the outlet of the Canagagigue Creek watershed, in Ontario, Canada. The performance of the three models was tested using both qualitative (graphical) and quantitative (statistical) methods.

For the comparison, use was made of the discharge monitored at the Floradale station, located at the outlet of Canagagigue Creek watershed, for the period 1990-1998. One year of data was used to initialize the models, while from the 8-year record of daily discharge values; four years were used for calibration of the models and the remaining 4 years to validate them.

All three models are able to simulate the hydrology of the watershed in an acceptable way. The calibration results for the three models were similar, though the models differed in concept and spatial distribution. Notwithstanding their similarity in modelling capacity, a comparative analysis showed the MIKE SHE model to be slightly better at predicting the overall variation in streamflow. The second best model was SWAT; its performance only differed from that of MIKE SHE in the validation period. APEX performance in predicting daily mean streamflow was not as good as that of the other models. This can be attributed to the fact that it was originally developed for small scale watersheds with a low concentration time. Therefore, APEX calculates monthly flow rates the better than daily flow rates. Both the SWAT and APEX models are based on Curve Number (CN) method for estimating surface runoff. It was expected that both models have relatively similar results. The reason for poorer performance of APEX can be due to the fact that the flexibility of SWAT for calibration is higher than of APEX. For example, in SWAT, the curve number can be manually manipulated and changed to better simulate the observed surface runoff but in APEX the CN values are calculated based on its components and cannot be entered directly.

CONNECTING TEXT TO CHAPTER 4

This chapter is a manuscript prepared to be submitted to Transaction of the ASABE. The format has been changed to be consistent within this thesis. All literature cited in this chapter is listed in the reference section at the end of this thesis. From the previous chapter, it can be concluded that both MIKE SHE and SWAT models do a comparable job in simulating watershed hydrology. The SWAT model is a good model for simulating surface hydrology but, like most of the watershed model, it is quite weak in subsurface hydrology simulations. In humid region of North America, most agricultural farms also have tile drains installed to ascertain trafficable conditions during spring and fall seasons. However, most watershed models include tile drainage system in the simulation in a rather simplistic manner. Therefore this chapter details on the development of a new watershed model called SWATDRAIN, which fully incorporates DRAINMOD, a well-known and well-tested subsurface hydrology model for tile-drained fields, into SWAT.

CHAPTER 4: SWATDRAIN, A New Model to Simulate the Hydrology of Agricultural Farmlands, Part I: Model Development

Golmar Golmohammadi, Shiv O. Prasher, Ali Madani, Mohamed Youssef and Ramesh Rudra

Abstract

Fluctuations in the water table depth are important for planning agricultural drainage management systems at the field and the watershed-scale. Subsurface drainage is a common water table management system used to maximize crop production in regions with seasonally high water tables. However, it is also a major source of nutrients, pesticides and other emerging pollutants in water bodies. Therefore, it is important that hydrologic models realistically simulate tile drainage flow and the water table depth. The goal of this study was to develop a model that can better simulate both surface and subsurface water flows in tile drained watersheds, and also to improve the water table dynamics on a watershed scale. This was accomplished by fully incorporating the DRAINMOD model into the Soil and Water Assessment Tool (SWAT) model. In this modeling approach, surface flow is simulated using the SWAT model, and subsurface flow is estimated using the DRAINMOD model. The newly developed model, referred to as SWATDRAIN, has the potential to perform simulations of multiple scenarios to determine cost-effective water management systems such as controlled drainage, subsurface irrigation and wastewater treatment at the watershed scale. The SWATDRAIN model was validated for both fully-drained agricultural and partially-drained mixed watersheds.

Key Terms: Hydrological modeling; SWATDRAIN; SWAT; DRAINMOD; Watershed scale

4.1. Introduction

Subsurface tile drainage is a common water management practice in agricultural regions with high water table soils. In humid regions of North America with fine textured soils, subsurface drainage systems are installed to enhance crop production by protecting crops from waterlogging caused by shallow water tables. In the provinces of Ontario and Quebec, approximately two million hectares of cropland, used mostly for corn and soybean production, are subsurface-drained (Helwig et al., 2002).

Although subsurface drainage provides many agronomic and environmental benefits, it increases leaching loss of nitrate-nitrogen (NO_3-N) (Gilliam et al., 1999). There is a growing concern relative to NO_3-N movement and its detrimental impact on both groundwater and surface water quality (Baker et al., 1975; Gilliam, 1987; Skaggs., 1994). In particular, subsurface drainage is known to expedite the transport of NO_3-N, pesticides, bacteria, and emerging contaminants into surface water (Thomas et al., 1992; Randall et al., 1997; Zucker and Brown 1998; Dinnes et al., 2002; Moriasi et al., 2012).

Research of a water resources system at the watershed level can be conducted by either field experiments or using watershed models. Field research in agriculture has been conducted without use of agricultural system models; it has been largely empirical and site-specific (Ma et al., 2000a).

Collecting long-term hydrologic and water quality data for a range of agro-climatic conditions is expensive, time-consuming, and often infeasible. Computer models, on the other hand, can easily be used with lower cost and less time to simulate the hydrological and biogeochemical processes for agro-ecosystems at different temporal and spatial scales. In many humid areas, agricultural drainage is an essential part of the water management system and its impact on the hydrology and water quality must be realistically simulated.

There are several hydrologic models designed to simulate subsurface hydrology. However, DRAINMOD (Skaggs, 1978) was among the first comprehensive models developed to simulate the water balance and the impact of subsurface water management of tile-drained fields. The first version of DRAINMOD was developed in the 1970s, with numerous modifications and additions continuing until the present (Skaggs, 2012).

The hydrologic component of the current version of the model includes freezing, thawing, and snowmelt components and is capable of simulating drainage phenomena in cold regions (Luo et al. 2000, 2001). DRAINMOD has been used and tested worldwide and is proven to be an effective model for simulating flows from poorly drained high water table soils, (Skaggs, 1982; Singh et al., 1994; Lou et al., 2000, 2001; Youssef et al., 2006; Yang et al., 2007; Wang et al., 2006; Dayyani et al., 2009, 2010a).

Numerous models can be used to simulate the hydrology of a watershed including the Hydrological Simulation Program-Fortran or HSPF (Bicknell et al., 1996), the European Hydrological System Model or MIKE SHE (Refsgaard and Storm, 1995), Areal Non-point Source Watershed Environment Response Simulation or ANSWERS (Dillaha, 2001), Annualized Agricultural Non-Point Source model or AnnAGNPS (Bingner et al., 1998), Watershed Analysis Risk Management Framework or WARMF (Chen et al., 1998), The Agricultural Policy/environmental eXtender (APEX) model (Williams and Izaurralde, 2006), Williams et al., 2006; Williams et al., 2008; Gassman et al., 2009), and Soil and Water Assessment Tool or SWAT (Arnold et al., 1998).

Each model has its own strengths and weaknesses. Simulation software is one of the key tools in recent research activities for watershed management; however, most of these models are focused on surface water systems; subsurface flows, including tile drainage, are usually handled in a rather simplistic way. The lack of an integrated, watershed management model, with a water table management simulation tool, has been noted in the literature.

SWAT is among the most widely used watershed scale hydrologic and water quality models. It is a conceptual, continuous-time model, developed as a tool for water resource managers to assess the impacts of changes in land use and management practices as well as potential climate change on water resources and nonpoint-source pollution in watersheds and large river basins (Arnold et al., 1998). SWAT has been widely applied in various scenarios and watersheds (Hanratty and Stefan, 1998).

SWAT2000 was enhanced by adding a subsurface drainage systems component assuming that these systems have already been designed for specific spacing and pipe size (Arnold et al., 1999). This enhanced version of SWAT was evaluated at the field scale with measured data and yielded satisfactory results. However, it was found that SWAT2000 was not able to accurately simulate subsurface flow and stream discharge when applied at a watershed-scale because the incorporated tile drainage algorithms did not accurately represent the water table dynamics at the watershed scale (Arnold et al., 1999). Additionally, these modifications did not allow for simulating of systems with varying tile spacing, depth, and size (Moriasi et al., 2009). Moriasi et al. (2007a) incorporated the Hooghoudt's (1940) steady-state and Kirkham's (1957) tile drain equations into SWAT, which have been successfully used in the DRAINMOD model (Skaggs, 1978); these alternative tile flow simulation methods take into account tile spacing and drain tube size in addition to the depth of the tile drain. This version of SWAT was tested at the watershed scale with satisfactory results; it simulated water balance components of a tile drained South Fork Watershed (Moriasi et al., 2012).

The rate of subsurface water movement into drain tubes, or ditches, depends on the lateral saturated hydraulic conductivity (K) of the soil as well as the drain spacing, size, and depth, the depth of the soil profile and the water table elevation (Skaggs, 1980). Therefore, it can be said that the tile drain outflow, at any given time, is determined by proximity of the water table to the ground surface. Therefore, in order to realistically simulate subsurface tile drainage flow, it is also important that a hydrologic model realistically simulates water table depth.

DRAINMOD model simulates fluctuations in shallow water table depth and the effect of tile drainage systems on the soil water balance. The model computes water table depth based on drainage volume versus water table depth relationship, where drainage volume is the effective air volume above the water table. This relationship is used to determine the distance that the water table falls or rises when a given amount of water is removed from or added to the soil profile. The drained water volume at various water table depths can be measured directly from large undistributed soil cores or it can be estimated from the soil water characteristics or from the drainable porosities of each layer (Skaggs, 1980).

Several attempts have been made to modify SWAT model to simulate shallow water table fluctuation (Du, et al., 2005; Neitsch et al., 2002a; Moriasi et al., 2009; Moriasi et al., 2011). In SWAT2005 (Neitsch et al., 2002a) water table depth is calculated using 30-day moving summations of precipitation, surface runoff and ET. In SWAT-M (Du, et al., 2005), a restrictive layer is set at the bottom of the soil profile and the water table depth (WTD) fluctuates from the soil surface down to the restrictive layer. The soil profile above the restrictive layer is allowed to fill to field capacity; additional water is allowed to fill the profile from the bottom soil layer upward, changing the height of the water table above the restrictive layers.

Moriasi et al. (2009) incorporated algorithms based on DRAINMOD model into SWAT relating drainage volume with water table depth. They used a calibration factor converting drainage volume into water table depth for hydrologic response units. In this approach, the water table depth is computed as a function of drainage volume using a simple linear water table depth prediction equation that closely matches the measured water table depth values. Moriasi et al., (2011) revised this approach by estimating the calibration factor as a function of soil physical properties. The approach used by Moriasi et al. (2009, 2011) to calculate water table depth differs from the DRAINMOD approach in the way of calculating the drainage volume and how drainage volume relates to water table depth.

In this version of SWAT, DRAINMOD was not fully integrated into SWAT and the water table depth calculation was different from that in DRAINMOD. Although, SWAT calculates tile drainage using the same equations used in DRAINMOD, Hooghoudt's (1940) and Kirkham's (1957) equations, the SWAT modifications by Moriasi et al. (2009, 2011) are different from DRAINMOD in the method of calculating the water table depth which affects the calculation of tile drainage on a daily basis. Thus, SWAT could not fully integrate the advantages of the DRAINMOD model into the subsurface drainage calculation. The soil water content distribution in the unsaturated zone does not follow the soil water retention relationship when there is tile drainage in the watershed. This can cause an error in computing evapotranspiration, drainage flux and the water table elevation.

Furthermore, the most recent SWAT model (SWAT2012), which includes the Hooghoudt's (1940) steady-state and Kirkham's (1957) tile drain equations and a modified DRAINMOD approach for calculating water table depth, is unable to simulate drainage water management practices such as controlled drainage, subirrigation and wastewater application. Thus this version of SWAT cannot predict the watershed scale hydrologic and water quality impacts of the application of drainage water management.

In this study, a new computer model was developed; this model combined SWAT, the surface hydrology simulation model with DRAINMOD, the subsurface water table management model. The integrated model could offer an effective decision-making system for predominantly subsurface drained agricultural watersheds. The new model would also allow for the evaluation of different management scenarios at the watershed scale. Therefore, the goal of this study was to fully incorporate the DRAINMOD model into SWAT to better simulate surface and subsurface flow in tile-drained watersheds and also to enable the new model to perform multiple scenario simulations to determine cost-effective water management systems.

4.2. Materials and Methods

4.2.1. SWAT Model Description

SWAT is a watershed scale model that operates on a daily time step (Arnold et al., 1998). SWAT was developed to predict the impact of management practices on hydrology, sediment, and water quality on an un-gaged watershed. Major components of this model include weather generation, hydrology, sediment, crop growth, nutrients and pesticides (Arnold et al., 1998). SWAT requires specific information about weather, soil properties, topography, vegetation, ponds or reservoirs (if present), groundwater, the main channel, and land management practices to simulate water quantity and quality (Neitsch et al., 2002a, 2002b). In the GIS version, AVSWAT2000 (Di Luzio et al., 2001), certain inputs, such as soil type, land use, elevation, streams, outlets, and gauges are introduced as ArcView files (shapes and grids). The model simulates a watershed by dividing it into subbasins, which are further divided into hydrologic response units (HRUs). These HRUs are the product of overlying soils, land use, and topography.

The processes are lumped at the HRU level, and no interaction occurs between HRUs within a subbasin. SWAT runs on a daily time step and computes, for each HRU in every subbasin, the soil water balance, groundwater flow, lateral flow, channel routing (main and tributary), evapotranspiration, crop growth and nutrient uptake, pond and wetland balances, soil pesticide degradation, and in-stream transformations of nutrients and pesticides (Vazquez-Amabile and Engel, 2005). The discharge of the subbasins is routed through the stream network to the main channel, and from the main channel to the basin outlet (Abu El-Nasr et al., 2002).

The hydrologic components include surface runoff, infiltration, ET, lateral flow, tile drainage, percolation/deep seepage, consumptive use through pumping (if any), shallow aquifer contribution to streamflow for a nearby stream (baseflow), recharge by seepage from surface water bodies (Neitsch et al., 2002a, 2002b). More detailed descriptions of the model are given by Arnold et al. (1998) and Neitsch et al. (2002a).

Daily average soil temperature is simulated at the center of each soil layer for use in hydrology and nutrient cycling. The temperature of the soil surface is estimated using daily maximum and minimum air temperature and snow, plant, and residue cover for the day of interest plus the four immediately preceding days. Soil temperature is simulated for each layer as a function of damping depth, surface temperature and the mean annual air temperature. Damping depth is dependent upon bulk density and soil water (Neitsch et al., 2002a).

4.2.2. DRAINMOD Model Description

DRAINMOD (Skaggs, 1978) is a field-scale, process-based, distributed simulation model originally developed to provide a means of quantifying, on a continuous basis, the performance of multicomponent drainage and related water management systems (Skaggs et al., 2012). The model was developed to describe the hydrology of poorly, or artificially, drained land and can be used to simulate the hydrology of land without drains, including wetlands.

DRAINMOD is the hydrologic component of the soil carbon and nitrogen dynamics model DRAINMOD-NII (Youssef et al., 2005), the soil salinity model

DRAINMOD-S (Kandil et al., 1995), and the recent, whole system models DRAINMOD-FOREST (Tian et al., 2012) and DRAINMOD DSSAT (Negm, 2011), which simulate the hydrology, biogeochemistry, and plant growth for drained forested and agricultural lands, respectively.

DRAINMOD predicts surface runoff, water table depth, drainage outflow, soil water content, evapotranspiration (ET), and infiltration on an hourly, daily, monthly, or annual basis in response to given soil properties, crop variables, climatological data, and site parameter inputs. The model simulates the performance of a given water table management system over a long period of the climatological record. The water management system can be a combination of subsurface drainage, controlled drainage, and sub-irrigation.

The model uses approximate methods to compute the water balance for a vertical soil column of unit surface area at drain mid-spacing. Water balance is conducted on a day-by-day and hour-by-hour basis and predicts surface and subsurface drainage, infiltration and ET. The rates of infiltration, ET, drainage, and distribution of soil water in the profile are calculated by various methods, which have been tested and validated for a wide range of soil and boundary conditions (Skaggs, 1980).

DRAINMOD includes freezing, thawing and snowmelt components and is capable of simulating drainage phenomena in cold regions (Luo et al., 2001). Further detailed descriptions of the hydrologic processes in DRAINMOD are given by Skaggs et al. (2012).

4.3. SWATDRAIN Model Development

DRAINMOD was incorporated into the subsurface hydrology module of the SWAT model as an alternative method for simulating tile drainage and water table depth. The main program of the integrated model, referred to as SWATDRAIN, is a modified version of the main program of SWAT. A new subroutine, termed DrainM.f, was written and incorporated into the SWAT model to affect the modifications by integrating the DRAINMOD model approaches to subsurface hydrology, including predicting tile drainage, water table depth and stored water in the profile in the SWATDRAIN model. The newly developed SWATDRAIN model is based on the DRAINMOD subsurface hydrology simulation and the SWAT surface hydrology simulation. Figure 4.1 demonstrates the SWATDRAIN modeling procedure.

SWATDRAIN computes the soil water balance, on a daily basis, for each HRU in every subbasin. For the first day of the simulation, all calculations were made in the SWAT model and the results, including the surface hydrology parameters, such as surface runoff, infiltration and evapotranspiration were ready for the first day and for all HRUs. According to the presence, or the absence, of a drainage system in each HRU across the watershed, it is termed drained or non-drained, respectively. Next, DRAINMOD is used for tile drained HRUs of the watershed to simulate subsurface hydrology in an unsaturated zone. Details on the integration of DRAINMOD and SWAT are given in the next section.

For this reason, the main surface hydrology parameters calculated by SWAT on an HRU basis would be passed on to DRAINMOD through the intermediary of the DrainM.f subroutine, added to the SWAT source code.

DRAINMOD, which is now part of the SWAT code, would then compute subsurface hydrology parameters including subsurface drainage, water table depth and soil water content in drained HRUs for the same day as the surface hydrology parameters were calculated by SWAT. In this way, the daily values of tile drainage are calculated in SWATDRAIN on a HRU basis using the DRAINMOD model, which computes the tile drainage flux based on the Kirkham and/or Hooghoudt equations and the hydraulic capacity as a function of the daily water table elevation midway between the drains.

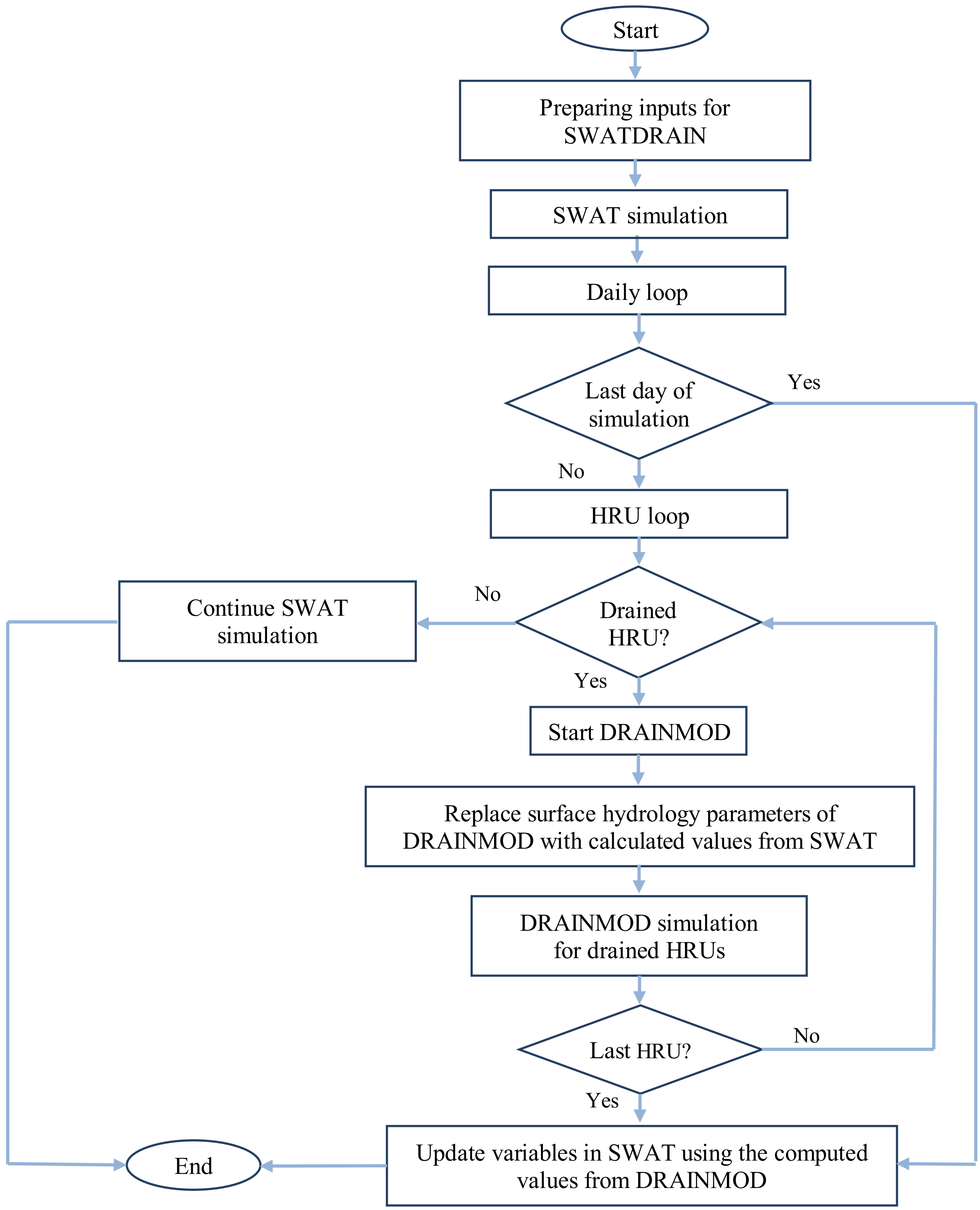

Figure 4.1. SWATDRAIN model flowchart

The water table depth is calculated based on drainage volume versus water table depth relationship. This method is used to determine how far the water table falls or rises when a given amount of water is removed or added to the soil profile. The relationship between drainage volume and water table depth is calculated from the soil water characteristics curve. The amount of water stored in the soil profile is calculated due to the “drained to equilibrium” assumption. In this approach, the water table depth is known from DRAINMOD, which is calculated for every day. By knowing the depth of the water table, using the Van Genuchten equation, the pressure head and soil moisture content of each layer is presented based on the soil water characteristics data available for that particular soil.

