Modeling Hydrology and Nitrogen Fate and Transport in a Tile-Drained Agricultural Watershed in a Cold Region

By

Shadi Dayyani Dardashti

Department of Bioresource Engineering

McGill University, Montreal

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ABSTRACT

Doctor of Philosophy Shadi Dayyani Dardashti **Bioresources Engineering**

Modeling Hydrology and Nitrogen Fate and Transport in a Tile-Drained Agricultural Watershed in a Cold Region

A new model, DRAIN-WARMF, has been developed by integrating WARMF and DRAINMOD models, to simulate surface and subsurface flows and nitrogen transport in a tile-drained watershed in eastern Canada. The new model takes advantage of the strong surface flow modeling capabilities of WARMF and the higher accuracy of subsurface flow modeling of DRAINMOD, and is thus superior performance-wise to both of these models individually. The new model allows for simulations to be carried out for scenarios and management practices which were not possible using these models individually. The DRAIN-WARMF model was applied to St. Esprit watershed, located in southwestern Quebec. Simulations were carried out from 1994 to 1996. The new model was able to adequately simulate hydrologic response and nitrate losses from the watershed. Comparing the observed daily/monthly flows with the model's outputs returned Nash-Sutcliffe coefficient of efficiency (E) values of 0.75/0.97 over the validation period (1996). The model improved predictions of monthly NO_3^--N loads, with an E value of 0.83. Overall, it was found that DRAIN-WARMF results, on a seasonal and monthly scale, were generally more reliable whereas daily simulations could be improved further by using a longer calibration period.

The potential impacts of climate change on flow and nitrogen pollution were also evaluated with DRAIN-WARMF. Simulations were performed based on the projected climate change conditions developed by the CRCM4.2.0 model for 1961 to 2100. The projected annual temperature and precipitation changes indicate that the climate in the study area would generally become warmer and wetter. The min/max temperatures would increase in winter, causing more rainfall-dominated regimes and less snow accumulations. The DRAIN-WARMF simulation results show an increase in the average annual surface and drainage outflows. The total flow will increase significantly during the months of March

and April. It appears that climate change will be altering both the magnitude and the seasonality of flows. The impact of changed hydrologic conditions on nitrate-nitrogen losses was also assessed. The annual loss of NO_3^--N will increase from the watershed. In general, results suggest that flow and nitrogen loads in the study area would experience significant changes in future years.

RÉSUMÉ

Doctorat en Philosophie Shadi Dayyani Dardashti **Génie des Bioressources**

Modélisation de l'hydrologie et du sort et transport de l'azote dans un bassin versant agricole de zone froide, en présence d'un réseau de drainage souterrain

Créé en intégrant les modèles WARMF and DRAINMOD, le modèle DRAIN-WARMF permit de simuler le transport de l'azote dans un bassin versant de l'est du Canada, desservi par un réseau de drainage souterrain. Ce nouveau modèle, surclassant ses composants, profita de l'excellente capacité de WARMF à simuler le ruissellement en surface, et de la grande précision de DRAIMOD quant à la modélisation de l'écoulement souterrain. Il permit aussi de simuler des situations et modes de gestions que les éléments composants du modèle n'étaient pas en mesure de faire individuellement. S'appuyant sur des données servant à l'étalonnage (1994, 1995) et à la validation (1996) provenant du bassin versant St. Esprit, situé au sud-ouest du Québec, DRAIN-WARMF se montra capable d'adéquatement simuler la réponse hydrologique et les pertes en nitrates du bassin versant. Une comparaison des débits quotidiens/mensuels aux prédictions du modèle pour la période de validation donna lieu à des valeurs du cœfficient d'efficacité Nash-Sutcliffe (E) de 0.75/0.97 (idéal 1.00). Le nouveau modèle améliora aussi la prédiction de la charge en NO_3^--N, présentant une valeur de E = 0.83. Sur l'ensemble, la précision obtenue avec DRAIN-WARMF fut plus élevée à l'échelle saisonnière ou mensuelle, tandis qu'à l'échelle quotidienne elle pourrait être améliorée par une période d'étalonnage plus longue.

DRAIN-WARMF servit aussi à évaluer les effets potentiels des changements climatiques, en particulier ceux projetés par le modèle CRCM4.2.0 pour la période de 1961 à 2100. Ces projections indiquent que le climat de la région deviendra plus chaud et plus pluvieux. Une augmentation des températures hivernales min/max augmenterait la fréquence d'évènements dominés par le pluie, tout en réduisant les accumulations de neige. Des simulations avec DRAIN-WARMF indiquèrent une augmentation des moyennes annuelles du débit en surface et de l'écoulement sous terrain. Le débit total augmentera fortement aux mois de mars

et avril. Les changements climatiques auront donc une influence à la fois sur l'ampleur et la saisonnalité des débits. Ces simulations indiquèrent aussi que ces modifications aux conditions hydrologiques auraient un impact sur les pertes en NO_3^--N, qui augmenteraient sensiblement. En général, ces résultats suggèrent que le débit et les charges en azote dans l'aire d'étude changeraient sensiblement dans les années à venir.

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Last, but definitively not least, I would like to take the pleasure in having this opportunity to put down in black and white my deepest gratitude to my parents, Batoul and Mortaza Dayyani, for their love, encouragement, patience, and countless sacrifices to provide me with the best opportunities in my life. Their everlasting support has always provided me with the confidence to aim high and achieve my goals. I also gratefully acknowledge the love of my sisters, Shahrzad, Shamim, and Sheida.

To my parents,

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 published or 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. He was also involved in editing and reviewing the manuscripts. Dr. Chandra Madramootoo is the thesis co-adviser, and provided advice and available datasets. Dr. Ali Madani, Professor at the Engineering Department of Nova Scotia Agriculture College, provided scientific advice, supervision and technical assistance during the Ph.D. and in the final stages of paper submission.

Mr. Peter Enright, professional associate and director of the Farm Management and Technology Program at McGill University, is another co-author for the first three manuscripts. His contribution includes valuable technical guidance and assistance in understanding the collected data. Guillaume Simard and Apurva Gollamudi are graduate students of the Department of Bioresources Engineering at McGill University, whom collected the data required for the first manuscript.

List of publications and scientific presentations related to the thesis:

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

Dayyani, S., C. Madramootoo, P. Enright, G. Simard, A. Gollamudi, S. Prasher and A. Madani (2009). "Field Evaluation of DRAINMOD 5.1 under a Cold Climate: Simulation of Daily Midspan Water Table Depths and Drain Outflows 1." JAWRA Journal of the American Water Resources Association 45(3): 779-792.

Dayyani, S., S. O. Prasher, C. A. Madramootoo, A. Madani, and Peter Enright (2008). “Modeling Water Table Depths, Drain Outflow, and Nitrogen Losses in Cold Climate Using DRAINMOD 5.1" Transactions of ASABE 53 (2): 385-395.

Dayyani, S., S. O. Prasher, C. A. Madramootoo A. Madani, and Peter Enright (2009). "Evaluation of Watershed Analysis Risk Management Framework (WARMF) for Flow and Nitrogen Transport in an Agricultural Watershed under a Cold climate." Transactions of ASABE (submitted; Manuscript Number: SW-08418-2010).

Dayyani, S., S. O. Prasher, C. A. Madramootoo and A. Madani, (2009). "Development of DRAIN-WARMF Model to Simulate Flow and Nitrogen Transport from an Agricultural Watershed." Journal of Agricultural Water Management (Accepted for publication).

Dayyani, S., S. O. Prasher, C. A. Madramootoo and A. Madani, (2009). "Impact of Climate Change on Nitrogen Pollution in an Agricultural Watershed in a Cold Region Using DRAIN-WARMF Model". Journal of Environmental Quality (submitted; Manuscript Number: Q09-0384).

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

Dayyani, S. Prasher, S., Madramootoo, C., Madani, A., 2009. Impact of Climate Change on Nitrogen Pollution in an Agricultural Watershed in a Cold Region. (Oral presentation). The 60th IEC of ICID (International Commission on Irrigation and Drainage) and 5th Asian Regional Conference, New Delhi, India, December 2009.

Dayyani, S. Prasher, S., Madramootoo, C., Madani, A., 2009. Development of DRAIN-WARMF Model to Simulate Flow & Nitrogen Transport and Evaluate the Impact of Climate Change on Water Pollution on Watershed Scale. (Oral presentation). The Canadian Society for Bioengineering (CSBE/ SCGAB) Annual Meeting, Charlottetown, PEI, Canada, July 12- 15.

Dayyani, S. Prasher, S., Madramootoo, C., Madani, A., 2009. Development of DRAIN-WARMF Model to Simulate Flow & Nitrogen Transport on Watershed

Scale. (Oral presentation). The American Society of Agricultural and Biological Engineers (ASABE) Meeting, Reno, Nevada, USA, June 21 – 24.

Dayyani, S. Prasher, S., Madramootoo, C., Madani, A., 2008. Modeling Nitrogen Movement on a Watershed Scale. (Oral presentation). ASAE Meeting, Providence, Rhode Island, USA, June 29 – July 2.

Dayyani, S. Prasher, S., Madramootoo, C., Madani, A., 2008. Modeling Surface and Subsurface Nitrogen Transport in an Agricultural Watershed: Subsurface modeling using DRAINMOD 5.1. (Oral presentation). CSBE/ SCGAB Annual Meeting, North Vancouver, Canada.

Dayyani, S. Prasher, S., Madramootoo, C., Madani, A., 2007. Modeling Surface and Subsurface Nitrogen Transport in an Agricultural Watershed: Linking DRIANMOD 5.1 and WAMRF model. (Oral presentation). ASAE Meeting, Minneapolis, Minnesota, USA, 17-21 June.

Dayyani, S. Prasher, S., Madramootoo, C., Madani, A., 2006. Modeling Surface and Subsurface Nitrogen Transport in an Agricultural Watershed: Fate and Transport of Nitrogen in subsurface flow. (Oral presentation). 22nd Eastern Canadian Symposiumon Water Quality Research. Montreal, Canada.

Dayyani, S., Prasher, S., Madramootoo, C, Madani, A., 2006. Modeling Surface and Subsurface Nitrogen Transport in an Agricultural Watershed. (Oral presentation). CSBE/ SCGAB annual meeting, Edmonton, Canada.

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LIST OF ABBREVIATIONS

AD	Average Deviation
AAD	Average Absolute Deviation
AnnAGNPS	ANNualized AGricultural Non-Point Source
ANSWERS	Areal Non-point Source Watershed Environment Response Simulation
BMP	Best Management Practices
CSTR	Continuously Stirred Reactor
DEM	Digital Elevation Model
DSS	Decision Support System
EPRI	Electric Power Research Institute
E	Modeling Efficiency
ET	Evapotranspiration
FD	Free Drainage
GIS	Geographic Information Systems
GUI	Graphical User Interface
HRU	Hydrologic Response Unit
LAI	Leaf Area Index
MK	Mann–Kendall
N	Nitrogen
NPS	Non-Point Source Pollution
NO3-N	Total Nitrate-Nitrogen
Obs.	Observed
P	Phosphorus
R^2	Coefficient of Determination
RMSE	Root Mean Square Error
RRMSE	Relative Root Mean Square Error
SI	Sub-Irrigation
Sim.	Simulated
SWAT	Soil and Water Assessment Tool
TMDL	Total Maximum Daily Loads
USEPA	US Environmental Protection Agency
WARMF	Watershed Analysis Risk Management Framework
WTD	Water Table Depth
WTM	Water Table Management

CHAPTER 1: Introduction

Water pollution originates from either point or non-point sources. A point source is a clearly defined location of discharge, such as a pipe outlet, and it is relatively easy to target actions for controlling pollution. In contrast, a non-point source (NPS) is a broad region, such as agricultural lands, and it is quite difficult to locate the actual source, which makes pollution control difficult. In Canada, several rivers draining agricultural lands have elevated nitrate, phosphorous and pesticide concentrations (Enright and Madramootoo, 2004). The most recent Water Quality Inventory reports that "Agricultural NPS is the leading source of water quality impacts to surveyed rivers and lakes, the third largest source of impairments to surveyed estuaries, and also a major contributor to groundwater contamination and wetlands degradation" (USEPA, 2009a).

The agricultural sector in Canada, particularly Quebec, has witnessed significant growth over the past decades. Increase in agricultural production can be attributed to different factors such as, mechanization of farm operations, use of organic and inorganic fertilizers, and improved crop varieties. As a consequence, this has placed the region's water bodies under severe environmental stress. In Quebec, it is estimated that agriculture is responsible for over 70% of the total NPS pollution (Enright et al., 1995). Progress has been made recently in the control of end-of-the-pipe pollution. However, it has been proven that non-point sources are more difficult to control and contribute to the majority of water quality problems (Chambers et al., 2001).

The risk of water contamination by nitrogen is rising in many humid areas of Canada's cropland, particularly where agriculture is intensive. High nitrate-nitrogen levels in surface waters contribute to algal growth and eutrophication (Chambers et al., 2001). In Canada, nitrogen (N) and phosphorus (P) loading from different sources are a matter of concern for causing problems in some forests, freshwater and coastal ecosystems, and therefore, are affecting quality of life for many Canadians (Chambers et al., 2001). Environmental risks may occur when large surpluses of mineral N are present in the soil, especially between cropping seasons in humid regions. Nitrogen is an essential nutrient that becomes available for crop use when it is in soluble form, such as nitrate. Nitrate-N can be leached into groundwater, which is an important source of drinking water in the rural communities and it may reach levels of harmful to humans. Nitrate-N can also enter surface waters, contributing to nutrient loading and possible eutrophication. The Canadian Water Quality Guidelines define a safe limit for nitrate-nitrogen in drinking water, which is 10 mgL^{-1}. High nitrate-N levels in drinking water may lead to methaemoglobinemia (blue baby syndrome), and have been implicated in increased risk of stomach cancer (Chambers et al., 2001).

A recent assessment of N losses from agricultural land, where the soils have a water surplus, revealed that 6% of Québec farmland produced runoff or seepage water with more than 14 mg NL^{-1} (MacDonald, 2000). Between 1981 and 1996 the estimated nitrogen content of water increased by at least 1 mgL^{-1} on most (77%) of Quebec’s farmland (MacDonald, 2000).

Across North America, particularly in humid regions with fine-textured soils, subsurface drainage systems have been used to effectively enhance crop production by alleviating crop-water stress, caused by shallow water tables. Approximately two million hectares of cropland in the provinces of Ontario and Quebec are subsurface-drained (Helwig et al., 2002). Over the past decade, subsurface drainage has been considered as a contributor to NPS, causing significant deterioration in the quality of surface waters. Applying organic and inorganic fertilizers has proven very effective in increasing crop yields, but at the same time, may also be detrimental to the goal of sustainable agriculture. This may raise the amount of nitrogen in groundwater and surface water downstream of the farmland, contributing to the degradation of aquatic ecosystems. Therefore, one of the major challenges environmentally-conscious crop producers are facing today is to determine fertilizer application rates that would optimize crop yield and profit, while minimizing the potential environmental damage. In fact, Best Management Practices (BMPs) and current approaches to NPS pollution mitigation have made important contributions in improving water quality.

With an increasing awareness of the problems related to agricultural pollution, a significant amount of resources has been invested to develop and promote BMPs. The most common way to achieve this information is to monitor water quality and evaluate trends. This however takes a long time, typically 10 to 25 years (Bujatzeck 1998). Thus, note should be taken that, the continuous monitoring of water flow and nutrient transport from a watershed is difficult, time consuming and expensive. Computer modeling offers an efficient and cost effective alternative to field experiments. Computer simulation models are widely used as tools to assess the environmental impacts of agricultural practices. Several management goals such as pollutant source detection and prioritization, estimation of water resources response to watershed nutrient control practices, and long term evaluation of influences of management efforts on watershed systems can be achieved using different modeling techniques. Models are expected to be accurate, easy to use, and comprehensive (Gustafson, 1995). Models now need to simulate water quality impacts, incorporate spatial information available at finer scales, and have friendlier interfaces for entering input parameters and for interpreting predicted results. Closely tied to the use of simulation models is the collection of observed data to validate them. Observed data are invaluable for evaluating the accuracy of modeling techniques and for improving modeling algorithms.

This study was conducted in the 24.4 km^2 St. Esprit Watershed located in southern Quebec, Canada. The watershed is a part of the 210 km^2 St. Esprit river basin, which is drained into the L'Assomption River. The climate in this watershed of southern Quebec is generally characterized by a dry summer with a cool and wet spring and fall, and a cold winter, which experiences freezing, thawing, and snowmelt (Enright et al., 1995; Gollamudi, 2006). The snowmelt process and daily freeze–thaw cycles can have a dominant effect on field hydrology during the winter and early spring periods (Kuz'min, 1972). Moreover, in the study area it is observed that the peak pollutant concentrations were associated with high runoff producing events. Also, the spring snowmelt was identified as a significant period for export of the pollutant material (Lapp et al., 1998).

1.1.Objectives

The primary objective of the research is to develop a comprehensive user friendly model (DRAIN-WARMF) by linking DRAINMOD (Skaggs, 1980) with WARMF (Chen et al., 1998) in order to improve water flow and nitrogen transport estimation from drained/partially-drained watersheds under frozen/unfrozen soil conditions. In this modeling approach, surface flow and nitrogen transport are simulated using watershed-scale WARMF model; and subsurface flow and nitrogen movement in unsaturated zone is simulated using field-scale DRAINMOD model. By linking WARMF 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 performance-wise superior to both. Moreover, using the linked model, several scenario analysis and management practices can be carried out.

Specific objectives were:

i. To evaluate DRAINMOD model for flow and nitrogen transport in a cold region.

ii. To evaluate WARMF model for flow and nitrogen transport in an agricultural watershed in a cold region.

iii. To develop a new model, DRAIN-WARMF, by linking WARMF & DRAINMOD to simulate surface and subsurface flow and nitrate-N losses on a watershed scale.

iv. To assess the potential impacts of climate change on flow and nitrate-N pollution in an agricultural watershed using DRAIN-WARMF model.

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, non-point source pollution, and watershed modeling is presented in Chapter 2. This chapter is followed by five sequentially connected manuscripts: the first manuscript (Chapter 3) details the methodology used in calibrating the hydrology component of DRAINMOD for a cold region; the second manuscript (Chapter 4) calibrates and validates the DRAINMOD performance for drain outflow, water table depth, and nitrogen losses in a cold region under different water table management systems. Chapter 5 presents an evaluation of WARMF model for simulating flow and nitrogen transport in an agricultural watershed in cold climate. The 6^{th} chapter of the thesis discusses the development of a new model, DRAIN-WARMF, for simulating flow and nitrogen transport in surface and subsurface flows in an agricultural watershed. Chapter 7 presents the application of DRAIN-WARMF model in simulating the potential impacts of climate change on nitrogen pollution in the future. 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.Watershed Hydrology

The hydrologic cycle is usually described in terms of 6 major components (Fig. 2.1): 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).

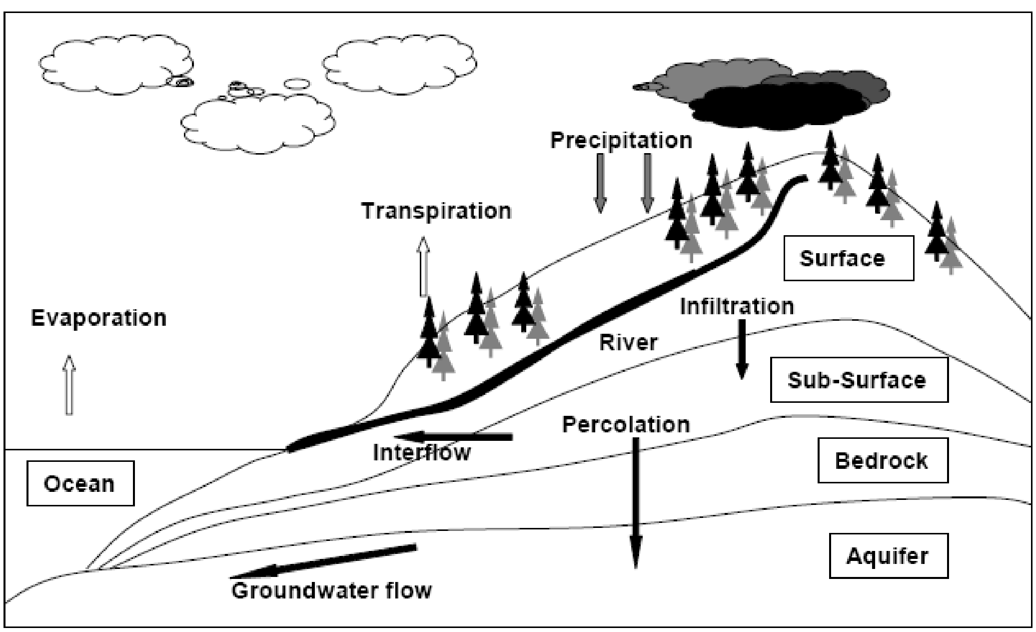

Figure 2.1: Schematic representation of the hydrologic cycle (Adopted from Ward and Trimble, 1995)

The main means of nutrient transport from agricultural fields to watercourses are identified as surface runoff and subsurface flow. When the amount of precipitation falling on the ground is greater than the infiltration rate, surface runoff occurs and carries sediment, phosphorus and nitrates in both soluble and insoluble forms into the watercourses. Subsurface flow could be through natural lateral flow or artificial tile drains installed to maintain water table depth at a desirable level for crop. 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.

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).

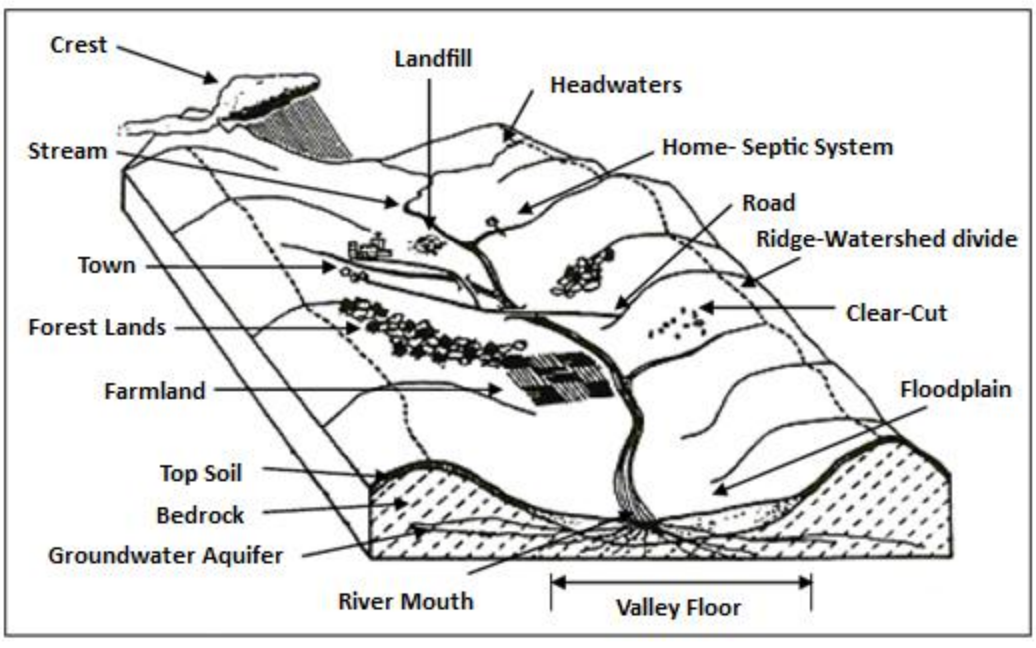

Figure 2.2: Schematic representation of a watershed system (Adopted from AGWA, 2004)

Usually, one watershed can consists of several sub-watersheds or can be a 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 at its outlet as well as of groundwater outflow. Different components of water balance in a watershed are shown in Figure 2.2.

2.2.Non-point Source Pollution (NPS)

Generally, water pollution originates from either point or non-point sources. A point source is a clearly defined location of discharge, such as a pipe. In comparison, NPS pollution can be defined as pollution that is not associated with a specific location and normally results from agricultural activities, urban and industrial runoff, precipitation, drainage, seepage, atmospheric deposition, and hydrologic modifications. It is caused by rainfall or snowmelt, as the runoff moves over and through the ground; it picks up and carries away both man-made and natural pollutants. These pollutants are normally deposited into rivers, lakes, coastal waters, wetlands, and groundwater. Some of the sources of non-point pollution include agricultural farms (e.g. fertilizers, manure), industrial runoff (e.g. heavy metals, phosphorous), urban runoff (e.g. oils, salts, various chemicals) and atmospheric fallout of airborne pollution.

While the implementation of efficient management plans and the up-gradation of water treatment systems have been successful in improving the quality of wastewater from point sources (Simard, 2005), non-point source pollution has contributed in hastening the natural processes of eutrophication and deoxygenating water bodies (Harker et al, 1998). This is due to the fact that non-point sources are more difficult to control because of the diversity of sources, interactions between land use and hydrology, and complex pathways to move above- and below-ground from the point of application to its reappearance at a point of concern. For water-quality investigations, various forms of nitrogen and phosphorus are the nutrients of interest (Chambers et al., 2001; Thornton et al., 1999). The forms include nitrate, nitrite, ammonia, organic nitrogen, and phosphates (orthophosphate and others). Nitrate is the most common form of nitrogen and phosphates are the most common forms of phosphorus found in natural waters (USGS, 2005). Agriculture is the dominant source of N and P pollution from both inorganic application of fertilizers and spreading of manure on crop and pasture lands (Chambers et al., 2001). It is estimated that each year, more than 304 thousand tonnes of nitrogen and 12 thousand tonnes of phosphorus enter Canada's groundwater and surface water systems (Chambers et al., 2001). There are no national estimates of nutrient losses due to leaching or runoff from agricultural fields, although an assessment of N losses from agricultural land, where the soils have water surplus, predicted that 17% of Ontario, 6% of Québec and 3% of Atlantic farmlands would produce runoff or seepage water with more than 14 mg NL^{-1} (MacDonald, 2000). In Quebec alone, agriculture is responsible for over 70% of the total non-point source pollution (Gollamudi, 2006).

Nitrogen is a key element in plant nutrition. High-yielding crops such as corn require large amounts of N fertilizer to reach optimum yield. In Quebec, corn is a major crop due to its high potential productivity (Elmi et al., 2000). A maximum grain corn yield of 15.2 Mg ha^{-1} has been reported resulting from the best combinations of hybrid, population density, fertilizer rate and irrigation (Liang et al., 1992). In order to reach such an optimal yield, high rates of N fertilizer are often applied, leading to a large amount of nitrate lost via leaching and eventually reaching groundwater (Prunty and Montgomery, 1991). In Quebec, Madramootoo et al. (1992) reported nitrate-N concentrations as high as 40 mg L^{-1} in the drainage outflow in a sandy loam field cropped to potato. The value is far exceeding the safety limit (10 mg L^{-1}; Chambers et al., 2001). High nitrate-N concentrations can be harmful to infants and are linked to blue baby syndrome which can ultimately result in the death of infants of up to 6 months (Fewtrell, 2004). The amount of leachable NO_3^--N in the soil profile generally increases with fertilizer application rate. Thus, a major challenge, now, for agricultural scientists is to develop management strategies which will minimize the adverse impacts of N fertilizers on the environment and water resources, without concomitant reductions in crop yield (Elmi et al., 2000).

In the past two decades, several studies have documented the problem of non-point source pollution in Quebec, at both the field and the watershed scale. These studies have reported high levels of NO_3^--N (Wiyo, 1991; Asselin et al, 1992, Madramootoo et al., 1992, and Mousavizadeh, 1998) in surface runoff and subsurface drainage.

2.3. Tile Drainage in Quebec

Artificial tile drainage systems are installed in many agricultural fields in eastern Canada. In the province of Quebec, subsurface drainage is necessary for several reasons. Firstly, 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 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 tile drainage systems is necessary to remove the excess water and improve crop production. Artificial drainage also reduces surface runoff, and subsequently soil erosion and particulate pollutant transport. In Quebec, the total area of drained fields in 2002 was estimated at 735,000 ha (Gollamudi, 2006).

Fields with artificial drainage systems contribute much more water to stream flow than naturally drained fields. Although particulate pollutants are reduced, the magnitude of water leaving tile drains has led researchers to conduct studies to measure and quantify the concentrations and loads of the different forms of nitrogen and phosphorus in tile drains (Jamieson, 2001). Over the past decade, subsurface drainage has been considered to contribute to non-point source pollution, which is responsible for the deteriorating quality of surface waters. Beside surface runoff, tile drainage is another pathway by which sediment and nutrients are transported from field to water bodies. Therefore, it is important to quantify and evaluate long-term nutrient loadings from agricultural fields, in order to control and manage the water quality in agricultural watersheds in Quebec (Gollamudi, 2006).

2.4.Hydrological and Water Quality Models

Understanding and evaluating the natural hydrologic processes which happen in watersheds is a challenge for scientists and engineers (Wu and Chen 2009). Hydrological and water quality models simulating these complex processes are useful tools to understand the problems and to find solutions through best management practices (Borah and Bera, 2003). Several management goals such as pollutant source detection and prioritization, estimation of water resources response to watershed nutrient control practices, and long term evaluation of influences of management efforts on watershed systems can be achieved using different modeling techniques.

Hydrologic models, simplified representations of actual hydrologic systems, simulate hydrologic responses and allow one to study the function and interaction of various inputs, and gain a better understanding of hydrologic events (Brooks et al., 1991). 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; they can also estimate changes in rates and quantities over time (Oogathoo, 2006).

Recently several methods of assessing pollution from NPS have been developed. Many of these methods have involved the development of computer-based models for automated, reliable, and repeatable analyses. Today, numerous different models exist, which were frequently developed for specific tasks. More recently, some of these models have been linked with geographic information systems (GIS) for ease of data management. It is being used to store, process, and visualize the spatial and non-spatial data used for water quality modeling (William and Shirmohammadi, 2001).

Hydrologic and NPS pollution models are categorized into continuous simulation models and event based models (Singh, 1995). They can also be based on distribution parameters or lumped parameter concept. In scope, they range from small field size application models to large watershed models (Singh, 1995).

Continuous simulation models are used for analyzing long-term effects of hydrological changes and agricultural management practices. While, event based models are useful for analyzing severe actual or design storm events and evaluating structural management practices (Borah et al., 2003). Most of the existing models are either continuous or storm event, only a few have both capabilities.

A clear understanding of a model is important for its appropriate use and for avoiding any misuse (Borah and Bera, 2003), and to know what the original purpose of the model is, under what conditions it will perform correctly, what accuracy can be expected under the best conditions, and what the limitations are. This leads to the selection of the best water quality model to meet one's needs (Parsons et al., 2004). It is important to bear in mind the needs of the water resource problem before developing, choosing or operating a model (Parsons et al, 2004). To meet the objectives of the present study, the main requirements for the model were: to be able to simulate hydrologic and nutrient transport processes for individual sub-watersheds with a single surface runoff output for each one; availability of data for calibration and validation of the model, in order to analyze the outputs; the scale at which model performs (field-scale or watershed-scale); capability of the model to simulate snowmelt hydrology as accurately as rainfall hydrology since snowmelt is a significant event in a region such as Quebec; ability to incorporate BMPs and management scenarios; and also being able to carry out continuous simulations.

Some of the common hydrological and water quality models are briefly described in this section: Annualized Agricultural Non-Point Source model or AnnAGNPS (Bingner et al, 1998); Soil and Water Assessment Tool or SWAT (Arnold et al., 1998); Areal Non-point Source Watershed Environment Response Simulation or ANSWERS2000 (Bouraoui and Dillaha, 1996); the European Hydrological System model or MIKE SHE (Refsgaard and Storm, 1995); DRAINMOD (Skaggs, 1980); and Watershed Analysis Risk Management Framework or WARMF (Chen et al. 1998).

2.4.1. AnnAGNPS Model

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. The AnnAGNPS model was designed to simulate surface runoff, sediment, nutrients and pesticide movement within an agricultural watershed. It is designed to analyze 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 is on a daily basis, while the model output is on an event, monthly, or annual basis (Bosch et al., 2001; Young et al., 1995).

The model was tested by Suttles et al. (2003) and Yuan et al. (2001). They 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 overestimated the nutrients and sediment loads. They recommended that proper cell discretization would improve runoff estimates. The model was applied in Australia and has shown satisfactory results for event flow predictions (Baginska et al., 2003). Das et al. (2004) showed that the model was able to simulate runoff with acceptable accuracy in a watershed in south-western Ontario. However, a study in Nepal (Shrestha et al., 2005) showed event-based peak flows to be over predicted. AnnAGNPS was applied to a watershed in an island of the Caribbean (Sarangi et al. 2007). The model estimated runoff volume reasonably well for days with high precipitation depths although the peak flows were generally overestimated. The model was less accurate in estimating runoff for days with lower precipitation amounts. It was also observed that model performance was poor in simulation of runoff for forest watersheds. The AGNPS was tested on the St-Esprit watershed in Quebec (Perrone, 1997). The results showed that the model simulated surface runoff and sediment yield accurately after calibration. However, simulation accuracy was poor during the winter; hence the authors suggested an investigation of seasonal parameters to improve the model performance (Perrone and Madramootoo, 1999).

The limitations of the AnnAGNPS model are: all runoff and associated sediment, nutrient, and pesticide loads for a single day are routed to the watershed outlet before the next day simulation. There is no tracking of nutrients and pesticides attached to sediment deposited in stream reaches from one day to the next. Point sources are limited to constant loading rates (water and nutrients) for the entire simulation period. Spatially variable precipitation is not allowed (Bingner, 2001).

2.4.2. SWAT Model

The Soil and Water Assessment Tool, SWAT, is a conceptual, physically-based, continuous simulation, watershed model, developed by Arnold et al. (1998) for the USDA Agricultural Research Service (ARS), aimed towards predicting the impact of management practices on water, chemical and sediment yields on large watersheds. The model has eight major components: hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. The hydrology component of model consists of surface runoff, including runoff over frozen soils, percolation, lateral subsurface flow, groundwater flow, snowmelt, evapotranspiration, transmission losses, irrigation water transfer, and ponds. The model operates on a daily time step. Runoff volume is determined using a modified SCS curve number method or the Green Ampt infiltration method. SWAT uses the modified Rational Formula or the SCS TR-55 method to calculate the peak runoff rate. The lateral subsurface flow and percolation are calculated together using a kinematic storage routine. Drainage is calculated using a simple method (Neitsch et al., 2005) which does not consider the detail information of the tile-drain system. The model considers base flow contribution to total stream flow by routing a shallow aquifer storage component to the stream. Potential evapotranspiration is estimated using Hargreaves, Priestley-Taylor or Penman-Monteith equations. The 2000 version of the model, AVSWAT, is integrated with the ArcView 3.2 interface.

Coefficient of determination (R^2) and Nash-Sutcliffe modeling efficiency (E) are the most widely used statistics to evaluate the performance of the different hydrological models (Gassman et al., 2007) and typically R^2 values greater than 0.5 are considered acceptable (Santhi et al., 2001). The E values ranging from 0.75-1.00, 0.65-0.75, 0.50-0.65, and ≤0.50 are considered as “very good”, “good”, “satisfactory”, and “unsatisfactory”, respectively.

Bosch et al. (2004) tested SWAT in a watershed in Georgia, United States, and reported good results on a monthly basis, but less accurate estimates on a daily basis. Monthly model efficiencies (E) were calculated as 0.80, while daily E values were negative (-0.03 to -0.24) for a six−year simulation period. In addition, the model did not provide baseflow estimations adequately (%error = 20% to 150%). The model tended to over-predict the discharge conditions observed on the watershed in the summer period (particularly when no flow was observed), and tended to under-predict the largest flow volumes. They suggested that a contributing factor to the inaccuracy appears to be the direct routing of surface runoff from the hydrologic response units (HRUs) into the stream by SWAT, while most upland surface runoff and subsurface flow has to travel through dense riparian buffers prior to entering the stream. Currently there is no component within the model to simulate infiltration of surface runoff between the upland and the stream. This would lead to the overprediction of storm and streamflow that was observed for the summer period (Bosch et al., 2004).

SWAT model failed to give reasonable runoff predictions on a daily basis in two studies conducted by Chu and Shirmohammadi (2004) and Spruill et al. (2000). Chu and Shirmohammadi (2004) reported that SWAT seemed to be unable to simulate the extremely wet hydrologic conditions. Values of Nash-Sutcliffe coefficient of efficiency (E) reported for monthly stream flow, monthly surface flow, and monthly subsurface flow, were 0.68, 0.35, and 0.53 (for calibration period) and 0.67, 0.77, and -0.02 (for validation period), respectively. Overall, they found that hydrology component of the SWAT model is able to perform an acceptable prediction of long-term simulations for management purposes, but fails to have reasonable predictions for short time intervals (i.e., daily). Spruill et al. (2000) used the SWAT model to simulate daily stream flow in a small central Kentucky watershed over a two-year period (1995-1996). Results showed that SWAT adequately predicted the trends in daily stream flow although Nash-Sutcliffe coefficient values were –0.04 and 0.19 for 1995 and 1996, respectively. The reported Nash-Sutcliffe coefficients for monthly total flows were 0.58 for 1995 and 0.89 for 1996 (Spruill et al., 2000). Peterson and Hamlett (1998) applied SWAT to model the hydrologic response of the Ariel Creek watershed of northeastern Pennsylvania. The results indicated that model calibration yielded a Nash-Sutcliffe coefficient of 0.04 and 0.14 when comparing daily and monthly flows, respectively. Results also showed the model's inability to accurately simulate snowmelt. Additionally, the model was not able to accurately simulate base flow. 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 underestimate spring peaks and to overestimate fall monthly stream flow. Annual simulated base flow suggested that SWAT tends to overestimate base flow in high runoff regions with deep soils. The Nash-Sutcliffe coefficient value of 0.65 was reported for monthly stream flow simulations during the validation period (Arnold et al., 2000). 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 a Nash-Sutcliffe coefficient of 0.70 and a correlation coefficient of 0.84. They concluded mean annual stream flow is underestimated by 4%. Bingner (1996) applied SWAT to a watershed in northern Mississippi and reported a Nash-Sutcliffe coefficient value of 0.80 for monthly stream flow. Gebremeskel et al. (2005) stated that the SWAT model performed well in simulating the monthly stream flow in a watershed of south-western Ontario. In this study they compared the monthly hydrology simulation results of AnnAGNPS and SWAT models over a forty-five-month period. The validation results of both models indicated that they predicted mean monthly flow with good correlation and fair agreement for both models (R^2= 0.50, E= 0.47 for AnnAGNPS; R^2= 0.62, E= 0.48 for SWAT). Gollamudi et al. (2007) applied SWAT to two agricultural fields in Quebec. They reported that SWAT satisfactorily reproduced field observations for sediment and nutrient transport, although it tended to underestimate the spring snowmelt and overestimate the surface runoff during the fall. Nitrates, which are mainly transported through the tile drains, were underestimated because of underestimation in simulated subsurface flow volumes. It also underestimated nitrate loads in subsurface drainage during spring snowmelt and large storms. The monthly coefficients of performance (C_p) after calibration ranged from 0.44 to 2.28 for subsurface flow; 0.63 to 4.36 for surface runoff; and 0.66 to 1.35 for total nitrate loads. In general, C_p values between 0.0-0.3 denote excellent model fit, 0.3-0.5 good; 0.5-0.7 average; 0.7-1.0 poor and C_p greater than one represents a prediction no better than taking the mean observed value (Gollamudi et al., 2007). Overall, it was found that SWAT's results on a seasonal scale were generally more reliable whereas daily or monthly simulations could be improved by using a longer calibration period or incorporating model changes (Gollamudi et al., 2007).

The limitations of the SWAT are: the model does not use proper method (for example Hooghoudt's equation) for simulating drainage outflow in tile-drained agricultural watersheds. SWAT is intended for long-term yield predictions and is not capable of detailed single-event flood routing. Each time only one pesticide is routed through the stream network. The model is not capable of specifying actual areas to apply fertilizers. It divides a large watershed into hundreds of HRUs resulting in many hundreds of input files, which are difficult to manage and modify without a solid interface. The current version does not have a good model post-processor.

2.4.3. 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 in West Lafayette, Indiana, to study management practice effects on sediment and nutrient transport. It is a physically-based, distributed parameter, continuous simulation, watershed-scale model, which allows for short-term and long-term simulations. ANSWERS works with an ArcInfo GIS interface for data input and processing. The model is limited to medium-size watersheds (500 to 3000 ha) where surface hydrologic processes dominate. The watershed is divided into uniform grid squares of one hectare or less, based on homogeneous soil properties, land use, slopes, crops, nutrients, and management practices. The model has a variable time-step. The hydrology component of ANSWERS-2000 addresses interception, surface retention/detention, infiltration, percolation, surface runoff (overland and channel flow), and evapotranspiration.

The ANSWERS model has been applied to different watersheds to assess surface runoff, nitrate pollution risk and sediment loads. ANSWERS-2000 was able to adequately simulate runoff during non-snow seasons at a watershed in Ontario (Bai et al., 2004); authors suggested that the model should be improved to allow simulation of winter conditions. 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.

Limitations associated with the model are: the absence of proper fertilization inputs, poor winter and snowmelt simulations and non-significant baseflow simulations (Dillaha et al, 2001).

2.4.4. MIKE SHE Model

MIKE SHE (Refsgaard and Storm, 1995) is one of the few hydrologic models that were initially developed to integrate surface water and groundwater modeling capabilities (DHI, 2004). The model was developed by a European consortium of three organizations: the U.K. Institute of Hydrology, the French consulting firm SOGREAH, and the Danish Hydraulic Institute, it was originally named SHE (Système Hydrologique Européen) model. MIKE SHE is a physically based, distributed, integrated hydrological and water quality modeling system. It consists of a water movement module 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). The related water quality modules are: advection-dispersion, particle tracking, sorption and degradation, geochemistry, biodegradation, and crop yield and nitrogen consumption (Refsgaard and Storm, 1995).

MIKE SHE is able to simulate 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 system has no limitations regarding watershed size, watershed is horizontally divided into an orthogonal network of grid squares; hence spatial variability in parameters such as elevation, soil type, land cover, precipitation and potential evapotranspiration 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 and Storm, 1995). MIKE 11 is a comprehensive, one-dimensional modeling system for the simulation of flows, sediment transport and water quality in rivers and other water bodies. The original channel simulation in MIKE SHE was relatively simple and had limited capabilities.

The model assumes that flow in unsaturated zone is one-dimensional and vertical. Some of the limitations for the MIKE SHE model include: need to purchase the model and multiple modules to take full advantage of the system; significant data needed to setup the model; lack of published studies on application of the model in agricultural watersheds; and limited capability for simulating agricultural best management practices.

2.4.5. WARMF Model

WARMF (Chen et al., 1998), the Watershed Analysis Risk Management Framework, 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 (Engineering, Data, Knowledge, Consensus, and TMDL; Fig. 2.3) under one, 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. The scientific basis of the model has undergone several peer reviews by independent experts under US EPA guidelines (EPRI, 2000).

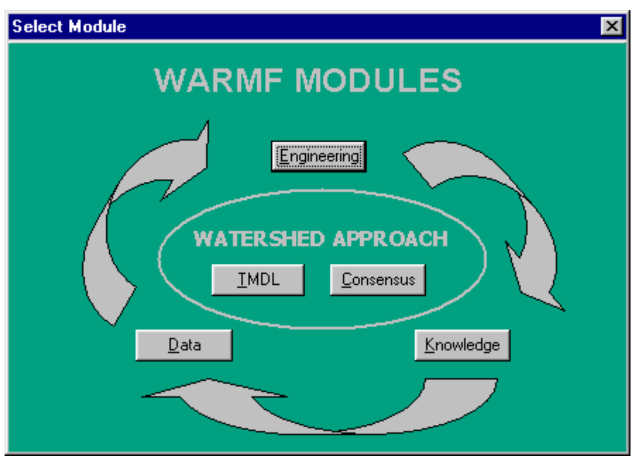

Figure 2.3. Modular design of WARMF

The algorithms for the model were derived from many well-established codes (Chen et al. 2001b). For example, the computing engine is taken from the Integrated Lake-Watershed Acidification Study (ILWAS) model (Chen et al., 1983). Algorithms for sediment erosion and pollutant transport from farm lands were adapted from ANSWERS (Beasley and Huggins, 1981), the universal soil loss equation. The sediment sorption-desorption of pesticides and phosphorus and the kinetics of nutrients and algal dynamics were adapted from WASP5 (Ambrose et al., 1991). The pollutant accumulation and wash-off from urban areas was adapted from the Storm Water Management Model (SWMM) (Agency 1992).

The model can simulate flow and water parameters such as pH, temperature, dissolved oxygen, ammonia, nitrate, phosphate, suspended sediments, coliform bacteria, 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 suitability for water supply, swimming, fish habitat, recreation or other uses (based on users’ or stakeholders' water quality criteria) can be presented. The model considers the input of the targeted nutrient and pollutant loadings to the watershed through atmospheric deposition, land-use practices (e.g., fertilization, pesticide application), and point source releases. The model transports the nutrients and pollutants through the watershed via hydrologic processes, and considers their uptake, release and transformation within the various units of watershed. Using a continuously stirred reactor (CSTR) formulation for each hydrologic unit, the concentrations of nutrients for each stream, lake, and reservoir are calculated. To simulate the temperature changes in the water bodies an energy balance is used based on input from solar heating as well as from point and non-point sources. The model can be used to estimate the TMDL of particular pollutants to meet water quality criteria set by the stakeholders in a particular sub-watershed, set of sub-watersheds or the entire watershed (EPRI, 2000).

Although WARMF can simulate subsurface flow/chemical transport, tile drainage systems are not taken into consideration by the model. Moreover, the subsurface flow component of the model tends to be somewhat simplistic. WARMF calculates the moisture of soil layers (up to 5 layers of soil) for every time step. If the moisture of a soil layer is below field capacity, the hydraulic conductivity of the said layer is zero. If the soil moisture is at saturation, the infiltration rate is the hydraulic conductivity. In between, WARMF interpolates the infiltration rate.

A more detailed description of the WARMF model is presented in the following sections.

2.4.5.1.Engineering Module

The Engineering Module is a GIS-based watershed model that calculates daily runoff, ground water flow, and water quality of river segments and reservoirs. The model divides the watershed into various components; including sub-watersheds, stream segments, and lake layers. Sub-watersheds are further divided into canopy and soil layers. Land surface is described by land use. In order to run water quality simulations, these components are connected into an integrated network allowing for the flow of pollutants between them. A hydrologic model within WARMF simulates canopy interception, snow pack accumulation and melt, infiltration through soil layers, evapotranspiration from soil, ex-filtration of groundwater to stream segments, and kinematic wave routing of stream flows. Figure 2.4 shows the conceptual model of hydrology for WARMF. A sub-watershed can have various land uses on the land surface. Below ground, the soils can have up to five layers (only 2 layers are shown in Fig. 2.4). The water table can rise or fall depending on the balance between vertical percolation from above and lateral outflow to the river segment.

In general, the hydrologic simulation is performed as follows (Chen et al., 2005): The rate of infiltration into the soil is limited by the vertical hydraulic conductivity of the top soil layer. If the soil is frozen or the water table rises to the ground level, the water from precipitation and snowmelt is backed up to the ground surface. The water retained on the ground surface fills surface depression storage. When surface depression storage is filled, the excess water flows to a river segment by sheet flow, which is calculated by Manning's equation. For each soil layer, percolation is calculated from the layer above and to the layer below. The soil layer has an allocation of evaporation according to the root distribution of plants. The model performs a water balance in each time step to update soil moisture by accounting for the evaporation, lateral flow and the difference in percolation to and from the soil layer. The hydraulic conductivity of soil layers is a function of soil moisture. The available void space in the soil is filled with the water, which percolates downward. When the percolation reaches the groundwater table, it raises the groundwater level. Groundwater can flow out to the river segment by lateral flow, which is calculated with Darcy's equation using horizontal hydraulic conductivity and slope. The unconfined aquifer is assumed to be watertight. Any known loss of groundwater to the deep confined aquifer must be specified as groundwater pumping for WARMF to extract water from the unconfined aquifer. Stream flow is routed by the kinematic wave method, and Manning's equation is used to calculate the outflow rate. Water depth in the river is determined by performing a flow balance by accounting for inflow from the upstream river segment, inflow from land catchments on both sides of the river segment, outflow to the downstream river segment, and the change of storage. Such simulations track the flow paths of precipitation from land into different water bodies.

Chemistry module performs various mass balance and chemical equilibrium calculations along each flow path (Weintraub et al., 2001a). A complete mass balance is performed, starting with atmospheric deposition and land application as boundary conditions. Pollutants are routed with water in throughfall, infiltration, soil adsorption, exfiltration, and overland flow. The sources of point and non-point loads are routed through the system with the mass so that the source of non-point loading can be tracked back to land use and location (Chen et al., 1998).

2.4.5.1.1. Runoff Hydrology

The runoff from a watershed comprises the surface runoff and groundwater exfiltration. For modeling, as mentioned earlier, the watershed is divided into canopy, snow pack, and soil layers. Each one is considered as a continuously stirred tank reactor (CSTR) for flow routing and mass balance calculation (Chen et al., 1983, Gherini et al., 1985). As mentioned earlier, Figure 2.4 presents a definition sketch of watershed. Only two soil layers are shown in the figure.

The model accepts meteorological data, simulates snow hydrology on the land surface, and calculates soil infiltration, groundwater exfiltration, surface runoff, and non-point source loading. They are subsequently routed to a stream segment or a reservoir layer (Chen et al., 2001b).