Lastly, DRAINMOD and SWAT were incorporated to collectively simulate the hydrology on a watershed scale. This newly developed model integrated a SWAT-driven surface flow and a DRAINMOD driven subsurface flow to improve the accuracy and efficiency of this new model.

The SWATDRAIN model development can be divided into two main procedures: 1) generating the required input data; and 2) integrating the different approaches of SWAT and DRAINMOD while computing the surface and subsurface hydrology components of the final integrated model. These two procedures are explained in the following sections.

4.3.1.1. Generating SWATDRAIN Input Data

The SWAT model requires three geographic information data layers, namely digital elevation model (DEM), soils, and land use. The DEM is used by the ArcSWAT interface to calculate the subbasin parameters, such as slope, and to define the stream network and subbasins. The DEM is also used to calculate the stream network characteristics, such as channel slope, length, and width. The soil map is used to generate the required soil physical and hydraulic parameters. The drainage area map is used to determine the tile drained HRUs. For this reason, the drainage area map is combined with the land use map to determine the extent of drainage in each HRU.

The SWATDRAIN model also requires a full set of DRAINMOD input files. In addition to soil input files in the SWAT model (.SOL file), SWATDRAIN requires two input files which are used as soil input files in the DRAINMOD model (.SIN and .MIS files). For each soil type in the watershed, these two input files are prepared using Rosetta or SoilPrep Programs.

For each type of land cover, a crop input file is required. The land cover information is taken from the land use map. The newly required crop input file for the SWATDRAIN model is in the same format as the DRAINMOD crop file (.CIN). This file is prepared for all available plant types across the watershed using the developed code for input file preparations in SWATDRAIN. The rain and temperature input files in SWATDRAIN corresponds to the SWAT input file format (.TEM) and contains the daily precipitation and the daily values of maximum and minimum temperatures.

4.3.1.2. SWATDRAIN Integration Procedure

4.3.1.2.1. Infiltration

In this step, infiltration is computed using the SWAT approach. SWAT uses either the SCS curve number procedure (SCS, 1972), or the Green and Ampt infiltration method (Green and Ampt, 1911), to estimate infiltration and surface runoff. Therefore, in the SWATDRAIN model the user specifies one of the two methods for calculating infiltration. Next, on a daily basis, the amount of infiltration computed by SWAT is transferred to DRAINMOD and used as the model's "precipitation" input. For this reason, the variable called PCPINFL, which is the amount of rainfall infiltrated every day in each HRU, is used as daily precipitation in the format of the DRAINMOD's rainfall input file (.RAI).

In order to transfer the computed daily values of infiltration for all HRUs, code was written and a function called PCP-INF was incorporated into the DrainM.f subroutine.

DRAINMOD's surface depression storage is set to a large value in order to prevent DRAINMOD from generating surface runoff in response to SWAT-predicted infiltration, which is considered as "precipitation" to DRAINMOD. In this case, all infiltration predicted by SWAT model infiltrates the soil in DRAINMOD simulation.

4.3.1.2.2. Evapotranspiration

There are different options for calculating daily potential evapotranspiration (PET) in the SWATDRAIN model. Potential evapotranspiration can be computed using the available methods of either SWAT or DRAINMOD. Three methods are used in SWAT for PET estimation: the Penman-Monteith method (Monteith, 1965), the Priestly-Taylor method (Priestly and Taylor, 1972), and the Hargreaves method (Hargreaves and Samani 1985). SWAT also has the option of entering the PET as an input file. In DRAINMOD, PET is either calculated by the model using the Thornthwaite method (Thornthwaite, 1948) or it can also be entered as daily or monthly PET input by the user. Therefore, in the SWATDRAIN model the user can choose any of these available methods for PET calculation.

Hence, the daily PET computed in SWAT for each HRU is used to create a DRAINMOD PET input file (.PET). Also, the user has the option to use the available PET calculation methods in DRAINMOD instead of transferring the PET from SWAT.

The simulated daily evapotranspiration values are calculated in SWATDRAIN using DRAINMOD approach, which is a function of the soil water supply within the root zone. In DRAINMOD approach, once the PET is determined, a check is made to determine if soil water conditions are limiting. As long as the soil water content in the root zone is above the lower limit of the water content (usually taken as wilting point), ET is equal to PET. As water is removed, a dry zone is created. When the dry zone depth becomes equal to the effective root depth, ET is limited by soil water conditions and is set equal to the rate of upward flux. Further details are given in the DRAINMOD Reference Report (Skaggs, 1980).

This was incorporated as part of the newly developed code in the form of a function in the DrainM.f subroutine.

4.3.1.2.3. Tile Drainage

In the SWATDRAIN model, there are three approaches to compute tile drainage that correspond to the available approaches in SWAT and DRAINMOD. The currently available approaches in SWAT can be chosen by setting a flag variable (ITDRN) in the tile drainage routine equal to 0 or 1.

In the first approach (ITDRN=0), tile drainage in an HRU is calculated as a function of drain depth, the amount of time required to drain the soil to field capacity, and the amount of lag between the time that water enters the tile until it exits the tile and enters the main channel. The second approach (ITDRN=1) utilizes the Hooghoudt and Kirkham equations, and requires additional inputs such as drain spacing and the drainage coefficient. Table 4.1 presents the tile drainage input parameters required for the two approaches available in SWAT.

In the newly added approach (ITDRN=2), the daily values of tile drainage are calculated using the DRAINMOD model, which computes the tile drainage flux based on the Kirkham and/or Hooghoudt equations and the hydraulic capacity as a function of the daily water table elevation midway between the drains.

Table 4.1. Tile drainage related input parameters in SWAT approaches

variable	Parameter description
SWAT Original	
ITDRN	Tile drainage routines flag: 0 = Original SWAT tile equations (Subroutine ORIGTILE)
DDRAIN	Depth to subsurface tile (mm)
TDRAIN	Time to drain soil to field capacity, time required to drain the water table to the tile depth (h)
GDRAIN	Drain tile lag time, the amount of time between the transfer of water from the soil to the drain tile and the release of water from the drain tile outlet to the channel (h)
DEP_IMP	Depth to impervious layer (mm)
	SWAT (Modified DRAINMOD approach)
ITDRN	Tile drainage routines flag: 1 = DRAINMOD tile equations (subroutine DRAINS)
ADEPTH	Actual depth from surface to impervious layer (mm)
DC	Drainage coefficient (mm day^{-1})
GEE	Factor G in Kirkham (1957) equation (dimensionless)
HDRAIN	Effective depth from drain to impermeable layer (mm)
SDRAIN	Distance between two drains (mm)
PC	Pump capacity (mm h^{-1}) (subirrigation)

In addition to the tile drainage prediction inputs (for each HRU) in the SWAT model, the SWATDRAIN model requires several new inputs according to the required drainage system design parameters in the DRAINMOD model. Table 4.2 presents the required tile drainage input parameters in the SWATDRAIN approach.

Table 4.2. Tile drainage input parameters in SWATDRAIN approach

variable	Parameter description
ITDRN	Tile drainage routines flag/code: 2 = DRAINMOD algorithm (subroutine DrainM)
	Drainage system design
B	Depth from soil surface to drains (cm)
L	Spacing between drains (cm)
Re	Effective radius of drains (cm)
H	Actual distance from surface to impermeable layer (cm)
De	Equivalent depth from drain to permeable layer (cm)
DC	Drainage coefficient (cm/day)
G	Kirkham's coefficient
W	Initial depth to water table (cm)
PC	Max. Subirrigation pump capacity (cm/day)
S_m	Maximum surface storage (cm)
S_l	Kirkham's depth for flow to drains (cm)
	Freeze/Thaw
ZA, ZB	Computational depth functions
TKA, TKB	Soil thermal conductivity function
Threshold temperatures	Average air temperature below which precipitation is snow (°C) Average air temperature above which snow starts to melt (°C) Snow melt coefficient (mm/d-°C) Critical ice content above which infiltration stops (cm^3/cm^3)
Initial and boundary conditions	Initial conditions (snow depth (cm) and temperature (°C) Snow depth (m) and density (kg/m^3) Phase lag for daily air temperature (hour) Soil temperature at the bottom of the profile (°C)
Freezing characteristics	Soil temperature (°C) and unfrozen water content (cm^3/cm^3)
	Controlled drainage and subirrigation
Weir setting	Weir setting for controlled drainage and subirrigation

In addition to the drainage design parameters in SWATDRAIN, the parameters related to freeze/thaw conditions should also be provided if the model is used for cold regions. This is another added advantage of the newly developed model.

Furthermore, the SWATDRAIN model is capable of performing scenario simulations such as controlled drainage, subirrigation, and wastewater application on farms across the watershed. Therefore, additional parameters for those scenarios need to be provided in the model.

Drainage design parameters vary over the watershed. These inputs are defined for each HRU with the presence of tile drainage, based on the available drainage systems on the farms. The recommended range of values for the tile drain parameters can be determined based on the literature. In order to prevent DRAINMOD from simulating surface runoff, the surface storage value is set to a large value to force all of the computed infiltration values from the SWAT model to infiltrate into the soil. Lateral saturated hydraulic conductivity is soil-specific and it is an input into the model from the soil file used for each HRU.

4.3.1.2.4. Water Table Depth

SWATDRAIN calculates the water table depth using the DRAINMOD approach, which is based on drainage volume versus water table depth relationship. This method is used to determine how far the water table falls or rises when a given amount of water is removed or added to the soil profile.

The relationship between drainage volume and water table depth is calculated from the soil water characteristics curve. In this approach, the drainage volume is calculated from a water balance computation in a daily time step. Based on the calculated drainage volume, the water table depth for that specific day is estimated using the soil water characteristics information. Therefore, by using this approach, the water table depth in the SWATDRAIN model is estimated for different types of soils in different HRUs.

4.3.1.2.5. Amount of Water Stored in the Soil Profile

In the new SWATDRAIN model, the amount of water stored in the soil profile is calculated based on DRAINMOD's "drained to equilibrium" assumption. In this approach, the water table depth is known from DRAINMOD, which is calculated for every day.

By knowing the depth of the water table, using the Van Genuchten equation, the pressure head and soil moisture content of each layer is presented based on the soil water characteristics data available for that particular soil. The amount of water stored in each soil layer, called SOL_ST (mm) in SWATDRAIN, is calculated by multiplying the value of the soil moisture content estimated from the soil retention curve by the depth of the layer (mm). It is important to note that SOL_ST is the stored water beyond the depth corresponding to the permanent wilting point.

4.3.1.2.6. Freezing and Thawing Algorithm

The SWATDRAIN model handles the freezing and thawing phenomena using the available freeze/thaw algorithm in the DRAINMOD model (Luo et al., 2000). The DRAINMOD model estimates thermal properties as a function of profile depth and numerically solves the heat flow equation to predict the soil temperature profile. When freezing conditions indicate that the temperatures are below zero, the model calculates the average ice content in the soil profile and modifies the soil hydraulic conductivity and infiltration rate accordingly (Luo et al., 2000). Therefore, integration of DRAINMOD into SWAT leads to a new model which is able to handle the freeze/thaw phenomena; these are not included in the SWAT model.

4.4. Summary and Conclusions

The SWATDRAIN model uses a well-known and well-tested subsurface flow model, such as DRAINMOD, and integrates it into SWAT in order to improve the simulation of both surface and subsurface flow as well as water table dynamics on a watershed scale.

Currently, there are two approaches used by SWAT to compute tile drainage. In the first approach, tile drainage in an HRU is simulated using a simple equation (Arnold et al., 1990). The second approach, incorporated by Moriasi et al. (2007) utilizes the Hooghoudt and Kirkham tile equations. The first approach does not allow for certain scenario simulations, such as varying tile spacing, size, drainage intensity, and water table management. In the second approach, tile drainage is calculated based on the Hooghoudt and Kirkham equations, but all features of the DRAINMOD were not completely integrated into the SWAT model.

In this study, the DRAINMOD model was added to the SWAT model to take advantage of the strong surface flow modeling capabilities of the former and the higher accuracy of subsurface modeling of DRAINMOD. SWATDRAIN calculates the water table depth using the DRAINMOD model, which is computed based on a drainage volume versus the water table depth relationship. It is used to determine how far the water table falls or rises when a given amount of water is removed or added. In this way, the soil water content follows the soil retention curve, unlike the standard SWAT, which usually underestimates the soil water content.

This incorporation also was intended to determine the impact of different water management scenarios on water quantity and quality at the watershed scale and to design a cost-effective and environmentally friendly tile drain water management system. Integration of DRAINMOD into SWAT would increase the capabilities of the new integrated model, SWATDRAIN, to perform scenario simulations such as controlled drainage, subirrigation and wastewater applications at the watershed scale. The previous version of SWAT did not allow for these kinds of scenario simulations. These scenarios will aid in designing a cost-effective water management system in agricultural regions with shallow water table depths. Additional studies required the evaluation of SWATDRAIN to determine how well it simulates the water budget and hydrology.

CONNECTING TEXT TO CHAPTER 5

This chapter is a manuscript prepared to be submitted to Transactions of the ASABE. The format has been changed to be consistent within this thesis. All literature cited in this chapter is listed in the reference section at the end of this thesis. Chapter 5 presents the evaluation of SWATDRAIN model for hydrology in a fully tile-drained agricultural watershed located in Ontario's climatic conditions. A description of the site instrumentation and data collection methodology is provided along with calibration procedures and statistical analyses. Simulation results for tile drainage and water table depth in an agricultural watershed have been presented.

CHAPTER 5: SWATDRAIN, A New Model to Simulate Hydrology of Agricultural Farmlands, Part II: Model Evaluation for a Fully Tile-Drained Agricultural Watershed

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Abstract

The DRAINMOD model was recently incorporated into Soil and Water Assessment Tool (SWAT) model (herein referred to as SWATDRAIN) as an alternative tile flow and water table depth simulation method, as well as a tool to design cost-effective tile drain water management systems. The goal of this study was to evaluate the SWATDRAIN model for the Green Belt watershed, located in southern Ontario. Measured tile drainage and water table depth (WTD) data from this watershed were used to evaluate the capability of the new model to simulate water balance components for this tile drained agricultural watershed. Along with hydrographs, the Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS) and R^2 statistics were used in evaluating the accuracy of SWATDRAIN tile flow and water table depth predictions in light of measured values. Simulations were carried out over the period from 1991 to 1993; 1991 and 1992 data were used for model calibration and 1993 data were used for validation. During both the calibration and validation period, SWATDRAIN simulated the hydrologic response at the watershed outlet adequately and the water table depth and tile flow very well. Model accuracy statistics for monthly mean and daily water table depth over the validation period were respectively 0.86 and 0.70 for R^2, 0.11 and 2.90 for PBIAS, and 0.80 and 0.67 for the NSE. Model accuracy statistics for events, monthly and daily tile drainage over the validation period were respectively 0.86, 0.88 and 0.70 for R^2, 11.7, 17.26 and 23.85 for PBIAS, and 0.84, 0.86 and 0.62

for the NSE. This clearly demonstrates that the integrated DRAINMOD approach provides a potential alternative tile flow simulation method and tile drainage design tool in SWAT.

Key Terms: Hydrological modeling; SWATDRAIN; SWAT; DRAINMOD; Watershed scale.

5.1. Introduction

Agricultural tile drainage systems are used to enhance crop production by protecting field crops from long periods of saturated conditions in the soil root zone, caused by shallow water tables. Though drainage improves soil structure, infiltration capacity, and aeration, it also affects the route of water transport from field to stream (Thooko et al., 1991).

Approximately two million ha of subsurface drained cropland, mainly in corn and soybean production, are located in the Canadian provinces of Ontario and Quebec (Helwig et al., 2002). In many humid areas, agricultural drainage is part of the water flow system and cannot be ignored. Therefore, it is important that hydrologic models realistically simulate tile drainage flow.

There are many hydrologic models developed to simulate subsurface hydrology. DRAINMOD (Skaggs, 1978) was the first comprehensive model developed to simulate the water balance and the impact of water management of tile-drained fields. The first version of DRAINMOD was developed in the late 1970s, with numerous modifications and additions continuing until the present (Skaggs, 2012).

The DRAINMOD model includes freezing, thawing, and snowmelt components and is capable of simulating drainage phenomena in cold regions (Luo et al. 2000, 2001). DRAINMOD has been used and tested worldwide and has been proven to be an efficient and accurate model in simulating flows from poorly-drained high water table soils experiencing freeze-thaw cycles (; Singh et al., 1994; Lou et al., 2000, 2001; Youssef et al., 2006; Yang et al., 2007; Dayyani et al., 2009, 2010a).

Numerous hydrologic models can be used to simulate the hydrology of a watershed. One watershed-scale model that contains a tile drainage component is the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Arnold and Fohrer, 2005).

SWAT is a conceptual, continuous-time model developed to assess the impact of management and climate on water quantity and quality in watersheds and large river basins (Arnold et al., 1998). SWAT has been widely applied under various scenarios and in different watersheds (Hanratty and Stefan, 1998). SWAT has proven to be an effective tool for assessing water resource and non-point source pollution problems for a wide range of scales and environmental conditions across the globe (Gassman et al., 2007).

SWAT2000 was enhanced by Arnold et al. (1999) with a subsurface drainage systems component operating on the basis of equations assuming that these systems have already been designed to a specific spacing and size. This version of SWAT was evaluated at the field scale with measured field data and yielded satisfactory results. However, SWAT2000 was not able to accurately simulate subsurface flow and stream discharge when applied at a watershed-scale because the incorporated tile drainage algorithms did not accurately represent the water table dynamics at the watershed scale (Arnold et al., 1999). The modifications applied to the model do not allow for simulations of systems with varying tile spacing, size, and water table management an essential feature of the model in order to be used for the design and evaluation of cost-effective water management systems (Moriasi et al., 2009).

Moriasi et al. (2007a) incorporated the steady-state Hooghoudt's (1940) and Kirkham (1957) tile drain equations into SWAT; this alternative approach determines subsurface drainage flow as a function of tile size and spacing in addition to tile drain depth. The shallow water table depth simulation methods which have been associated in the SWAT model are the SWAT-M (Du, et al., 2005), SWAT2005 (Neitsch et al., 2002a), modified DRAINMOD (Moriasi et al., 2009) and the recently incorporated, revised modified DRAINMOD (Moriasi et al., 2011). In the SWAT-M model approach (Du, et al., 2005), a restrictive layer is set at the bottom of the soil profile which simulates a confining layer and is used as the maximum water table depth (WTD). The soil profile above the restrictive layer is allowed to fill to field capacity; additional water is allowed to fill the profile from the bottom soil layer upward, from which the height of the water table above the restrictive layers is computed. The SWAT2005 (Neitsch et al., 2002a) routine computes WTD using 30-day moving summations of precipitation, surface runoff and ET (Neitsch et al., 2002a).

The most recent SWAT model (SWAT2009), which includes the steady-state Hooghoudt's (1940) and Kirkham (1957) tile drain equations, as well as the revised modified DRAINMOD approach to water table depth, is unable to perform multiple scenario simulations such as controlled drainage, subirrigation and wastewater application to determine cost effective water management systems at the watershed scale. On the other hand, DRAINMOD is a well-known drainage model, which has been successfully tested and applied to subsurface simulation at the field scale, and is capable of simulating the different water management scenarios (Ale et al., 2009; Singh et al., 2007).

Therefore, a new computer model, combining SWAT the surface hydrology simulation model, with DRAINMOD the subsurface water table management model, was developed. This incorporation also was intended to determine the impact of different water management scenarios on water quantity and quality at the watershed scale and to design an effective decision-making system for predominantly subsurface-drained agricultural watersheds.

The objective of this study was to evaluate the capability of the SWATDRAIN model to simulate hydrology in an agricultural tile drained watershed using measured tile flow and water table depth data from the Green Belt watershed near Ottawa in Ontario.

5.2. Materials and Methods

5.2.1. SWATDRAIN Model Overview

DRAINMOD model was fully incorporated into the subsurface hydrology module of the SWAT model as an alternative method for simulating tile drainage and water table depth. The newly-developed SWATDRAIN model is based on the DRAINMOD subsurface hydrology simulation model and the SWAT surface hydrology simulation model.

SWATDRAIN computes the soil water balance, on a daily basis for each hydrological response unit (HRU) in every subbasin on the watershed under study. For the first day of the simulation, all calculations are made through the SWAT model. The results, including surface hydrology parameters, initiate the system for the first day and for all HRUs.

Each HRU across the watershed is categorized as drained or non-drained according to the presence or absence of a drainage system. Next, DRAINMOD is implemented for the watershed's tile-drained HRUs to simulate subsurface hydrology in an unsaturated zone. For this reason, the main surface hydrology parameters calculated by SWAT at the HRU level are passed on to DRAINMOD through an intermediary of the subroutine added to the SWAT source code. DRAINMOD, which is now incorporated into the SWAT code, would then compute subsurface hydrology processes in drained HRUs for the same day as the surface hydrology processes calculated by SWAT. After simulating the subsurface hydrology components, including subsurface drainage, water table depth, and soil moisture content, the values of these parameters would be used in

SWAT on a per-HRU basis by the added subroutine. This newly-developed model integrated the SWAT-driven surface flow and the DRAINMOD-driven subsurface flow to improve the accuracy and efficiency of the new model.

SWAT uses either the SCS curve number procedure (SCS, 1972), or the Green Ampt infiltration method (Green and Ampt, 1911), to estimate infiltration and surface runoff. Therefore, in the SWATDRAIN model, the user specifies one of the two methods for calculating infiltration.

Different methods can be used in SWATDRAIN for potential evapotranspiration (PET) estimation: the Penman-Monteith method (Monteith, 1965), the Priestly-Taylor method (Priestly and Taylor, 1972), the Hargreaves method (Hargreaves and Samani 1985), the Thornthwaite method (Thornthwaite, 1948) or PET can also be entered as daily or monthly PET input by the user. In SWATDRAIN, the daily values of tile drainage are calculated using the DRAINMOD model (Skaggs et al., 1978), which computes the tile drainage flux based on the Kirkham and/or Hooghoudt's equations as a function of the daily water table elevation midway between the drains and in some cases is limited by the hydraulic capacity of the system (Skaggs, 2012).

SWATDRAIN calculates the water table depth using the DRAINMOD model approach, which is based on a drainage volume *vs.* WTD relationship. This method is used to determine how far the water table falls or rises when a given amount of water is removed or added to the soil profile. The relationship between drainage volume and WTD is calculated from the soil water characteristics. In this approach, drainage volume is calculated from a water balance computation on a daily time-step. Based on the calculated drainage volume, the WTD for that specific day is estimated using the soil water characteristics information. The relationship between water table depth and drainage volume for each soil is defined as an input parameter. Therefore, by using this approach, the WTD in the

SWATDRAIN model is estimated by the DRAINMOD model for different types of soils in different HRUs.