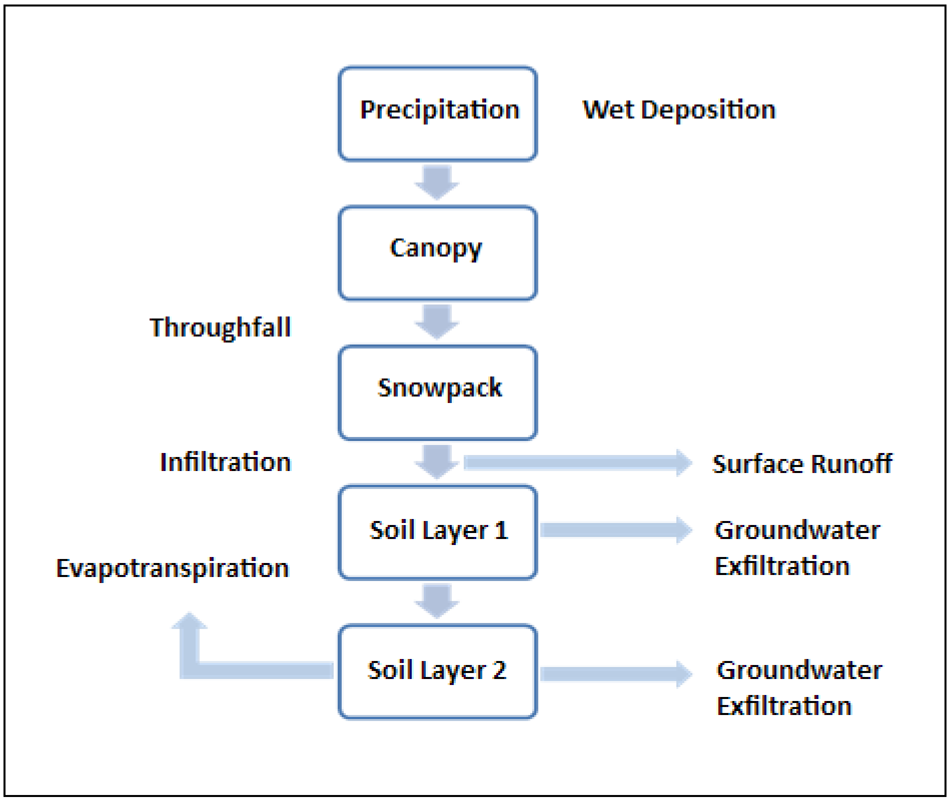

Figure 2. 4. Definition Sketch for the Compartments of a watershed (Chen et al. 2001b)

2.4.5.1.1.1. Rainfall and Snowfall

WARMF can account for snowfall, snowstorms with rain, and rain on snow (Chen et al., 2005), and simulate them using equations adopted from the U.S. Army Corps of Engineers (1960) and Chow (1964). The model calculates the rainfall and snowfall fractions of daily precipitation according to daily maximum and minimum temperatures. If the minimum air temperature is above the snow formation temperature, which is an input parameter with a value near zero degrees Celsius, all precipitation is considered as rain. The precipitation is treated as snow if the maximum air temperature is below the snow formation temperature. A mixture of rain and snow occurs if the minimum and maximum temperatures straddle the snow formation temperature (Chen et al., 2001). The snow fraction is added to the snowpack and the rain fraction is applied as rain on snow, in which the latent heat of rain is used to melt the snowpack. The snowmelt equation includes terms for maximum and minimum air temperatures, the aspect, and slope of watershed. The snowmelt water equivalence is subtracted from the snowpack depth. The model calculates soil temperatures based on advection and diffusion. If the soil is frozen, the model sets the soil hydraulic conductivity to zero (Chen et al., 2005).

If the snow formation temperature (T_s) is between the maximum (T_{max}) and minimum (T_{min}) temperatures, the rainfall amount (P_r) is (Chen et al., 2001b),

$$P_r = P \frac{(T_{max} - T_s)}{T_{max} - T_{min}} \tag{2.1}$$

where P is the amount of precipitation (cm day^{-1}). The amount of snowfall (P_s) is,

$$P_s = P - P_r \tag{2.2}$$

2.4.5.1.1.2. Canopy Interception

Leaf area index (LAI) describes the surface area of the canopy, which is defined as the leaf surface area per unit land area of the watershed. Since LAI can vary seasonally, 12 monthly values of LAI are required as model input. WARMF specifies the maximum potential canopy interception for the highest LAI. The potential interception storage of any month is calculated by (Chen et al., 2001),

$$I(mon) = D_{max} \frac{L(mon)}{L_{max}} \tag{2.3}$$

where I(mon) is the potential canopy interception (cm) of the month evaluated; D_{max} is the maximum canopy interception for the highest LAI value of a year; L(mon) is the LAI of the month evaluated; and L_{max} is the highest LAI. During a time step, the rain water will fill the potential interception storage. The actual amount of water intercepted will depend on the amount of water remaining on the canopy from the previous time step. The potential canopy interception is (Chen et al., 2001b):

$$I_p(t) = I(mon) - I(t-1) \tag{2.4}$$

where $I_p(t)$ is the potential interception of the time step (cm); $I(mon)$ is the maximum canopy interception for the month; $I(t-1)$ is the amount of water remaining on the canopy in the time step before. If the precipitation is less than $I_p(t)$, all precipitation will be intercepted and the amount of water remaining on the canopy will be increased accordingly. If the precipitation is higher than $I_p(t)$, the canopy interception will be filled to the full extent. The remainder becomes a throughfall (Chen et al., 2001b):

$$T_f = P - I_p(t) \tag{2.5}$$

where T_f is throughfall (cm day^{-1}); P is precipitation (cm day^{-1}); and $I_p(t)$ is the interception potential (cm day^{-1}).

2.4.5.1.1.3. Evapotranspiration

The potential evapotranspiration (ET) is the evaporation from free surface water, soil surface, and transpiration extracted from the soil. The potential ET is the maximum that can occur and if there is not enough water to meet the potential demand, only the available amount is transpired. The potential ET for each month is calculated as a function of latitude using Hargreaves equation (Hargreaves 1974) and then is converted to daily potential by (Chen et al., 2001b):

$$E_p(t) = \frac{E_P(mon) T_a E_c C_H}{n} \tag{2.6}$$

where Ep(t) is potential ET (mm day^{-1}); E_p(mon) is monthly ET based on the empirical equation of Hargreaves (mm $^oF^{-1}$ month^{-1}); T_a is mean ambient temperature of the day (^{o}F); E_c is a calibration parameter; and C_H is the humidity correction factor. C_H is determined by (Chen et al., 2001b):

$$C_H = 0.166(100 - H)^{0.5} \quad 2.7$$

where H is the relative humidity in percent. For H less than 64 percent, the value of C_H is set equal to unity.

The steps to satisfy the potential ET of the day are: first water is evaporated from the canopy surface; then is evaporated from the detention storage on the ground; the rest is extracted from soil layers in proportion to the given root distribution among the soil layers. The moisture of soil layers can only be drawn down to the wilting point.

2.4.5.1.1.4. Snow Hydrology

WARMF simulates the snowpack accumulation, snowmelt by air, and snowmelt by rain on the snow. It accounts for a difference in snowmelt rate for open areas and areas sheltered by a canopy. For snowpack simulation, the areas with deciduous trees are treated as open. The model also accounts for the sun angle due to the aspect of the watershed. The equations for these processes are adopted from Chow (1964) and Army Corps of Engineers (1960). The water equivalent of the snowpack is calculated by (Chen et al., 2001b):

$$S(t) = S(t-1) + (P_s - B - M)\Delta t \quad 2.8$$

where S(t) is snowpack depth (cm); S(t-1) is snowpack depth from the previous time step; P_s is snowfall rate (cm s^{-1}); B is the constant snow sublimation rate (cm s^{-1}); M is the snow melt rate (cm s^{-1}); and Δt is the time step (s). The snow melt rate M is as follows (Chen et al., 2001b):

$$M = f_o M_o + f_f M_f + M_r \quad 2.9$$

where f_o is the fraction of the land surface which is open and f_f is the fraction of land surface which is shaded by forest. The temperature induced snowmelt in the open area and in shaded forest area is calculated by (Chen et al., 2001b):

$$M_o = \alpha(T - T_m)X \qquad 2.10$$

$$M_f = \gamma(T - T_m)X \qquad 2.11$$

where M_o = the snow melt rate in the open areas; α and γ are degree-day snow melt rates (cm $^oC^{-1}$ day^{-1}); T = ambient air temperature (^oC); and T_m = the incipient snow melting temperature (^oC). The α and γ are coefficients accounting for the declination angle of the sun and vary by time. X accounts for the sun angle with respect to aspect and slope (m m^{-1}) of individual sub-watersheds (β degrees measured clockwise from north).

$$X = 0.4 + 0.6\frac{\sin(\theta_{base} + \theta_{slope})}{\sin(\theta_{base})} \qquad 2.12$$

$$\theta_{base} = 90 + L - \theta_{decl} \qquad 2.13$$

$$\theta_{slope} = 45^o(s)\cos(\beta) \qquad 2.14$$

θ_{base} is the sun's angle relative to perpendicular for the watershed (degrees); θ_{slope} is the angle of the watershed slope in the north-south direction (degrees); θ_{decl} is the declination angle of the sun (degrees) north of the equator; and L is the latitude of the watershed (degrees) north of the equator.

The rain-induced snowmelt rate is calculated by (Chen et al., 2001b):

$$M_r = 0.0039(T - T_m)P \qquad 2.15$$

where M_r is rain-induced melt rate (cm s^{-1}); and P is throughfall (cm s^{-1}).

2.4.5.1.1.5. Soil Hydrology

The water from precipitation and snowmelt on pervious surfaces may infiltrate into the ground and soil layers, or may remain on the surface for detention storage, or flows as surface runoff. The water on impervious surfaces is subjected to immediate runoff.

2.4.5.1.1.6. Soil Layer

There can be up to five soil layers in each sub-watershed; each layer has its own volumetric soil moisture content, horizontal and vertical hydraulic conductivity, field capacity, and saturated soil moisture content. The vertical hydraulic conductivity of a soil layer is dynamically calculated as a function of soil moisture (Chen et al., 2001b):

$$K_{vj} = K*_{vj} \frac{(\theta_j - \theta_{fcj})}{(\theta_{sj} - \theta_{fcj})} \tag{2.16}$$

where K_{vj} is vertical hydraulic conductivity for layer j adjusted for the soil moisture; $K*_{vj}$ is the intrinsic vertical hydraulic conductivity of the soil layer j; θ_j is the volumetric moisture content of soil layer in percent; θ_{fcj} is the field capacity of the soil layer in percent; and θ_{sj} is the saturated moisture content of the soil layer in percent.

According to this equation, the hydraulic conductivity is negative when the soil moisture drops below field capacity. In the simulation, the hydraulic conductivity is set to zero when the soil moisture is below field capacity. The water in the soil will not flow by gravity; it can only be extracted by plant roots for ET.

The model also adjusts the hydraulic conductivity when the soil is frozen. There is no adjustment when the soil temperature is above 0 ^{o}C, but when the soil temperature is between 0 and -4 ^{o}C, the adjustment is made as follows (Chen et al., 2001b):

$$K_{vj} = K_{vj}\left[1 - \left(\frac{\theta_j}{\theta_{sj}}\right)\left(\frac{T_j}{-4}\right)\right] \tag{2.17}$$

Where T_j is soil temperature (^oC). When the soil temperature is below -4 ^oC, the adjustment is made for the fraction of void with water in it,

$$K_{vj} = K_{vj}\left(1 - \frac{\theta_j}{\theta_{sj}}\right) \tag{2.18}$$

The above equations are for the vertical hydraulic conductivity. If the subscript "v" is replaced by "h", the equations become the adjustment for horizontal hydraulic conductivity.

2.4.5.1.1.6.1. Infiltration

For the top layer, the ground surface may include impervious areas. The model assumes that the water on impervious areas is subject to immediate runoff. The water on pervious areas can infiltrate into the top layer of the soil. The amount of infiltration into the top layer can be limited by two terms: first the amount of water available for infiltration on the ground surface, and second the amount of water that can be absorbed by the soil layer. The available air space (cm^3) in the top layer is (Chen et al., 2001b):

$$I_{v1} = A_1(\theta_{s1} - \theta_1)Z_1 \tag{2.19}$$

where I_{v1} is potential vertical infiltration to fill the void of layer 1 (cm^3/time step); A_1 is surface area of layer 1 (cm^2); θ_{s1} is saturated moisture content of layer 1 in percent by volume; θ_1 is the moisture content of layer 1 at time zero; and Z_1 is the thickness of layer 1 (cm).

The water available for infiltration on pervious area is,

$$I_{A1} = A_{PA}(D + T_f + M) \tag{2.20}$$

where I_{A1} is potential water available for infiltration (cm^3); A_{PA} is the pervious area of the watershed (cm^2); D is detention storage at the beginning of the time step; T_f is newly arrived throughfall (cm); and M is new snowmelt (cm).

The actual infiltration to the first layer is the lesser of I_{V1} and I_{A1}. The infiltration from a soil layer to the layer below is limited by three terms: firstly, by the amount of water available for infiltration from the layer above, secondly, by the void space available in the layer below, and finally, by the vertical infiltration rate by which the water can infiltrate from the layer above to the layer below.

For example, the amount of water available for infiltration from layer 1 to layer 2 is,

$$I_{A2} = A_1(\theta_1 - \theta_{fc1})Z_1 \qquad 2.21$$

where 1 and 2 stand for the first and second layer. According to this equation the water available for percolation is the soil moisture above field capacity. When the soil moisture is below the field capacity, the term I_{A2} is set to zero. The amount of infiltration to fill the void of layer 2 is,

$$I_{v2} = A_2(\theta_{s2} - \theta_2)Z_2 \qquad 2.22$$

The maximum rate of percolation from layer 1 to layer 2 is,

$$I_{P2} = K_{V1}A_1\Delta t \qquad 2.23$$

where I_{P2} is the maximum percolation rate from layer 1 to layer 2 (cm^3/time step); K_{V1} is the vertical conductivity of layer 1 (cm s^{-1}); A_1 is surface area of layer 1 (cm^2); and Δt is the time step (s). The actual percolation from layer 1 to layer 2 is the smaller of I_{V2}, I_{P2}, and I_{A2}. The percolation from layer 2 to layer 3, layer 3 to layer 4 and so on is calculated by similar equations.

2.4.5.1.1.6.2. Lateral Flow

The water exfiltrated from soil layer j is calculated using Darcy's Law (Chen et al., 2001b):

$$Q_j = K_{hj}SWZ_j \qquad 2.24$$

where Q_j is the lateral exfiltration (cm^3); K_{hj} is the horizontal hydraulic conductivity adjusted for moisture, freezing temperature, and the hydraulic conductivity of any downstream sub-watershed; S is the slope of the sub-watershed; W is the width of the catchment parallel to its receiving stream, or perpendicular to the direction of ground water flow; and Z_j is the thickness of the soil layer.

If a sub-watershed is adjacent to another sub-watershed instead of a river or reservoir, the lateral flow out of the upstream segment will enter the downstream sub-watershed. If the horizontal hydraulic conductivity of the downstream segment is less than that of the upstream sub-watershed, the minimum value will be used to determine lateral flow.

2.4.5.1.1.6.3. Lateral Inflow

To determine the lateral inflow from an upstream sub-watershed, it is assumed that the sub-watersheds are linked layer to layer, regardless of layer thickness. The transfer of lateral flow between two linked sub-watersheds is limited by two terms: 1) the amount of ground water flow leaving the upstream sub-watershed, and 2) the void space available in the downstream. The amount of ground water flow leaving the upstream sub-watershed is calculated as described in equation 2.24. This flow is limited by the horizontal hydraulic conductivity of both watersheds.

The amount of lateral flow to fill the void of layer i in the downstream watershed is (Chen et al., 2001b):

$$L_{Vi} = A_i\left(\theta_{si} - \theta_i\right)Z_i \qquad 2.25$$

The actual lateral flow from layer i of the upstream watershed to layer i of the downstream watershed is the lesser of L_i and L_{Vi}.

2.4.5.1.1.6.4. Water Balance

The equations described earlier are used to calculate infiltration into each layer, percolation from each layer to the layer below, lateral inflow into each layer, and lateral exfiltration from each soil layer to a sub-watershed, a stream, or a lake segment. A final water balance is used to determine the saturated zone (Chen et al., 2001b). Percolation and lateral inflow are adjusted when they are impeded by the saturated ground water.

The final water balance is performed from the bottom layer to the top layer, one at a time. For each soil layer, the overall water balance is as follows (Chen et al., 2001b):

$$V_j = V_{jo} + I_j - I_{j+1} + L_j - E_j - Q_j \qquad 2.26$$

where V_j is the volume of water in soil layer j; V_{jo} is the volume of water in soil layer j at the beginning of the time step; I_j is the infiltration to layer j; I_{j+1} is the percolation from layer j to layer j+1; L_j is the lateral inflow from an upstream segment; E_j is the ET assigned to layer j; and Q_j is the exfiltration flow from layer j. The solution algorithm solves for the soil moisture θ implicitly to determine the new water volume, infiltration, percolation, and lateral flow.

The soil layer is already saturated if the volume of saturated soil moisture (V_{sj}) is smaller than V_j. The infiltration and lateral flow into the layer is impeded by the groundwater. The excess is returned to the layer above. Lateral flow takes priority over infiltration. First, infiltrated water is moved to the layer above and then the lateral flow is moved up if needed. These calculations proceed from the bottom layer to the top layer. The excess term will become zero for the layer which is partially saturated. If all layers are completely saturated, excess lateral and infiltrated flow will be returned to the ground surface (Chen et al., 2001b).

2.4.5.1.1.6.5. Overland Flow

Surface water which does not infiltrate into the soil may be ponded on the surface or run off as sheet flow. Detention storage is assumed to be a percentage of all the surface water on pervious surfaces (Chen et al., 2001b):

$$D = \left(I_{A1} - I_1\right)\left(\frac{d}{100}\right) \qquad 2.27$$

where D is the detention storage (cm); I_{A1} is the water available for infiltration into the top soil layer (cm); I_1 is the amount of water which actually infiltrates into the top soil layer (cm); and d is the percent of surface water retained as detention storage. The water available for sheet flow is,

$$Z_o = I_{A1} - I_1 - D \qquad 2.28$$

where Z_0 is the water depth on ground surface for sheet flow. The sheet flow is calculated by Manning's equation,

$$Q_s = \frac{WZ_oS^{1/2}}{n * 0.01^{1/3}} \qquad 2.29$$

where Q_S is runoff from the pervious surfaces of the watershed ($m^3\ s^{-1}$); and n is Manning's roughness coefficient. The total surface runoff from watershed is the sum of water on impervious surfaces plus runoff from pervious surfaces calculated using Manning's equation (Chen et al., 2001b).

2.4.5.1.2. Runoff Quality

The water, which runs off the surface, can take different flow paths to reach a stream segment or a lake element, thus the chemistry associated with each flow must be tracked separately. WARMF determines the concentrations of constituents associated with overland flow and groundwater exfiltration from each soil layer.

There are different types of land uses in the watershed. Each land use has its own vegetation characteristics and percent pervious surface. When chemical constituents fall from the canopy, they are typically aggregated over all land uses as they are applied to the ground surface. No distinction is made between different land uses on the ground surface and within the soil, except when one land use is kept separate within the soil such as for a designated surface mining land use or when a land use is irrigated (Chen et al. 2001b). The concentrations of multiple chemical constituents are simulated simultaneously. The mass balance equation will be derived for only one constituent and the same equation is used to track the concentrations of others. More detailed information can be found in WARMF Technical Report (Chen et al., 2001b).

In order to simulate the runoff quality, WARMF model considers the followings (Chen et al., 2001b): atmospheric deposition, foliar exudation, canopy reactions, throughfall chemistry, snowpack chemistry, leaf litter, sediment erosion, buffer strip, fertilization, livestock exclusion, soil temperature, nutrient uptake, root respiration, anion and minor cation adsorption, cation exchange, mineral weathering and acid mine drainage, earth breathing process, cation precipitation/complex ion formation, nitrification and denitrification, ferrous ion oxidation, septic systems, mass balances. Some of these processes are explained below. The more detailed information is available in Chen et al. (2001b)

Atmospheric Deposition: WARMF takes into account: dry air particles which are deposited on the canopy surface or falling directly to the snowpack and soil surface; the gaseous SO_x and NO_x absorbed into leaf tissue through the stomata (Chen et al., 2001b).

Throughfall Chemistry: The model tracks the mass of individual chemical constituents on the canopy due to dry deposition, foliar exudation, and water retained on the canopy from the previous time step. The precipitation water is mixed with the mass of chemical constituents on the canopy. The resulting concentrations are assigned to the throughfall as well as the water retained on the canopy for the next time step (Chen et al., 2001b).

Snowpack Chemistry: The snowpack is modeled as a continuous stirred tank reactor (CSTR). The model makes a mass balance calculation for the chemical constituents in the snowpack, accounting for the new snow fall, new throughfall, and new atmospheric dry deposition which occur in the time step. It assumes negligible nitrification due to the cold temperature. The model also simulates the leaching of ions from the snowpack. Thus, the snow melt leaching will lead to an exponential decrease of chemical constituent concentrations remaining in the snow. Conversely, higher constituent concentrations will be found in the initial phase of snow melt water (Chen et al., 2001b).

Leaf Litter: Leaves falling from the canopy become coarse litter, coarse litter decays into fine litter, fine litter decays into humus, and humus decays into organic acids. The model uses a mass balance equation to track the changing mass of each species, accounting for the source (from the decay of parent species) and sink (from its own decay to daughter species). The by-products of decay are added to the pool of non-structural ions in the litter (Chen et al., 2001b).

Sediment Erosion: WARMF simulates the transport of clay, silt, and sand separately and combines the result for total suspended sediment. The erosion processes include the detachment of soil particles from the land surface, the suspension and deposition of detached soil particles in the overland flow, and the bed load transport of sand fraction on land. It is assumed that sediment transport does not occur when there is snow cover on the ground. It is also assumed that the ground water flows do not carry sediments (Chen et al., 2001b).

Fertilization: Monthly loading rates are applied upon the surface of the watershed, including not only fertilization, but also livestock waste in pasture lands; pet waste, trash, and other sources in urban areas; and other sources such as wildlife. The loading builds up on a daily basis until the time that precipitation reaches the land surface or until the maximum accumulation time (days) is reached. Precipitation carries the loading to the subsurface or in surface runoff (Chen et al., 2001b).

Livestock Exclusion: In cases of direct access of livestock to streams, a portion of their waste will go directly to the stream instead of the land surface. Model diverts this waste from fertilizer to direct stream loading and removes this amount from the loading to the land surface (Chen et al., 2001b).

Soil Temperature: The hydrology and water quality of soil are affected by soil temperature. Organic matter decomposition rates are highly dependent on temperature. To model soil temperature it is assumed that the canopy shades the soil. The heat fluxes into and out of the soil and between soil layers are due to conduction and advection. Advection accounts for heat carried by water that percolates from one layer to the next (e.g. infiltration and groundwater lateral flow). Conductive heat transfer occurs between adjacent soil layers; for the bottom layer, there is zero heat transfer with the bedrock below; for the top layer, there is heat transfer between the soil and the air above. The soil surface temperature is normally the same as the air temperature, although when there is a snow cover, the temperature at the snow/soil interface is calculated. A heat budget equation for a soil layer is written. By consolidating the terms for infiltration and exfiltration, this heat budget equation can be reduced to expressing the new temperature of a soil layer as a function of the old temperatures of itself and the layers above and below (Chen et al., 2001b).

Nutrient Uptake: Nutrients are extracted from soil according to net plant productivity specified in the input for each land use. The input data also provides a long term productivity increase per year, a seasonal pattern of nutrient uptake, a monthly litterfall, a stoichiometric content of plant biomass, and a root distribution among soil layers from which plants extract nutrients. The model calculates the nutrient demand for chemical component, and then the total demand is the sum of the nutrient demand for leaf growth and the demand for productivity (net biomass growth). A mass balance is conducted so the amount required for growth for each chemical component of the biomass is taken from the soil. The monthly nutrient uptake (an input) is used to divide the annual demand into monthly demand. The daily nutrient demand is calculated by dividing the monthly nutrient demand by the number of days in the month. The daily nutrient demand is extracted from soil layers in proportion to the root distribution. In case that there is not enough of a chemical constituent in any soil layer to satisfy the nutrient demand, crop growth will be reduced to the percentage of growth that can be supported by the most restrictive constituent. Constituents adsorbed to soil particles are equally accessible for uptake as dissolved constituents. The vegetation has equal preference for NH_4^+ and NO_3^-—N and they are removed in proportion to their concentrations in the soil solution. NO_x and SO_x absorbed by leaves go toward satisfying the demand for nitrogen and sulfate before those nutrients are removed from the soil (Chen et al., 2001b).

Nitrification and Denitrification: Nitrification takes place in the presence of oxygen, while denitrification takes place in the absence of oxygen. WARMF uses the first order rate equation to model nitrification and denitrification. However, it checks for the availability of oxygen for a reaction to proceed (Chen et al., 2001b).

Mass Balances: The equations for each of the mentioned individual processes are assembled into a mass balance equation. This equation is solved for the concentration of each chemical constituent associated with surface runoff and groundwater exfiltration. For surface runoff, the water on the land surface is modeled as a continuous stirred tank reactor (CSTR). The constituent in the surface water retained from the previous time step is mixed with the constituent associated with the new arrivals from throughfall, snowmelt, direct wet deposition and dry deposition. The final concentration is the concentration for surface runoff, groundwater infiltration and surface water retention for the next time step. The constituent contained in the surface runoff becomes the non-point source load from the land. For the groundwater, each soil layer is modeled as a CSTR. A soil layer has three phases: solid, liquid, and gas. The volume of the liquid phase plus the gas phase equals the volume of soil void. Soil moisture content controls the partitioning between gas and liquid phases. During a time step, the water already present from the previous time step is mixed with the water percolated into the soil layer from above. It accounts for the sink term if the constituent is subject to decay and the source term if the constituent is a by-product of decay from another constituent. The resulting concentration is the concentration for the water exfiltrated to the river segment and the water percolated to the layer below. The constituent contained in the ground water exfiltration is included in the non-point source load from the land (Chen et al., 2001b).

2.4.5.1.3. Stream Hydrology

Stream hydrology is based on conservation of mass. Water is routed from the most upstream tributaries down to the lower rivers in the watershed. For every stream segment, change in storage is the inflow minus the outflow (Chen et al., 2001b):

$$I - O = \frac{dV}{dt} \qquad 2.30$$

where I is summation of all inflows to the stream segment; O is the outflow from the segment; dV is change in volume of the segment; and dt is time step. Inflows to a stream segment include outflow from upstream river segments, outflow from upstream reservoirs, local inflow from surrounding land sub-watersheds, and inflow from point sources. Local inflows include both subsurface (groundwater exfiltration) and overland flow. The kinematic wave approach is used to solve the mass balance equation. The outflow from the stream segment is calculated using Manning's equation (Chen et al., 2001b):

$$O_m = \frac{D^{2/3} S^{1/2} A_s}{n} \qquad 2.31$$

where O_m is the outflow estimated by Manning's equation; S is slope of stream segment; A_s is surface area of the river segment; and n is Manning's roughness coefficient. Based on the mass balance equation, the outflow can also be calculated by:

$$O_t = I - \frac{V(t) - V(t-1)}{\Delta t} \qquad 2.32$$

where O_t is the outflow calculated by mass balance equation; $V(t)$ is the volume of water at time t; $V(t-1)$ is the volume of water at beginning of the time step t-1; and Δt is the time step. The volume of water in a river segment is a function of depth (D) which is an input to the model. Through iterations, the model finds D such that O_m is equal to O_t (Chen et al., 2001b).