This model is evaluated for two different watersheds. This study focuses on a heavily instrumented small watershed. SWATDRAIN also has been tested for a 18 km^2 watershed.

5.2.2. Watershed Description

The experimental site was a 14 ha watershed located at the Greenbelt Research Farm (Agriculture and Agri-Food Canada, Ottawa, Ontario, Canada) (Figure 5.1). The primary soil type was a Typic Haplaquent (Dalhousie Association, Brandon series) with loamy-textured Ap and B horizons underlain by silty clay at a depth of approximately 0.60 m. The field was flat level, with a mean slope of roughly 0.2%.

Tile drainage was installed on the site in 1986, with laterals installed 1 m below the soil surface at spacing of 15 m. The 14 ha field was divided into four plots. Roughly 0.20 m high berms were built around the periphery of each plot to prevent surface water flow across plots. Each plot was about 3 ha and was drained by four or more tile laterals. Tile effluent from each plot was routed to separate monitoring stations, located in insulated 2.4 m × 1.8 m × 1.8 m plywood shelters, each equipped with a flameless catalytic propane heater for winter monitoring. Continuously flow monitoring was achieved with 152 mm and 229 mm H-flumes and Belfort liquid level recorders. Tile flow data were collected from February 1991 to December 1993.

Flow recording was interrupted for a few days during the spring thaw period due to flooding of the monitoring stations due to water backing up in the tile main from the downstream ditch. Monitoring stations were similarly flooded for a few hours following an intense rainstorm during one flow event (17 to 24 July 1992).

Tile drainage was assumed to be negligible for the duration of the flood periods (Patni et al 1996).

The water retention capacity of the soil was determined by applying tension (-50 to -350 mm of water) to 75 mm × 75 mm intact soil cores collected at depths of 0-0.15 m a 0.15-0.30 m in May 1991, August 1991, and May 1992. Soil moisture was measured *in situ* between 8 June and 17 October 1993, using time-domain reflectometry (Topp, 1993) as reported by Patni et al (1996).

The WTD midway between tile laterals was continuously monitored with a Belfort stage recorder (Belfort Instrument Co., Baltimore, MD) mounted on a 3.0 m deep by 100 mm I.D. perforated pipe. Between June 1991 and December 1993 the WTD was also monitored at 12 observation wells.

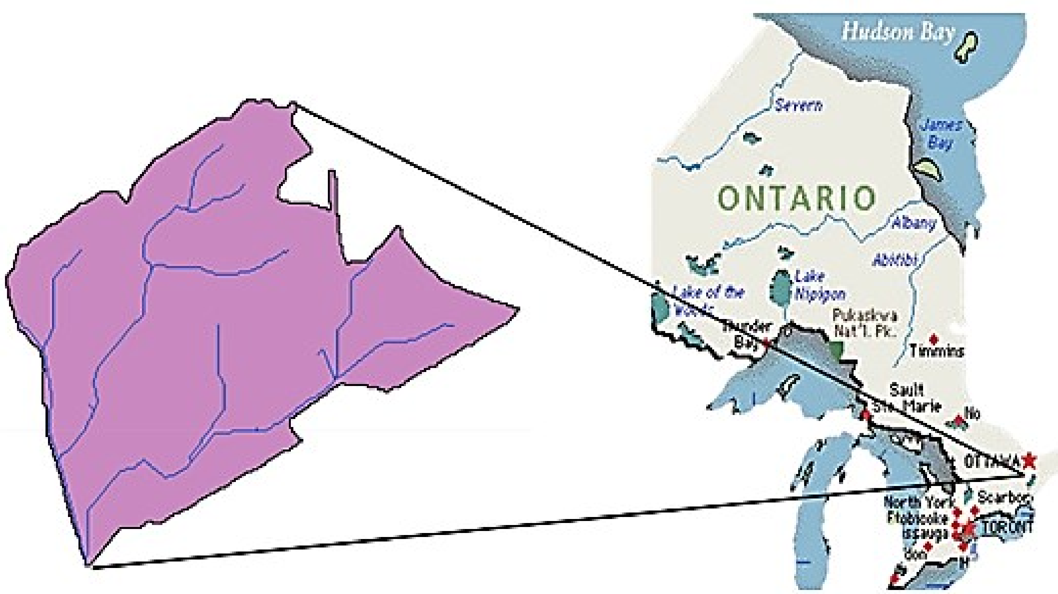

Figure 5.1. Location of the study area

Fluctuation in WTD over the study period was similar at all 12 monitoring sites in the study area. Variation in WTD among the 12 locations generally increased as the water table depth recorded but was relatively small during recharge or rapidly draining periods.

During non-freezing period (mid-April to mid-October) rainfall was collected on site using Belfort Universal rain gauges. Precipitation values for the remainder of the year were obtained from the Agriculture and Agri-Food Canada weather station located 12 km from the experimental site. Monthly rainfall during the study period is given in Figure 5.2.

Annual precipitations values were close to the 75-year regional average of 864 mm, except in 1991 when precipitation was below the average, such that the WTD exceeded 3.0 m during most of the growing season. In 1992, during the growing season, two months of July and August was particularly wet, while in the year 1993, the spring was particularly wet with 127 mm of rain in April. In addition to the weather data inputs, the model requires a Digital Elevation Model (DEM), soils and land use and agricultural management data.

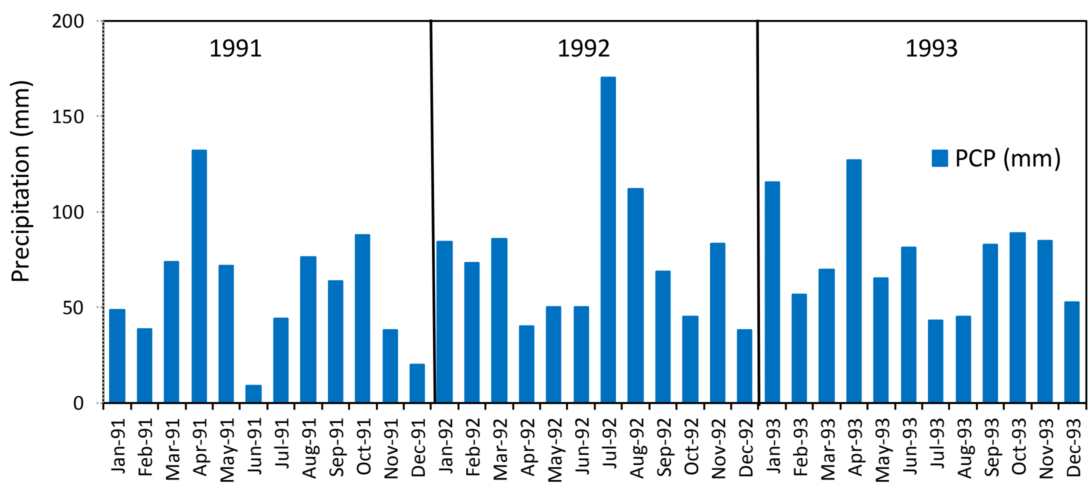

Figure 5.2. Monthly precipitation

The DEM is used by the interface to calculate sub-basin parameters, such as slope and slope length, and to define the stream network.

5.2.3. Different Approaches of Tile Drainage and Water Table Depth Calculation in SWATDRAIN

In this study, two different available approaches of simulating tile drainage and water table depth in SWAT model and SWATDRAIN model were evaluated and compared. Table 5.1 compares the three algorithms used in this study to calculate tile drainage and WTD.

Table 5.1. List of the different tile drainage and WTD calculation algorithms used in this study

Algorithm	Tile drainage	WTD
Original SWAT	ITDRN=0, original tile drainage equation	IWTDN=0, the soil profile above the confining layer is allowed to fill with water up to field capacity
Modified SWAT	ITDRN=1, incorporates Kirkham and Hooghoudt tile drainage equations	IWTDN=1, drainage volume converted into WTD using a variable water table factor
SWATDRAIN	ITDRN=2, DRAINMOD approach of tile drainage determination incorporated	IWTDN=2, DRAINMOD approach of WTD determination incorporated

5.2.4. Model Performance Evaluation Methods

In addition to graphical methods such as hydrographs, the Nash-Sutcliffe efficiency (NSE; Nash and Sutcliffe, 1970), coefficient of determination (R^2) and percent bias (PBIAS; Gupta et al., 1999) statistics were used to evaluate the performance of the three approaches (Table 5.1) in predicting streamflow.

In this study, monthly hydrographs were used to show model bias and differences in the timing and magnitude of peak flows. R^2 describes the proportion of the variance in measured data explained by the model. It ranges from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable (Santhi et al., 2001, Van Liew et al., 2003).

The Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model under-estimation bias, and negative values indicate model over-estimation bias (Gupta et al., 1999). PBIAS is calculated as:

$$PBIAS = \left(\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim} \right) * (100)}{\sum_{i=1}^{n} \left(Y_i^{obs} \right)} \right) \tag{5.1}$$

where,

Y_i^{obs} is the observed value,

Y^{mean} is the mean observed value,

Y_i^{sim} is the predicted value, and

n is the total number of observations.

NSE indicates how well the plot of observed versus simulated data fits a 1:1 relationship. NSE ranges between -∞ and 1 (1 inclusive), with NSE=1 being the optimal value. Values between 0 and 1.0 are generally viewed as acceptable levels of performance, whereas values less than 0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance. NSE is computed as:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}\right] \tag{5.2}$$

The coefficient of determination, R^2, (Equation 3), which ranges from 0 to 1, describes the proportion of the variance in measured data explained by the model, with higher values indicating less error variance. Typically $R^2 > 0.5$ is considered acceptable (Santhi et al., 2001, van Liew et al., 2003). R^2 is computed as:

$$R^2 = \left[\frac{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)\left(P_i - \overline{P}\right)}{\sqrt{\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^2}\sqrt{\sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2}}\right] \qquad 0 \le R^2 \le 1 \tag{5.3}$$

5.2.5. Data Availability for Model Calibration and Validation

The model was manually calibrated (1991 to 1992) and validated (1993) for streamflow discharge from the Green Belt watershed. The calibration and validation periods, chosen because of data availability, were representative of the catchment with rainfall ranging from 737 mm in 1991 to 911 mm in 1993.

Limited water table depth and tile flow data were available, so the data were split into two periods whose conditions were similar to those shown in Figure 5.3. The average annual precipitation for the three-year period was 850 mm. During the calibration and validation period, the annual precipitation did not deviate much from the annual average value, with the values ranging between 737 mm (-13%) in 1991 to 911 mm (+7%) in 1993. Thus, the calibration parameter values can be considered representative of the climatic conditions prevailing during the validation period.

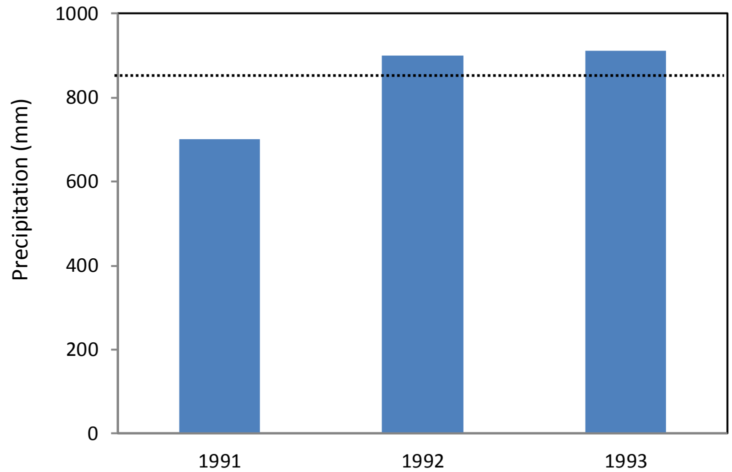

Figure 5.3. Annual precipitation during the calibration and validation periods

Ideally, a good calibration should cover a long time period to ensure that dry, average, and wet conditions are used to determine robust parameter values, thus reducing the chances of huge differences in the simulation of water table depth or any other hydrologic component of interest during the validation period (Moriasi et al., 2009).

5.2.6. Model Calibration and Validation

In a first step, SWAT model was manually calibrated (1991 to 1992) and validated (1993) for streamflow discharged from the outlet of the Green Belt watershed. This process was conducted by comparing monthly and daily observed streamflow and water table depth with monthly and daily flow simulated by the model. Simultaneously, daily and monthly water table depth were simulated and compared with the data recorded by Patni et al (1994) for 12 monitoring wells in the study area. Observed and simulated results were compared by means of correlation coefficient (R^2), the Nash-Sutcliffe model efficiency (NSE) and percent bias (PBIAS). Although parameter input values can be determined by model calibration within the recommended range of values, known parameter values from previous studies can be used as well. In this study, a 2.0 m depth to impervious layer (DEP_IMP) and a drain depth (DDRAIN) of 1.0 m were used throughout the Green Belt cropped fields to account for tile flow. The drainage lag time (GDRAIN) was set to 72 hours. Two methods of calculating surface runoff and infiltration in SWAT including the SCS curve number procedure (SCS, 1972), and the Green and Ampt infiltration method (Green and Ampt, 1911) were tested during calibration. The Green and Ampt method using hourly rainfall data has been selected in this study. Some calibration parameters varied in this study included the curve number coefficient (CNCOEF), surface runoff lag coefficient (SURLAG), initial soil water storage expressed as a fraction of field capacity water content (FFCB) for surface runoff. Other adjustments were also tried during the calibration process, such as running the model with different evapotranspiration methods of Penman-Monteith and Hargreaves and Pristley-Taylor and changing the evaporation soil correction (ESCO), which did not improve the accuracy of the model especially with the Penman-Monteith method which has been selected for this study.

Since this area has significant snowfall and snowmelt during winter and early spring, based on the literature some parameters important to the snow-water mass balance were investigated for their sensitivity to surface runoff, baseflow, evapotranspiration and streamflow within the watershed under study. These parameters were SMTMP (snow melt base temperature), SFTMP (snowfall temperature), TIMP (snow pack temperature lag factor), SMFMN (melt factor for snow on December 21) and SMFMX (melt factor for snow on June 21). The calibrated parameter values for SWAT model used in this study are presented in Table 5.2.

Additional calibration parameters were required for the modified SWAT approach (ITDRN=1, and IWTDN=1) (Moriasi et al, 2007; Moriasi et al., 2011). Based on several tile drainage studies in southern Ontario, drainage coefficient (DC), the lateral hydraulic conductivity multiplication factor (LATKSATF) and effective radius of drains (RE) were set at 16.7 mm d-1, 1.1 mm h-1, and 15 mm, respectively (Thooko et al., 1990). The value selected for the drainage coefficient (16.7 mm d^{-1}) was based on the outlet H-flume capacity (Thooko et al., 1990). This is the maximum flow rate that the system can handle. In this study, the recommended subsurface drainage system for cropped fields (HRUs) was simulated with a drain spacing (SDARIN) of 15 m and a drain depth (DDRAIN) of 1.00 m, operated in free drainage mode, and a constant deppresional surface storage (Sd) value of 25 mm was used in this study (Thooko et al., 1990).

Table 5.2 presents the additional calibration parameters and chosen values for the modified DRAINMDOD approach. The values of the other calibration parameters were the same as with original SWAT's approach. All other parameters (Neitsch et al. 2002b) were kept at the SWAT default values.

Additional calibration was required for the SWATDRAIN model, compared to the original and modified SWAT model, given the new input parameters in SWATDRAIN model (e.g., soil retention curve parameters, saturated hydraulic conductivities of different soil layers, ET monthly factors, rooting depths and all additional parameters regarding freeze/thaw conditions). These additional parameters can be determined by calibration process; however, in this study real values based on several tile drain studies in southern Ontario (Patni et al. 1996; Patni et al., 1998; Thooko et al., 1990) were used to evaluate the SWATDRAIN model

Also, other tile drainage system design parameters such as drain depth and spacing, drainage coefficient, effective drain radius are required for SWATDRAIN model. These parameters were maintained as the calibrated values in modified SWAT simulations.

Table 5.2. Calibrated values of adjusted parameters for streamflow calibration of the SWAT model for the Green Belt watershed

Parameter	Description	Calibrated value
ITDRN	Tile drainage routines flag/code: 0: Original SWAT tile equations, 1: DRAINMOD tile equations, 2: SWATDRAIN	0
IWTDN	Water table depth flag/code: 0: Original SWAT tile equations, 1: DRAINMOD tile equations, 2: SWATDRAIN	0
ESCO	Soil evaporation compensation factor	1.00
EPCO	Plant uptake compensation factor	0.62
FFCB	Initial soil water storage expressed as a fraction of field capacity water content	0.95
SURLAG	Surface runoff lag coefficient (d)	0.20
ICN	Curve number method flag	1
CNCOEFF	Curve number coefficient	1.3
DDRAIN	Depth to subsurface tile (mm)	1000
DEP_IMP	Depth to impervious layer (mm)	2000
ITDRN	Tile drainage routines flag/code: 0: Original SWAT tile equations, 1: DRAINMOD tile equations, 2: SWATDRAIN	1
IWTDN	Water table depth flag/code: 0: Original SWAT tile equations, 1: DRAINMOD tile equations, 2: SWATDRAIN	1
SDRAIN	Distance between two drains (mm)	15000
DC	Drainage coefficient (mm d^{-1})	16.7
LATKSATF	Multiplication factor to determine lateral hydraulic conductivity (mm h^{-1})	1.1
RE	Effective radius of drains (mm)	15

The relationships between water table depth and both drained volume and the upward flux were derived from the soil water characteristics of each layer using a soil preparation program, supplied with DRAINMOD. Water table depth calibration In SWATDRAIN was carried out by varying the amounts of drainage volume-water table depth curve layer by layer.

Table 5.3. Calibrated values of adjusted parameters for streamflow calibration of the SWATDRAIN model for Green Belt Watershed

Parameter	Description	Calibrated value
ITDRN	Tile drainage outflow routines flag/code: 0: Original SWAT tile equations, 1: DRAINMOD tile equations, 2: SWATDRAIN	2
IWTDN	Water table depth flag/code: 0: Original SWAT tile equations, 1: DRAINMOD tile equations, 2: SWATDRAIN	2
Ks	Lateral hydraulic conductivity (cm h^{-1})	Varies
Re	Effective radius of drains (mm)	15
Dc	Drainage coefficient (mm d^{-1})	16.7
Drain spacing (L)	Distance between two drain or tile tube (mm)	15000
Drain Depth (B)	Depth from soil surface to drain (mm)	1000
Rooting depth		Varies
TKA, TKB	Thermal conductivity functions	0.55, 2.5
TLAG	Diurnal phase lag of air temperature (h)	9
TB	Soil temperature at profile bottom (°C)	8
Tsnow	Rain/snow-dividing temperature (°C)	0
Tmelt	Snowmelt base temperature (°C)	2
CDEG	Snow melt coefficient (mm d^{-1} °C^{-1})	5
CICE	Critical ice content (cm^3 cm^{-3})	0.4

In SWATDRAIN, lateral saturated hydraulic conductivity is soil-specific and it is read into the model by the soil file used for each HRU. These measured values of hydraulic conductivities were obtained from previous studies (Patni et al, 1996; Thooko et al, 1990). The effective root depth is a difficult parameter to determine. An initial depth of 0.45 m was used for the maximum effective rooting depth. In this study, only conventional drainage is considered and the weir setting was set at or below the elevation of the tile drains. An initial estimated depth of 200 cm from the surface to the restrictive layer was used for the soil in this study. The calibrated parameter values for SWATDRAIN model used in this study are presented in Table 5.3.

5.3. Results and Discussion

5.3.1. Water Table Elevations

Time series plots of daily WTDs during calibration and validation periods are shown in Figure 5.4. The calibration and validation model performance results for the daily time steps are presented in Table 5.5. Based on the NSE values (Table 5.4 and Table 5.5), the SWATDRAIN model simulated WTD adequately during the calibration (NSE = 0.80 daily; NSE = 0.90 monthly) and validation (NSE = 0.67 daily; NSE = 0.80 monthly) period. Both the original and the modified versions of SWAT simulated WTD poorly (Tables 5.4 and 5.5), with the WTD being either over-predicted or under-predicted during both the calibration and validation periods (e.g., Figure 5.4). In original SWAT, WTD was under-predicted during the summer season and over-predict during the winter season. While, during the validation year, it is apparent that the modified SWAT predicts considerably shallower water tables compared to the original SWAT.