2.4.5.1.4. Stream Water Quality

As the water flows from one stream segment to the next, the river water can pick up non-point source and point source loads from adjacent lands. The water and pollutants will mix within the stream segment. On the water surface, convective heat exchange, reaeration, and CO_2 exchange occur (Chen et al., 2001b). Sediment organic matters (SOD) and dissolved organic carbon (BOD) may decay and consume dissolved oxygen. Ammonia may be oxidized to nitrate and consume dissolved oxygen in the process. Fecal coliform may die-off. Detailed information on various physical and chemical processes that may take place in the stream segment can be found in WARMF Technical Report (Chen et al., 2001). Detailed information on different processes considered in quality of the stream water can be found in Chen et al. (2001b).

2.4.5.2.Data and Knowledge Modules

The data module contains meteorology, air quality, point source, and flow diversion data used to run the model. It also contains observed flow and water quality data used for model calibration purposes. The data is accessed using a map-based interface and can be viewed and edited in both graphical and tabular format. Supplemental watershed data, documents, case studies, or reports of past modeling activities are stored in the Knowledge Module for easy access by model users (Chen et al., 1998).

On the watershed map, users can view the locations of point source dischargers, meteorology stations, stream gages, and water quality monitoring stations. All of this data can be viewed and updated through the data module.

2.4.5.3.Consensus and TMDL Modules

The last two watershed approach modules are roadmaps providing guidance for stakeholders during the decision making process. The Consensus Module provides information in a series of steps for stakeholders to learn about the issues, formulate and evaluate alternatives, and negotiate a consensus. It provides a simple menu for scenario generation that allows stakeholders, without extensive WARMF knowledge, to reduce point loads, non-point loads, atmospheric deposition, or diversion quantities by a percentage. User requires knowledge of the models and interfaces to run more detailed scenarios (e.g., changes in land use distribution, changes in fertilizer application rates, etc.).

USEPA (United States Environmental Protection Agency) regulations require the calculation of total maximum daily loads (TMDLs) of pollutants when a water body's designated uses are impaired (USEPA, 2009a). A TMDL is the sum of point and non-point loads that can be discharged upstream of a water quality limited section (WQLS) without violating the water quality criteria of its designated use. Through the TMDL Module, calculations are made for a series of control points from upstream to the downstream of a watershed. Iterative sets of simulations can be performed to calculate various combinations of point and non-point loads that the water body can accept and meet the water quality criteria of the designated uses (Chen et al., 1998).

2.4.6. DRAINMOD Model

DRAINMOD (Skaggs, 1980) is a deterministic, field-scale, hydrologic model that began as a tool for the design and evaluation of agricultural drainage and related water management systems. The model simulates the performance of a given water table management system over a long period of climatological record. The water management systems can be a combination of subsurface drainage, controlled drainage, and sub-irrigation. The model uses approximate methods to compute a 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 evapotranspiration. Figure 2.5 presents the schematic diagram of hydrologic processes simulated by the model.

The rates of infiltration, evapotranspiration, drainage, and distribution of soil water in the profile are calculated by various methods, which have been tested and validated for a range of soil and boundary conditions (Skaggs, 1980). The Green-Ampt 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) and read by the model as input data. 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 ponded surface using Kirkham's steady state flow equation. Deep seepage rates are calculated with an application of Darcy's law.

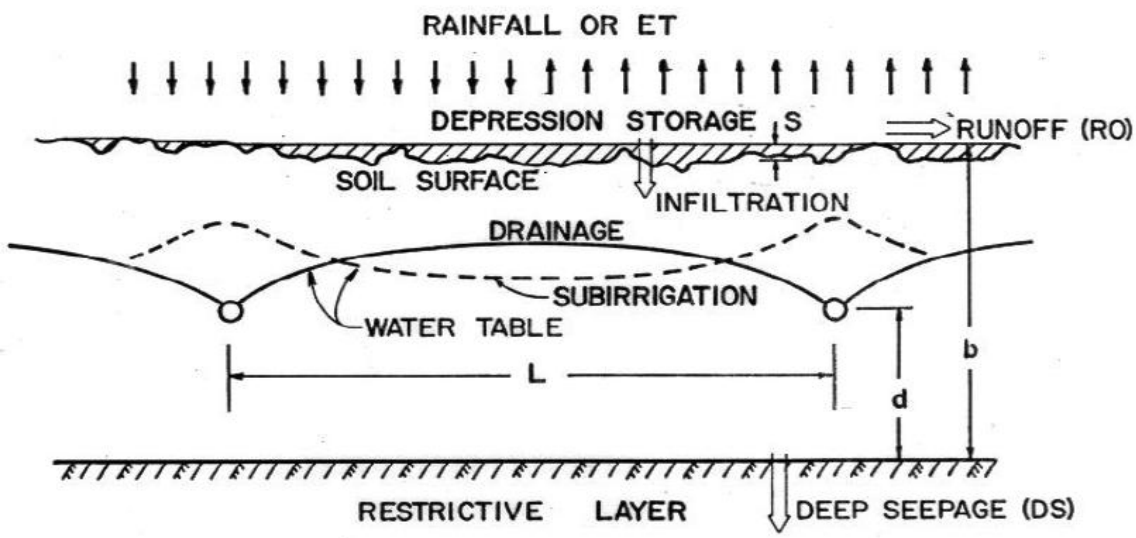

Figure 2. 5. Schematic diagram of hydrologic processes simulated by DRAINMOD (Adapted from Skaggs, 1980)

In DRAINMOD, the calculation of evapotranspiration and subsurface drainage depends on the position of the water table depth and the soil water distribution in the unsaturated zone. Soil water is assumed to be in two zones - the wet zone extending from the water table up to the root zone, or possibly through the root zone to the surface, and the dry zone. The water content distribution in the wet zone is assumed to have been drained to equilibrium. When the maximum rate of upward water movement, determined as a function of the water table depth, is not sufficient to supply the ET demand, water is removed from root zone storage creating a dry zone. The rooting depth in the model defines the zone from which water can be removed to supply ET. The dry zone, therefore, can extend equally to the root zone. When the dry zone depth becomes equal to the rooting depth, ET is limited by soil water conditions and is set equal to the upward water movement. The sum of wet and dry zone depths gives the water table depth at a time step. Further detailed descriptions of the hydrologic processes in DRAINMOD are given in Skaggs (1980).

The basic relationship in the model is a water balance for a thin section of soil of unit surface area which extends from impermeable layer to the surface and is located midway between adjacent drains (Skaggs, 1980).

$$\Delta V_a = D + ET + DS - F \qquad 2.33$$

where ΔV_a is the change in the air volume (cm), D is the lateral drainage (cm) from (or sub-irrigation into) the section, ET is the evapotranspiration (cm), DS is the deep seepage (cm), and F is the infiltration (cm) entering the section during the time increment Δt.

The terms on the right hand side of Equation 2.33 are calculated in terms of water table elevation, soil properties, soil water content, drainage system parameters, crop and stage of growth, and atmospheric conditions. The surface runoff and surface storage is computed using a water balance at the soil surface for each Δt, and can be written as,

$$P = F + \Delta S + RO \qquad 2.34$$

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.

The DRAINMOD model, version 5.1, includes freezing, thawing, and snowmelt components and is capable of simulating the drainage phenomena in cold regions. The model simultaneously solves the water flow equation and heat flow equation based on the principles of mass and energy conservation. It predicts soil temperature to simulate processes controlling field hydrology under cold conditions such as freezing, thawing, and snowmelt (Luo et al., 2000).

DRAINMOD 5.1 also includes a one-dimensional nitrogen cycling model (Breve et al., 1992). This version of the model uses the water balances and fluxes from DRAINMOD as inputs to a one-dimensional advective-dispersive-reactive equation for nitrogen fate and transport. The model considers a simplified version of the nitrogen cycle using nitrate as the main pool. The nitrogen balance considers fertilizer dissolution, mineralization of organic nitrogen, denitrification, and plant uptake using first order rate equations. At each daily time step, first order rate equations are used to balance transformations to and from the nitrate pool. The DRAINMOD simulated hydrology provides the necessary water contents, soil water contents and fluxes for simulating the nitrate transport. Crop potential yield, nitrogen content of the crop, and nitrogen fertilizer application amounts and dates are specified. Other inputs include nitrate concentration in the rain and the dispersivity and reaction rate coefficients for the nitrogen transformations.

Over the past two 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., 2006a; Youssef et al., 2006; Yang et al., 2007).

2.4.7. Model Selection

A good approach to modeling the hydrology and water quality issues in agricultural watersheds in colder humid regions is to use a model that can adequately address the hydrology of both un-drained and tile-drained areas. WARMF and DRAINMOD models were selected as together they meet these requirements very well.

The WARMF model was selected for surface flow/nitrogen simulations, since it incorporates algorithms derived from many well-established codes. It was designed to take stakeholders through a series of steps to develop and evaluate water quality management alternatives for a watershed. The model also provides a procedure to calculate the total maximum daily load (TMDL) of pollutants. Moreover, it is user friendly and can be applied to large watersheds. The model relies on its own implementation of a graphics interface and GIS functionality, which makes the model stand alone and applicable without requiring purchase of additional software. WARMF runs in a relatively short time (minutes) for large watersheds; individual sub-watersheds can be run separately, once the entire watershed has been calibrated, saving significant time in developing management scenarios for a particular region of the watershed, which is particularly useful for evaluating management scenarios for only one portion of the watershed. The model saves the different scenarios that are simulated (user's choice) and can display several of them for comparison of model output, both graphically and in spreadsheet format. It relies on proven hydrologic and bio-geochemical models for its formulation and is well documented. WARMF is more than a simple watershed model by including other elements to support a decision-making process involving multiple parties. To the best of author’s knowledge, the model has not been tested before for flow and nitrogen simulation in Canada.

Although WARMF 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 subsurface drainage, controlled drainage or sub-irrigation systems. As mentioned earlier, artificial tile drainage systems are installed in many agricultural fields in eastern Canada. Moreover, Quebec has a cool and wet spring and fall seasons, and a cold winter, and thus experiences freezing, thawing, and snowmelt. In this respect, DRAINMOD appears to be a good candidate for subsurface flow simulation. DRAINMOD was developed primarily for humid regions but it does not account for surface flow and transport of water and agricultural pollutants. Therefore, it was decided to work on integrating these two models and the resulting model, DRAIN-WARMF, can simulate surface/subsurface flow and nitrogen transport processes in a rational way for agricultural watersheds in humid regions. The new model allows for simulations to be carried out under different scenario analyses and management practices, which were not possible using the mentioned models individually.

CONNECTING TEXT TO CHAPTER 3

This chapter addresses the first objective of the thesis, validating the hydrology component of DRAINMOD model for subsurface flow simulations. This paper covers the various aspects of field-scale hydrological modeling using DRAINMOD model. A description of the site instrumentation and data collection methodology is provided along with calibration procedures and statistical analyses. Simulation results for subsurface drain flow and water table depths on an agricultural field have been presented.

This chapter is a manuscript published in the Journal of the American Water Resources Association in 2009. The manuscript is co-authored by my supervisors Drs. S. O. Prasher and C.A. Madramootoo; Dr. A. Madani, Professor in the Engineering Department of Nova Scotia Agriculture College; Mr. Peter Enright, professional associate and director of the Farm Management and Technology Program at McGill University; and Mr. Apurva Gollamudi and Guillaume Simard, graduate students in the Department of Bioresource Engineering at McGill University. 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: Field Evaluation of DRAINMOD 5.1 under a Cold Climate: Simulation of Daily Mid-span Water Table Depths and Drain Outflows

Shadi Dayyani , Chandra A. Madramootoo , Peter Enright , Guillaume Simard , Apurva Gollamudi , Shiv O. Prasher , and Ali Madani

Abstract:

The hydrologic performance of DRAINMOD 5.1 was assessed for the southern Quebec region considering freezing/thawing conditions. A tile drained agricultural field in the Pike River watershed was instrumented to measure tile drainage volumes. The model was calibrated using water table depth and subsurface flow data over a 2-year period, while another 2-year data set served to validate the model. DRAINMOD 5.1 accurately simulated the timing and magnitude of subsurface drainage events. The model also simulated the pattern of water table fluctuations with a good degree of accuracy. The R^2 between the observed and simulated daily water table depth for calibration was > 0.78, and that for validation was 0.93. The corresponding coefficients of efficiency (E) were >0.74 and 0.31. The R^2 and E values for calibration/validation of subsurface flow were 0.73/0.48 and 0.72/0.40, respectively. DRAINMOD simulated monthly subsurface flow quite accurately (E> 0.82 and R^2> 0.84). The model precisely simulated daily/monthly drain flow over the entire year, including the winter months. Thus DRAINMOD 5.1 performed well in simulating the hydrology of a cold region.

Key Terms: DRAINMOD 5.1; Subsurface Drainage; Freezing-thawing; Simulation Model; Cold Climate.

3.1.Introduction

Subsurface drainage is installed in many agricultural fields in eastern Canada. In the province of Quebec, subsurface drainage is necessary for two main reasons. Firstly, 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 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 tile drainage systems is necessary in order to make soil conditions favorable for crop production in early spring.

Over the past decade, subsurface drainage has been considered to contribute to non-point source pollution, which is responsible for the deteriorating quality of surface waters. The agriculture-intensive Pike River watershed in southern Quebec, where this study was conducted, drains into the agriculturally polluted Missisquoi Bay of Lake Champlain. Surface runoff and tile drainage are the two principal pathways by which sediment and nutrients are transported from field to surface waters. Therefore, it is important to quantify and evaluate long-term nutrient loadings from agricultural fields, in order to control and manage the water quality in Missisquoi Bay.

Although models have been extensively used in different parts of the world to evaluate the hydrology of artificially drained lands, less is known in the colder regions, where soil freezing and snowmelt routinely occur. The climate in southern Quebec is generally characterized by a dry summer with a cool and wet spring and fall, and a cold winter, which sees freezing, thawing, and snowmelt. It is known that frozen soil and snowmelt have significant effects on field hydrology. Frozen surface layers reduce infiltration and, as a result, surface runoff from rainfall or snowmelt increases (Johnsson and Lundin, 1991; Kane and Chacho, 1990). The snowmelt process and daily freeze–thaw cycles can have a dominant effect on field hydrology during the winter and early spring periods (Kuz'min, 1963; 1972).

Collecting long-term hydrologic data for a range of climatic conditions is an expensive and time-consuming process. Incorporation of real-time field data with a validated hydrological and water quality simulation model is economical and time-efficient. Currently, several computer simulation models are available that can simulate surface and subsurface flows as well as chemical transport through soil [ANSWERS (Bouraoui et al., 2002), SWAT (Arnold et al., 1998), ADAPT (Alexander, 1988), and DRAINMOD (Skaggs, 1980)]. However, only a few of these models can effectively simulate the dynamics of heat and water flow in soils which are subjected to freezing and thawing cycles (Stahli et al., 1999). Models that ignore the effect of soil freezing and snow accumulation tend to overpredict flow during winter months and underpredict flow during early spring. The modified DRAINMOD model, version 5.1, includes freezing, thawing, and snowmelt components, and is thus capable of simulating the drainage phenomena in such regions (Luo et al., 2001).

The modified DRAINMOD calculates a daily average soil temperature profile, incorporates the effect of ice formation on soil hydraulic conductivity and infiltration, simulates water flow from precipitation, and keeps track of the snow depth. DRAINMOD 5.1 considers precipitation as snowfall when the average daily temperature is below a rain/snow dividing base temperature. Snow accumulation on the ground is simulated until air temperature rises above a snowmelt base temperature. Soil surface temperature is recalculated when snow cover exists. Initially, snow density is an input in DRAINMOD, and then it is updated daily according to the old snow remaining, new snowfall, and snowmelt. When the air temperature rises above a snowmelt base temperature, snowmelt is calculated using the degree-day method. Daily snowmelt water is added to rainfall, which may infiltrate or run off, depending on the soil freezing conditions. The frozen soil condition is simulated by simultaneously solving the water flow equation and heat flow equation based on the principles of mass and energy conservation (Luo et al., 2000; Nixon, 1975; Fuchs et al., 1978). In addition, in the new version, infiltration is limited by a critical ice value, above which no infiltration takes place and snowmelt or precipitation leaves the field as runoff (Christopher and Cooke, 2003; Luo et al., 2000). When freezing conditions are indicated by a below–zero temperature, the model calculates ice content in the soil profile (Luo, et al., 2000). The impact of ice formation on infiltration and soil permeability may be estimated by modifying soil hydraulic conductivities according to ice content. Soil temperature as a function of time and depth is calculated on a daily basis by solving the heat equation using numerical methods (Hanks et al., 1971; Campbell, 1985). Initial tests of the model in Plymouth, North Carolina; Truro, Nova Scotia; Lamberton, Minnesota; and Carsamba, Turkey (Luo et al., 2000, 2001) showed improved seasonal drainage prediction.

The hydrology component of the model was field tested in the Lower Coastal Plain of North Carolina (Youssef et al., 2003). The experimental site was planted in a corn–wheat-soybean [Zea mays L. - Triticum æstivum L. - Glycine max (L.) Merr.] rotation and managed with either conventional or controlled drainage. The results showed that DRAINMOD 5.1 could reliably predict drain outflows and water table fluctuations. Wang et al. (2006a) have also used the model to simulate nitrogen movement in a cold region. Their results showed that DRAINMOD 5.1 performed better in winter months than the original model. However, Wang et al. (2006a) had calibrated the model based on monthly drain outflow values, and they did not calibrate the model for water table depth (WTD). Sands et al (2004) also found that the DRAINMOD model could be a useful tool for investigating the impact of drainage depth over long climatic records and examining the interaction of soil type and drainage depth in cold climates.

The older version of the model, DRAINMOD 5.0, which does not have the freezing thawing component, has been used by Helwig et al. (2002) to simulate WTD, drain outflows, and nitrogen losses in drainage waters in southwestern Quebec. The model was validated for the growing season only. The model has not been validated for both daily WTD and drain outflows in a cold region, with frozen soil conditions during winter months. Youssef et al. (2006) evaluated DRAINMOD-NII, an enhanced version of DRAINMOD-N, for a drained agricultural research site in the lower coastal plain of North Carolina, and the model was parameterized based on the literature data rather than field or laboratory measurements. Zwierschke et al (2002) also validated the capability of DRAINMOD 5.1 to simulate the effect of water table management practices on nitrate and nitrogen in drainage water. The results, which only presented WTD, showed the model to adequately predict the WTD under conventional and combined drainage at a site in Piketon, Ohio.

The goal of this study therefore, was to evaluate the capacity of DRAINMOD 5.1 to simulate WTD and subsurface drain outflows throughout the year in a southwestern Quebec field. The specific objectives were to evaluate the performance of DRAINMOD 5.1 using four-site years of data from an agricultural site in the Pike River watershed, in simulating WTD and subsurface flows on agricultural fields on a daily basis in frozen/unfrozen soil conditions.

3.2. Materials and Methods

3.2.1. Site Description

The experimental agricultural field was situated in the Pike River watershed near the town of Bedford (45o 7’ 30” N, 73o 3’ 45” W), approximately 70 km southeast of Montreal and 15 km north of the Quebec-Vermont border. (Fig. 3.1) The site belongs to a swine and cash crop producer, and has a surface drainage area of 7.0 ha and subsurface drainage area of 7.8 ha. According to the soil survey map, the soil has three layers and the soil types are a mix of Suffield clay loam (9.4%), St. Rosalie clay loam (69.9%, predominant soil type - humic gleysol) and Bedford sandy clay loam (20.7%). Table 3.1 shows the soil physical properties of the predominant soil type (St. Rosalie clay loam).

Table 3.1. Soil physical properties (Abou_Nahra, 2006)

Depth (cm)	0-30	30-60	60-90
% Sand	21	16	17
% Clay	32	40	50
Textural class	silty clay loam	silty clay loam	clay
Bulk Density (g cm^{-3})	1.7	1.75	1.74
K_{sat} (cm day^{-1})	6.18	5.81	3.68

Subsurface drainage at the site was installed with a trenchless plow in a systematic pattern, with 110 mm diameter plastic corrugated laterals and 210 mm diameter outlets (Eastman, 2008). Instrumentation on the site was installed in the fall of 2000. Hydrologic and meteorological data were collected continuously from October 2000 (Gollamudi, 2006). During the study period (2001 - 2004), the principal crop grown was corn. The field was drained with corrugated tile at a depth of 1.20 m from the soil surface. Drains were placed 21.34 m apart. All the drains were connected to a major outlet that discharged into a ditch connected to the Pike River. The field had a mean slope of 0.8% (east to west) that promoted surface runoff towards only one exit, situated at the lowest part of the field. Average depth of surface depression storage was around 25 mm in the field. Figure 3.2 simplifies the design of the field installation.

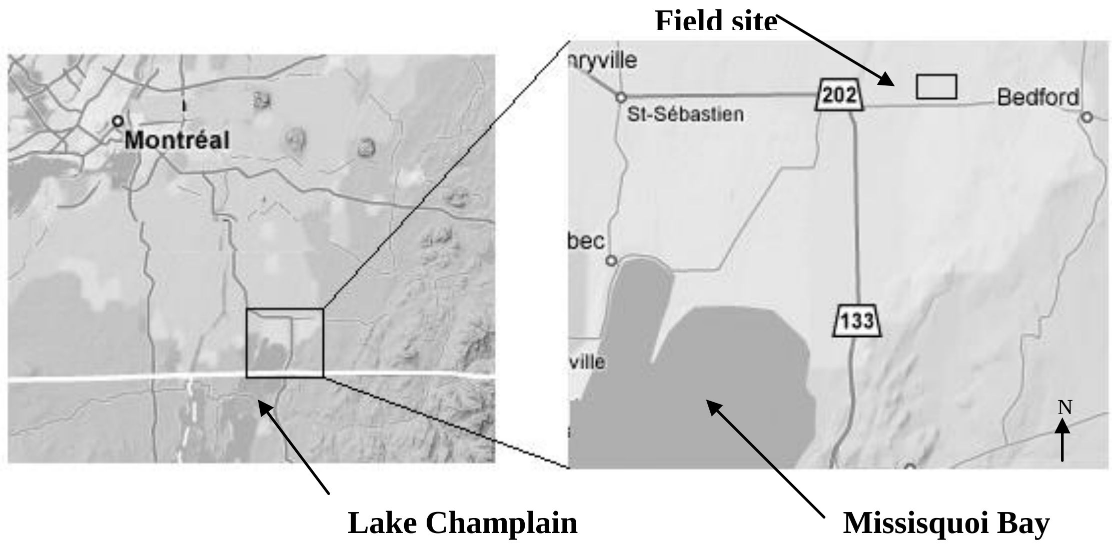

Figure 3.1. Location of the study area.

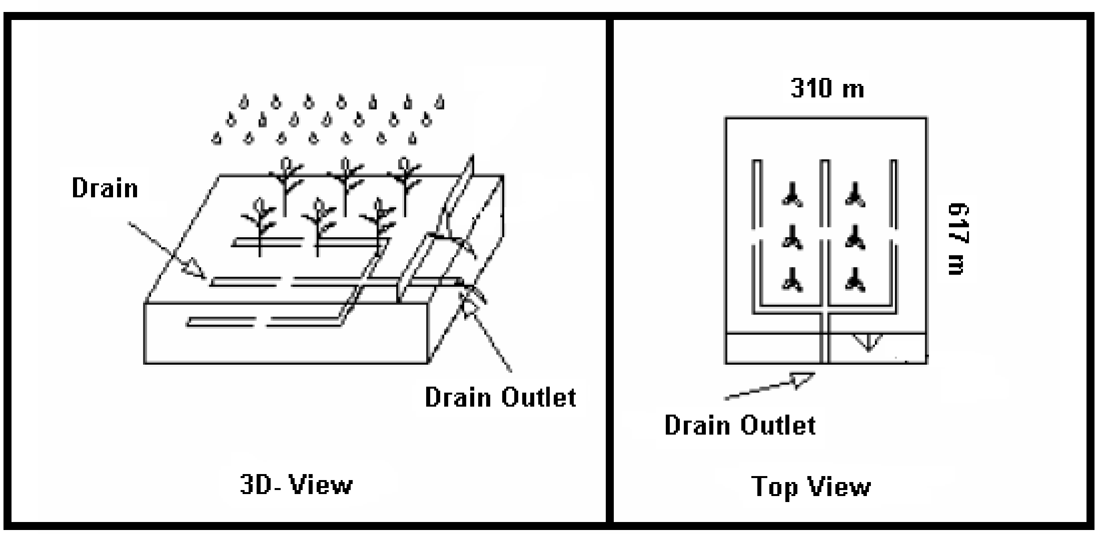

Figure 3.2. Simplified field installation (Adapted from Simard, 2005).

3.2.2. Measurements

Daily precipitation, hourly air temperature, daily WTD and subsurface drain outflow were measured at the site. Precipitation was measured using tipping bucket rain gauges (Texas Electronics Tipping Bucket Rain Gauge, 0.1 mm tip). Data from the Environment Canada, Philipsburg weather station, located approximately 9 km south of the site, were also collected to supplement missing or erroneous data. A thermocouple was used to measure hourly air temperature (Campbell Scientific Temperature Probe, P107). Snowfall was not measured on the field site, but obtained from the Philipsburg station.

To measure subsurface flow, the tile drainage collector was connected to an ultrasonic flow meter (Endress & Hauser Prosonic Flow DMU – 93 Ultrasonic flow measurement system), which served as the primary measurement device. An insertion flow meter (Global Water IF – 200 insertion flow meter) served as the back-up sensor (Enright and Madramootoo, 2004). The installation also includes water table level loggers and remote data access capabilities, enabling year-round recording. At the site, ten water table wells were installed, and three of the wells had level-loggers (Solinst Levelogger) installed. The level-loggers automatically recorded WTD and the measurements were verified by a manual depth sensor. Depths of the wells varied between 0.80 m and 1.20 m. A more detailed and complete description of site instrumentation and monitoring procedures is given by Enright and Madramootoo (2004).

3.2.3. Model Inputs

Model inputs included soil properties, drainage volume–WTD relationship, upward flux, infiltration parameters, crop data, drainage system parameters, surface storage, daily max/min temperature and hourly precipitation. The drainage volume, upward flux and infiltration parameters were calculated by an internal DRAINMOD subroutine, which uses the soil water characteristic of each layer of the soil to produce values of volume drained for water table positions ranging from the surface to the bottom of the soil profile (Skaggs, 1980). The soil water available to the plant is limited by the upward flux from the water table to the plant roots. The soil preparation program includes a routine which calculates the maximum WTD that will support a given upward flux value (Skaggs 1980). For each horizon, the soil water characteristic data for the predominant soil type were determined on soil cores using pressure plate tests, which allowed a calculation of the volumetric water content at pressures of -10, -20, -33, -50, -100, -200, -500, -1000, and -1500 kPa (Klute, 1986). Abou_Nahra (2006) determined the saturated hydraulic conductivity by the falling-head soil core method, using a soil water permeameter (Eijkelkamp Agrisearch Equipment, Giesbeek, Netherlands).

The Green-Ampt equation is used to simulate infiltration. The infiltration parameters, A and B, are calculated by the model using the soil moisture retention curve of the topsoil. The moisture retention data were obtained using intact soil cores. The Green - Ampt parameters are calculated as a function of water table depth. The parameters A and B are calculated using these equations:

$$A = K_s * M * S_{av} \tag{3.1}$$

$$B = K_s \tag{3.2}$$

Where Ks is the vertical saturated hydraulic conductivity, M is the fillable porosity (water content at saturation in cm^3/cm^3 less the water content at a given water table depth) and S_{av} is the suction at the wetting front in cm.

DRAINMOD uses the “drained-to-equilibrium” principle to estimate the pressure head at the soil surface. So, the fillable porosity will vary with the water table depth. S_{av} values depend on soil texture and can be obtained from published literature. Table 3.2 contains the Green-Ampt parameters calculated by the model in this study as a function of water table depth.

Based on the 'drained to equilibrium' assumption DRAINMOD determines the relationship between volume drained and water table depth. At various water table depths the pressure head is equal to negative WTD. Using the soil water characteristic curve of the profile, volume of water in the soil profile is calculated for various water table positions ranging from the surface to the bottom of the soil profile. The volume drained per unit area, when the water table drops from the surface to different depths in the profile, is calculated by taking the difference between volumes of water in the soil at these depths.

Table 3.2. Green-Ampt infiltration parameters

Water Table (cm)	A Coefficient	B Coefficient
0	0	0.5
10	0.09	0.5
20	0.23	0.4
40	0.32	0.31
60	0.42	0.31
80	0.52	0.31
100	0.85	0.31
150	1.96	0.21
200	1.96	0.21
1000	1.96	0.21

DRAINMOD calculates the upward flux at any point using the Darcy-Buckingham equation. Using the 'drained to equilibrium' assumption, the pressure head is known at various locations in soil profile. Also the unsaturated hydraulic conductivity for each node is obtained from the unsaturated hydraulic conductivity function of the appropriate layer. The flux is calculated by determining the hydraulic gradient and unsaturated hydraulic conductivity.

Meteorological data inputs were based on daily precipitation data from the tipping bucket rain gauge at the site, while daily snowfall data was obtained from the Philipsburg weather station. Table 3.3 shows the monthly precipitation based on rainfall and snowfall data measured at the site and the Philipsburg weather station, respectively. Using the DRAINMOD weather utility, the observed daily precipitation was uniformly distributed over 6h (from 16:00 to 22:00) to obtain the hourly precipitation.

Potential evapotranspiration (PET) can be entered directly (e.g. calculated using the Penman-Monteith method) or calculated during simulation using the Thornthwaite equation. Table 3.4 shows the monthly temperature data for simulation years. Thornthwaite PET was calculated using a latitude of 450 18', an average heat index of 45, which was calculated for the study site, and daily max/min temperatures recorded at the study site. Monthly ET adjustment factors have been used to improve the Thornthwaite ET predictions. The initial ET adjustment factors for all months were 1.0. The final values used are given in Table 3.5. In order to reflect the freezing and thawing phenomenon, additional inputs were required (Luo et al., 2000), including the two constants relating soil thermal conductivity to soil water content, the rain/snow-dividing temperature, the snow melt base temperature and degree–day coefficient for snowmelt, the critical ice content above which infiltration stops, the initial soil temperature distribution and a base temperature as the lower boundary condition, the phase lag for daily air temperature sine wave, the initial snow depth and density, and soil freezing characteristics which indicate the relationship between unfrozen water content and soil temperature.

Table 3.3. Measured monthly precipitation at the site

	Precipitation (mm)				
	2002	2003	2004	2005	2006
January	56	33.2	20	25.8	83.8
February	42	43.2	31	27.8	44.7
March	60.2	95.2	66.2	38.2	40.9
April	77.6	42.5	42.6	74.6	68.35
May	117.7	69.5	73.3	23.6	159.05
June	158.1	86.1	65.3	92.5	117.95
July	66.2	71.1	115.9	56	81.55
August	58.3	169.1	102.3	99	122.9
September	144	63.3	64.9	92.7	55.4
October	77.2	153.1	34.4	152.65	124.15
November	75.2	134.2	45.4	123.3	89.25
December	39.4	171.8	80	73.15	62.15
Total	971.9	1132.3	741.3	879.3	1050.15

Table 3.4. Monthly temperature (^oC) for simulation years

	Max & Min Temperature (^oC)									
	2002		2003		2004		2005		2006	
January	1	-9	-5	-18	-9	-19	-4	-16	2	-9
February	2	-11	-3	-16	1	-19	1	-15	0	-10
March	6	-6	5	-9	7	-5	5	-11	6	-5
April	14	2	11	-1	12	0	15	1	16	0
May	18	5	22	7	21	8	19	6	21	9
June	25	12	27	11	25	10	29	15	26	14
July	29	15	29	15	29	15	31	15	31	17
August	29	14	29	15	27	13	30	14	28	12
September	26	10	25	10	25	10	26	10	23	9
October	14	2	15	3	17	2	15	5	14	2
November	6	-3	9	-2	9	-2	10	-2	10	1
December	1	-9	1	-11	0	-11	0	-11	4	-5

Table 3.5. DRAINMOD input parameters for hydrologic predictions

Parameter	Value	Unit
Drainage system		
Drain depth	1.2	m
Drain spacing	11	m
Effective radius of drains	1.5	cm
Drainage coefficient	1.2	cm day^{-1}
Maximum surface storage	2.5	cm
Kirkham's depth for flow to drains	0.1	cm
Lateral saturated hydraulic conductivity (1st, 2nd, 3rd layer)	0.19, 0.45, 1.5	
Soil temperature		
Thermal conductivity function coefficients	a= 0.553; b= 1.963	W m^{-1} ^oC
Diurnal phase lag of air temperature	9	h
Soil temperature at the bottom of the profile	7	^oC
Rain/snow dividing temperature	0	^oC
Snowmelt base temperature (^oC)	2	^oC
Snowmelt coefficient	5	mm day^{-1} $^oC^{-1}$
Critical ice content	0.2	cm^3 cm^{-3}
ET monthly factors		
Jan = 1, Feb = 1, March = 1, April = 0.5, May = 0.8, June = 1		
July = 0.7, Aug = 0.5, Sept = 1, Oct = 0.7, Nov =0.5, Dec = 0.7		

In this study it was noted that the model is not sensitive to critical ice content, and the difference in its value did not affect the simulation noticeably. Therefore, the critical ice content was set to 0.2, based on published literature (Willis et al., 1960; Luo et al., 2000). Kuz'min (1972) suggested 2°C for snowmelt base temperature on the typical topography of the plains; snow would begin to melt when the average air temperature exceeds 2°C. The snowmelt degree–day coefficient was generally about 5 mm/°C day (Kuz'min, 1972). The water content of freshly fallen snow varies from 40 mm to 400 mm per meter of snow (Schwab, 1993). The values of the above-mentioned parameters were used in this study, and are listed in Table 3.5.

3.3. Results and Discussion

3.3.1. Model Calibration

DRAINMOD was manually calibrated by comparing observed and simulated WTD and drainage volumes. Calibration parameters were selected based on previously cited literature and adjusted on a trial-and-error basis using daily drain flow and WTD data. Based on the literature, DRAINMOD has been calibrated using different parameters, such as: soil hydraulic parameters (Singh et al. 2006); effective lateral hydraulic conductivity, soil surface storage, and crop rooting depth (Zhao et al. 2000); monthly ET adjustment factors (Jin and Sands, 2003); drainage coefficient, maximum surface storage, saturated soil water content, residual soil water content, lateral saturated hydraulic conductivities in soil layers, and the minimum air volume required to work the land (Haan and Skaggs, 2003); and vertical hydraulic conductivity of the restrictive layer and the lateral hydraulic conductivity of the bottom soil layer (Wang et al., 2006b). In this study DRAINMOD was calibrated based on lateral saturated hydraulic conductivities of the three layers, vertical hydraulic conductivity of the restrictive layer, soil surface storage, and monthly ET factors. The parameters were varied from 10 to 15 mm h-1, 0.01 to 0.02 mm h-1, 10 to 50 mm, and 0.01 to 1, respectively.

Model results were most sensitive, in order, to the vertical saturated hydraulic conductivity of the restrictive layer, lateral hydraulic conductivity of the soil layers, soil surface storage, and monthly ET factors. Representative values for the whole field could not be measured for these calibrated parameters. The initial lateral saturated conductivity values for different soil layers were set at twice the vertical saturated conductivity as suggested by Skaggs (1980). The calibrated values of lateral Ksat are reported in Table 3.5. The DRAINMOD 5.1 requires inputs for the initial soil temperature profile, upper boundary condition and a base temperature as the lower boundary condition. The appropriate value for the upper boundary condition is the soil surface temperature. Since a long record of measured soil surface temperatures is not usually available for most applications, air temperature was used instead (Luo et al., 2000). The lower boundary was assumed to be a constant soil temperature, which can be approximated as the long term average air temperature (Penrod et al., 1958). The calibration parameters were adjusted, and the time series of simulated and observed WTD and drain outflows were plotted. Several trial and error runs were performed by varying various input parameters. The results for both WTD and drain outflows were plotted and the quality of simulation was initially evaluated by examining the plots visually for a match between the observed and predicted values. This evaluation looked at the proximity between the simulated and observed values and the timing of peak flows. For the best simulation thus determined, in terms of both WTD and drain outflow, further assessment was made by computing various statistical parameters (Table 7).

The calibration parameters that gave the best overall results were selected, and are given in Table 3.5. In order to validate the model, the field measurements were divided into two portions (Table 3.6). The 2004 - 2005 data was used to calibrate WTD and drain outflow, whereas 2002 – 2003, and 2006 were used to validate drain outflow, and 2006 was used to validate WTD.

In this research, monthly ET adjustment factors were used to improve the Thornthwaite ET predictions and subsequently DRAINMOD’s prediction of observed drainage values (Barnett et al., 1998). Thus, although DRAINMOD is a physical model, some adjustment in parameters is needed. In addition, due to spatial variability of soil and crop conditions, it is difficult to estimate representative parameters for the entire field. Therefore, adjustment is needed.

Table 3.6: Data availability for this study

WTD data		Drain outflow data	
Calibration	Validation	Calibration	Validation
1 April- 7 May, 2004 13 June- 19 Oct, 2004		Jan-Dec 2004	Jan-Dec 2002
			Jan-Dec 2003
29 June- 16 Sept, 2005	20 July- 7 Oct, 2006	Jan-Dec 2005	Jan- Sept, 2006

A qualitative evaluation of model performance was done by a comparison of the time series graph of predicted values with that of the measured values. Objective evaluation was done by calculating statistical parameters including: average deviation (AD), average absolute deviation (AAD), Relative Root Mean Square Error (RRMSE), coefficient of determination (R^2), and coefficient of efficiency (E).

The average deviation (A.D.) indicates whether the model has over- or under-estimated the values. It is defined as (James and Burges, 1982):

$$\mathrm{AD} = \frac{\sum_{i=1}^{n}\left(\mathrm{O_i} - \mathrm{P_i}\right)}{\mathrm{n}} \qquad 3.3$$

where O_i is the i^{th} observed value, P_i is the i^{th} predicted value, for a total number of events ‘n’, which is the total number of days.

The AAD (also referred to as mean absolute error, MAE) value shows the overall magnitude of deviation of simulated values from observed ones and is given by (Janssen and Heuberger, 1995):

$$\mathrm{AAD} = \frac{\sum_{i=1}^{n} \left| \mathrm{O_i} - \mathrm{P_i} \right|}{\mathrm{n}} \quad 3.4$$

Relative Root Mean Square Error (RRMSE) which has a minimum value of 0.0, with a better agreement close to 0.0 (El-Sadek et al. 2003a):

$$\mathrm{R.R.M.S.E.} = \frac{\sqrt{\frac{\sum \left(\mathrm{O_i} - \mathrm{P_i}\right)^2}{\mathrm{n}}}}{\mathrm{O_{avg}}} \quad 3.5$$

where O_{avg} is the mean observed value.

Although the coefficient of determination, R^2 has limitations in describing the degree of association between observed and predicted values, it is commonly used (El-Sadek et al, 2001 and 2003b; Singh et al., 2001; Fernandez et al., 2006). It is defined as:

$$\mathrm{R}^2 = \left(\sum_{i=1}^{n} \left(\mathrm{O_i} - \mathrm{O_{avg}}\right)\left(\mathrm{P_i} - \mathrm{P_{avg}}\right) \right)^2 \Big/ \sum_{i=1}^{n} \left(\mathrm{O_i} - \mathrm{O_{avg}}\right)^2 \sum_{i=1}^{n} \left(\mathrm{P_i} - \mathrm{P_{avg}}\right)^2 \quad 3.6$$

The coefficient of efficiency E has been widely used to evaluate the performance of hydrologic models. Nash and Sutcliffe (1970) defined the coefficient of efficiency, or modeling efficiency (EF) as:

$$E = 1 - \frac{\sum_{i=1}^{n} \left(O_i - P_i\right)^2}{\sum_{i-1}^{n} \left(O_i - O_{avg}\right)^2} \quad 3.7$$

It ranges from minus infinity to 1.0, with a value of 1.0 representing a perfect prediction, a value of 0 (zero) representing a prediction no better than using the mean of measured values, and lower values representing a progressively worse prediction. Values of E between 0.50 and 1.00 are considered acceptable.

3.3.1.1. Simulation of WTDs

The measured and simulated WTD are presented for calibration years (2004 - 2005) in Figures 3.3 and 3.4, respectively. Generally, DRAINMOD 5.1 simulated the pattern of water table fluctuations with a good degree of accuracy for both years. Observed and simulated water tables often rise rapidly in response to rainfall, causing rapid fluctuations and time lags which result in a lower E value. In this situation E values were in the range of 0.7 to 0.8, values considered very good for water table predictions (Youssef et al., 2006), considering WTD fluctuated rapidly in response to rainfall. Comparisons are made based on end-of-day values, so the simulated WTD's rise either led or lagged behind the observed response by a few hours near the end of day; the difference in simulated and observed WTD could be large, e.g., 40 to 60 cm. Despite this the coefficient of efficiency (E) over the simulated period was 0.77 for 2004 and 0.74 for 2005 (Table 3.5). These E values show a very good agreement between observed and simulated WTD.

On average, predicted water table depths were within 89 mm in 2004, and 63 mm in 2005 of observed values, indicating good results (AAD, Table 3.7). Helwig et al. (2002) had reported similar values of 174 to 254 mm for a field in southwestern Quebec in 1998 – 1999 and considered them reasonable. The small positive AD values for 2004 -2005 indicate that the WTD depth was marginally under-estimated (shallower depths). The R^2 values over the simulated period were 0.78 and 0.81 for the two years, which also indicates a very good relationship between the observed and predicted WTDs. The regression parameters (slope and intercept) are shown in Table 3.7. Ideally, the slope should be equal to 1.0 and the intercept 0.0, which would indicate a perfect fit. In modeling studies, the slope is rarely equal to 1.0 and the intercept is seldom zero (Bera et al., 2005). It can be seen that the model performed well in 2005 for WTD simulation (the slope is close to 1 although the intercept is significantly different from zero). In 2004, although the slope and intercept are significantly different from 1.0 and zero, respectively, these were numerically close to the ideal values. On the basis of visual evaluation and the statistical indices, it may be concluded that the model performed well in simulating WTD over the calibration period.

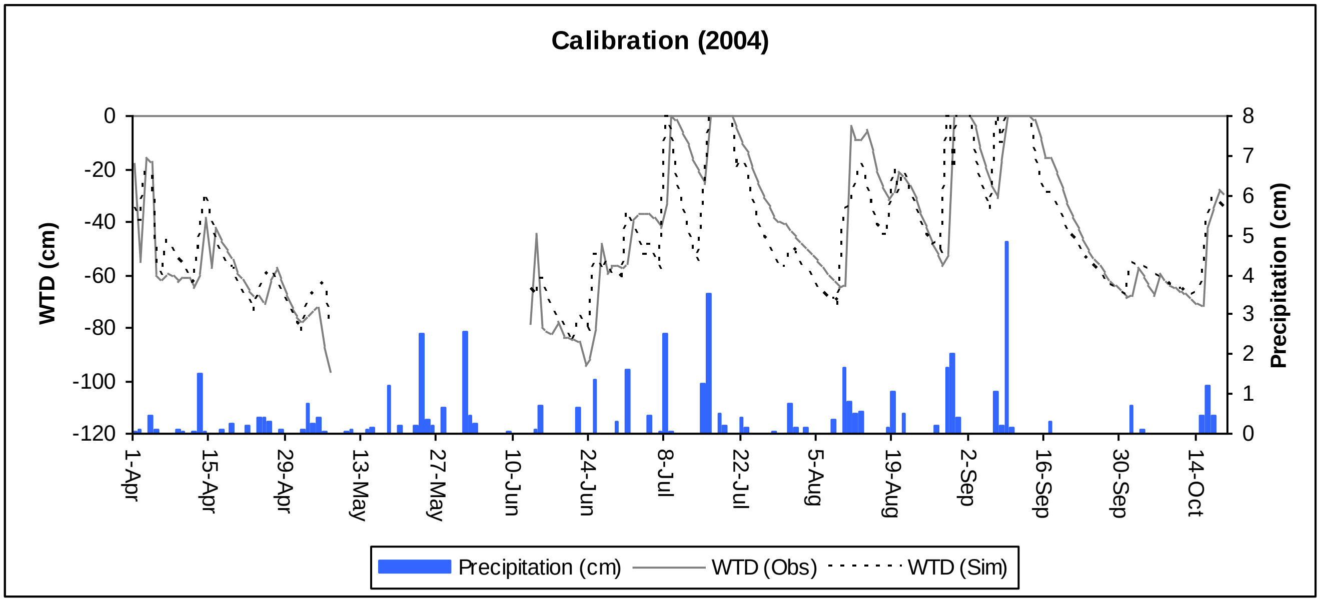

Figure 3.3. Observed and simulated water table depths for 2004.

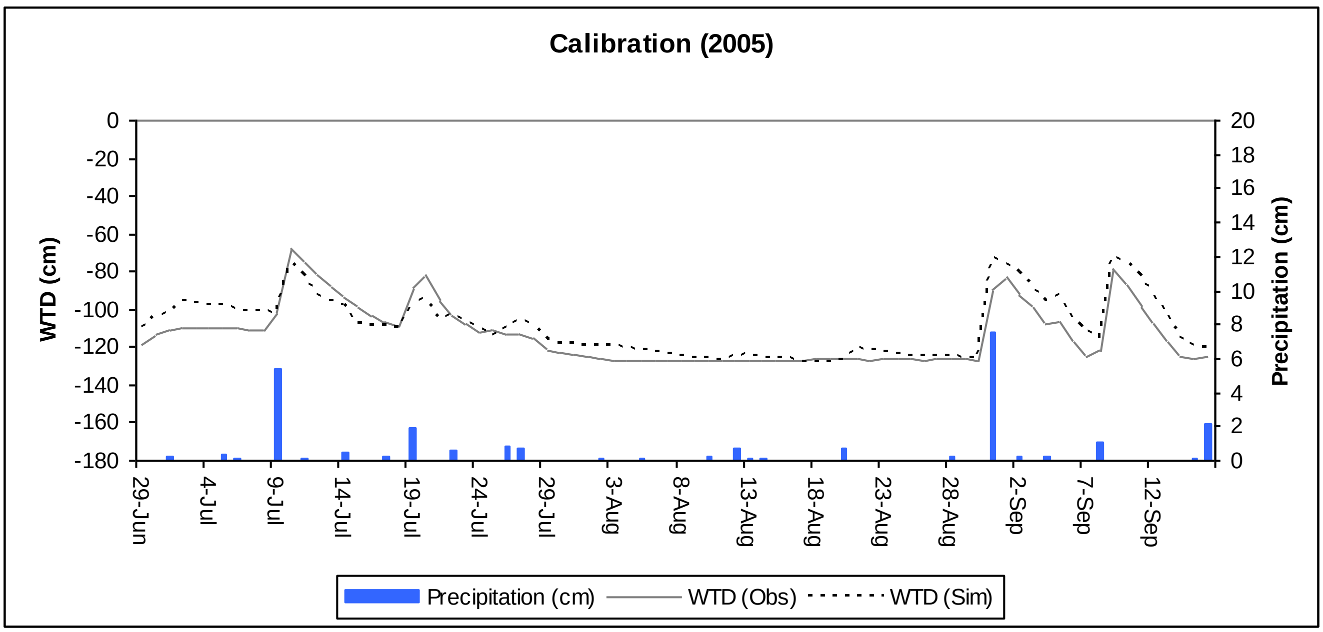

Figure 3.4. Observed and simulated water table depths for 2005.

3.3.1.2. Simulation of Drain outflows

The predicted and observed daily drain outflows for calibration years are plotted in Figure 3.5. The model predictions closely follow the trend of the observed values (Table 3.7; Fig. 3.5). The peak drainage flows were also simulated quite accurately. Although in some instances, simulated peak flows were slightly over- or under-estimated, the timing of simulated and observed peaks matched reasonably well. Overall, DRAINMOD accurately simulated the pattern of drain outflows over the entire calibration period (2004-2005), including periods of frozen soil conditions. From January to April 2004, December 2004 to April 2005 and in December 2005 the simulated subsurface flow closely matched observed values. This indicates that the model was calibrated very well for frozen soil/snowmelt conditions.

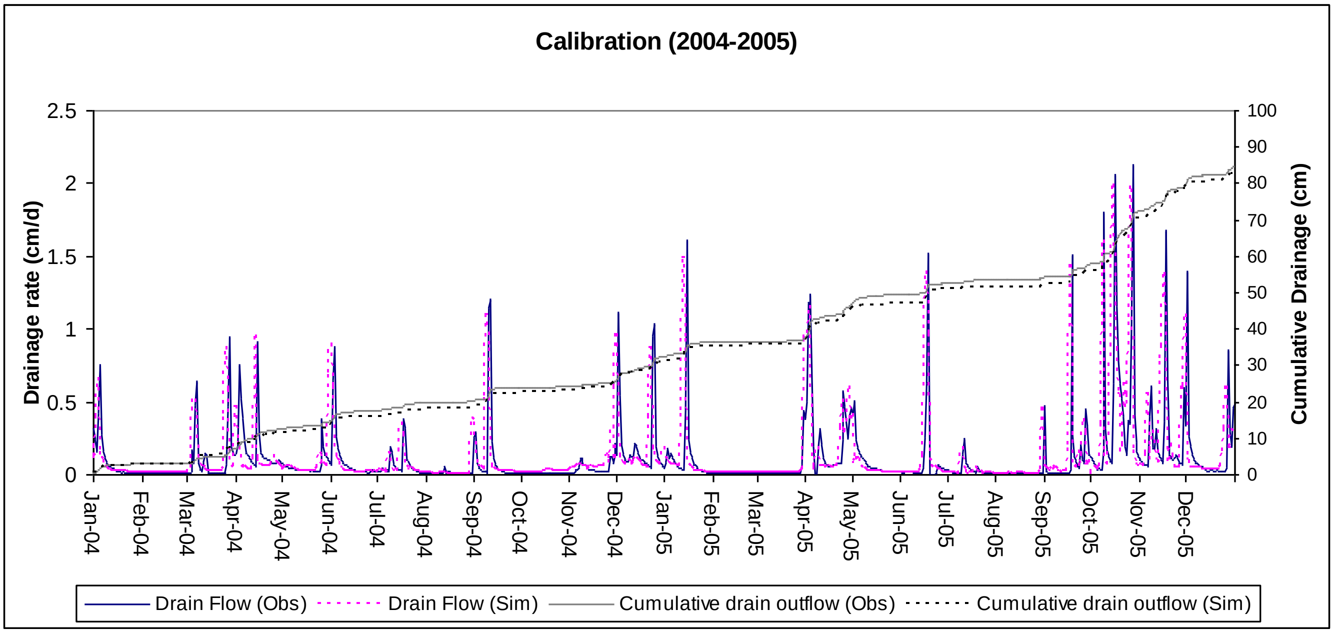

Figure 3.5. Observed and simulated daily and cumulative subsurface drainage over calibration period (2004-2005).