Table 5.4. Monthly WTD calibration and validation statistics comparing measured and simulated data

	Calibration			Validation		
Index	Original SWAT	Modified SWAT	SWATDRAIN	Original SWAT	Modified SWAT	SWATDRAIN
R^2	0.24	0.59	0.75	0.00	0.41	0.86
PBIAS	11.03	-18.92	11.59	14.58	47.77	0.11
NSE	0.48	0.45	0.90	-0.33	0.40	0.80

Table 5.5. Daily WTD calibration and validation statistics comparing measured and simulated data

	Calibration			Validation		
Index	Original SWAT	Modified SWAT	SWATDRAIN	SWAT (original)	Modified SWAT	SWATDRAIN
R^2	0.44	0.57	0.72	0.00	0.40	0.70
PBIAS	-21.20	-13.85	-3.75	9.22	40.26	2.90
NSE	0.42	0.41	0.80	-0.15	0.38	0.67

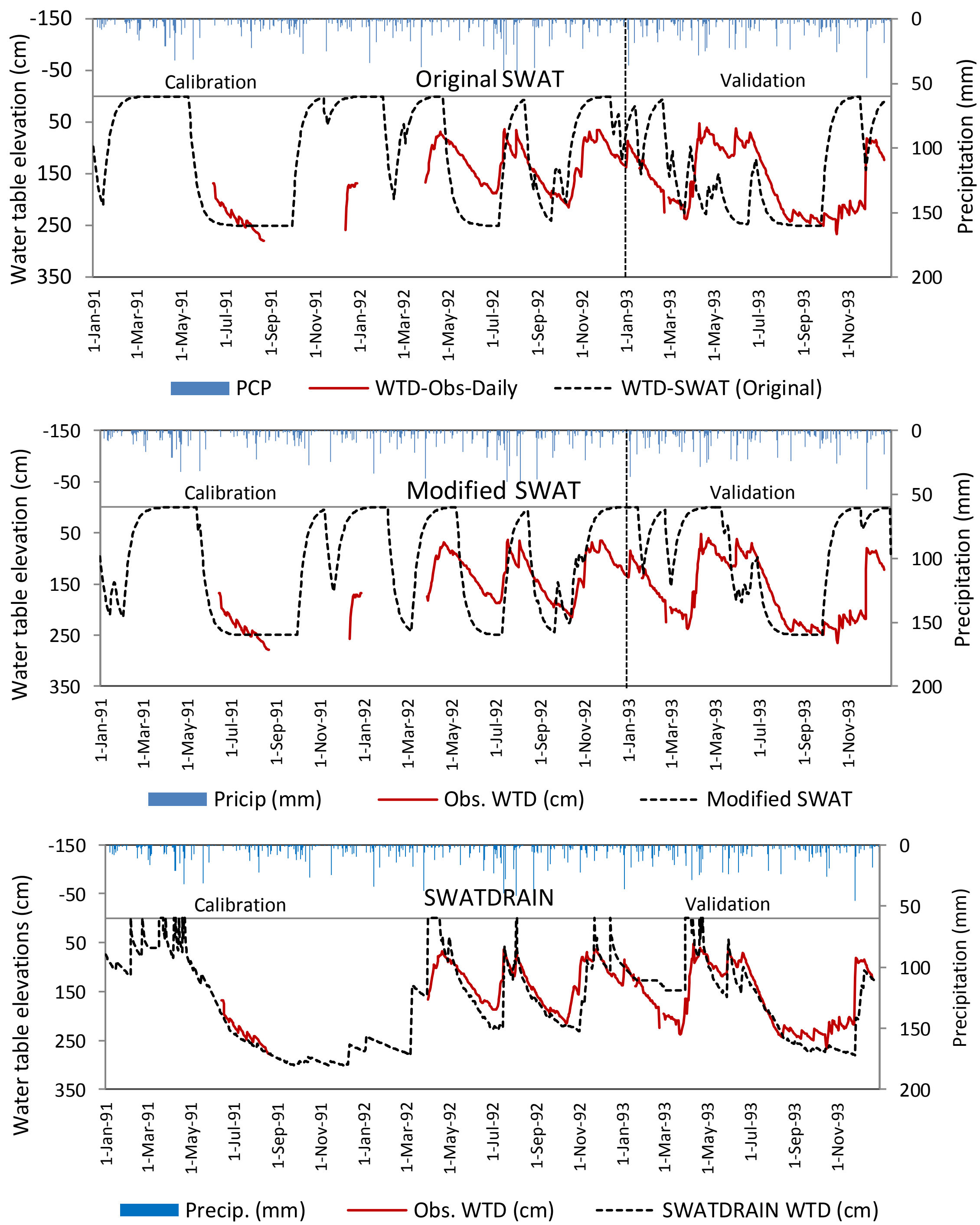

Figure 5.4. Measured daily precipitation and water table depth measured in the Green Belt watershed compared to simulated values derived from the original SWAT, Modified SWAT and SWATDRAIN models.

The differences between the daily observed and simulated WTD fluctuations can be the results of improper soil water relationship characterization and drained volume relationship (He et al., 2002). The differences in the observed and simulated WTD values at different times may also be due to uncertainty in soils data (as explained above), the precipitation records used, as well as the general uncertainty of the equations used by the new Modified DRAINMOD method to estimate WTD.

In general, there were no major differences between the observed WTD fluctuations and the WTD patterns simulated by SWATDRAIN. In the dry year (1991), WTD was at least 2.0 m below the soil surface for most of the growing season, and from mid-August to mid-December exceeded 3.0 m (i.e., below the bottom of the monitoring wells. SWATDRAIN simulations followed this pattern very closely. During the relatively wet crop year (1992), the WTD remained mostly within 2.0 m of the soil surface, rising to within 0.5 m of the soil surface following high precipitation events in July, August, and November (after harvest), and similarly in April 1993 during the snowmelt. These water table depth fluctuation patterns were well simulated by SWATDRAIN, but the model over-estimated the WTD for the April snowmelt event. In 1993, the WTD remained relatively shallow until the end of June and then slowly dropped until October.

With respect to the effect of large rainfall events or periods of high cumulated multi-day rainfall, a number of cases were noted: (i) at the end of March 1992, snow-melt and a 40-mm rainfall event caused the average WTD to rise from 2.6 m to 0.5 m below the soil surface over a 14-day period, (ii) in July 1992, the water table rose by 1.3 m in 7 days, following 122 mm of rainfall in 14 days, and (iii) in December 1993, a 55-mm rainfall event, over a 2 day period, raised the water table by 1.4 m in 18 h, to 0.5 m below the surface. In these cases Water table depth fluctuation patterns were well simulated using the SWATDRAIN approach. However, the tile drainage system generally lowered the water table to 1.0 m below soil surface within a few days.

This occurred from August to December 1993, when WTD did not respond to precipitation: the SWATDRAIN model predicted the WTD correctly, whereas the original and modified approaches did not, likely because of SWATDRAIN's more accurate drainage simulation.

Observed water table data suggest that the top 3 m soil profile was draining relatively well, and an intense rainfall event could rapidly recharge the groundwater, except when a well-established crop canopy was present. Precipitation is perhaps the most critical input that determines how accurately watershed hydrology is simulated. While during non-freezing weather (mid-April to mid-October) rainfall was measured on site using Belfort Universal rain gauges, for the remainder of the year precipitation and maximum and minimum temperatures were obtained from the records of an Agricultural and Agri-Food Canada weather stations located 12 km from the experimental site. These weather data were assumed to be representative of the weather conditions at the observation wells. However, there can be some spatial variability in precipitation, causing inaccuracies in the model evaluation.

5.3.2. Tile Drainage

Time series plots of observed and simulated daily tile drainage during calibration and validation periods (Figure 5.7) show that observed and simulated daily drain outflows were in a good agreement. The calibration and validation model performance results for the daily and monthly time steps presented in Table 5.6 and 5.7.

During the calibration period using the original SWAT model, the monthly and daily NSE values were 0.89 and 0.67, respectively, while the PBIAS values at the monthly and daily time steps were 9.61 and 18.23 (Table 5.7 and 5.8).

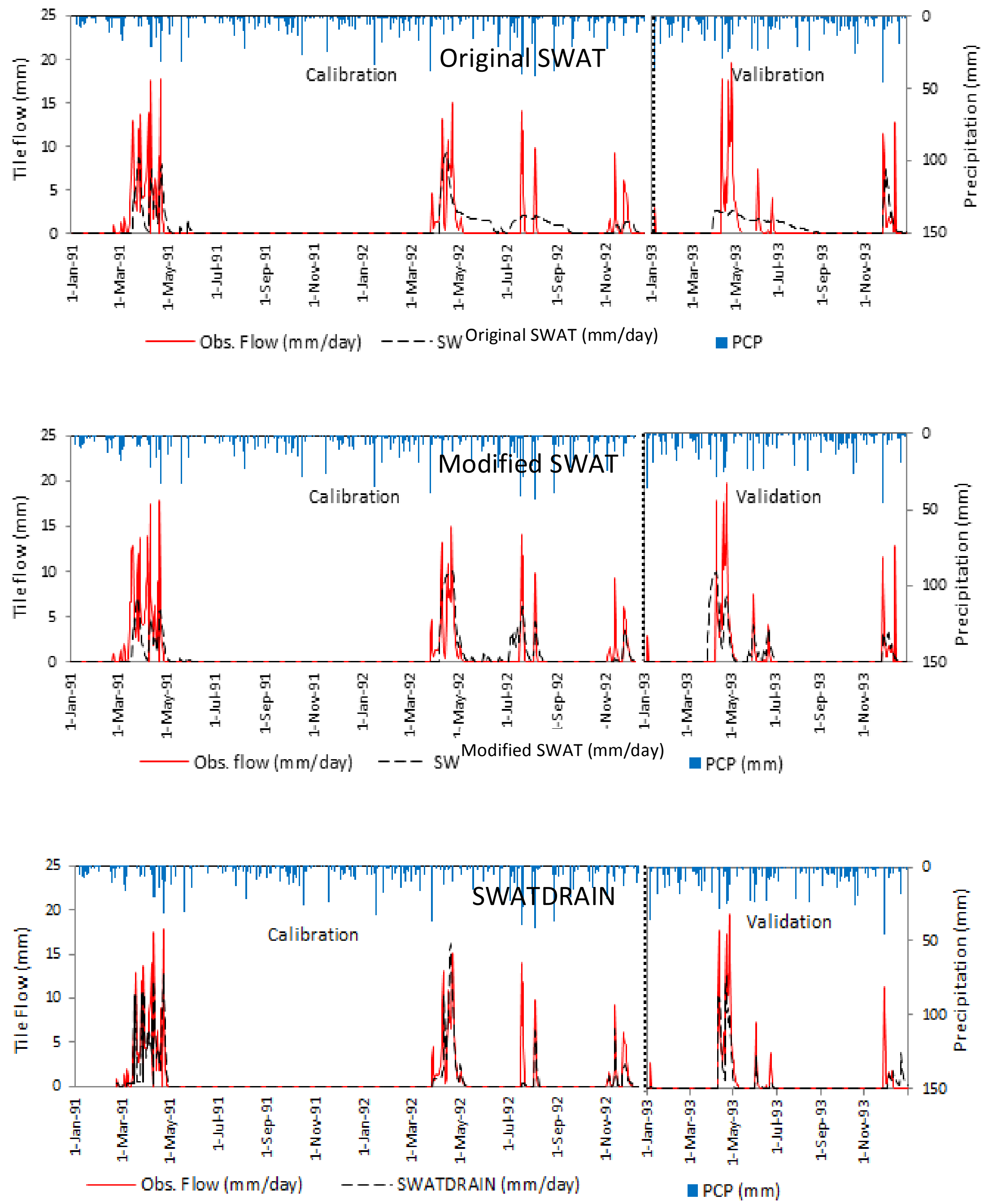

Figure 5.5 Measured daily tile flow in the Green Belt watershed compared to simulated values derived from the original SWAT, Modified SWAT and SWATDRAIN models.

Using the SWATDRAIN model, the monthly and daily NSE values were 0.89 and 0.67, respectively, while the PBIAS values at the monthly and daily time steps were 9.61 and 18.23 (Table 5.7 and 5.8). According to Moriasi et al. (2007b), a model is considered calibrated for flow if monthly NSE $\geq$ 0.65 and PBIAS $\leq \pm10\%$. Therefore, three original, modified and SWATDRAIN models were well calibrated as shown by the statistics in Table 5.7.

During the validation period the monthly and daily NSE values were 0.88 and 0.62, respectively, while the PBIAS values at the monthly and daily time steps were 17.26 and 23.85 (Table 5.7 and 5.8). Therefore, in this study due to Moriasi et al. (2007b), the model simulation performance rating was good according to NSE, and satisfactory according to PBIAS. All tile drainage flow from February 1991 to December 1993 was divided into 20 consecutive flow events (Figure 5.5). An event lasted from an initial low (less than 0.05 mm/h) or no flow condition to the next low or no flow condition. Events consisted of one or more peaks in the hydrograph. In 1991, data for two or three short duration events with extremely low flows during snowmelt were grouped with the next event. During the year 1991, tile drains had flow during both the snowmelt (early spring) and the spring periods, but no further flow occurred from May 1991 to 27 March 1992. Only three flow events occurred from March to May 1992, during the snowmelt and spring periods in 1992. In 1992-1993 flow events occurred in every season except during the 1993 snowmelt when a rapid thaw and ice blockage in the drainage ditch downstream of the tile discharge site caused the water table to rise to the soil surface and temporarily flood the tile flow monitoring stations. In 1993, drains had intermittently flow until the end of the June.

The SWATDRAIN model simulated all the events very closely to the observed ones, except events 16 and 17 (Figure 5.6) which were under-estimated by the model. SWATDRAIN model simulated tile flow events adequately during the calibration due to the high NSE values (NSE = 0.84) and validation (NSE = 0.88) period (Table 5.5).

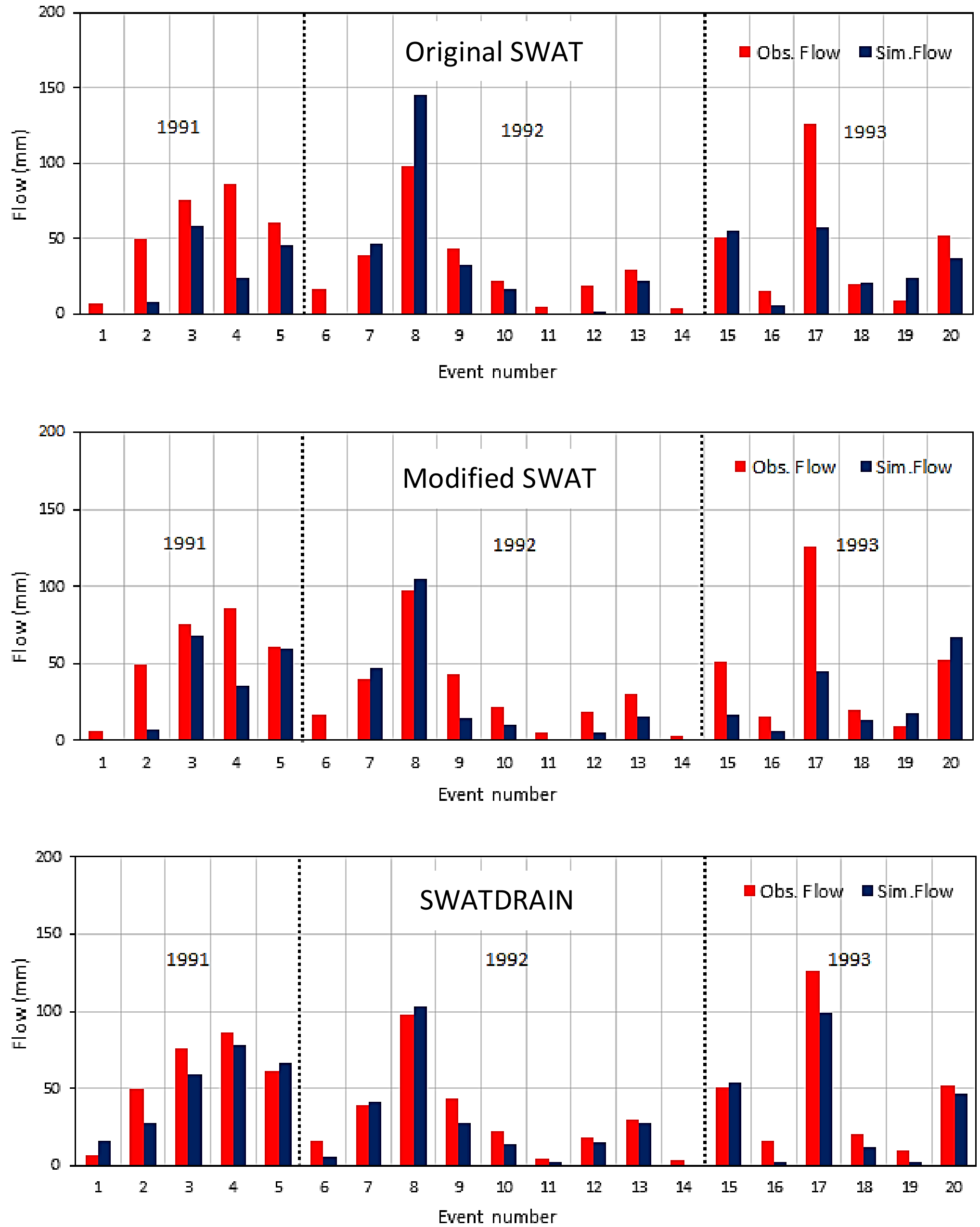

Figure 5.6. Measured tile flow during precipitation events in the Green Belt watershed compared to simulated values derived from the original SWAT, Modified SWAT and SWATDRAIN models.

Table 5.6. Statistics comparing measured and simulated tile flow during calibration and validation for 20 events

	Calibration			Validation		
Index	Original SWAT	Modified SWAT	SWATDRAIN	Original SWAT	Modified SWAT	SWATDRAIN
R^2	0.55	0.68	0.89	0.18	0.68	0.86
PBIAS	13.75	18.35	11.80	15.29	16.34	11.7
NSE	-0.05	0.30	0.83	-0.08	0.56	0.84

Table 5.7. Monthly tile flow calibration and validation statistics of the measured and simulated data

	Calibration			Validation		
Index	Original SWAT	Modified SWAT	SWATDRAIN	Original SWAT	Modified SWAT	SWATDRAIN
R^2	0.75	0.80	0.92	0.45	0.77	0.88
PBIAS	12.34	1.44	9.61	-15.84	-15.04	17.26
NSE	0.65	0.69	0.89	0.42	0.73	0.86

Table 5.8. Daily tile flow calibration and validation statistics comparing measured and simulated data

	Calibration			Validation		
Index	Original SWAT	Modified SWAT	SWATDRAIN	Original SWAT	Modified SWAT	SWATDRAIN
R^2	0.35	0.54	0.73	0.19	0.52	0.70
PBIAS	3.53	14.15	18.23	0.21	-18.47	23.85
NSE	0.35	0.52	0.67	0.17	0.48	0.62

The results of SWATDRAIN simulations (Figure 5.6) show that the model under-predicts high tile outflow peaks for events 16, 17 and 18, which mostly happened in April and May 1993. At this time the soil had high moisture content due to spring snowmelt. In general, when additional water is introduced from rainfall, it infiltrates, evaporates, and remains on the surface as depression storage or move as surface runoff. In the study area, there was no surface runoff leaving or coming into the field for the evaluation period (Patni et al 1996)..

Evapotranspiration was relatively low in April. Therefore, infiltrated water from rainfall moved into the drains, or deeper into the water table. This resulted in high tile flow during the month of April. Model simulations appear to agree with this observation. Drain flow underprediction by the model can also be attributed to inaccurate rainfall data, given the distance (12 km) to the weather station.

During this period, comparison of observed and predicted water table depths indicates that the model overpredicted the water table depths. The overprediction of WTD would have resulted in the under-prediction of tile outflows.

5.3.3. Water Balance

As part of hydrologic calibration, the overall water balance was calculated for each year. The annual water balance summaries for the three hydrologic years of the simulation are presented in Table 5.8. The simulated water balance showed that from 45% to 51% of the annual precipitation across the watershed was simulated to have been lost as evapotranspiration.

During the study, surface runoff occurred for a few days during the snowmelt period only and it was not measured (Patni et al, 1994). There was no surface runoff during 1991. In 1992, surface runoff occurred during four days only. In 1993, surface flow was observed only in three days in late March and in early April, it occurred in every plot for five days. The simulated surface runoff values for three years are in a good agreement with the observed surface runoff.

Table 5.9. Watershed water balance during the simulation period for different approaches of SWAT original and Moriasi and SWATDRAIN

Approach	Year	PCP (mm)	Tile Q_{obs}	ET	TileQ_{sim} (mm)	SQ (mm)
Original SWAT	1991	736.0	276.0	512.0	154.2	0.0
	1992	899.6	272.5	568.8	247.4	14.49
	1993	904.9	277.3	591.7	250.7	27.19
Modified SWAT	1991	736.0	276.0	485.0	164.0	0.0
	1992	899.6	272.5	588.4	256.1	13.5
	1993	904.9	277.3	585.6	257.2	27.2
SWATDRAIN	1991	736.0	276.0	446.8	247.2	0.0
	1992	899.6	272.5	550.9	286.0	13.9
	1993	904.9	277.3	530.0	288.4	21.1

Notes: PCP: precipitation. ET: evapotranspiration. TileQ: tile drain flow. SQ: surface runoff. SW: the amount of water which stored in the soil profile

5.4. Summary and Conclusions

The water table depth from soil surface has an important impact on farm trafficability, crop productivity and water management systems. Subsurface drainage is a common water management system used to maximize crop production in regions with seasonal high water tables, and represents a major source of nutrients in water bodies.

In light of these significant impacts of water table depth proximity to the surface and tile drainage on agricultural production, it is important for a hydrologic model to be able to simulate both water table depth and tile outflow. The water table depth simulation approaches used in SWAT do not accurately simulate water table depth fluctuation in soil profiles, especially during relatively short dry periods followed by short wet periods (Moriasi et al., 2009).

In this study, the SWATDRAIN model, which uses the DRAINMOD approach to simulate tile drainage and water table depth, was evaluated for a fully tile-drained agricultural watershed in Ontario, Canada. During the calibration period, the monthly and daily NSE values for water table depth were 0.90 and 0.80, respectively, while the equivalent PBIAS values for both the monthly and daily time steps were 11.59 and -3.75 for water table depth.

For tile drainage flow, during the calibration period, the monthly and daily NSE values were 0.89 and 0.67, respectively, while the equivalent PBIAS values for the monthly and daily time steps were 9.80 and 18.23. According to Moriasi et al. (2007b), (a model is considered calibrated for flow if monthly NSE $\geq$ 0.65 and PBIAS $\leq \pm 10\%$), the SWATDRAIN model was well calibrated.

During the validation period, the monthly and daily NSE values for water table depth were 0.88 and 0.67, respectively, while the equivalent PBIAS values for both the monthly and daily time steps were 0.11 and 2.9 for water table depth. For tile drainage flow, during the validation period, the monthly and daily NSE values were 0.86 and 0.62 respectively, while the equivalent PBIAS values for the monthly and daily time steps were 17.26 and 23.85.

Analysis of water table depth and tile flow during the study period showed that, in the year 1991, which has less precipitation compared to the other two years and was thus relatively dry, the water table depth remained more than three m below the soil surface for most of the growing season, which SWATDRAIN simulated quite well. During this year, tile flow occurred only in March and April.

The year 1992, was particularly wet, during the growing season and it was the only year in which tile drains had flow during each of the four seasons. By looking at the water table depths over this year, it was clearly shallower and rose above the tile drain depth following high precipitation events.

The water table depth predictions from SWATDRAIN followed all the rises and falls in water table depth very closely, except in the month of April when the model overestimated the water table depth. In this particular case model predicted a water table depth at the soil surface for a few days, while the observed data showed it to be over 0.50 m from the surface. The year 1993 was wet during the spring with 127 mm of rain during April and, but relatively dry in July and August. During this year, drains showed intermittent flow until the end of June. The results from SWATDRAIN showed the same trend. The water table depth remained mostly above drain depth during the snowmelt and spring, and SWATDRAIN was remained in close agreement with the observations.

CONNECTING TEXT TO CHAPTER 6

This chapter is a manuscript prepared to be submitted to Agricultural Water Management Journal. The format has been changed to be consistent within this thesis. All literature cited in this chapter is listed in the reference section at the end of this thesis. Chapter 6 presents the evaluation of SWATDRAIN watershed-scale model for hydrology in southern Ontario's climatic conditions. Simulation results for tile drainage and water table depth in an agricultural watershed have been presented.