The statistical indices calculated from the predicted and observed daily drainage outflows are given in Table 3.7. The AD (0.1 mm) was very small, and R^2 (0.73) and E (0.72) values were high. The regression parameters, although significantly different from their ideal values, were fairly close (Table 3.7). Year 2005 had a wet fall; 311 mm of precipitation accumulated between September and December. Total observed subsurface drainage experienced at site was 526 mm. This is 30% greater than the previous three-year average discharge. The increase in subsurface discharge during 2005 is explained by the milder and wetter fall and winter seasons (Eastman, 2008). Above normal temperatures and consistent rainfall throughout these seasons prevented frost formation in the soil, therefore allowing the subsurface drainage system to remain active. It can be seen that the model was well calibrated since it simulated the timing and volume of drain outflow quite accurately.

From Figure 3.6 it can be seen that the monthly drain outflows were predicted well (E= 0.95) and the simulated values were in good agreement with the observed values (R^2 =0.96). Wang et al. (2006a) calculated values of R^2 ranging from of 0.70 to 0.84 for monthly drainage flows when the model was calibrated on the basis of drain outflows for Nova Scotia. Despite the fact that we calibrated the model for both WTD and drain outflow together, we obtained an R^2 of 0.86 for Quebec, showing relatively better results than those of Wang et al. (2006a). This indicates that the model is capable of simulating drain flow accurately in cold regions.

The comparison between the observed and predicted cumulative drainage (Fig. 3.5) shows that in 2 years simulated annual subsurface drainage was only about 30 mm less than observed.

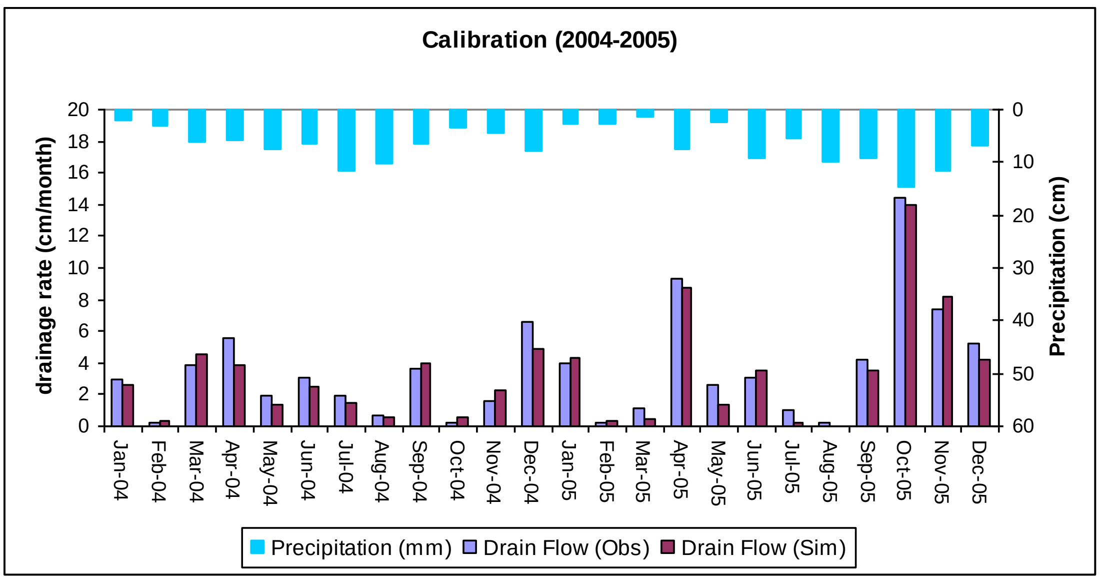

Figure 3.6. Simulated vs. observed monthly drainage outflows (2004-2005).

3.3.2. Model Validation

During the calibration years, DRAINMOD might be expected to perform well since input parameters were adjusted to obtain the optimal agreement between the predicted and observed WTD/subsurface drainage. These adjusted parameters, therefore, were validated for another period of data by comparing the simulated and observed daily/monthly subsurface drainage and daily WTD. DRAINMOD 5.1 was validated over the period of March 2002 to December 2003 and January to September 2006 for drain outflows, and from July to October 2006 for WTD according to availability of data (Table 3.6). Year 2006 was a wet year with 1050.15 mm of precipitation. It was found that DRAINMOD 5.1 tended to simulate a shallower WTD for 2006 (Fig. 3.7), which might be due to the lesser amount of evapotranspiration simulated under wet conditions. The model accurately simulated the pattern of water table fluctuations over the validation period resulting in a high R^2 (0.93). The other parameters show that overall the model simulated WTDs reasonably well.

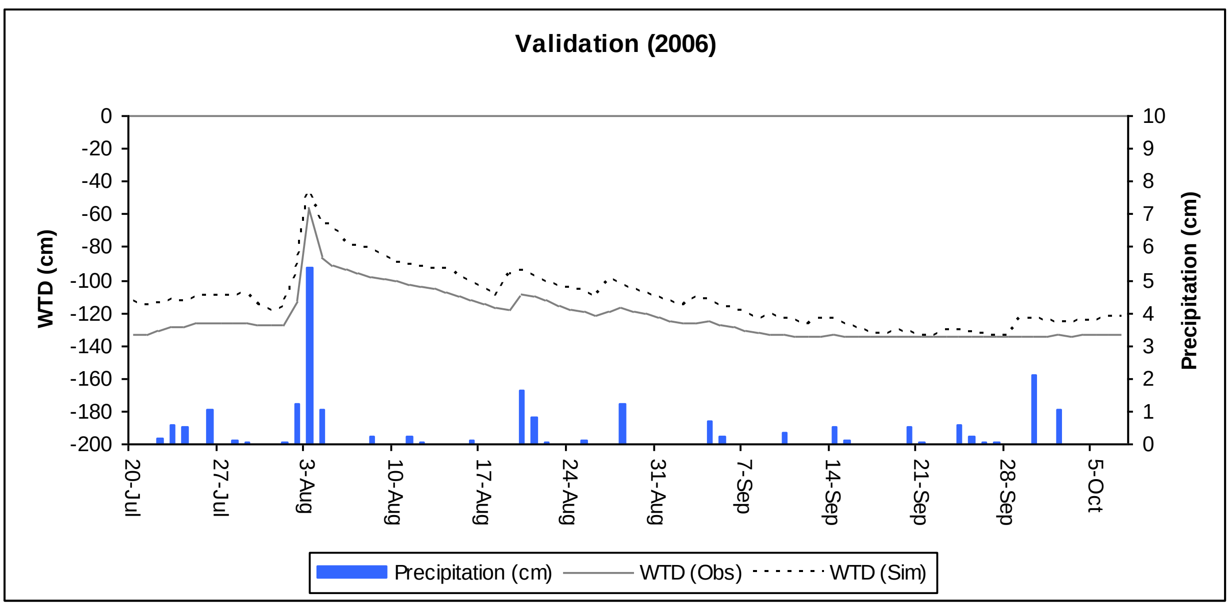

Figure 3.7. Observed and DRAINMOD predicted WTDs for 2006.

The accuracy and reliability of DRAINMOD's prediction of subsurface drainage was also evaluated by comparing the observed and simulated subsurface drainage flow for 2002, 2003, and 2006 (Figs. 3.8 and 3.9; Table 3.7). Although some under- and over-estimations occurred for certain events, most simulated subsurface flow peaks matched corresponding observed values well, both in terms of timing and quantity, especially in the cold months. In the validation period, simulated drainage rates deviated most from observed values during June 2002 and October 2003. This could be due to heavier rainfall during these months compared to the calibration years. The cumulative subsurface flow over the entire period matched very well (Figs. 3.8 and 3.9). Thus, it can be concluded that the model performed satisfactorily over the validation period, including the winter months.

Table 3.7. Comparison of simulated and observed WTDs and drain outflows for calibration/ validation years.

Statistical Parameter	Calibration period		Validation period	
WTD	2004	2005		2006
AAD (cm)	8.97	6.34		10.87
AD (cm)	2.51	3.85		10.87
E	0.77	0.74		0.31
R^2	0.78	0.81		0.93
RRMSE	-0.29	0.07		0.1
Regression parameters				
Slope	0.72*	0.9		1.16*
Intercept (cm)	13.9*	7.18*		-30.5*
Daily drain outflow				
	2004-2005		2002-2003	2006
AAD (mm)	0.58		0.77	0.1
AD (mm)	0.1		-0.06	0.01
E	0.72		0.4	0.87
R^2	0.73		0.48	0.9
RRMSE	1.14		1.56	0.8
Regression parameters				
Slope	0.79*		0.67*	0.74*
Intercept (mm)	0.14*		0.45*	0.04*
Monthly drain flow	2004-2005		2002-2003	2006
AAD (mm)	6.35		8.55	1.3
AD (mm)	3		0.62	0.2
E	0.95		0.82	0.86
R^2	0.95		0.84	0.95
RRMSE	0.22		0.31	0.3
Regression parameters				
Slope	0.96		0.96	0.67*
Intercept (mm)	-1.52		0.72	1.58*

* Slope and intercept are significantly different ($P \leq 0.05$) from their idea values of 1 and 0, respectively.

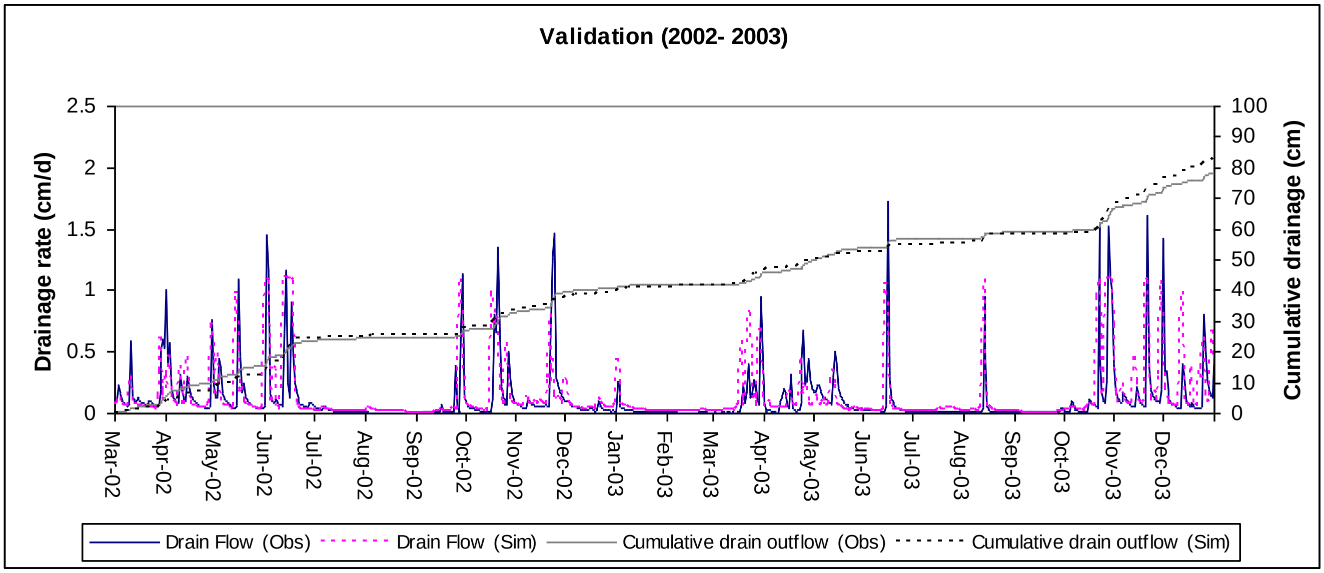

Figure 3.8. Comparison of subsurface flow in daily observed and simulated values for 2002-2003.

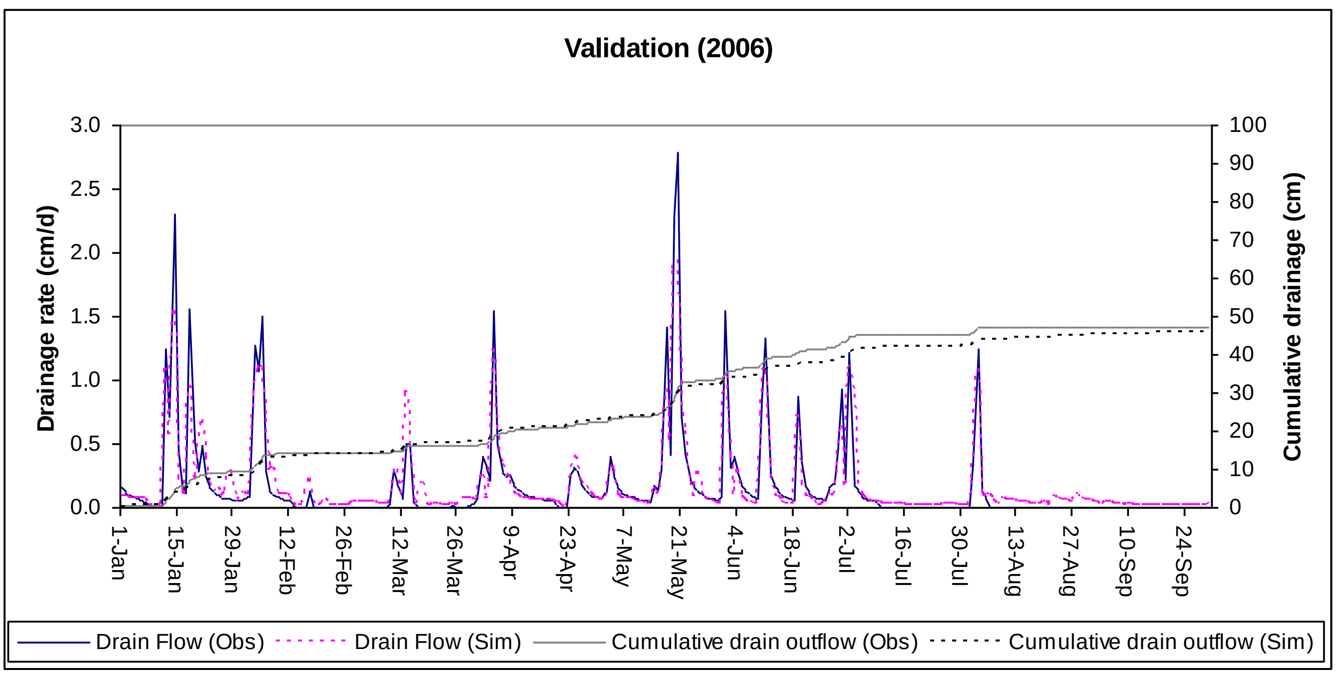

Figure 3.9. Comparison of subsurface flow in daily observed and simulated values for 2006.

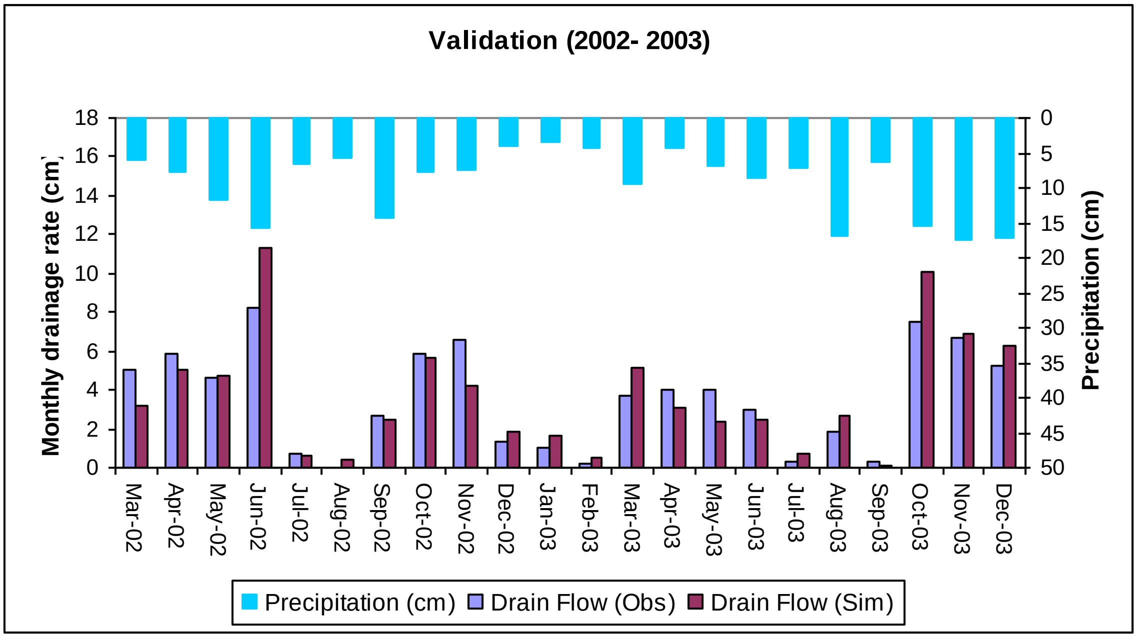

Figure 3.10. Simulated vs. observed monthly drainage outflows for 2002-2003

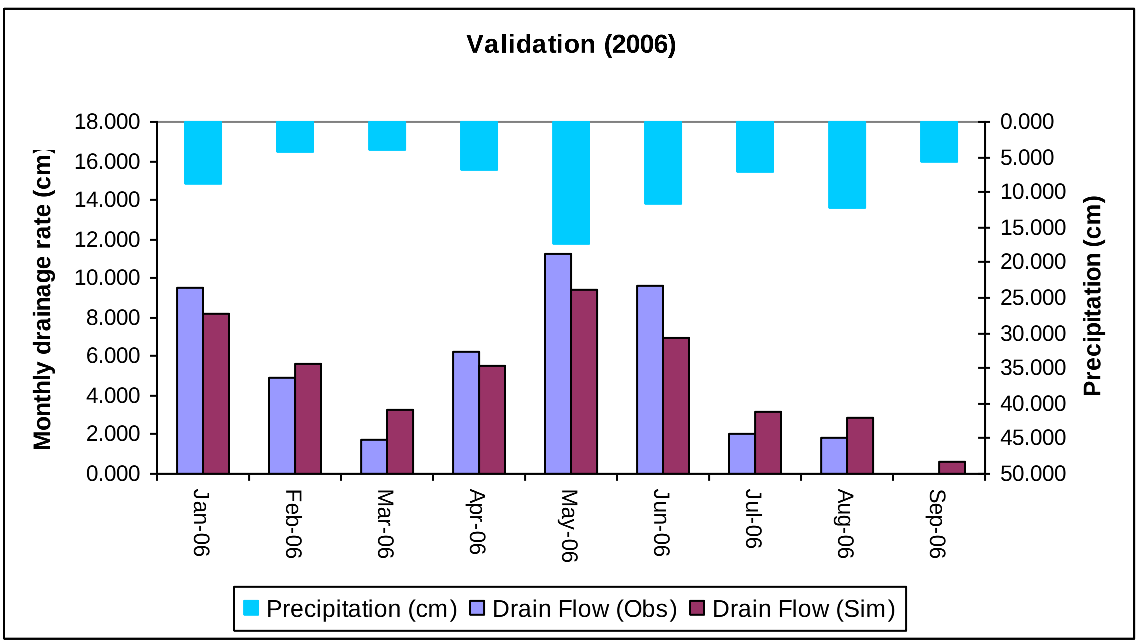

Figure 3.11. Simulated vs. observed monthly drainage outflows for 2006

3.4.Conclusions

DRAINMOD 5.1, a field scale water balance simulation model, was employed to predict WTD and subsurface drain outflows from an agricultural field in southern Quebec. Version 5.1 includes algorithms for predicting soil freeze/thaw and snowmelt components so simulations under cold conditions can be conducted. The model predicted daily WTD and drainage outflows in good agreement with the measured values. The R^2 values were in the range of 0.48-0.95 and 0.78-0.93 for drainage outflow and WTD, respectively. DRAINMOD 5.1 generally performed well in simulating the pattern of daily drain out flows and the peak flows in all seasons. The model also gave good results for drain outflow in cold months owing to its ability to address frozen soil conditions. For WTD, the coefficient of efficiency, E, a statistical index used to judge model performance, was 0.77 and 0.74 for calibration years (2004 - 2005) and 0.31 for the validation year (2006). For the subsurface flow results, the E values were 0.72 for calibration years and 0.48 for validation years (2002 - 2003). These values are indicative of an acceptable model performance in a colder region of North America.

CONNECTING TEXT TO CHAPTER 4

This chapter addresses the first objective of the thesis. In this paper, we evaluated the performance of DRAINMOD model for simulation of nitrogen transport in unsaturated zone for a tile-drained research site, under cold climate condition for different water management systems (sub-irrigation and free drainage). A comparative evaluation of field monitoring and simulation results are presented for drain outflow, water table depths and nitrate loads in subsurface drainage (under both sub-irrigation and free drainage treatments).

This chapter is a manuscript published in the Transactions of the American Society of Agricultural Engineers in 2010. The manuscript is co-authored by my supervisors Drs. S. O. Prasher and C.A. Madramootoo; Dr. A. Madani, Professor in the Engineering Department of Nova Scotia Agriculture College; and Mr. Peter Enright, professional associate and director of the Farm Management and Technology Program at McGill University. 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 4: Modeling Water Table Depth, Drain Outflow, and Nitrogen Losses in Cold Climate Using DRAINMOD 5.1

Shadi Dayyani , Chandra A. Madramootoo , Shiv O. Prasher , Ali Madani, and Peter Enright

Abstract:

The performance of the DRAINMOD 5.1 model was tested for conditions which included freezing and thawing, prevailing at a 4.2 ha field research facility located at St. Emmanuel, Quebec. Using 2 years (1998, 1999) of data collected from the site, the model's ability to predict water table depth (WTD), drain outflow, and nitrate (NO_3^--N) loads in drain water was tested. The site was arranged in a split-plot design, with two N-fertilizer rates (120 and 200 kg ha^{-1} - main plots), factorially combined with two modes of water table management [subirrigation (SI) at a WTD of 0.6 m vs. free drainage (FD) at a drain depth of 1.0 m - subplots]. The model was calibrated using water table depth and subsurface flow data from 1998, and validated with 1999 data. The model's accuracy was evaluated using the coefficient of determination (R^2) and modeling efficiency (E), and other statistical parameters. DRAINMOD 5.1 performed well at simulating the number and timing of drainage events in both snowmelt and later–season periods. The model underestimated annual drain outflow under free drainage and sub-irrigation by 12 mm and 20 mm, respectively, in both years. The model simulated the pattern of water table fluctuations fairly well, the R^2 values ranged from 0.81 to 0.91, indicating good model fit. The model performed well in predicting total NO_3^--N loads in subsurface flow, even though there was a tendency to underestimate loads under both free drainage and sub-irrigation treatments. The model predicted monthly NO_3^--N losses with the R^2 and E values of greater than 0.9 under both free drainage and sub-irrigation.

Key Terms: DRAINMOD 5.1; Subsurface Drainage; Freezing-thawing; Water table management; Cold Climate; Nitrogen

4.1. Introduction

Across North America, particularly in humid regions with fine-textured soils, subsurface drainage systems have been used effectively to enhance crop production by alleviating excess-water stress, caused by shallow water tables. Approximately 2 million ha of cropland in the provinces of Ontario and Quebec are subsurface-drained, mostly for corn and soybean production (Helwig et al., 2002). However, while subsurface drainage removes excess water and improves crop productivity, it increases the leaching of agro-chemicals from agricultural fields.

In Quebec, nitrogen (N) contamination of watercourses and lakes is largely attributed to non-point source pollution from agricultural fields. Surface runoff and tile drainage are the two principal pathways by which nutrients and sediment are transported from agricultural lands to watercourses. Nitrate (NO_3^-) is particularly susceptible to leaching due to its negative charge, and high solubility in water. Worldwide, annual agricultural runoff contributes about 4.65 million tons of N to off-farm aquatic ecosystems, primarily in the form of nitrate (Duttweiler and Nicholson, 1983). Drainage water (NO_3^--N) concentrations as high as 40 mg L^{-1} have been observed in eastern Canada (Milburn et al., 1990; Madramootoo et al., 1999). Water table management (WTM) has been identified as a best management practice to reduce NO_3^-N losses from subsurface drainage systems. This occurs through two mechanisms: (i) reduction of drain outflow volume, and (ii) promotion of anaerobic conditions needed for denitrification, which effectively reduce dissolved NO_3^--N levels. This technique has been adopted on farms in Quebec and other Canadian provinces.

The understanding of nitrogen dynamics under Quebec's cold climate is limited (Gollamudi, 2006). Finding an effective solution to N pollution necessitates in-depth, long-term, field-scale monitoring to assess the effects of water and agronomic management practices on nutrient transport. Collecting long-term hydrologic and water quality data for a range of climatic conditions is not only a time-consuming process but its applicability in real-time is quite difficult. Thus, the application of hydrological and water quality simulation models, validated with field data, can be cost-effective and time-efficient.

Although models have been extensively used in different parts of the world to evaluate the hydrology of artificially drained lands, less is known in the colder regions, where soil freezing and snowmelt routinely occur. The climate of the St. Lawrence Lowlands of Eastern Canada is generally characterized by a dry summer with a cool and wet spring and fall, and a cold winter, which sees freezing, thawing, and snowmelt. It is known that frozen soil and snowmelt have significant effects on field hydrology. Frozen surface layers reduce infiltration and, as a result, surface runoff from rainfall or snowmelt increases (Johnsson and Lundin, 1991; Zuzel et al., 1982). The snowmelt process and daily freeze–thaw cycles can have a dominant effect on field hydrology during the winter and early spring periods (Kuz'min, 1963; 1972). Currently, several computer simulation models are available that simulate surface and subsurface flows, and chemical transport through the soil profile [SWAT (Arnold et al., 1998), ADAPT (Alexander, 1988), and DRAINMOD (Skaggs, 1999)]. However, few such models can effectively simulate the dynamics of heat and water flow in soils subjected to freezing and thawing cycles (Stahli et al., 1999). Models that ignore the effect of soil freezing and snow accumulation tend to over-predict flow during the winter months and under-predict flow during early spring.

Although SWAT can simulate surface and subsurface flows it is not capable of evaluating the impacts of water management practices (sub-irrigation and controlled drainage) on drain outflow and water table fluctuations. ADAPT model is quite complex and requires substantially more effort for calibration. Despite the complexity ADAPT did not produce a better result than DRAINMOD (Sands et al., 2003). DRAINMOD model (Skaggs 1980; Luo et al., 2001) includes freezing, thawing, and snowmelt components, and is thus capable of simulating drainage patterns more precisely in cold climates considering the drainage system design. DRAINMOD has been used and tested worldwide and proven to be a reliable model in simulating subsurface flows coming out of poorly drained, high water table soils.

DRAINMOD 5.1 is linked to a one-dimensional nitrogen cycling module (Breve et al. 1992). This module uses the water balances and fluxes from DRAINMOD as inputs to its one-dimensional advective-dispersive-reactive equation for nitrogen fate and transport. The model considers a simplified version of the nitrogen cycle using nitrate as the main pool. The nitrogen balance considers fertilizer dissolution, mineralization of organic nitrogen, denitrification, and plant uptake using first order rate equations. At each daily time step, first order rate equations are used to balance transformations to and from the nitrate pool. The DRAINMOD simulated hydrology provides the necessary soil water contents and fluxes for simulating the nitrate transport. The nitrogen module uses the daily outputs from DRAINMOD as the hydrology inputs. Crop potential yield, nitrogen content of the crop, reaction rate coefficients for the nitrogen transformations, and nitrogen fertilizer application amounts and dates are specified.

DRAINMOD 5.1 calculates a daily mean soil temperature profile, incorporates the effect of ice formation on soil hydraulic conductivity and infiltration, simulates water flow from the precipitation, and keeps track of snow depth. Recorded precipitation is separated as rain or snow, according to whether the daily mean air temperature is above or below a rain/snow threshold temperature. Snow accumulation on the ground is simulated until air temperatures rise above a snowmelt threshold temperature. Soil surface temperature is recalculated when snow cover exists. Daily snowmelt water is added to rainfall, which may infiltrate or run off, depending on the soil's frozen state. In addition, infiltration is controlled by a critical ice value, above which no infiltration takes place and snowmelt or precipitation leaves the field as runoff (Luo et al., 2000; Christopher and Cooke, 2003).

The hydrology component of the model was field-tested in North Carolina (Youssef et al., 2003). Their result shows that DRAINMOD 5.1 can reliably predict drain outflows and water table fluctuations. Wang et al. (2006a) have also used it to simulate nitrogen movement in cold regions. Their results show that DRAINMOD 5.1 performed better than the original version for the winter season. They calibrated the model based on monthly drain outflow values, and found the performance of the model satisfactory. However, they neither used daily outflow values nor water table depths (WTD) for calibration of the model. Luo et al., (2001) tested this version of model with both water table depth and drain flow data for a site in Turkey. Also they tested the model for two sites in Minnesota and Nova Scotia for drain outflow. The older version of the model, DRAINMOD 5.0, which does not have the freezing thawing component, has been used by Helwig et al. (2002) to simulate water table depths, drain outflows, and nitrogen losses in drainage waters in southwestern Quebec. The model was evaluated for the growing season only. Zwierschke et al. (2002) also validated the capability of DRAINMOD 5.1 to simulate effect of water table management practices on nitrate and nitrogen in drainage water. The results, only presented for water table heights, shows that the model adequately predicted the water table heights under conventional and combined (controlled/sub-irrigated) drainage at Piketon site, Ohio.

The goal of this study was to evaluate the capability of DRAINMOD 5.1 to simulate WTD, subsurface drain outflow and nitrogen transport throughout the year in the Quebec region. The specific objectives of this study were to calibrate and validate DRAINMOD 5.1 and evaluate its performance in simulating WTD, subsurface flow, and nitrogen transport from water-table managed agricultural fields on a daily basis under seasonally frozen soil conditions.

4.2. Materials and Methods

4.2.1. Site Description

The research was conducted on a 4.2 ha privately-owned experimental site, located at St-Emmanuel near Côteau-du-Lac, Quebec, approximately 30 km southwest of the Macdonald Campus of McGill University. Based on wells dug in the region and measurements of soil hydraulic conductivity, the impermeable layer was estimated to be 5 m deep. The site was under pasture prior to 1991, and subsequently under mono-cropped corn (Zea mays L.). Site design and instrumentation are described fully by Tait et al. (1995). Although the topsoil (0–0.25 m) is a well-drained Soulanges sandy loam, clay layers - sandy clay loam (0.25–0.55 m) and clay (0.55–1.0 m) - deeper in the soil profile, impede natural drainage (Elmi et al., 2004). Selected soil physical parameters were determined during a 1992 site survey (Mousavizadeh, 1992) and are shown in Table 4.1.

Table 4.1. Soil physical properties

Depth (cm)	0-25	25-50	50-100
% Clay	10	20	39
% Sand	56	58	32
Textural class	Sandy loam	Sandy clay loam	Clay loam
Bulk density (mg m^{-3})	1.63	1.6	1.49
Saturated hydraulic conductivity, K_{sat} (cm hr^{-1})	1.88	1.46	0.54

Surface topography was generally flat with a mean slope of less than 0.5%. Lateral subsurface drains, 76-mm-diameter, 15 m apart on a 0.3% slope, were installed at a maximum depth of 1.0 m. There were three 0.9 ha blocks, each mono-cropped to corn, containing eight adjacent treatment plots (15 m × 75 m). Experimental plots were under a conventional tillage system, the common practice in the region. A 30-m wide strip of undrained land separated the blocks. Blocks were arranged from east to west, with block A at the eastern end, bordered to the east by a 15-m strip of undrained land, followed by a 2.5 m deep × 3.0 m wide surface drain, which collected runoff from the surrounding agricultural land. The plots were separated by 6-mil (0.6 mm) polyethylene sheeting, installed to a depth of 1.5 m, to minimize seepage and chemical flow between plots. Drain flow from each pipe was directed to tipping buckets in heated buildings, allowing continuous drainage discharge measurements (Tait et al., 1995), and collection of water samples for flow weighted NO_3^--N determinations. The field was seeded to grain corn (Pioneer hybrid 3905) on May 8, 1998 and May 4, 1999, at a planting density of 75,000 plants ha^{-1} and a 0.75-m row spacing (Helwig et al., 2002).

Field layout and treatment arrangements are detailed in Elmi et al. (2000). Briefly, the site was arranged in a split plot design, with two N-fertilizer rates (120 and 200 kg ha^{-1}, N120 and N200), factorially combined with two modes of WTM: sub-irrigation at a WTD of 0.6 m (SI) vs. free drainage at a drain depth of 1.0 m (FD). In addition, adjacent to each WTM treatment were buffer plots with the same drainage treatment (Fig. 4.1).

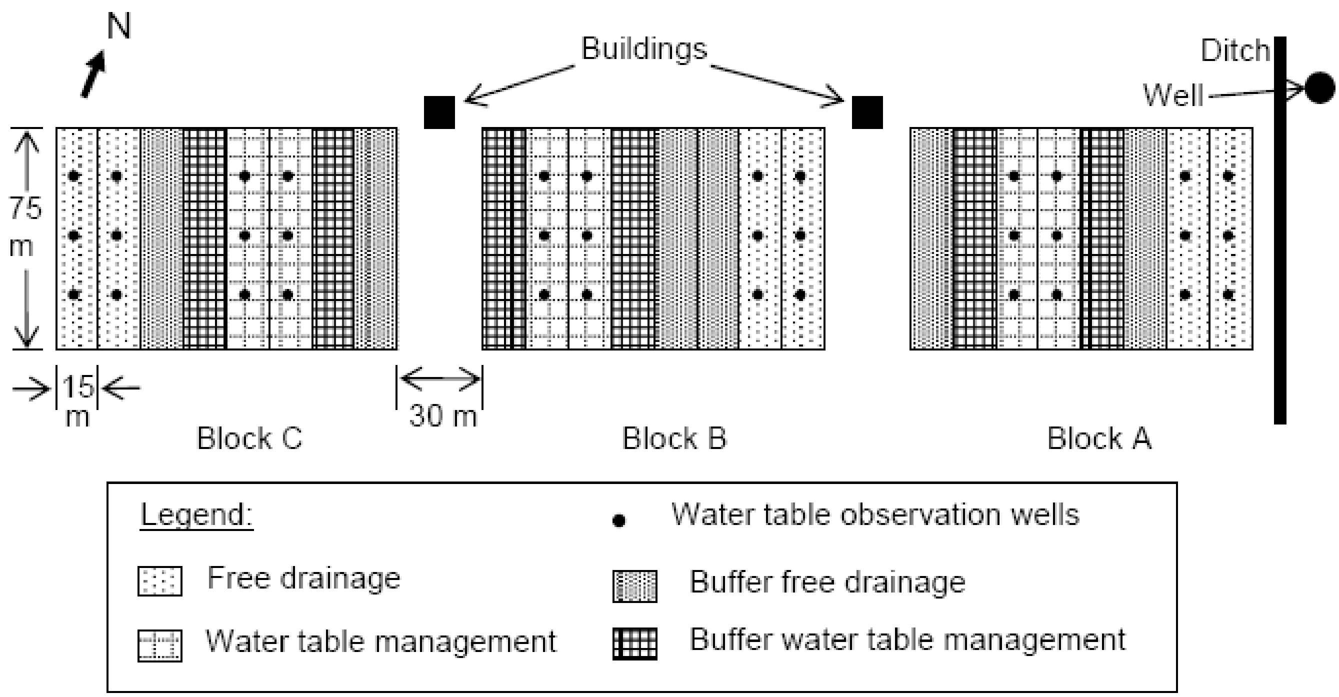

Figure 4.1. Field layout, adapted from (Hebraud 2006)

Sub-irrigation was implemented in the last week of May and shut off in the last week of September. Nitrogen fertilizer was applied in a split dose: 23 kg N ha^{-1} banded as ammonium phosphate (18-46-0) at seeding, and 97 or 177 kg N ha-1 broadcast as ammonium nitrate (34-0-0) one month after planting (June 8 1998;

June 10, 1999), resulting in rates of 120 kg N ha^{-1} (N120) or 200 kg N ha^{-1} (N200), respectively. All buffer plots received 120 kg N ha^{-1}. A more detailed description of the fieldwork and plot descriptions is presented in Madramootoo et al. (1999) and Elmi et al. (2000).

4.2.2. Measurements

Water table depths were monitored three times a week in each plot. Observation wells (perforated, 12-mm-diameter polyethylene pipes with a geotextile sleeve) were installed to a depth of 1.4 m on the north and south sides of each plot. The pipes were installed immediately after planting (mid-May) and were removed in mid-September when the SI plots were returned to FD to facilitate field operations. A water sensor was used to monitor WTD. For each plot, the mean WTD was calculated by averaging the values from two locations (Helwig et al., 2002).

Drain flow was measured using tipping buckets, located at the outlet of each subsurface drain. Water samples were collected in plastic containers (20 L), connected to each pipe, using a water sampling valve, located just upstream from the tipping buckets. Samples were stored in 20 L bottles, forming composite samples, from which 20-mL sub-samples were subsequently extracted and analyzed for NO_3^--N using the modified colorimetric method, recommended by Keeney and Nelson (1982). The total NO_3^--N losses from tile drains were calculated by multiplying the NO_3^--N concentration in drain flow with the drainage volume for the period since the last collection of samples. In general, water samples were analyzed every two weeks during dry periods and at least twice a week during wet periods (Helwig et al., 2002). In this study, the model is calibrated and validated using 1998 and 1999, respectively. This is the only period that the whole year flow data was available for the experimental site.

4.2.3. Model Inputs

4.2.3.1. Water Flow Parameters

Model inputs include soil properties, a drainage volume – WTD relationship, upward flux, infiltration parameters, crop data, drainage system parameters, surface drainage, daily max/min air temperature and hourly precipitation. To facilitate the input of soils data, DRAINMOD 5.1 contains a soil utility program. Soil-water characteristic data, rooting depth and saturated hydraulic conductivities are required for each layer of the soil profile, which were taken from Mousavizadeh (1992). The soil moisture characteristic curve for each layer was measured using a pressure plate apparatus (Mousavizadeh, 1992). From this information, DRAINMOD 5.1 calculated the relationships between WTD and drained volume and between WTD and maximum steady upward flux.

The Green-Ampt equation is used to simulate infiltration. The infiltration parameters are calculated by the model, as a function of water table depth, using the soil moisture retention curve of the topsoil. Precipitation and air temperature data were obtained from the Côteau du Lac, Environment Canada Weather Station, located about 500 m from the experimental site. Table 4.2 shows monthly precipitation measured at the site at this location.

Using the DRAINMOD weather utility, the observed daily precipitation was uniformly distributed over 6h to obtain the hourly precipitation. The model gives user an option of using observed ET data or applying daily maximum and minimum temperatures for the calculation of ET using the Thornthwaite equation. In this research, Thornthwaite ET was calculated by the model, based on latitude of 45o 18’ and mean heat index. An average heat index of 40 is computed for the study area, using 1998-1999 data.

In order to account for the freezing and thawing phenomenon, additional inputs were required, including two constants (TKA and TKB) relating soil thermal conductivity to soil water content, the rain/snow-dividing temperature, the snowmelt threshold temperature and the degree–day coefficient for snowmelt, the critical ice content above which infiltration stops, the initial soil temperature distribution and a threshold temperature as the lower boundary condition, a phase lag for daily air temperature sine wave, the initial snow depth and density, and soil freezing characteristics which indicate the relationship between unfrozen water content and soil temperature. In this study, it was noted that the model is not sensitive to critical ice content, and the difference in its value did not affect the simulation noticeably. Therefore, the critical ice content was set to 0.2, based on published literature (Willis et al., 1960; Luo et al., 2000). Values of other parameters calculated for the study area are reported in Table 4.4.

Table 4.2. Monthly precipitation (mm) from the Environment Canada, Coteau-du-Lac Weather Station

	1998	1999	Mean 1961-1990
January	49.5	107.7	
February	43.2	23.5	
March	78.1	69.4	
April	45.4	25	73.5
May	69.6	53.2	68.3
June	229.8	94.6	82.5
July	128.4	104.8	85.6
August	78	60.2	100.3
September	127	169.2	86.5
October	86.8	106.8	72.5
November	86.2	61.4	92.1
December	49.6	67.2	
Total	1071.6	943	

4.2.3.2. Nitrogen Movement and Fate Parameters

Nitrogen-related parameters, required in DRAINMOD 5.1, include standard rate coefficients for denitrification (K_{den}) and net mineralization (K_{min}), soil dispersivity (λ), and the nitrogen content in rain and crops. Brevé et al. (1997) showed that the NO_3^--N loss in the subsurface drains is most sensitive to the standard rate coefficients for denitrification and mineralization, mildly sensitive to N content in the crop, and practically insensitive to dispersivity and NO_3^--N content in rainfall. Dates of seeding and fertilizer application are shown below in Table 4.3. Elmi et al. (2000) measured denitrification on a seasonal basis for the same site. By knowing these values it was possible to back-calculate K_{den}. Values of 0.5 × 10-5 day-1 and 1.08 day^{-1} were used for the coefficient of mineralization, K_{min}, and coefficient of denitrification, K_{den}, respectively.

Table 4.3. Agronomic Practices (N200= 200 kg/ha and N120=120 kg/ha)

Event	1998	Amount ($kg\ ha^{-1}$)	1999	Amount ($kg\ ha^{-1}$)
Seeding	May 8^{th}	-	May 4^{th}	-
N_{200}: First application	May 8^{th}	23	May 4^{th}	23
N_{200}: Second application	June 8^{th}	177	June 10^{th}	177
N_{120}: First application	May 8^{th}	23	May 4^{th}	23
N_{120}: Second application	June 8^{th}	97	June 10^{th}	97
Drains opened for harvesting	Sept. 28^{th}	-	Sept. 17^{th}	-
Field Harvested	Oct. 20^{th}	-	Oct. 22^{nd}	-

In DRAINMOD 5.1, denitrification is approximated by a first-order equation as:

$$N_{den} = K_{den} \times F_{den} \times F_{temp} \times \theta \times [NO_3^{-}\text{-N}] \qquad 4.1$$

$$N_{den} = 0 \quad \text{for } \theta < \theta_{den} \qquad 4.2$$

where, N_{den} is the denitrification rate [$M\ L^{-3}\ T^{-1}$], K_{den} is the denitrification rate coefficient [T-1], F_{den} and F_{temp} are dimensionless soil water content, and temperature adjustment factors, [NO_3^{-}-N] is the soil profile NO_3^{-}-N content [$M\ L^{-3}$], θ is the volumetric soil moisture content [$L^3\ L^{-3}$], and θ_{den} is the threshold soil moisture content below which denitrification does not occur [$L^3\ L^{-3}$]. Values for model input parameters, as used in this study, are listed in Table 4.4.

Table 4.4. DRAINMOD 5.1 input parameters

Parameter	Value
Drainage system	
Drain depth (m)	1
Drain spacing (m)	15
Effective radius of drains (cm)	1.5
Actual distance to impermeable layer (m)	5
Drainage coefficient (cm/day)	1.2
Maximum surface storage (cm)	1.5
Kirkham's depth for flow to drains (cm)	1
Lateral saturated hydraulic conductivity of 3 layers (cm hr^{-1})	1.91, 1.45, 0.54
Vertical conductivity of restrictive layer (mm hr^{-1})	0.035
Soil temperature	
Thermal conductivity function coefficient (W/m^{o}C)	a= 0.553, b= 1.963
Phase lag for daily air temperature sine wave (hr)	9
Rain/snow dividing temperature (^{o}C)	0 (Luo et al., 2001; Wang et al., 2006)
Snowmelt base temperature (^{o}C)	2 (Wang et al., 2006)
Snowmelt coefficient (mm/°C day)	5 (Kuz'min, 1961)
Critical ice content (cm^3/cm^3)	0.2 (Luo et al., 2000)
Chemical characteristics (Helwig et al., 2002)	
Net mineralization rate (1/d)	0.000025
Denitrification rate (1/d)	1.08 (Elmi et al., 2000)
Soil dispersivity (cm)	5
Fertilizer application (kg/ha)	120 or 200
Initial NO_3^- concentration in the soil	10 mg/l at 1 m
Nitrate concentration of rain (mg/l)	0.5
Nitrogen in yield (%)	1.5
Initial organic N concentration (mg/l)	2
ET monthly factors	
Jan= 1, Feb= 1, March= 1, April= 0.8, May= 0.6, June= 0.8, July= 0.8, Aug= 0.8, Sept= 1, Oct= 1, Nov= 1, Dec= 0.6	

4.3.Methods of Evaluation

The model was evaluated using both graphical and statistical methods. In order to validate the model, field measurements were divided in two portions. The 1998 data were used to calibrate WTD and drain outflow, whereas the 1999 data was used to validate the model. DRAINMOD was manually calibrated by comparing observed and simulated WTD and drainage volumes. Calibration parameters were selected based on previously cited literature and adjusted on a trial-and-error basis using daily drain flow and WTD data. Based on the literature, DRAINMOD has been calibrated using different parameters, such as: soil hydraulic parameters (Singh et al. 2006); effective lateral hydraulic conductivity, soil surface storage, and crop rooting depth (Zhao et al. 2000); monthly ET adjustment factors (Skaggs 2001; He et al. 2002; Jin and Sands 2003; Wang et al. 2006b); drainage coefficient, maximum surface storage, saturated soil water content, residual soil water content, lateral saturated hydraulic conductivities in soil layers, and the minimum air volume required to work the land (Haan and Skaggs 2003); and vertical hydraulic conductivity of the restrictive layer and the lateral hydraulic conductivity of the bottom soil layer (Wang et al. 2006a). In this study, DRAINMOD was calibrated based on lateral saturated hydraulic conductivity values of the three soil layers, soil surface storage, and monthly ET factors. Field measurements of hydraulic conductivity showed variations from 0.5 to 1.9 cm h-1 (Table 4.1). Accordingly, this range was used in the calibration process. Average depth of surface depression storage was around 25 mm in the field. Generally, the range for sandy loam soil is 10 to 25 mm (Skaggs 1980). Although, DRAINMOD calculates the ET based on local temperature, using Thornthwaite method, it is suggested to use monthly ET adjustment factors (varied here from 0.1 to 2) to refine the values and model performance (Fouss et al. 1987; Skaggs 2001). The calibrated values are reported in Table 4.4.

Model results were most sensitive, in order, to lateral hydraulic conductivity of the soil layers, soil surface storage, and monthly ET factors. Representative values for the whole field could not be measured for these calibrated parameters. The initial lateral saturated conductivity values for different soil layers were set at twice the vertical saturated conductivity as suggested by Skaggs (1980). The DRAINMOD 5.1 requires inputs for the initial soil temperature profile, upper boundary condition and a base temperature as the lower boundary condition. The appropriate value for the upper boundary condition is the soil surface temperature. Since a long record of measured soil surface temperatures is not usually available for most applications, air temperature was used instead (Luo et al., 2000). The lower boundary was assumed to be a constant soil temperature, which can be approximated as the long term average air temperature (Penrod et al. 1958). The calibration parameters were adjusted, and the time series of simulated and observed WTD and drain outflows were plotted. Several trial and error runs were performed by varying various input parameters. The results for both WTD and drain outflows were plotted and the quality of simulation was initially evaluated by examining the plots visually for a match between the observed and predicted values. This evaluation looked at the proximity between the simulated and observed values and the timing of peak flows. For the best simulation thus determined, in terms of both WTD and drain outflow, further assessment was made by computing various statistical parameters (Table 4.5).

Once the hydrologic simulations were completed, a set of nitrogen simulations were conducted, using 1998 data, to calibrate the nitrogen component of the model. Nitrogen simulations were validated using 1999 data. The simulated monthly total NO_3^--N losses via subsurface drainage were compared with observed data. An objective evaluation was performed by calculating the more commonly used statistical parameters of average absolute deviation (AAD) (Salazar et al. 2009), the coefficient of determination (R^2) (Singh et al. 2001; El-Sadek et al. 2003b; Fernandez et al. 2006), and coefficient of efficiency (E) (Amatya et al. 1997; Fernandez et al. 2006; Salazar et al. 2009). The AAD (also referred to as mean absolute error, MAE) value shows overall magnitude of deviation of predicted values from the observed ones and is given by (Janssen and Heuberger, 1995):

$$\mathrm{AAD} = \frac{\sum_{i=1}^{n} \left| \mathrm{O_i} - \mathrm{P_i} \right|}{\mathrm{n}} \tag{4.3}$$

The coefficient of determination, R^2 (also known as the goodness of fit) which describes the degree of association between observed and predicted values (Aitken, 1973) is defined as:

$$\mathrm{R}^2 = \left(\sum_{i=1}^{n} \left(\mathrm{O_i} - \mathrm{O_{avg}}\right)\left(\mathrm{P_i} - \mathrm{P_{avg}}\right) \right)^2 \Big/ \sum_{i=1}^{n} \left(\mathrm{O_i} - \mathrm{O_{avg}}\right)^2 \sum_{i=1}^{n} \left(\mathrm{P_i} - \mathrm{P_{avg}}\right)^2 \tag{4.4}$$

where, O_i is the i^{th} observed value, Pi is the i^{th} simulated value, and O_{avg} is the mean of observed values, for a total number of events 'n', which is the total number of days.

The modeling efficiency, also known as Nash–Sutcliffe coefficient, relates the goodness-of-fit of the model to the variance of the measurement data and thus describes the modeling success with respect to the mean of the observations. The coefficient of efficiency (E) has been widely used to evaluate the performance of hydrologic models. The value of 1 represents the perfect match. Nash and Sutcliffe (1970) defined the coefficient of efficiency, or modeling efficiency (EF) as:

$$E = 1 - \frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i-1}^{n} (O_i - O_{avg})^2} \tag{4.5}$$

For nitrogen simulation the average deviation (A.D.) parameter was also calculated to be able to compare the results with the previous studies done at the same site. This parameter indicates whether the model has over - or under - predicted the values. It is defined as (James and Burges, 1982):

$$\mathrm{AD} = \frac{\sum_{i=1}^{n} (\mathrm{O_i} - \mathrm{P_i})}{\mathrm{n}} \tag{4.6}$$

4.4. Results and Discussion

4.4.1. Hydrologic Simulation

4.4.1.1. Simulation of WTD

Observed and simulated water table fluctuated throughout the growing seasons, responding mainly to rainfall events. Despite all efforts to help maintain water table at the desired depth, it was still difficult to sustain a constant depth of 0.6 m due to deep seepage. However, it is worth emphasizing that, on average, depths of water table were consistently higher with SI plots as compared to FD for both years.