CHAPTER 6: Evaluation of SWATDRAIN Model for a Partially Tile Drained Watershed in Ontario, Canada

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Abstract

Recently, DRAINMOD model was incorporated into Soil and Water Assessment Tool (SWAT) model as alternative tile flow and water table depth simulation methods and a tool to design cost effective tile drain water management systems. The goal of this study was to evaluate the SWATDRAIN model for a partially tile drained Canagagigue Creek watershed located in Southern Ontario. The measured Stream flow were compared with that predicted by SWATDRAIN using the Nash-Sutcliffe efficiency (NSE), PBIAS and R^2 statistical methods in addition to hydrographs. Simulations were carried out from 1975 to 1984; data from 1975 to 1979 was used for model calibration and data from 1980 to 1984 was used for validation. The new model was able to adequately simulate the hydrologic response at the outlet of the watershed. Comparing the observed monthly and daily tile drainage with the model's output over the validation period returned the R^2 values of 0.75 and 0.62, PBIAS of 13.96 and 17.99 and modeling efficiency of 71.27 and 61.62.This clearly demonstrates that the DRAINMOD approach is a potential alternative tile flow simulation method and tile drainage design tool in SWAT.

Key Terms: Hydrological modeling; SWATDRAIN; SWAT; DRAINMOD; Watershed scale

6.1. Introduction

In humid regions, with fine-textured soils, agricultural tile drainage systems have been used effectively to facilitate seedbed preparation, planting and enhance crop production by alleviating excess-water stress, caused by shallow water tables. In Ontario, the vast majority of land is used for agricultural purposes and approximately 90% of the Grand River Basin is agricultural land some of which is tile drained. These tile drains, which cover approximately 15% of the total land of the watershed, are installed to augment field drainage. Tile drains are located on agricultural land where soils such as heavy clays and silts do not allow the groundwater to readily drain. Tile drains cover approximately 99,800 ha of agricultural land in the Grand River Basin with this being approximately 15%, of the total Grand River Watershed area. The tile drains prevent the fields from becoming water logged with this potentially having an effect on the crop yield.

Not only does subsurface drainage allow for greater soil aeration, possible earlier planting dates and overall better field conditions (Zhou et al., 2010), but some researchers have also concluded that subsurface drainage has the potential to reduce surface runoff and pollutants associated with surface runoff (Bengston et al., 1995).

Over the past few decades, great strides have been made in technology and modeling techniques that allow users to make informed and relatively accurate representations of ungagged watersheds that previously would have been impractical (Frana, 2012). Several hydrologic models have been extensively used to simulate hydrological conditions of watersheds. With proper calibration, physically based models can be applied to widely varying landscapes with very useful results (Frana, 2012).

One of the watershed-scale models that contain a tile drainage component is the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998; Arnold and Fohrer, 2005). SWAT is a conceptual, continuous-time model developed to help water resource managers in assessing the impact of management and climate on water supplies and nonpoint-source pollution in watersheds and large river basins (Arnold et al., 1998). Extensive research has been implemented on SWAT applications under the worldwide conditions (Das et al., 2007; Gupta et al., 1999; Moriasi et al., 2007a; Santhi et al., 2001; Wang and Melesse, 2005; Wu and Johnston, 2007).

DRAINMOD (Skaggs, 1980) was the first comprehensive computer model developed to aid in the design and evaluation of agricultural drainage and water table management systems for poorly drained, high water table soils. The model includes freezing, thawing, and snowmelt components and thus, it is capable of simulating drainage phenomenon in cold regions. DRAINMOD has been used and tested worldwide and it is proven to be an efficient model in simulating flows from poorly drained high water table soils (Skaggs, 1982; Singh et al., 1994; Lou et al., 2000, 2001; Youssef et al., 2006; Yang et al., 2007; Wang et al., 2006; Dayyani et al., 2009, 2010a; Skaggs, 2012).

SWATDRAIN a new computer model which was developed recently, has the advantage of using the subsurface hydrology simulation of DRAINMOD in the SWAT model. Also, SWATDRAIN is capable of simulating different water management scenarios on water resources at the watershed scale in order to design effective decision-making system for predominantly subsurface drained agricultural watersheds.

The objective of this study was to evaluate the SWATDRAIN model to simulate water balance components and also determine a range of values for new tile drain parameters for the agricultural tile drained Canagagigue Creek Watershed located in southern Ontario, using measured stream flow data.

6.2. Materials and Methods

6.2.1. SWATDRAIN Model Overview

SWATDRAIN model is a new model which was developed by incorporating DRAINMOD into SWAT. The newly developed SWATDRAIN model is based on the DRAINMOD subsurface hydrology and the SWAT surface hydrology simulation. SWATDRAIN computes the soil water balance, on a daily basis, for each HRU in every subbasin. The daily values of tile drainage are calculated using the DRAINMOD model (Skaggs et al., 1980), which computes the tile drainage flux based on the Kirkham and/or Hooghoudt's equations and the hydraulic capacity as a function of the daily water table elevation midway between the drains. SWATDRAIN uses either SCS curve number procedure (SCS, 1972), or the Green and Ampt infiltration method (Green and Ampt, 1911), to estimate infiltration and surface runoff. SWATDRAIN calculates the water table depth using the DRAINMOD model approach, which is based on drainage volume versus water table depth relationship. This method is used to determine how far the water table falls or rises when a given amount of water is removed or added to the soil profile. The relationship between drainage volume and water table depth is calculated from the soil water characteristics. In this approach, the drainage volume is calculated from a water balance computation in a daily time step. Based on the calculated drainage volume, the water table depth for that specific day is estimated using the soil water characteristics information. Different methods can be used in SWATDRAIN for potential evapotranspiration (PET) estimation: the Penman-Monteith method (Monteith, 1965), the Priestly-Taylor method (Priestly and Taylor, 1972), the Hargreaves method (Hargreaves and Samani 1985), the Thornthwaite method (Thornthwaite, 1948) or PET can also be entered as daily or monthly PET input by the user. In SWATDRAIN, the daily values of tile drainage are calculated using the DRAINMOD model (Skaggs et al., 1978), which computes the tile drainage flux based on the Kirkham and/or

Hooghoudt's equations and the hydraulic capacity as a function of the daily water table elevation midway between the drains.

6.2.2. Watershed Description

The Grand River Basin, located in the heart of south western Ontario, includes all the land drained by the Grand River and its tributaries. This large basin of almost 7,000 km^2 area in southern Ontario contributes about 10% of the drainage to Lake Erie.

The Canagagigue Creek has a total drainage area of 143 km^2 and is a tributary of the Grand River. It lies between latitudes 43°36' N and 43°42' N and longitudes 80°33' W and 80°38' W, and is about 25 kilometers northwest of the city of Guelph, Ontario. About 80% of the land within the watershed is productive agricultural land and 10% is woodlot (Carey et al., 1983). The climate of the area, according to Koppen-Geiger climatic classification system, can be characterized as humid continental with warm summers and moderate winters.

Based on the availability of observed flow data and also the presence of tile drainage in agricultural regions mostly located in the west portion of the Canagagigue watershed, this study targeted the upstream portion of the Canagagigue Creek west. The major land use is agriculture. The station at the Canagagigue west is described as "Canagagigue Creek near Floradle" by Atmospheric Environment Service, Environment Canada with an area of 1790 ha. It has available historical observation data for daily flow rate for the period 1974-1984. The general slope is less than 1.5%. The topography of the watershed is flat to gently undulating with a slight slope towards the outlet in the south. The average elevation is 417 m. Figure 6.1 shows the location of Canagagigue Creek and subwatershed used in this study.

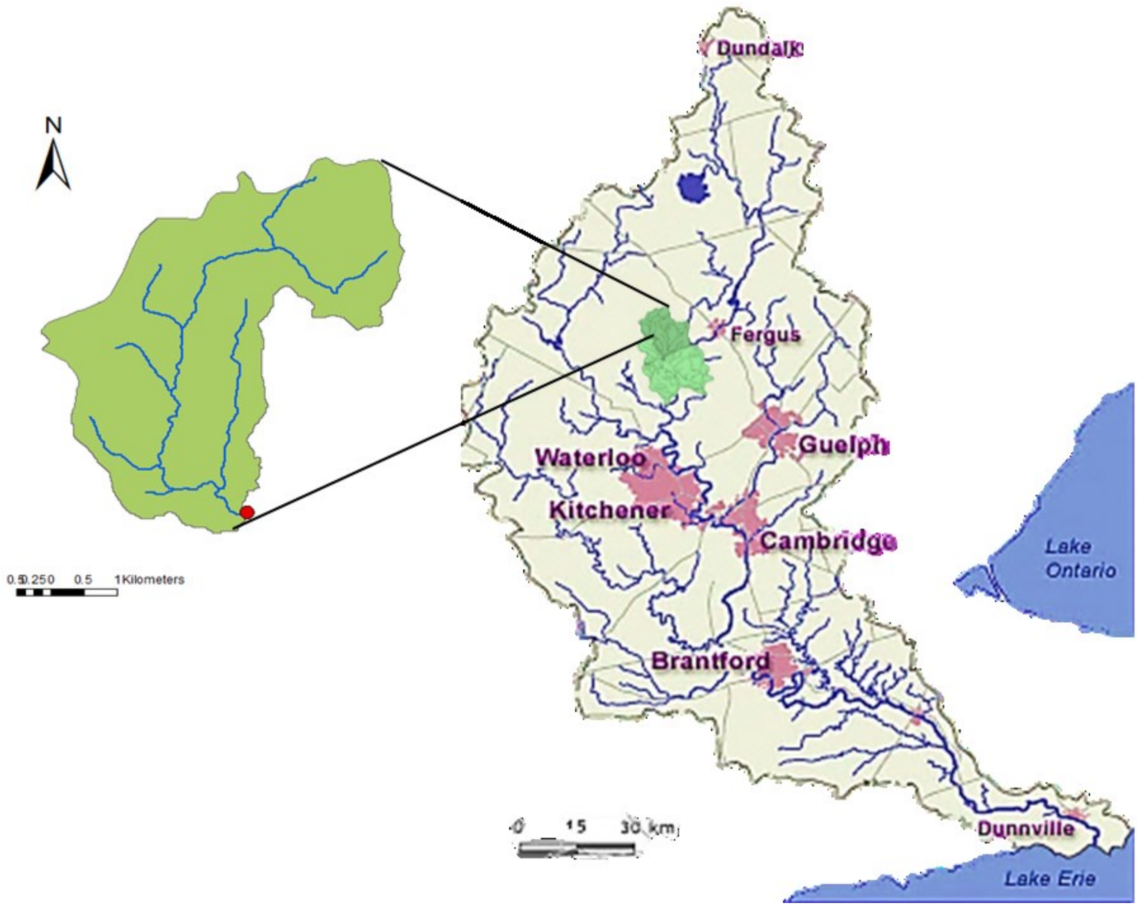

Figure 6.1. Location of the study area in Grand River Basin, the river network, the discharge and rainfall stations

6.2.2.1. Input Data

Daily weather data were obtained from the Fergus station. In addition to the weather data inputs, the SWAT model requires Digital Elevation Model (DEM), soils and land use and agricultural management data if applicable. A DEM with a 100 m × 100 m spatial resolution was obtained from the Grand River Conservation Authority.

The DEM is used by the interface to calculate subbasin parameters, such as slope and slope length, and to define the stream network. The resulting stream network was used by the ArcSWAT interface to define a layout of 13 subbasins (Figure 6.2). The DEM is also used to obtain the stream network characteristics, such as channel slope, length and width.

The soil and land use classification across the watershed was defined by polygon shape files, provided by the Ontario Ministry of Agriculture and Food. The combination of land use and soil type resulted in 67 HRUs. Figure 6.2 shows the distribution of the main soil types in the watershed.

The soil surveys of Waterloo County presented by Presant and Wicklund (1971) and Wellington County presented by Hoffman et al. (1963) indicated that the major portion of the watershed has 200 to 600 millimeters of loam or silty loam of the Huron and Harriston series overlying a loam till. In the northern part of the watershed, clay loam is predominant. Loam is the main soil type in the southern portion of the watershed. The topography of the watershed is flat to gently undulating with a slight slope towards the outlet in the south.

Figure 6.4 demonstrates the land use characteristics of studied watershed. Approximately 93.02% of the total area was under agricultural production, with the majority of land use under winter wheat, followed by corn, soybean, agricultural land row crops, and hay. The remaining 6.98% of the area was occupied by forest and residential lands.

Table 6.1. Land use distribution on Canagagigue Watershed

Landuse	Area (ha)	Area (%)
Winter wheat	540.58	30.56
Corn	476.14	26.92
Soybean	404.46	22.87
Agricultural land-row crops	133.21	7.53
Forest	121.90	6.89
Hay	90.98	5.14
Residential Medium density	1.58	0.09
Total	1768.86	100.00

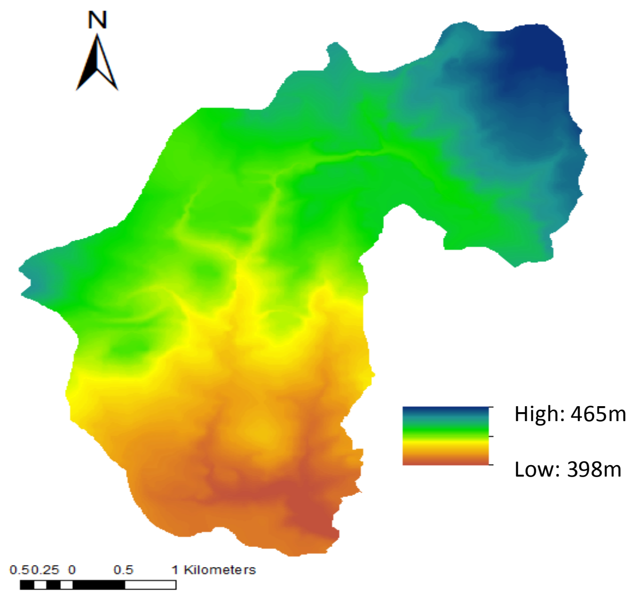

Figure 6.2. DEM and subwatersheds

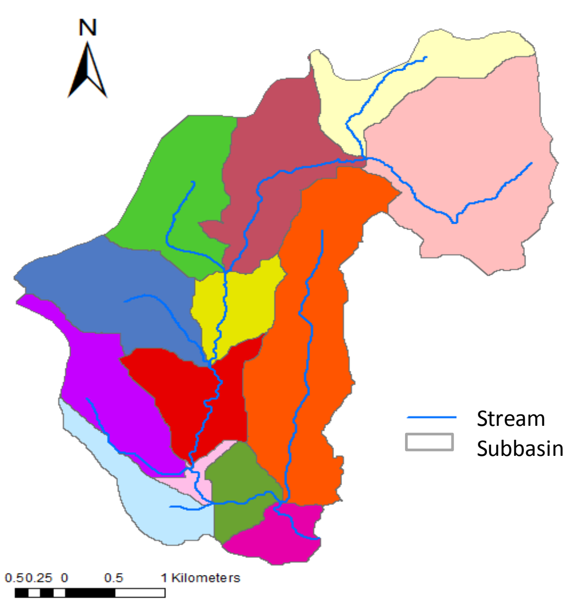

Figure 6.3. Subwatersheds

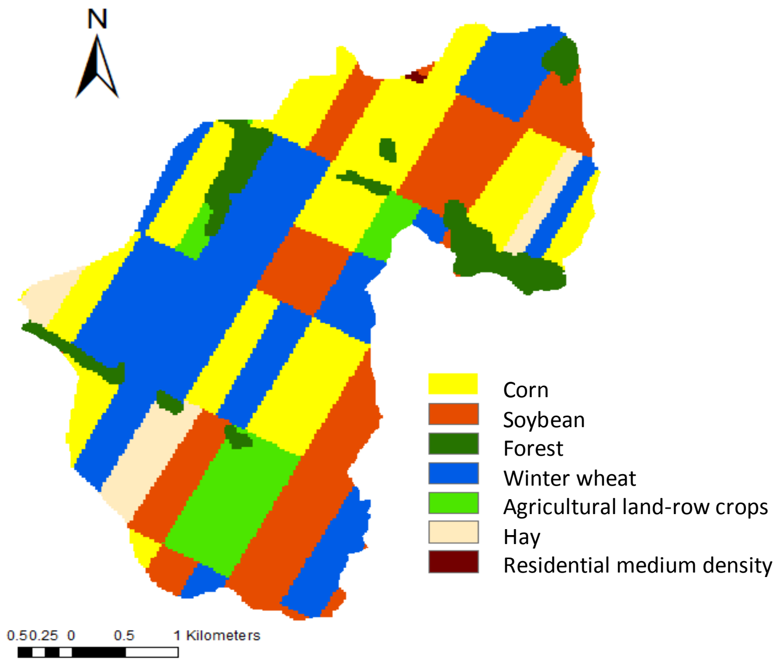

Figure 6.4. land use

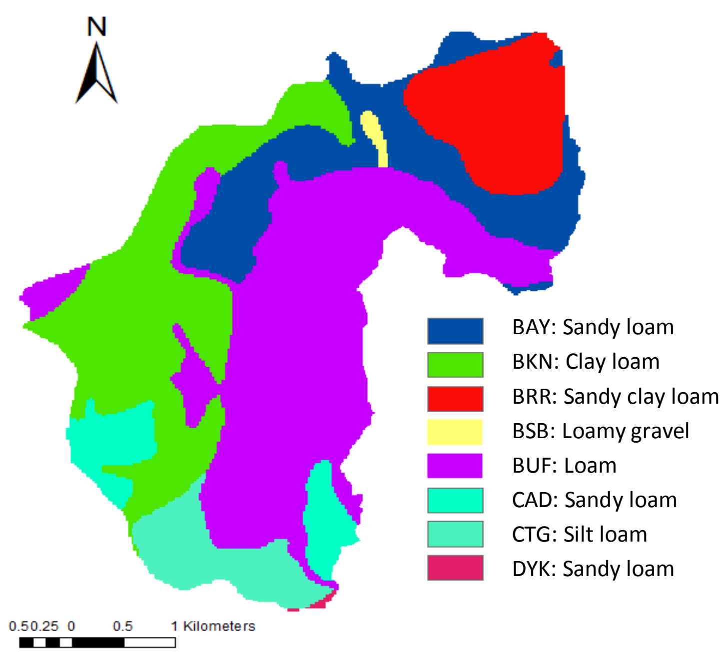

Figure 6.5. Soil

Tile drained area across the watershed was determined based on the tile drainage map obtained from the Land Information Ontario. Most of the agricultural regions are under tile drainage.

6.2.3. Model Performance Evaluation

In addition to graphical methods such as hydrographs, the Nash-Sutcliffe efficiency (NSE); Nash and Sutcliffe 1970), coefficient of determination (R^2) and percent bias (PBIAS) (Gupta et al., 1999) statistical methods were used to evaluate the performance of the model. In this study, monthly hydrographs were used to show model bias and differences in the timing and magnitude of peak flows. R^2 describes the proportion of the variance in measured data explained by the model. R^2 ranges from 0 to 1, with higher values indicating less error variance, and typically values greater than 0.5 are considered acceptable (Santhi et al., 2001, Van Liew et al., 2003).

$$R^2 = \left[\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_{Mean}^{obs}\right)\left(Y_i^{sim} - Y_{Mean}^{sim}\right)}{\sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_{Mean}^{sim}\right)^2} \sqrt{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_{Mean}^{sim}\right)^2}} \right]^2 \quad 0 \leq R^2 \leq 1 \qquad (6.1)$$

RSR standardizes RMSE using the observations standard deviation, and it incorporates the benefits of error index statistics and includes a scaling/normalization factor, so that the resulting statistic and reported values can apply to various constituents (Moriasi et al., 2007b). RSR varies from the optimal value of 0, to a large positive value. The lower RSR, the lower the RMSE, the better the model performance.

$$RSR = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}\right]} \tag{6.2}$$

Percent bias (PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al., 1999). The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias (Gupta et al., 1999). PBIAS is calculated with equation 6.3:

$$PBIAS = \left(\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) * (100)}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right) \tag{6.3}$$

NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE ranges between -∞ and 1 (1 inclusive), with NSE=1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values less than 0.0 indicate that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance. NSE is computed as shown in equation 6.4:

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}\right] \tag{6.4}$$

Where Y_i^{obs} is the observed value, Y_{Mean}^{obs} is the mean observed value, Y_i^{sim} is the predicted value, Y_{mean}^{sim} is the mean simulated value, and n is the total number of observations.

6.2.4. Model Evaluation

SWATDRAIN model was manually calibrated (1975 to 1979) and validated (1980 to 1984) for streamflow discharged from the Canagagigue Creek Watershed. The calibration and validation periods, chosen due to of data availability, were representative of the catchment with rainfall ranging from 817 mm in 1978 to 1039 mm in 1975. These periods were selected such that each period contained dry, average, and wet years.

Although parameter input values can be determined by model calibration within the recommended range of values, known parameters values from previous studies can be used as well. In this study, based on the previous studies in this area (Rong et al., 2009; Oogatho et al., 2009), the recommended subsurface drainage system for crop fields (HRUs) was simulated with a SDARIN of 15 m at a DDRAIN of 1.00 m, operated as an approach of free drainage at the drain outlet.

The initial Soil Conservation Service runoff curve number to moisture condition II (CN2) values calibrated using the SWAT model ranged from 66 to 78 (Rong et al., 2009) using the curve number (CN) method which bases CN on plant evapotranspiration (ICN=1). The calibration parameters which in this study include the curve number coefficient (CNCOEF), surface runoff lag coefficient (SURLAG), and initial soil water storage expressed as a fraction of field capacity water content (FFCB) for surface runoff.

The values of other streamflow calibration parameters were obtained from previous Canagagigue Creek Watershed studies (Rong et al., 2009). The range of parameter values and the calibrated and used values for this study are presented in Table 6.2.

Table 6.2. Calibrated values of parameters for streamflow calibration of the SWATDRAIN model for Canagagigue Creek Watershed

Parameter	Description	Value
ITDRN	Tile drainage routines flag: 0: Original SWAT tile equations, 1: DRAINMOD tile equations, 2: SWATDRAIN	1
ESCO	Soil evaporation compensation factor	0.70
EPCO	Plant uptake compensation factor	0.62
FFCB	Initial soil water storage expressed as a fraction of field capacity water content	0.95
SURLAG	Surface runoff lag coefficient (day)	2.0
ICN	Curve number method flag	1
CNCOEFF	Curve number coefficient	1.30
DDRAIN	Depth to subsurface tile (mm)	1.00
DEP_IMP	Depth to impervious layer (mm)	2400
SDRAIN	Distance between two drains (mm)	20000
DC	Drainage coefficient (mm day^{-1})	25
RE	Effective radius of drains (mm)	15
Additional SWATDRAIN calibration parameters		
Ks	Lateral hydraulic conductivity (cm/hr)	Variable
Re	Effective radius of drains (mm)	15
Dc	Drainage coefficient ($mmday^{-1}$)	25
Drain spacing (L)	Distance between two drain or tile tube (mm)	15000
Drain Depth (B)	Depth from soil surface to drain (mm)	1000
ET monthly factors	---	Variable
Rooting depth	---	Variable
Freeze/Thaw Parameters		
TKA, TKB	Thermal conductivity functions W m^{-1} ^oC	a=0.553,b=1.963
TLAG	Diurnal phase lag of air temperature (h)	9
TB	Soil temperature at the bottom of the profile (^oC)	7
Tsnow	Rain/snow-dividing temperature (^oC)	0
Tmelt	Snowmelt base temperature (^oC)	1
CDEG	Snow melt coefficient (mm day^{-1} $^oC^{-1}$)	5
CICE	Critical ice content (cm^3 cm^{-3})	0.3

Additional tile drain input parameters which are required for SWATDRAIN model such as, saturated hydraulic conductivities of different soil layers, ET monthly factors, rooting depths and all parameters regarding freeze/thaw conditions can be determined by calibration. The range of parameter values and the calibrated and used values for SWATDRAIN model used in this study are presented in Table 6.2.

In this study, CN method, which bases daily CN computation on plant ET (ICN = 1) was used (Neitsch et al., 2002). According to Neitsch et al. (2002), computation of daily CN value as a function of plant evapotranspiration was added because the soil moisture method was predicting too much runoff in shallow soils. When ICN =1, the amount of surface runoff is set using the CNCOEF. In this study, during the calibration, ICN=1 has been selected for calculating surface runoff with better results due to presence of the shallow water table.

The calibrated parameters for this study are presented in Table 6.2. The range of values for the SWATDRAIN tiled drain parameters in Table 6.2 are based on previous studies. The other parameters calibrated based on the water balance component proportions determined from results of previous Canagagigue studies in addition to optimizing simulated streamflow NSE and PBIAS statistics.

6.3. Results and Discussion

Figure 6.6 shows a scatter plot of observed and simulated monthly streamflow values for the entire period of simulation. On the basis of visual analysis of the observed and predicted streamflow (Figure 6.4), the overall simulation appears to be reasonably good and value of the coefficient of determination of 0.89 indicates a good correspondence between simulated and measured streamflow values.

The calibration and validation model performance results for the daily and monthly time steps are presented in Table 6.3. Time series graphical of plot of daily and monthly streamflow during calibration and validation period is illustrated in Figures 6.7 to 6.10.

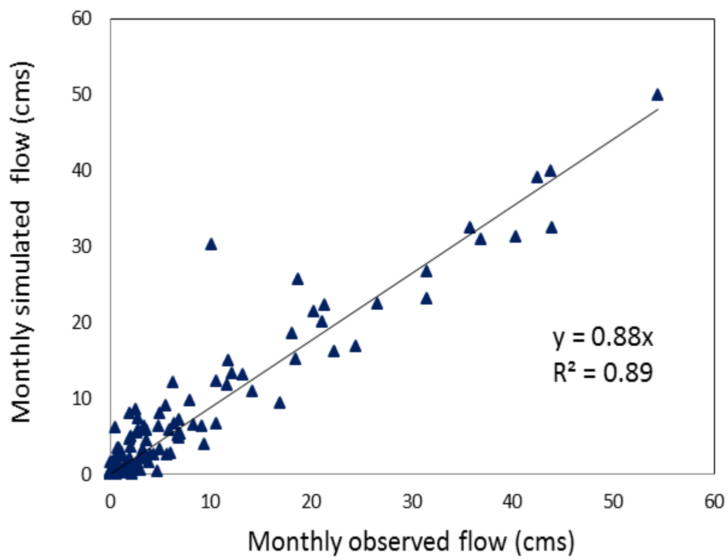

Figure 6.6. Scatter plot of observed and simulated precipitation for the period from 1974 to 1984

Table 6.3. Monthly streamflow calibration and validation statistics of the measured and simulated data

	Monthly		Daily	
Index	Calibration	Validation	Calibration	Validation
R^2	0.92	0.75	0.76	0.62
RSR	0.32	0.54	0.51	0.62
PBIAS	5.34	13.96	16.57	17.99
NSE	0.90	0.71	0.76	0.62

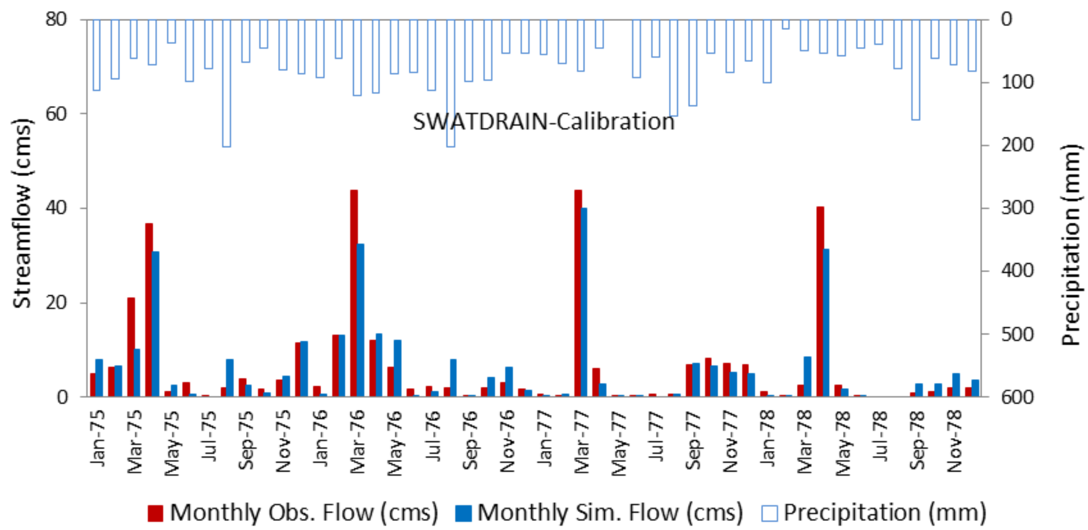

Figure 6.7. Monthly streamflow for Canagagigue watershed during calibration period

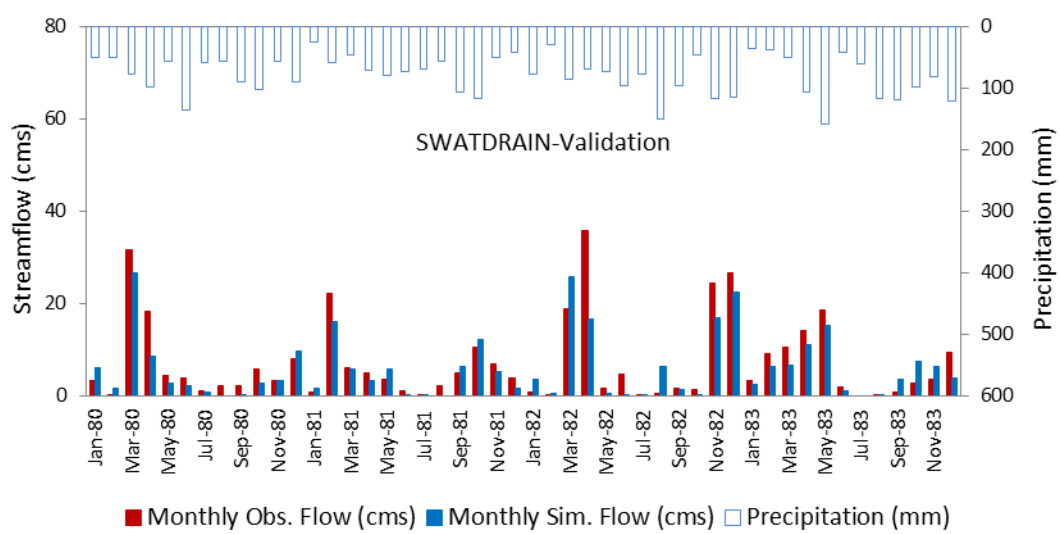

Figure 6.8. Monthly streamflow for Canagagigue Watershed during validation period

During the calibration period the monthly and daily NSE values were 71.27 and 61.62, respectively, while the PBIAS values at the monthly and daily time steps were 5.34 and 16.57 (Table 6.3). According to Moriasi et al. (2007b), a model is considered calibrated for streamflow if monthly NSE $\geq$ 0.65 and PBIAS $\leq \pm$10%. Therefore, the SWATDRAIN model was well calibrated as shown by the statistics in Table 6.3 and supported by the monthly hydrograph (Figures 6.7 and 6.10). The statistical results during the validation period were not as well as during the calibration period (Table 6.3 and Figures 6.7 to 6.10).

Some of the peaks were under-predicted during the validation, which mostly occurred specifically during the snowmelt period most visible in April 1982. This could be due to the typical tile drainage parameters such as drain depth and drain spacing and other drainage related parameters which have been used for the calibration. This could be also, due to adherence to the water budget component proportion constrains determined from the simulated hydrologic budget outputs and the measured precipitation and streamflow in previous Canagagigue Creek Watershed studies (Rong et al., 2009; Oogathoo et al., 2008).

Therefore, adjustment of the drainage system parameters for the drained HRUs may minimize the over-prediction of the peaks. Time series plots of observed and simulated daily tile drainage during calibration and validation periods (Figures 6.9 and 6.10) show that observed and simulated daily drain outflows were in a good agreement.

In this study, model performance was determined based on the monthly time step statistics during the validation period. According to Moriasi et al. (2007b), the model simulation can be judged as good if NSE > 0.65 and RSR $\leq$ 0.60 and PBIAS $\leq \pm$15 for streamflow. Therefore, in this study the streamflow trends simulation performance rating was good (NSE=71.27, PBIAS=13.96, RSR= 0.54).

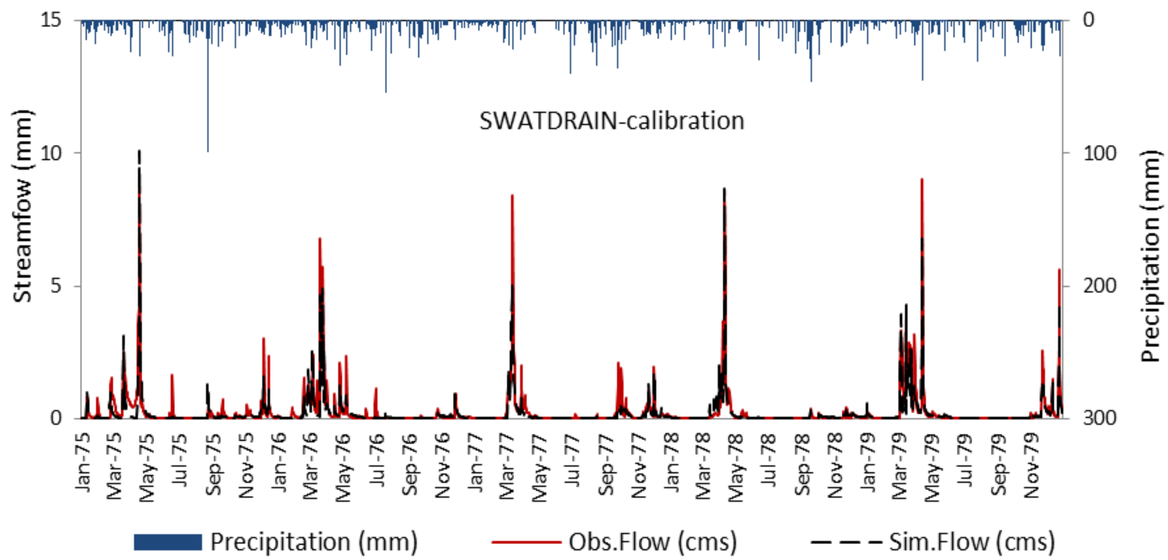

Figure 6.9. Daily streamflow for Canagagigue Watershed during calibration period

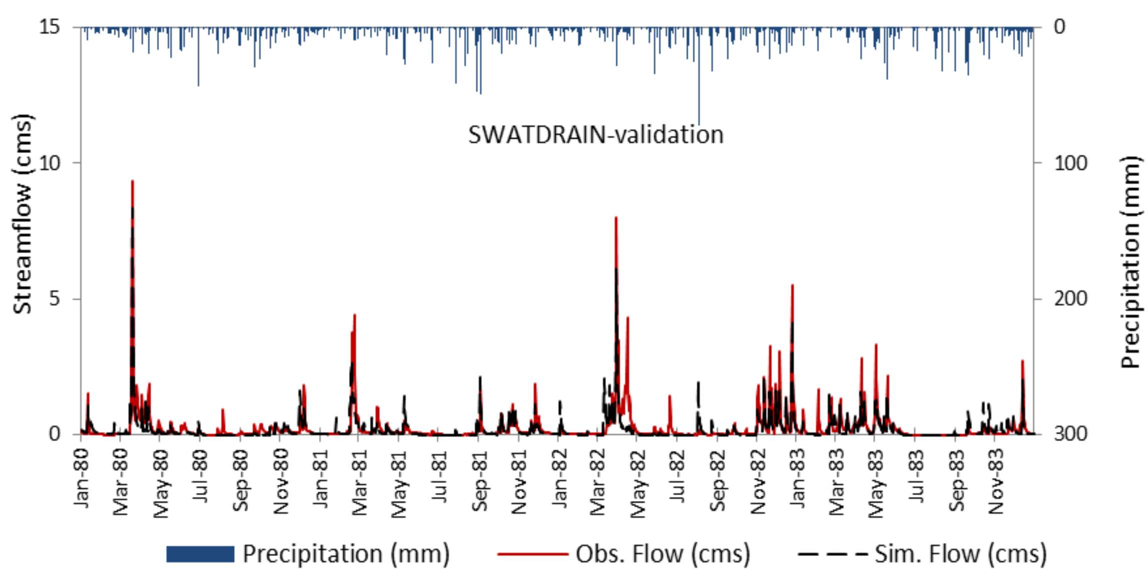

Figure 6.10. Daily streamflow for Canagagigue Watershed during validation period

6.3.1. Impact of Tile Drainage on Water Yield

As part of the hydrologic calibration, the overall water balance was calculated for each year. The annual water balance summaries for 10 hydrologic years of simulation are presented in Table 6.4.

Based on the simulated average annual water balance results, ET with tile drainage (481.1 mm) was lower than the ET without tile drainage (514.0 mm). The simulated water balance showed that from 47% to 55% of the annual precipitation was simulated as being lost in evapotranspiration across the watershed under drainage. While if there is no tile drainage present in the watershed, 49% to 59% of the annual precipitation was simulated as being lost in evapotranspiration.

Also, tile drainage was significantly different based on the simulated annual water balance with and without tile drainage. In this study, CNCOEF calibration value of 0.6 returned an annual average surface runoff of 169.98 mm and 275.29 mm in watershed with and without tile drainage respectively, which indicated that the surface runoff with and without surface runoff was different. For areas where conditions allow use of the traditional method (ICN=0), daily CN is computed based on the soil profile water content (Neitsch et al., 2002).

The average annual simulated streamflow with tile drainage was not different than the streamflow without tile drainage. This is not in agreement with the fact that tile drainage increases agricultural production due to drier soil profiles, which is counteracted by increased streamflow (Moriasi et al., 2012). The reason can be due to size of this watershed which is small, and the amount of tile drainage is always less than 6% of the precipitation, therefore the effect of tile drainage on the water balance is not significant.

Table 6.4. Impact of tile drainage on annual water balance for simulation period

Year	PCP (mm)	Flow (mm)	Drained Sflow (mm)	Drained SRO (mm)	Drained Latflow (mm)	Drained Gflow (mm)	Drained Tflow (mm)	Drained ET (mm)	Non-drained Sflow (mm)	Non-drained SRO (mm)	Non-drained Latflow (mm)	Non-drained Gflow (mm)	Non-drained Tflow (mm)	Non-drained ET (mm)
1975	1039.2	465.5	465.3	329.6	42.4	16.7	46.7	505.6	471.5	366.9	75.0	29.6	0.0	525.0
1976	1031.4	433.06	454.3	298.8	47.9	23.5	54.1	499.2	454.2	316.2	92.7	45.3	0.0	541.0
1977	902.6	396.0	401.0	272.1	45.0	22.5	31.5	475.4	394.2	276. 5	78.3	39.4	0.0	491.0
1978	816.9	285.8	337.5	211.1	41.5	22.9	32.1	420.5	329.6	220.7	70.5	38.5	0.0	471.0
1979	935.0	553.4	448.5	305.2	49.6	25.3	38.4	488.9	444.9	316.0	84.4	44.5	0.0	522.8
1980	922.9	399.9	345.0	208.6	40.6	18.8	46.9	489.8	340. 6	228. 7	76.3	35.6	0.0	515.1
1981	892.1	318.9	366.5	223.4	51.6	24.0	37.5	494. 9	358.8	217.7	95.4	45.7	0.0	528.1
1982	1033.1	566.6	484.0	323.3	65.4	31.8	33.5	492.2	488.6	313.1	117.4	58.1	0.0	509. 6
1983	1026.2	359.1	375.7	179.9	80.0	39. 5	46.4	493.1	376.8	154.8	147.6	74.5	0.0	534.6
1984	902.8	550.4	500.0	343.5	58.9	33.8	33.9	451.8	503.8	342.4	101.9	59.5	0.0	502.2
Average	950.2	430.16	417.8	269.5	52.3	25.9	40.1	481.1	416.3	275.3	93.9	47.1	0.0	514.0

Notes: PCP: precipitation. Sflow: Stream flow. SRO: Surface runoff. Latflow: Lateral flow. Gflow: Groundwater flow. Tflow: Tile flow. ET: Evapotranspiration.

6.4. Conclusions

In this study, SWATDRAIN model which uses the DRAINMOD model approach to simulate subsurface hydrology was evaluated using the measured streamflow from Canagagigue watershed in southern Ontario. In SWATDRAIN model the daily values of tile drainage are calculated using the DRAINMOD model (Skaggs et al., 1980), which computes the tile drainage flux based on the Kirkham and/or Hooghoudt's equations and the hydraulic capacity as a function of the daily water table elevation midway between the drains. Furthermore, SWATDRAIN calculates the water table depth using the DRAINMOD model approach, which is based on drainage volume versus water table depth relationship. This method is used to determine how far the water table falls or rises when a given amount of water is removed or added to the soil profile. The relationship between drainage volume and water table depth is calculated from the soil water characteristics.

In this approach, drainage volume is calculated from a water balance computation in a daily time step. Based on the calculated drainage volume, the water table depth for that specific day is estimated using the soil water characteristics information. Therefore, by using this approach, the water table depth in SWATDRAIN model is estimated by DRAINMOD model for different types of soils in different HRUs.

Model calibration and validation were carried out based on measured daily streamflow for the period from 1975 through 1983. During the calibration period the monthly and daily NSE values were 71.27 and 61.62, respectively, while the PBIAS values at the monthly and daily time steps were 13.98% and 17.99%.

The model performance was determined based on the monthly time step statistics during the validation period and according to Moriasi et al. (2007b) (the model simulation can be judged as good if NSE > 0.65 and RSR ≤ 0.60 and PBIAS ≤ ±15 for streamflow),Therefore, streamflow trends simulation performance rating was good (NSE=71.27, PBIAS=13.96, RSR= 0.54).

Canagagigue Creek watershed is located in an agricultural region in southern Ontario and drainage is used as a common water management practice in many farms across the watershed due to shallow water table depth. The results of this study showed that the SWATDRAIN approach is a potential alternative tile drainage simulation method in SWAT model.

CONNECTING TEXT TO CHAPTER 7

This chapter is a manuscript to be submitted to the Journal of Agricultural Water Management. The format has been changed to be consistent within this thesis. All literature cited in this chapter is listed in the reference section at the end of this thesis. The previous chapter described the application of SWATDRAIN model for hydrology for an agricultural watershed in the Southern Ontario climatic conditions. This chapter presents the results of an application of SWATDRAIN model in evaluating the effects of controlled drainage on water resources in an agricultural watershed in eastern Ontario.

CHAPTER 7: Effect of Controlled Drainage on Watershed Hydrology

Golmar Golmohammadi, Shiv O. Prasher, Ali Madani, Mohamed Youssef and Ramesh Rudra

Abstract

The recently developed SWATDRAIN model was calibrated and validated for Canada's Green Belt watershed, then employed to compare subsurface drainage and surface runoff under conventional tile drainage and an alternative controlled-drainage water management scenario. Controlled drainage was defined with a depth of 1.0 m to restrict flow at the drain outlet to maintain the water table at 0.5 m below the surface level during the winter (November-April) and at 0.6 m during the summer (June-August) months. The effects of the absence or implementation of drainage water management were predicted for the 4-year period of 2004-2007. Implementing controlled drainage resulted in an 18% reduction in mean annual drain flow, while increasing surface runoff by as much as of 30% in specific years. This demonstrated that overall watershed hydrology could be significantly impacted by the implementation of controlled drainage.

Key Terms: Hydrological modeling; SWATDRAIN; Watershed scale; Controlled drainage

7.1. Introduction

Artificial subsurface drainage is essential to provide trafficable conditions for farming operations and to protect crops from excessive soil water conditions (Skaggs, 1999). This is a necessary water management practice in the agricultural areas of humid regions with seasonally high water tables during the growing season. On most occasions drainage systems are designed to lower the water table sufficiently enough to satisfy drainage conditions (Evans et al., 1992). In the provinces of Ontario and Quebec, approximately two million hectares of cropland, mostly cropped to corn and soybean, are subsurface drained (Helwig et al., 2002).

Although subsurface drainage provides many agronomic and environmental benefits, it increases the export of soil nitrate-nitrogen (NO_3-N) and phosphorous to surface water bodies, where it can have detrimental effects on water quality (Baker et al., 1975; Gilliam, 1987; Skaggs 1994). Studies by the Quebec Ministry of Environment (MENV) have reported that most rivers in Quebec draining from agricultural lands have elevated nitrate and phosphorous concentrations (Enright and Madramootoo, 2004).

Soil wetness is a major concern in humid regions, where variation in weather conditions can result in crops periodically suffering from drought stresses and thereby, in some years, suffering substantial yields losses (Evans et al., 1992). Drainage systems designed for providing trafficability during extreme wet periods tend to remove more water than necessary during drier periods, leading to temporary over-drainage. A strategy that can provide sufficient drainage through wet periods, yet not be subject to over-drainage during dry periods, would be ideal (Evans et al., 1992). This can be achieved by shifting from conventional drainage to water table management systems.

Conventional drainage systems require minimal maintenance and management after their initial installation; however, they raise environmental concerns, particularly with respect to loading of agricultural pollutants, especially NO_3^--N and P, from subsurface drainage systems (Ale et al., 2009).

A drainage water management system requires the installation of a water table control structure at the outlet of the subsurface drainage system, whereby the outlet elevation can be raised or lowered according to the season (Ale et al., 2009). Controlled drainage leads to the storage of water in the soil profile by reducing the gradient for subsurface drainage. A controlled drainage weir in the ditch or a riser in a drainage pipe outlet structure prevents drainage outflow from the system until the water level in the ditches/pipe rises above the weir/riser elevation. Compared to conventional drainage, controlled drainage may delay tile drainage outflow, thereby reducing total tile-flow contributed water at the watershed outlet (Skaggs et al., 2006).

Controlled drainage has been applied at both the field and the watershed scales to conserve water, improve water quality, and increase crop yield (Doty et al., 1984; Parsons et al., 1987; Busscher et al., 1992; Evans et al., 1992). Several field and modeling studies have reported that controlled drainage practices reduce tile drainage flow and associated NO_3^--N loading, while maintaining the necessary drainage rates during critical stages of the growing season, and for periods of high water table levels during spring, summer, and early autumn (Evans et al., 1995; Lalonde et al., 1996; Breve et al., 1998; Fausey. 2004; Sing et al., 2007; Ale et al., 2009).

While it is well established that the impact of controlled drainage depends heavily on local conditions (Singh et al., 2007), only few studies have been conducted in Ontario to assess the impact of water table management on crop production and nitrogen loading (Drury et al., 1996; Lalonde et al. 1996; Ng et al., 2001). These show the potential for large reductions in tile flow and nutrient loads with drainage water management.

Drury et al. (1996) reported a 25% decrease in mean NO_3^--N loads, and a 49% decrease in the total annual NO_3^--N load when drainage water management was implemented on a clay loam soil in southwestern Ontario. Lalonde et al. (1996), working with a 2-year corn/soybean rotation on a silt loam soil in Quebec, measured reductions, compared to conventional subsurface drainage of 59% and 65% in drain flow, and 76% and 69% in NO_3^--N concentration reduction for outlet levels of 0.25 and 0.50 m above drain level in drainage water management systems, respectively. Drainage researchers estimate that drainage water management can lead to a 30% reduction in mean annual NO_3^--N loads, particularly in regions where appreciable drainage occurs in late fall and winter (Cooke et al., 2005).

Of the few available models capable of simulating drainage water management systems for soils, DRAINMOD (Skaggs, 1978) is one of the most widely used (Wright et al., 1992; Singh et al., 2007; Ale et al., 2009). Singh et al. (2007) used DRAINMOD to predict the impact of controlled drainage on subsurface hydrology and crop production in an Iowa watershed, found a reduction in tile drainage outflow of up to 18% under controlled *vs.* conventional drainage. Operating at the Purdue University Water Quality Field Station, Ale et al. (2009) showed a 60% reduction in predicted mean annual drain flows upon the implementation of a drainage water management strategy.

Simulation software is one of the key tools in recent watershed management research. Several hydrologic models [e.g., Simulation Program-Fortran or HSPF (Bicknell et al., 1996); the European Hydrological System Model or MIKE SHE (Refsgaard and Storm, 1995); Areal Non-point Source Watershed Environment Response Simulation or ANSWERS (Dillaha, 2001); Annualized Agricultural Non-Point Source model or AnnAGNPS (Bingner et al., 1998); Watershed Analysis Risk Management Framework or WARMF (Chen et al., 1998); The Agricultural Policy/environmental eXtender (APEX) model (Williams and Izaurralde, 2006; Williams et al., 2006; Williams et al., 2008; Gassman et al., 2009); Soil and Water Assessment Tool or SWAT (Arnold et al., 1998)] can be used to simulate the hydrology of a watershed.

Such models each have their own strengths and weaknesses, but one of their most common limitations is the lack of a good, integrated, watershed management model with a drainage simulation tool capable of simulating different water table management scenarios.

The water table estimation in the existing watershed management models such as SWAT, WARMF, ANSWERS, and HSPF are based on a soil water balance. But practices such as control drainage and subsurface irrigation have not been addressed. Others like MIKE-SHE solve the water flow equation in the unsaturated zone numerically, which requires high computational power and several costly input data. In addition, simulating tile drainage is not easy to implement in MIKE-SHE and controlled drainage is not considered at all.

To the best of the author's knowledge, no modeling study in Canada has investigated the potential effects of controlled drainage at the watershed scale, and conversely no watershed-scale models, including SWAT, have been capable of adequately simulating the hydrological consequences of controlled drainage.

In many watersheds with tile drainage systems, it is necessary for managers to compare different scenarios in order to achieve the best management practices and achieve higher crop production. Therefore, it is important for hydrologic models to be able to simulate water management practices such as controlled drainage.

In this study, a new watershed-scale model named SWATDRAIN, integrating SWAT-driven surface flow and DRAINMOD-driven subsurface flow capacities was developed to improve on the accuracy and efficiency of the new model. The SWATDRAIN model is capable of simulating more complicated drainage water management scenario simulations such as controlled drainage and subirrigation. The newly developed model was used to predict the potential impact of the water management operational strategy of controlled drainage on the watershed scale hydrology of the Green Belt watershed, located in eastern Ontario, Canada.

7.2. Materials and Methods

7.2.1. Watershed Description

The experimental site was a 14 ha (approximately 450 m×315 m) watershed at the Greenbelt Research Farm at Agriculture and Agri-Food Canada, near Ottawa, Ontario. The watershed was characterized by a Typic Haplaquent (Dalhousie Association, Brandon series) soil with loamy-textured Ap and B horizons underlain by silty clay at a depth of approximately 0.60 m. The field was nearly level, with a mean slope of approximately 0.2% (Patni et al., 1996). The site was tile drained in 1986, with laterals 15 m apart and 1.0 m below the soil surface. Roughly 0.20 m high berms were built around the periphery of the plots to prevent surface water flow across the plots. Each plot was about 3 ha and was drained by four or more tile laterals. Tile effluent from each plot was routed to a separate monitoring station. Tile flow data were collected for February 1991 until December 1993. Flow could not be recorded for a few days each spring due to flooding of the monitoring stations by water backed up in the tile main from the downstream ditch. Monitoring stations were similarly flooded for a few hours following an intense rainstorm during one flow event from 17th July to 24th July 1992. Tile drainage was assumed to be negligible for the duration of the flood periods (Patni et al., 1996).

The soil's water retention capacity was determined by applying tension (-50 to -350 mm of water) to 75 mm I.D. × 75 mm height intact soil cores collected at 0-0.15 m and 0.15-0.30 mm depths in May 1991, August 1991, and May 1992. Soil moisture was measured *in situ* between 8th June and 17th October 1993, using a time-domain reflectometry (TDR) method (Patni et al., 1996).

The water table depth (WTD), midway between tile laterals, was continuously monitored with a Belfort stage recorder (Belfort Instrument Co., Baltimore, MD) mounted on a 3.0 m deep by 100 mm I.D. perforated pipe. The

WTD was also monitored between June 1991 and December 1993 at 12 observation wells. The water table fluctuation over the study period was similar at all 12 monitoring sites in the study area.

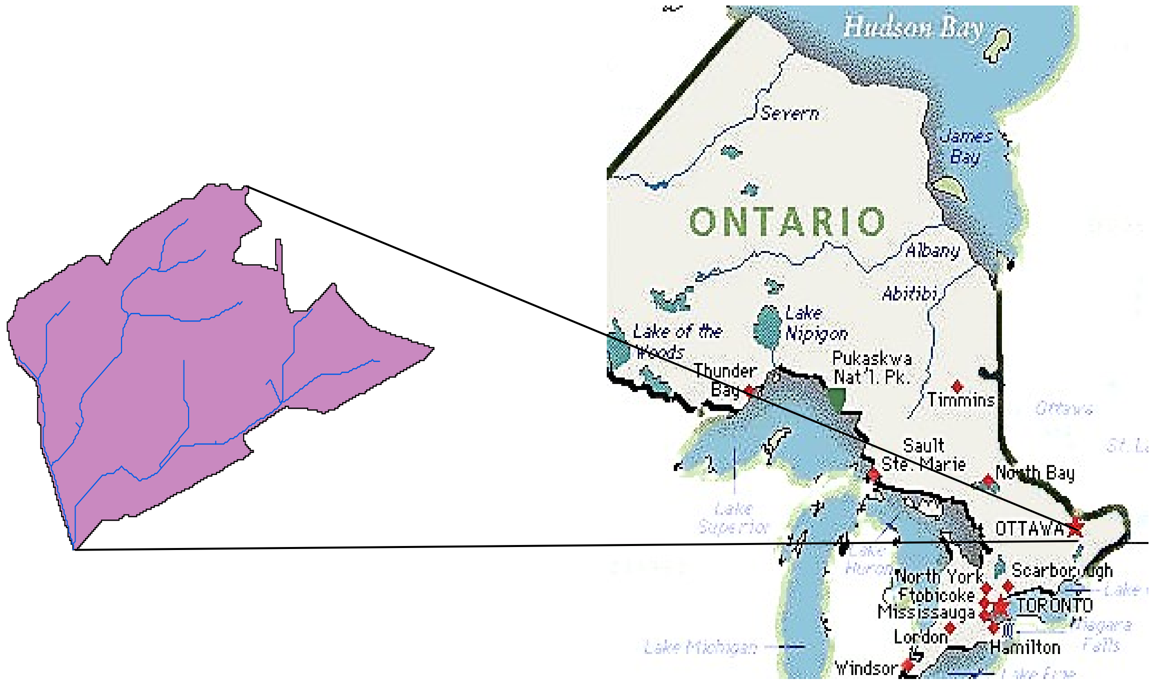

Figure 7.1. Location and stream pattern of the study area

During non-freezing periods (mid-April to mid-October), rainfall was measured on-site using Belfort Universal rain gauges. Precipitation values for the remainder of the year were obtained from the Ottawa Macdonald Station weather station operated by Agriculture and Agri-Food Canada, and located 12 km from the experimental site. Monthly rainfall totals during the study period are shown in Figure 7.2.

The annual precipitation was close to the regional mean of 864 mm, except in 1991, when precipitation was below average and the water table depth was more than 3 meters below the soil surface for most of the growing season. In 1992, the growing season was relatively wet. The spring of 1993 was particularly wet with 127 mm of rain in April.

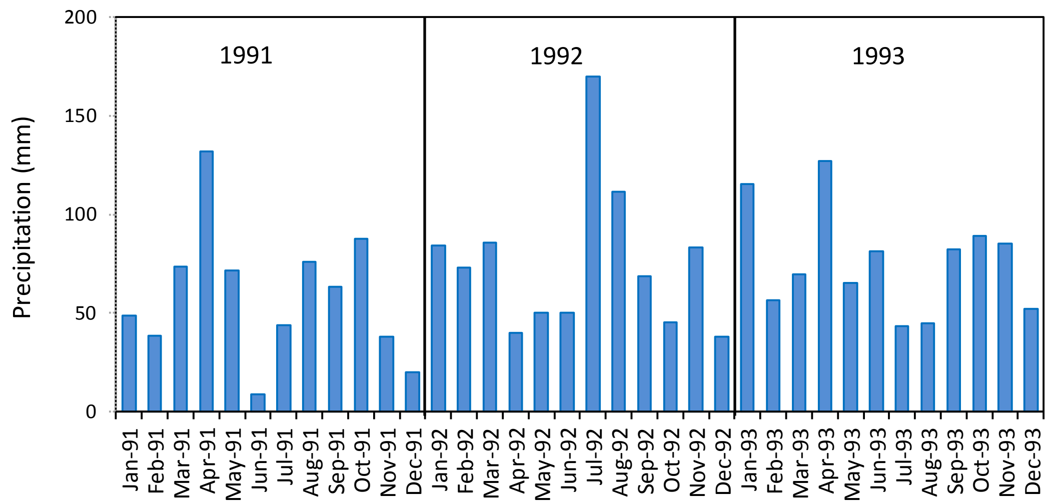

Figure 7.2. Monthly precipitation for the calibration and validation period from 1991 to 1993

7.2.2. SWATDRAIN Model Overview

DRAINMOD was incorporated into the subsurface hydrology module of the SWAT model as an alternative method for simulating tile drainage and water table depth. The newly-developed SWATDRAIN model is based on the DRAINMOD subsurface hydrology simulation model and the SWAT surface hydrology simulation model. SWATDRAIN computes the soil water balance, on a daily basis for each hydrological response unit (HRU) in every subbasin of the watershed under study. For the first day of the simulation, all calculations were made through the SWAT model. The results, including surface hydrology parameters, initiated the system for the first day and for all HRUs.

Each HRU is flagged as drained or non-drained based on the presence or absence of subsurface drainage. For the HRUs flagged as drained, DRAINMOD is used to simulate subsurface hydrology. In order to do so, surface hydrology parameters for any given day are transferred to DRAINMOD using 'DrainM.f,' a newly developed subroutine added to the SWAT source code. At this stage, DRAINMOD computes the subsurface hydrology parameters for each drained HRU for the given day in SWAT. The parameters calculated in DRAINMOD (*e.g.*, subsurface drainage flow, WTD, and soil moisture content) are then transferred back to the SWAT for each HRU, again using the 'DrainM.f' subroutine.

SWAT uses either the SCS curve number procedure (SCS, 1972), or the Green and Ampt infiltration method (Green and Ampt, 1911), to estimate infiltration and surface runoff. Therefore, in the SWATDRAIN model the user specifies one of the two methods for calculating infiltration.

Different methods can be used in SWATDRAIN to estimate potential evapotranspiration (PET): the Penman-Monteith method (Monteith, 1965), the Priestly-Taylor method (Priestly and Taylor, 1972), the Hargreaves method (Hargreaves and Samani 1985), the Thornthwaite method (Thornthwaite, 1948), or PET can also be entered as daily or monthly PET input by the user. In SWATDRAIN, the daily values of tile drainage are calculated by the DRAINMOD portion of the model (Skaggs et al., 1978), which computes the tile drainage flux based on the Kirkham and/or Hooghoudt's equations, and the hydraulic capacity as a function of the daily water table elevation midway between the drains.

In SWATDRAIN, how far the water table falls or rises when a given amount of water is removed or added to the soil profile is calculated according to the drainage volume. SWATDRAIN calculates the drainage volume for each HRU on a daily time step based on a water balance computation. The water table depth is estimated using the relationship between drainage volume and water table depth. This relationship is a model input for any given soil in the watershed.

7.2.3. Drainage Water Management Simulations

Controlled drainage systems serve mainly to maintain a shallow water table near the effective crop root zone by restricting tile drainage outflow using a control structure at the drain outlet. Bryant (1986) used a value of 75 cm for the maximum effective root depth for Ontario condition. Rudra et al., (1995) used a value of 50 cm, for loam soil, in their study of CREAMS.

The effective depth of a corn crop's root zone in present study is about 0.60 m under Ontario conditions. Also, for trafficability, the water table depth of 0.60 m or deeper at planting (May-June) and at harvest (September-October) would be adequate. Therefore, free drainage was assumed for these months and controlled drainage was simulated by maintaining an outlet control level of 0.60 cm below the soil surface during the summer (June-August) and 0.50 m below the soil surface during the winter (November-April), while a conventional free drainage prevailed the remainder of the year.

The SWATDRAIN model was used to simulate the drainage water management scenario of controlled drainage within the Green Belt watershed for the period of 2004 to 2006. Controlled drainage was applied in the watershed from 15 June to 15 August through the use of weir with an outlet 0.60 m below the soil surface, while from November 1 to April 30 the weir was set at 0.50 m, otherwise full drainage was implemented. The purpose of this treatment was to conserve water during the growing season; while the purpose of the controlled drainage during the winter (November through March) was to reduce the NO_3^--N load in the soil profile.

7.3. Results and Discussion

In a recent study, the SWATDRAIN model was evaluated for the fully tile drained Green Belt agricultural watershed in Ontario (Golmohammadi et al., 2014). During the calibration period, the monthly and daily NSE (Nash-Sutcliffe Efficiency) values for water table depth were 0.92 and 0.82, respectively, while the equivalent PBIAS (Percent Bias) were 11.59 and -3.75.

For tile flow, during the calibration period, the monthly and daily NSE values were 0.91 and 0.67, respectively, while the equivalent PBIAS values were 9.61 and 18.23. Such results showed the model to be well calibrated. Similar values were obtained during validation (Golmohammadi et al., 2014).

In the present study, the validated SWATDRAIN model served to simulate and evaluate the potential performance of controlled drainage in the watershed for the period of 2004 to 2007 (Figures 7.3). This period represented a relatively wet period in the watershed and thus might better highlight the impact of controlled drainage on watershed flow. In wet periods, the WTD may reach or exceed drain depth for extended periods.

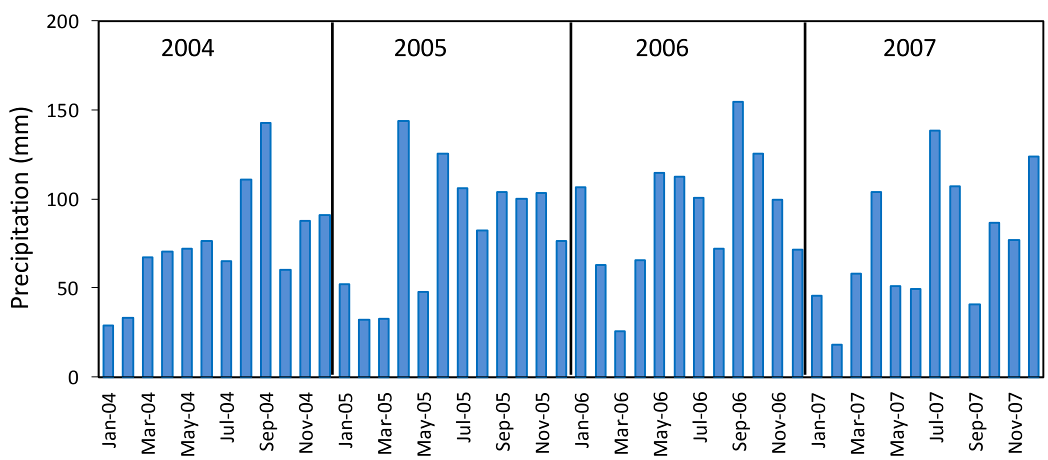

Figure 7.3. Monthly precipitation for the period from 2004 to 2007

Daily precipitation, maximum and minimum temperatures (Ottawa Macdonald Station) for the simulation period of 2004 to 2007 were used. Mean monthly precipitation varied from 58 mm in January to 102 mm in July. The remaining input parameters remained the same as those of the conventional drainage simulation.

7.3.1. Effects of Drainage Water Management Practice

Controlled and conventional drainage practices were compared in terms of predicted streamflow, tile drainage outflow and water table depth for the relatively wet period extending from January 2004 to December 2007. Under drainage water management, the outlet was raised to a depth of 60 cm from June 15 to August 15 during the growing season and to a depth of 50 cm from November 1 to April 30 during the non-growing season. From May 1 to June 14, and Sept 16 to Oct 31, the outlet was at the drain level.

The results from this study showed that controlled drainage systems do not affect the total amount of annual streamflow from the watershed substantially; it was 4% less than the streamflow under conventional drainage.

However, there was a change in the monthly pattern of streamflow under controlled drainage practice. Changes mostly happened during the snowmelt period in April and May (Figure 7.4).

Both decrease and increase in streamflow during the months of April and May likely happened because of the tile drain outflow decrease and increase during these months. The tile drainage component in this watershed is more than 80% of the total streamflow.

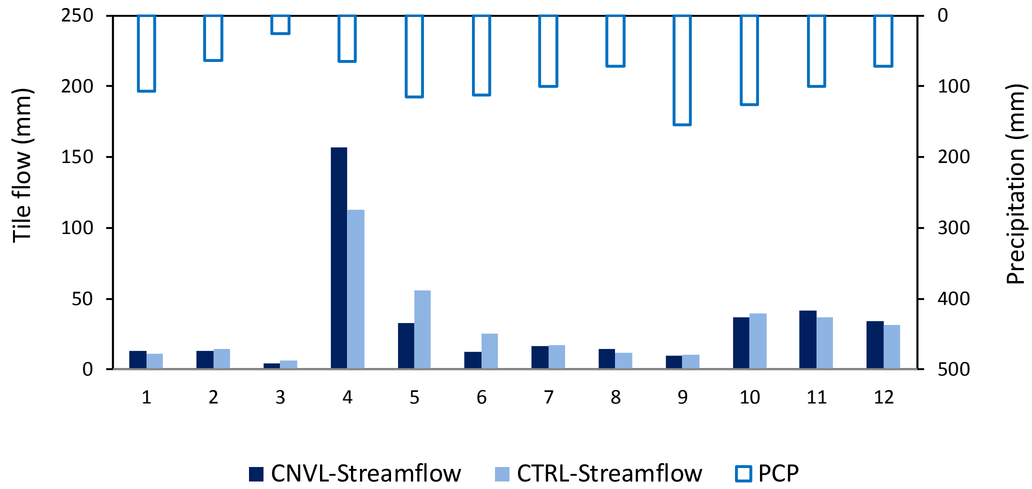

Figure 7.4. Monthly streamflow for conventional and controlled drainage. Note: CNVL: conventional; CTRL: controlled; PCP: precipitation

On average across the study period (2004-2007), controlled (*vs.* conventional) drainage led to greater evapotranspiration through greater water availability to plants, as well as a concurrent decline in subsurface drainage (Figure 7.4). This is the most significant benefit of drainage water management since it can conserve water in the soil profile during the growing season and increase crop yield. Since the controlled drainage system would allow less water to drain, the water table would remain shallower than under conventional drainage. This shallower water table would, in turn, lead to a wetter soil profile, which, according to the simulations, resulted in greater surface runoff.

While controlled drainage reduced subsurface drainage on the order of 18% compared to conventional drainage, it increased surface runoff by 30% (Table 7.1).

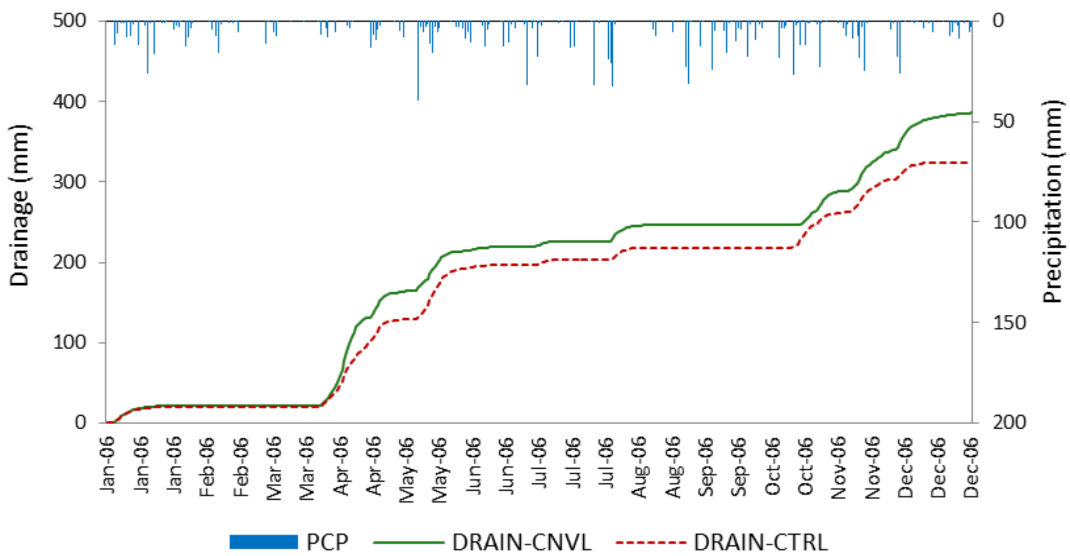

Figure 7.5. Impact of controlled drainage on cumulative drain outflow component of streamflow. Note: PCP:precipitation; CNVL: conventional; CTRL: controlled

There is limited information regarding the impact of controlled drainage on surface runoff in the literature. However, the results show that the reduction in subsurface drainage due to controlled drainage was reflected in an increase in surface runoff at the watershed scale. This can be attributed to higher water tables due to controlled drainage which, in turn, causes higher soil moisture in the unsaturated zone and an increase in surface runoff.

Surface runoff and tile drainage are the two major pathways by which nutrients and sediments are transported from agricultural land to waterways. In general, the increase in surface runoff can have different impacts on watershed management. It may increase the amount of nitrogen loading from farmlands at the watershed scale. This also may lead to increased soil erosion and sedimentation in the watershed. The surface runoff in agricultural watersheds carries pollutants such as fertilizers and herbicides directly to streams and rivers, where they seriously harm water quality.

Therefore, a balance between the controlled drainage system to increase the water availability for plant, and lower water pollution from reduced drain outflows, and increase in surface runoff should be made to make it a best management practice for the watershed.

The results from this study showed that the surface runoff increase mostly happened during the snowmelt period in April and also it has been slightly increased during the month of November (Figure 7.5).

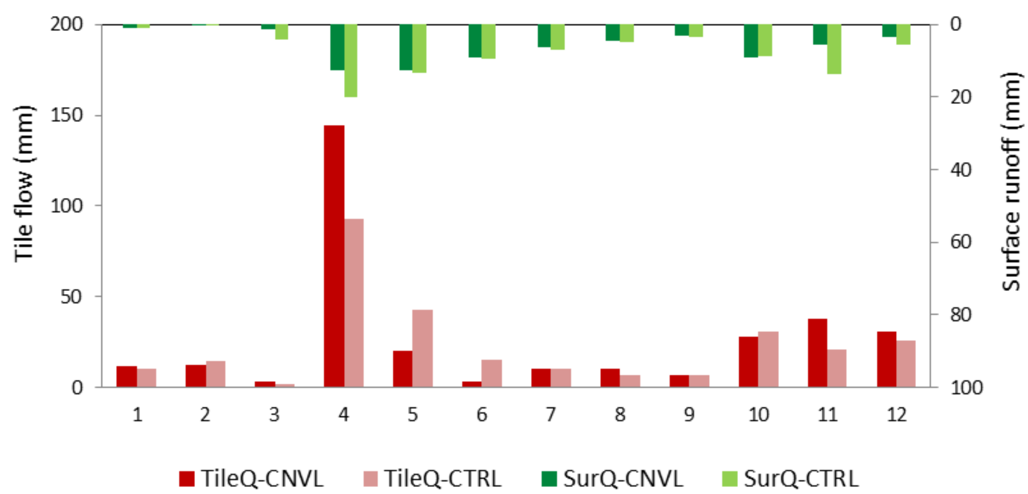

Figure 7.6. Monthly surface runoff and tile drainage for conventional and controlled drainage. Note: CNVL: conventional; CTRL: controlled; TileQ: tile drainage; SurQ: surface runoff

However, the snowmelt runoff from relatively flat fields is not likely to carry high pollutant concentrations (Patni et al., 1994). Therefore, higher amount of surface runoff in flat watersheds during the snowmelt period may not cause a serious pollution problem.

The results also show that approximately 49% of annual subsurface drain outflow under conventional drainage occurred in the months of April and May (Figure 7.6 and 7.7). In controlled drainage fields, the outlet was set at 0.5 m depth, thus leading to lesser drain outflow, from these fields. In the month of May, in order to obtain trafficable condition and to ascertain good soil water environment in the top soil, controlled drainage is not practiced in Ontario. The depth of the outlet control is set at 1.0 m below the soil surface, causing the system to behave like a conventional drainage system. This led to somewhat similar tile flows under both scenarios for the month of May (Figure 7.6).

Table 7.1. Annual subsurface drainage and surface runoff for conventional and controlled drainage

Management	Conventional		Controlled	
Year	Tile flow (mm)	Surface runoff (mm)	Tile flow (mm)	Surface runoff (mm)
2004	142.2	31.6	136.5	33.4
2005	205.4	64.7	176.1	83.7
2006	385.4	89.7	324.5	139.7
2007	276.3	40.97	249.7	39.5
Average	252.3	56.7	221.7	74.1

In fact, excess water that has been stored in the soil profile during the winter and early spring months is released when the control structure is opened to lower the water table for trafficability in May.

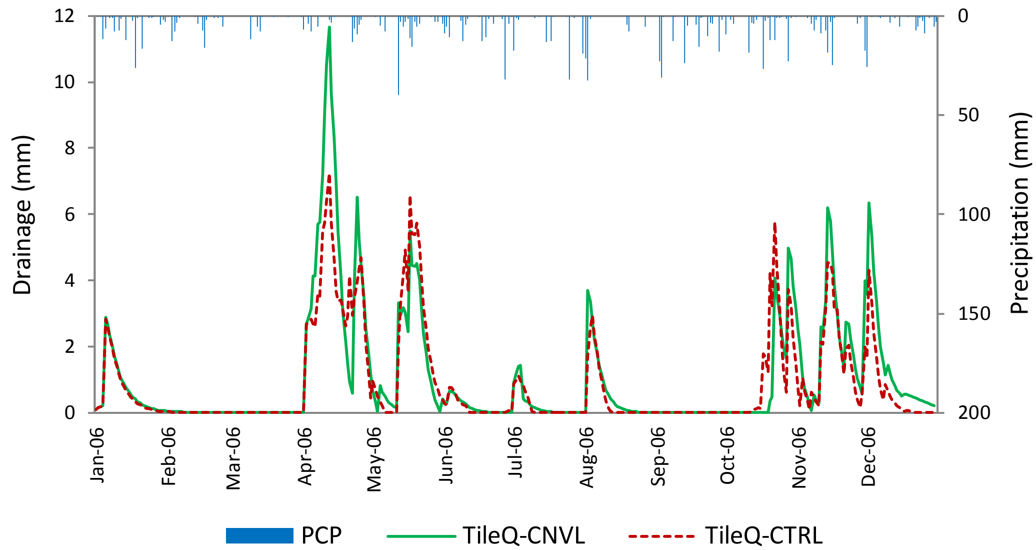

Figure 7.7. Impact of controlled drainage on daily drainage outflow component of streamflow. Note: PCP:precipitatio; CNVL: conventional; CTRL: controlled

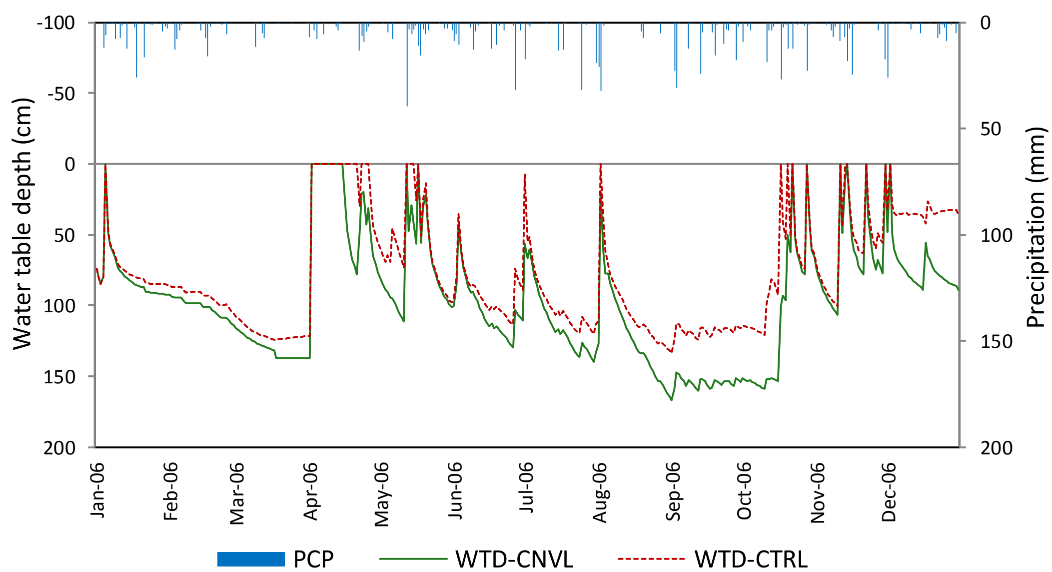

Figure 7.8. Impact of controlled drainage on water table depth. Note: PCP:precipitatio; CNVL: conventional; CTRL: controlled

Therefore, in some years, there is slightly higher subsurface drainage in May under controlled drainage as compared to free drainage (Figure 7.5).

Table 7.2 shows the maximum water table differences between conventional and controlled drainage water management for every year during the winter period and the cropping period. Due to controlled drainage management, the water table rose above the conventional drainage level during both winter and cropping periods in all years. Figure 7.8 shows that the water table remained shallower under controlled drainage than under free drainage.

In general, due to the shallower water table depth under controlled drainage, especially during the growing season, the water table depth might remain shallower and thereby might reach the crop root zone more frequently than under conventional drainage under high precipitation events.

However a large rainfall event under CD (or SI) can result in ponding/flooding (water above surface of soil), soybean is relatively resistant to extended periods of excess moisture, whereas corn is rather adversely affected.

Table 7.2. Maximum difference in water table depth between conventional and controlled drainage systems

Year	Winter period		Cropping period	
	Maximum rise (m)	Date	Maximum rise (m)	Date
2004	0.327	March 30	0.364	May 24
2005	0.617	March 1	1.095	June 16
2006	0.385	December 16	0.301	July 13
2007	0.502	March 31	0.511	June1

Therefore, the average number of days with depth to water table depth less than 30 cm might increase under controlled drainage. One way to review potential excess water stress on crop production when devising a controlled drainage scenario is to count the number of days with depth to water table less than 30 cm below the soil surface during the crop growing season.

7.4. Conclusions

The SWATDRAIN model has the potential to accurately simulate the effects of conventional and drainage water management scenarios at the watershed scale. The model was used to simulate the effects of controlled drainage in the Green Belt watershed located in Eastern Ontario, Canada. The SWATDRAIN model was used to identify the impact of controlled drainage on hydrologic variables such as water table depth and tile drainage outflow. This study further suggests that controlled drainage has the potential to reduce subsurface drainage as compared to conventional drainage. Implementing the controlled drainage strategy from June 15 to August 15 during the crop season and also from November 1 to April 1 in the non-growing season resulted in a reduction of the average annual drain flow by 18 % in individual years.

However, most of the reduction in subsurface drainage due to controlled drainage was reflected in an increase in surface runoff. The simulated average surface runoff in this watershed was increased by 30% under controlled drainage, as compared to conventional drainage. The simulations showed little change in estimated evapotranspiration, but there is the possibility that evapotranspiration could be increased under certain controlled drainage scenarios.

The results of the SWATDRAIN simulations here described highlight the potential effectiveness of controlled drainage on improving watershed hydrology under Ontario conditions. Therefore, the decrease in subsurface drainage due to controlled drainage is expected to have a positive impact on conserving soil water content and consequently reducing soil nutrients. This, in turn, can increase the crop yield and water use efficiency.

These simulations used a set scheme for controlled drainage management during the winter and summer months, and free drainage during crop planting and harvesting months. However, there is a potential that a more flexible scheme of controlled drainage may reduce or increase the impact of controlled drainage on tile drainage, surface runoff and number of days with depth to water table less than 0.30 m below the soil surface.

CHAPTER 8: General Summary and Conclusions

A new model, SWATDRAIN, has been developed in this study by fully integrating SWAT and DRAINMOD models. The model was evaluated for two tile drained agricultural watersheds in Ontario, Canada.

SWAT excels as a surface flow and transport model; however, subsurface flow is handled in the model in a rather simplistic way. Also, the model does not account for subsurface drainage, controlled drainage or sub-irrigation systems and thus it is not truly applicable on watersheds under humid regions in North America.

On the other hand, DRAINMOD is a one-dimensional water and solute transport model which was developed primarily for humid regions but it does not account for surface flow of water and agricultural pollutants in a logical way. Therefore, it was decided in this study to work on integrating these two models and the resulting model, SWATDRAIN, can simulate surface/subsurface flow and transport processes in a rational way for agricultural tile drained watersheds in humid regions.

The new model, SWATDRAIN, was developed by linking SWAT and DRAINMOD models, thereby taking advantage of the strong surface flow modeling capabilities of the former and the higher accuracy of subsurface modeling of the latter. The new model is superior performance-wise to both of the models individually. Moreover, the new model allows for simulations to be carried out under different scenario analyses and management practices which were not possible using these models individually.

SWATDRAIN computes the soil water balance, on a daily basis, for each HRU in every subbasin. For the first day of the simulation, all calculations were made on the SWAT model and the results, including the surface hydrology parameters, were ready for the first day and for all HRUs. According to the presence or the absence of a drainage system in each HRU across the watershed, it is termed drained or non-drained, respectively. Next, DRAINMOD is used for tile drained HRUs of the watershed to simulate subsurface hydrology. DRAINMOD, which is now part of SWAT code, computes subsurface hydrology parameters for the same day, as the surface hydrology parameters were calculated by SWAT. After simulating the subsurface drainage, water table depth, and soil moisture content, the values of these parameters are used in SWAT for the next day of simulation.

The performance of the new model was tested on two watersheds in Ontario. A first test of the model was conducted on a 14 ha fully drained Green Belt watershed located at agriculture and Agri-Food Canada, near Ottawa, Ontario. This watershed lies in a cold and humid region of central Canada. The goal of this study was to evaluate the SWATDRAIN model for the Green Belt watershed located in Southern Ontario. The measured tile drainage and water table depth data from this watershed were used to evaluate the capability of the new model to simulate water balance component for this tile drained agricultural watershed. The measured tile flow and WTD were compared with that predicted by the SWATDRAIN using the Nash-Sutcliffe efficiency (NSE), PBIAS and R^2 statistical methods in addition to hydrographs. Simulations were carried out from 1991 to 1993; data from 1991 to 1992 was used for model calibration and data from 1993 was used for validation.

The new model was able to adequately simulate the hydrologic response at the outlet of the watershed. During the calibration and validation period, the SWATDRAIN simulated WTD and Tile flow very well. The new model simulated tile drainage outflow and water table depth better than the SWAT model alone.

The second application of the model was conducted on the partially drained 18 km^2 Canagagigue Creek west watershed located in the Grand River basin in southern Ontario. The data collected was used in calibrating and validating SWATDRAIN, the newly developed model, SWATDRAIN. Simulations were carried out from 1975 to 1983; data from 1975 to 1979 was used for model calibration and data from 1980 to 1983 was used for validation. The new model was able to adequately simulate the hydrologic response at the outlet of the watershed.

It was found that the SWATDRAIN model was capable of simulating well surface and subsurface hydrology at the watershed-scale. Based on the results obtained in this study, it can be concluded that the new model is capable of simulating the hydrology of tile-drained watersheds where subsurface drainage systems are the main mechanisms for removing excess water and nutrients from the root zone.

The specific conclusions from the study are as follows:

i) The performance of three popular watershed scale models MIKE SHE, APEX and SWAT, was evaluated for their ability to simulate the hydrology of 52.6 km^2 Canagagigue Watershed, located in Grand River Basin in southern Ontario, Canada. All three models were calibrated for 4-year period and validated using an independent 4-year period by comparing simulated and observed daily, monthly and annual streamflow. Simulated flows generated by the three models are quite similar, and closely match observed flow, particularly for the calibration results. The mean daily/monthly flow at the outlet of the Canagagigue watershed simulated by MIKE SHE and SWAT was more accurate than that simulated by APEX model, during both calibration and validation periods. Moreover, for the validation period, MIKE SHE and SWAT predicted the overall variation of streamflow slightly better than APEX.

ii) The goal of this study was to incorporate the DRAINMOD model into the Soil and Water Assessment Tool (SWAT) to better simulate surface and subsurface flow in tile-drained watersheds and also to improve the prediction of the water table depth. This was accomplished by full integration of the DRAINMOD model, which has been well-tested and widely used to simulate the performance of drainage and water table control systems on a continuous basis at field scale. In this modeling approach, surface flow is simulated using the SWAT model, and subsurface flow is estimated using the DRAINMOD model. The newly developed model referred to as SWATDRAIN shows great potential to perform simulations of multiple scenarios to determine cost-effective water management systems such as controlled drainage, subsurface irrigation and wastewater treatment at the watershed scale.

iii) SWATDRAIN model was evaluated for the Green Belt watershed located in eastern Ontario. The measured tile drainage and water table depth data from this watershed were used to evaluate the capability of the new model to simulate water balance component for this tile drained agricultural watershed. The measured tile flow and WTD were compared with that predicted by the SWATDRAIN using the Nash-Sutcliffe efficiency (NSE), PBIAS and R^2 statistical methods in addition to hydrographs. Simulations were carried out from 1991 to 1994; data from 1991 to 1993 was used for model calibration and data from 1980 to 1984 was used for validation. The new model was able to adequately simulate the hydrologic response at the outlet of the watershed. During the calibration and validation period, the SWATDRAIN simulated water table depth and Tile flow very well. Comparing the observed monthly and daily water table depth with the model's output over the validation period returned the R^2 values of 0.86 and 0.70, PBIAS of 0.11 and 2.9 and modeling efficiency of 0.80 and

0.67. Also, observed event based and daily tile drainage with the model's output over the validation period returned the R^2 values of 0.86 and 0.70, PBIAS of 11.7 and 23.85 and modeling efficiency of 0.84 and 0.62. This clearly demonstrates the DRAINMOD approach is a potential alternative tile flow simulation method and tile drainage design tools in SWAT.

iv) SWATDRAIN model was applied to the Canagagigue Creek watershed located in southern Ontario. The measured stream flows were compared with that predicted by the SWATDRAIN using the Nash-Sutcliffe efficiency (NSE), PBIAS and R^2 statistical methods in addition to hydrographs. Simulations were carried out from 1975 to 1983; data from 1975 to 1978 was used for model calibration and data from 1980 to 1983 was used for validation. The new model was able to adequately simulate the hydrologic response at the outlet of the watershed. Comparing the observed monthly and daily water table depth with the model's output over the validation period returned the R^2 values of 0.75 and 0.62, PBIAS of 13.96 and 17.99 and modeling efficiency of 0.71 and 0.62.

v) The effects of a drainage water management operational strategy on hydrology in the Green Belt watershed in Canada were simulated by SWATDRAIN. Controlled drainage was defined with a depth of 1.0 m restricts flow at the drain outlet to maintain the water table at 0.5 m below the surface level during the winter (November-April) and at 0.6 m during the summer (June-August) months. These drainage management modifications were evaluated over a four-year period against a conventional drainage system installed at a drain depth of 1.0 m with free drainage at the drain outlet. Implementing the controlled drainage strategy from June 15 to August 15 during the crop season and also from November 1 to April 1 in the non-growing season resulted in a reduction of the average annual drain flow by 18 %, while it increased the surface runoff in the order of 30% in individual years. The results showed that the surface runoff increase mostly happened during the snowmelt period in April and also it was slightly increased during the month of November. However, higher amount of surface runoff in flat watersheds during the snowmelt period may not cause a serious problem.

CHAPTER 9: Contributions to Knowledge and Recommendations for Further Research

9.1. Contributions to Knowledge

The work presented here provides original contributions to the body of knowledge pertaining to surface and subsurface hydrology of a watershed, especially agricultural watersheds with tile drainage. The main contributions of this dissertation are as follows:

1. A new model, called SWATDRAIN, has been developed, by fully incorporating DRAINMOD into SWAT in order to improve its capability to predict subsurface hydrology of agricultural tile drained watersheds. The model presents better prediction of the flows and water table dynamics on a watershed scale. Thus the new model is able to simulate better both surface and subsurface hydrology of rural watershed. The model works for both fully drained and partially drained watersheds.

2. SWATDRAIN can simulate drainage water management scenarios on watershed scale and their impacts on watershed hydrology very well. The impact of practices such as controlled drainage and subirrigation can be simulated on watershed scale by the model. The results could serve as a guideline for planning water management systems on a watershed scale for cold humid regions.

9.2. Recommendations for Further Research

1. Currently, the SWATDRAIN model has been validated for hydrology only. All aspects of water quality need further testing and refinement. Therefore, the model needs further verification to assess its ability to simulate water quality, sediment and nitrogen loading from farmlands at the watershed

scale. Approaches such as modifications of different components of the model, which support more accurate simulation of specific processes, or integrating the model with other models are suggested.

2. The model should be used to carry out more complex watershed scale scenario simulations, such as the implementation of alternative water table management systems, such as subirrigation, waste water treatment applications as well as controlled drainage and subirrigation in sequence at the watershed scale.

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