A graphical comparison of FD and SI treatments during 1998 (calibration year), shows a good agreement between simulated and observed pattern of daily WTD fluctuations (Fig. 4.2). Total rainfall from May to October in 1998 was 29% above normal (Table 4.2). About 34% and 20% of the total seasonal rainfall in 1998 occurred in June and July, respectively. These two months of high rainfall resulted in periods of shallowest water table depths, particularly in plots under SI treatment (Fig. 4.2), and produced the greatest volume of drainage outflows, especially in FD plots (Fig. 4.3). It is notable that the rainfall events during the August (Fig. 4.3), raised the water table in the SI treatment to as shallow as 0.1 m below the soil surface (Fig. 4.2), but did not cause a significant increase in drain discharge (Fig. 4.3). A possible explanation for this observation was that a heavy rainfall event preceded by dry conditions may not cause significant water percolation to the subsurface drains. The R^2 values were 0.91 and 0.85 for FD and SI, respectively (Table 5). These values suggest that there was a good agreement between the observed and simulated WTDs. The corresponding AAD values were 8.21 cm and 10.24 cm, indicating that discrepancies between the observed and simulated WTD were quite low. Helwig et al., (2002) had reported similar values of 19.2 cm (FD) and 25.4 cm (SI) for the same site, over the same period using DRAINMOD 5.0, while others have calculated values ranging from 4 to 19.4 cm for various sites (Chang et al., 1983; Mackenzie and Prasher, 1988; Workman and Skaggs, 1989). The E values (0.86 and 0.83) are also indicative of good calibration (Table 4.5).

The model was validated by running the calibrated model with field data of 1999. In this year, while total May to October rainfall was 13% higher than the normal, May and August received 23% and 35% lower rainfall than the normal. The first week of July, just three weeks after the N application, received frequent precipitation resulting in a flush of drain outflow from SI plots (Fig. 4.3) and the shallowest water depth (Fig. 4.2) of the growing season. Water table under FD almost remained deeper than 1.0 m, whereas under SI, water table was on average 0.8 m below the soil surface. On average, predicted water table depths were within 5.7 cm for FD and 9.9 cm for SI of observed values, indicating good results (AAD, Table 4.5). Luo et al., (2001) calculated AAD values ranging from 10.5 to 14.9 cm for an experimental site in Nova Scotia. The E for FD was slightly low (0.69) due to the fact that the variation in the observed water table was small. Overall, there was a good agreement between observed and simulated WTD values (Fig. 4.2 and Table 4.5): the R^2 (0.84 FD and 0.81 SI), and E (0.69 FD and 0.73 SI).

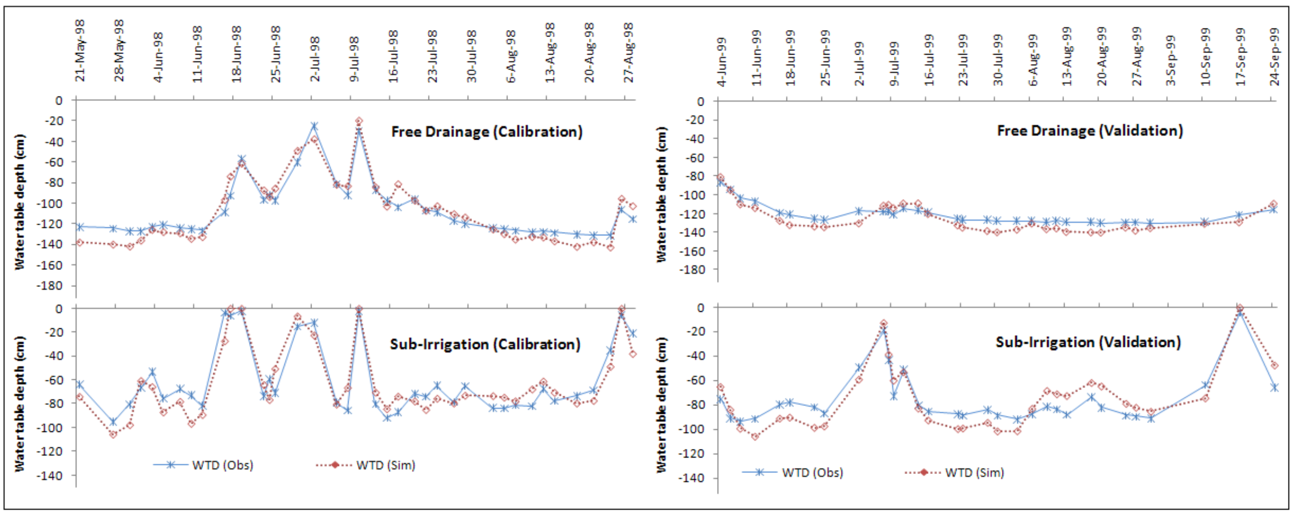

Figure 4.2. Observed and DRAINMOD predicted water table depths for FD and SI (1998-1999).

4.4.1.2. Simulation of Drain outflows

For the calibration year (1998), simulated and observed subsurface flow hydrographs for both FD and SI treatments (Fig. 4.3) showed simulated values to match measured ones fairly close, though over- or under-predictions were apparent. The statistical parameters for the simulated vs. observed daily and monthly drainage outflows are given in Table 4.5. In sub-irrigated plots there was an increase in the drain outflow at the end of September. This increase coincided with the opening of drains (SI switched to FD mode), thus that water stored in the soil started to drain out in October. Rainfall in September and October was 7% and 9% below normal, respectively, supporting the fact that the increased drainage outflow in the SI plots (Fig. 4.3) was from water stored in the soil profile due to sub-irrigation, rather than rainfall. For FD and SI treatments, the AAD values were 0.29 mm and 0.21 mm, for daily drain flow, and 3.1 mm and 2.1 mm for monthly drainage totals, indicating a close agreement between simulated and observed values for the calibration phase. Luo et al. (2001) had calculated AAD values ranging from 0.7mm to 0.9 mm for an experimental site in Nova Scotia. DRAINMOD 5.1 simulated the pattern of daily drain flow and its peaks well ($R^2 \geq 0.84$; $E \geq 0.84$). Model seems to underestimate the total yearly flow under both treatments by %7 for FD and %8 for SI. This might be due to the fact that in reality, the soil's conductivity could be altered by cultivation operations. Similarly, root development and the enhanced activities of earthworms and other organisms could result in preferential flow through macropores. The model does not consider bypass flow, thus it is not possible to simulate seasonal variations in hydraulic conductivity. The measured and simulated subsurface drainage outflow for 1999, the validation year, is shown in Figure 4.3. Largest amount of drain discharge occurred in the fall of 1999 due to heavy rains. For daily outflow, AAD values were 0.1 and 0.12 mm for FD and SI, while for monthly outflows they were 1.93 mm and 1.25 mm (Table 4.5), indicating that the model followed the trend of observed values. For the validation year, under FD and SI, $E \geq 0.83$, $R^2 \geq 0.84$ for daily outflows indicate a very good correspondence between simulated and observed values. Statistical comparisons (Table 4.5) showed good agreement between simulated and measured monthly drainage outflows during the study period (Fig. 4.4). Observed and simulated cumulative drain outflows (Fig. 4.4) were also in an excellent agreement. However, compared with observed values, the simulated cumulative drain outflows under FD and SI were underestimated by 4% and 6% for validation year.

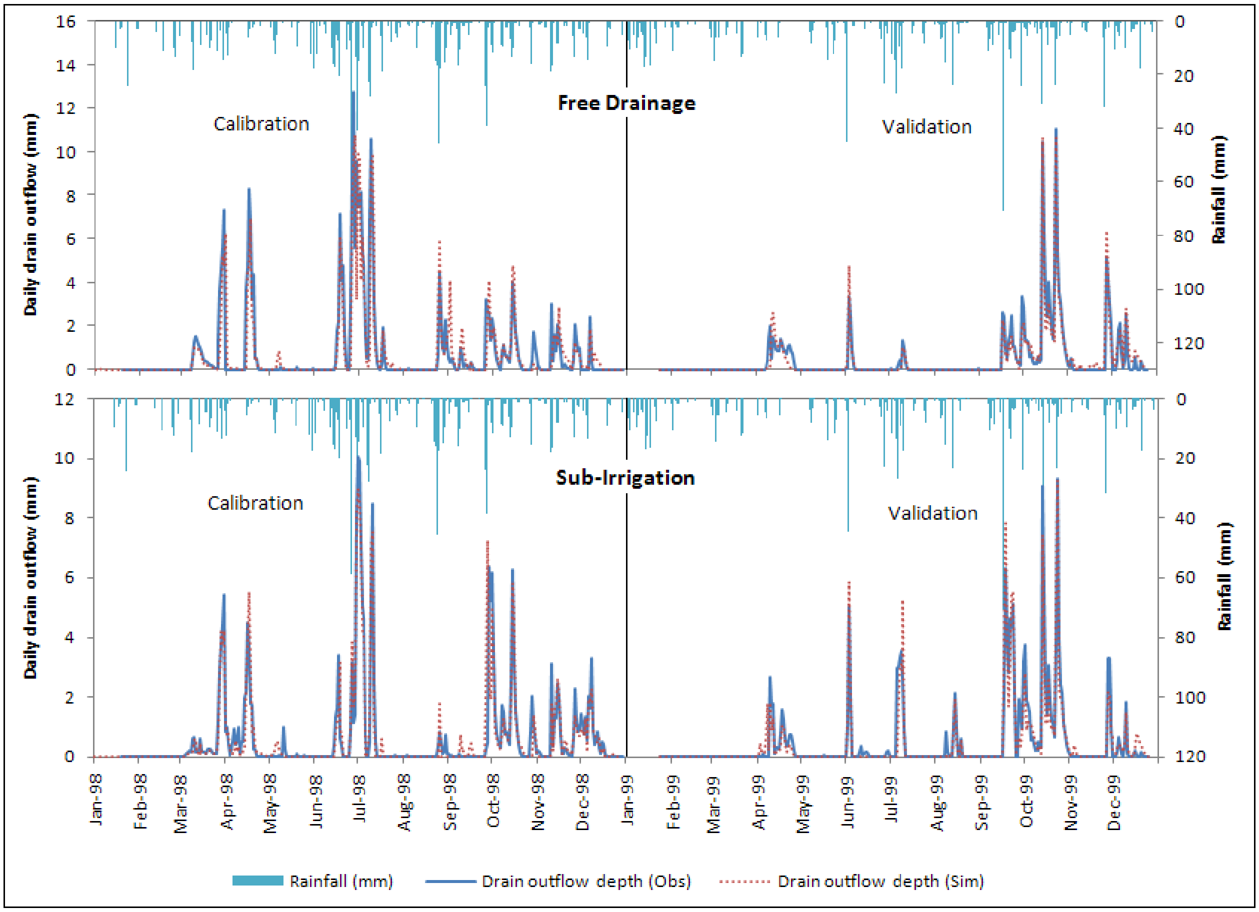

Figure 4.3. Observed and DRAINMOD predicted drain outflows (1998-1999) for SI/FD.

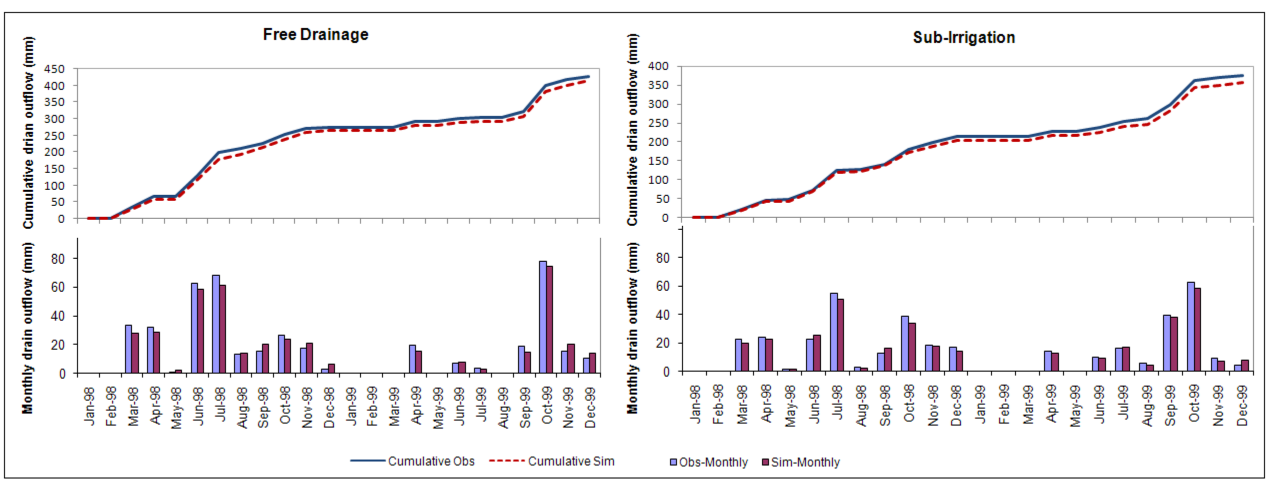

Figure 4.4. Simulated vs. observed monthly and cumulative drainage outflows for FD/SI (calibration and validation years)

Table 4.5. Comparison of simulated and observed WTDs and drain outflow rates

Statistical Parameter	Free Drainage		Sub Irrigation	
	1998	1999	1998	1999
WTD (cm)				
AAD	8.21	5.7	10.24	9.99
E	0.86	0.69	0.83	0.73
R^2	0.91	0.84	0.85	0.81
Daily drain flow (mm)				
AAD	0.29	0.09	0.21	0.12
E	0.88	0.87	0.84	0.83
R^2	0.88	0.87	0.84	0.84
Monthly drain flow (mm)				
AAD	3.11	1.93	2.06	1.25
E	0.94	0.95	0.95	0.96
R^2	0.95	0.96	0.96	0.97

4.4.2. Nitrogen Simulations

Once DRAINMOD 5.1 was calibrated and validated to adequately simulate WTD and drain outflows; a set of nitrogen simulations (for all year-WTD-N fertilization combinations) was conducted to calibrate the nitrogen component of the model using 1998 data and then validate it with 1999 data. Initial runs of DRAINMOD 5.1 to simulate [NO_3^--N] in the drainage water at the site were conducted using Helwig's nitrogen input values (Helwig et al., 2002). The main parameters, Kden, Kmin and λ, were selected for calibration based on literature (Helwig et al., 2002; Zwierschke et al., 2002; Wang et al., 2006a). These parameters were calibrated so as to obtain the closest possible agreement between the predicted and observed NO_3^--N losses in subsurface drainage on the basis of statistical parameters. The calibrated values were used as input in nitrogen simulations for 1999 (validation year). All plots were assumed to have the same initial distribution of nitrate through the soil profile, and the same initial organic N. For the SI plot simulations, the model was switched over to subirrigation mode on May 15 when the subirrigation system was turned on, and turned back to conventional drainage mode in mid-September when the subirrigation system was turned off to facilitate field operations and crop drying. The results of monthly cumulative NO_3^--N losses in subsurface drainage under sub-irrigation and free drainage treatments for 1998 and 1999 are shown in figures 4.5 and 4.6. The statistical parameters, comparing simulated and observed monthly NO_3^--N losses, are shown in Table 4.6. It is apparent from the results that leaching losses were reduced by the implementation of subirrigation. During the cropping seasons, drainage water from plots receiving 200 kg N ha^{-1} under FD contained the greatest concentration of NO_3^--N (Figs. 4.5, 4.6).

In the calibration and validation periods, simulated NO_3^--N losses are in good agreement with the observed values (Fig. 4.5). Average deviation values, ranging from $-0.05 < AD < 0.05$ kg ha^{-1} $month^{-1}$ (Table 4.6), indicated that monthly over- or under- estimations of nitrate-nitrogen losses were small.; Helwig et al. (2002) reported $0.19 < AD < 1.54$ kg ha^{-1} $month^{-1}$ using DRAINMOD 5.0 for the same site over the same period. Coefficients of determination were almost similar under both treatments ($0.91 \leq R^2 \leq 0.94$) for calibration and validation years, indicating a close correlation between observed and simulated NO_3^--N losses.

The movement of NO_3^--N has been intimately associated with the movement of water in agricultural soils in several studies (Armstrong and Burt 1993). In this study, the NO_3^--N losses in drain outflows were strongly dependent on outflow rates (Figs 4.5, 4.6). In 1998, heavy rainfall events occurred soon after the second surface fertilizer application (8 June). Both June and July had well above average rainfall, while the months of September to November had below average rainfall (Table 4.2). Consequently, the majority of NO_3^--N leaching occurred early in the season rather than during the fall months. Comparatively, in 1999, the situation was reversed. Thus, the leached nitrogen in 1998 may have come directly from the applied granular fertilizer or from nitrate in the very top soil layer, compared to 1999, when the nitrate would have had the whole season to become distributed through the soil profile. As pointed out earlier, heavy rains in the fall of 1999 producing the largest amount of drain discharge (Fig. 4.3) might have caused

NO_3^--N leaching with percolation water (Fall 1999; Fig. 4.5, 4.6). The comparison between the observed and simulated monthly and cumulative nitrate-nitrogen losses (Figs. 4.5, 4.6) shows that the model performed quite well, although tended to slightly under-predict cumulative losses, which could be due to the flow underestimation by the model.

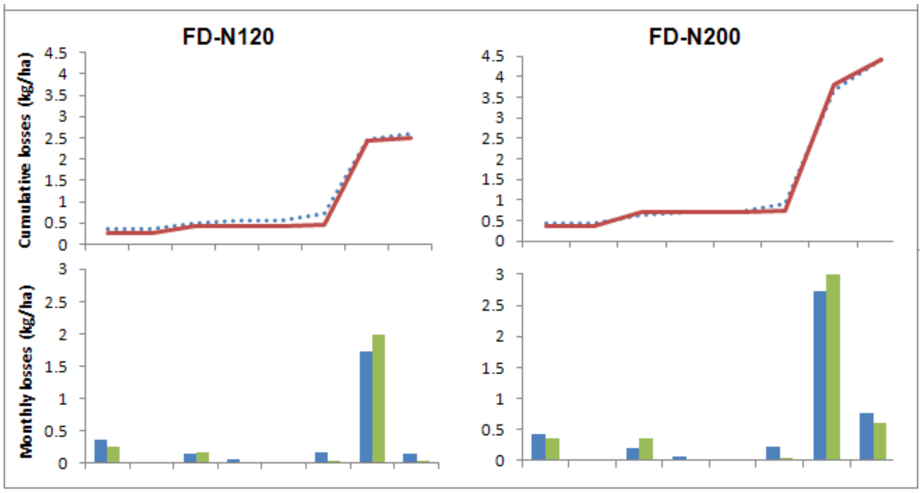

Figure 4.5. Simulated vs. observed monthly & cumulative NO_3^--N losses in subsurface drainage under FD (N120 and N200)

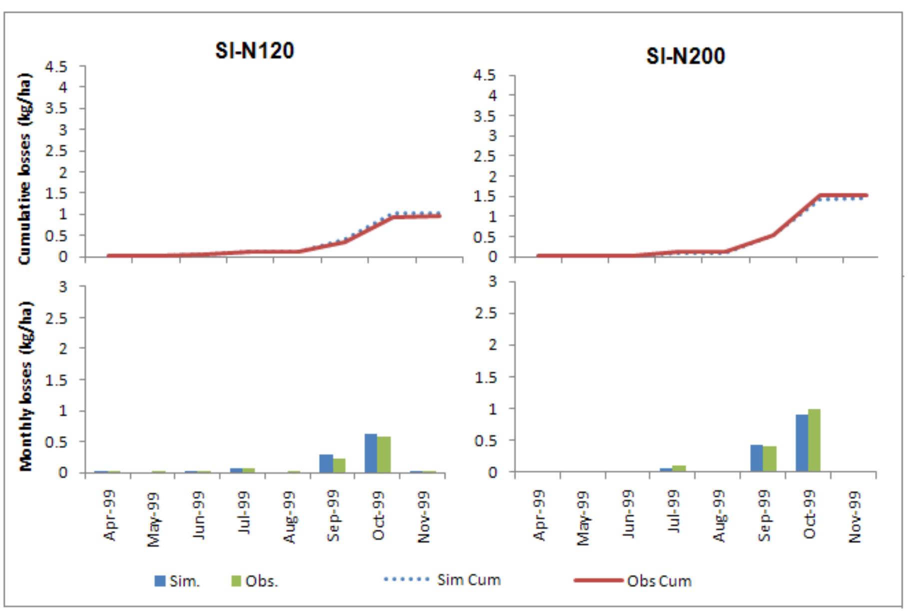

Figure 4.6. Simulated vs. observed monthly & cumulative NO_3^--N losses in subsurface drainage under SI (N120 and N200)

A summary of selected studies on NO_3^--N leaching associated with corn production in various humid and temperate regions of North America compiled by Milburn and Richards (1994) showed mean annual NO_3^--N concentrations of drainage discharge ranging from 4 to 43 mg L^{-1}. Our results fall within the low end of this range.

Table 4.6. Statistical comparison of simulated and observed monthly total NO_3^--N losses (kg. ha^{-1} $month^{-1}$) to subsurface drains

Statistical Parameter	1998				1999			
	N120		N200		N120		N200	
	FD	SI	FD	SI	FD	SI	FD	SI
AAD	0.06	0.06	0.31	0.16	0.04	0.02	0.01	0.04
AD	-0.05	0.03	0.05	0.05	0.03	0.01	0.04	0.04
E	0.93	0.9	0.92	0.91	0.93	0.92	0.9	0.91
R^2	0.94	0.93	0.94	0.93	0.94	0.94	0.91	0.92

4.5.Conclusions

DRAINMOD 5.1 was calibrated and validated for WTD, tile drainage volume and NO_3^-–N losses in southern Quebec (cold climate) under water table management practices, such as free drainage and sub-irrigation, over a period of two years. Compared to version 5.0, this version permits simulation under cold climates because soil freeze/thaw and snowmelt components have been added. The revised model predicted the daily WTDs, daily drainage outflows, and monthly nitrate-nitrogen losses with a good degree of accuracy for both FD and SI water table management practices. The hydrologic component of the model generally performed well for water table and drained volume predictions. The R^2 values were in the range of 0.84-0.88 for daily drainage outflow. Thus, the model simulated the pattern of daily drain outflows and the peak flows fairly well. The leached NO_3^-–N component gave good results for both sub-irrigation and free drainage [R^2 (FD and SI) $\geq$ 0.91], although underestimating cumulative losses to some extent under both treatments. The difference between simulated and observed over a 2-year period was only 0.2-0.65 kg ha^{-1} for FD and 0.3-0.68 kg ha^{-1} under SI. Thus, the performance of model was deemed satisfactory and it may be concluded that the DRAINMOD 5.1 model can be effectively used to simulate WTD depth, drainage outflows and NO_3^-–N losses in cold regions.

CONNECTING TEXT TO CHAPTER 5

This chapter addresses the second objective of the thesis, evaluating WARMF model for an agricultural watershed in Quebec. This paper presents the calibration and validation of WARMF watershed-scale model for flow and nitrogen transport, and evaluates its applicability in Quebec'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 stream flow and nitrate loads in an agricultural watershed have been presented.

The manuscript is in review for publication in Transaction of ASABE, co-authored by my supervisors Drs. S. O. Prasher and C.A. Madramootoo; Dr. A. Madani, Professor in the Engineering Department of Nova Scotia Agriculture College; Mr. Peter Enright, professional associate and director of the Farm Management and Technology Program at McGill University. All literature cited in this chapter is listed in the reference section at the end of this thesis.

CHAPTER 5: Evaluation of WARMF Model for Flow and Nitrogen Transport in an Agricultural Watershed under a Cold Climate

Shadi Dayyani, Chandra A. Madramootoo, Shiv O. Prasher, Ali Madani, and Peter Enright

Abstract:

The Watershed Analysis Risk Management Framework (WARMF) model was adapted to simulate flow and nitrate-N transport in an agricultural watershed in Quebec, Canada. WARMF divides the watershed into a network of sub-watersheds, stream segments, and stratified lakes. WARMF applies daily meteorology data to sub-watersheds to simulate runoff and non-point source (NPS) loads. The NPS loads are routed together with point source loads to predict water quality in rivers and lakes. The model was evaluated for the St. Esprit watershed (24.3 km^2), which is a part of the 210 km^2 St. Esprit river basin, a tributary of the L'Assomption watershed (4220 km^2). WARMF's hydrologic calibration and validation was performed using data from the gage station located at the outlet of the watershed. Water-quality data collected was used to guide water quality calibration/validation. The data from 1994 to 1996 was used to carry out the simulations; 1994 and 1995 data were used for model calibration and data from 1996 was used for model validation. The model performed reasonably well in simulating the hydrologic response and nitrate losses at the outlet of the watershed. The R^2 between the observed and simulated monthly stream flow for calibration was 0.92, and that for validation was 0.94. The corresponding coefficients of efficiency (E) were 0.89 and 0.91. The R^2 and E values for calibration/validation of NO_3^--N loads simulation were 0.89/0.84 and 0.86/0.75, respectively. Thus the model simulated monthly flow and nitrogen losses with a good degree of accuracy over the entire year.

Key Temrs: WARMF, Hydrological Modeling, Water quality Modeling, Cold Climate, Watershed Scale.

5.1. Introduction

The agricultural sector in Canada in general and Quebec in particular has witnessed substantial growth over the past decades. Increase in agricultural production can be attributed to several factors, such as mechanization of farm operations, soil and water management, use of chemical fertilizers, and improved crop varieties. At the same time, this has placed the region's water bodies under severe environmental stress. In Quebec, agriculture is responsible for over 70% of the total non-point source pollution (Enright and Madramootoo, 2004). Increased levels of phosphorus and nitrogen in lakes and rivers promote eutrophication, a phenomenon responsible for the release of poisonous cyanobacteria that deplete dissolved oxygen levels of the water and render it hazardous for aquatic as well as human life. In Quebec, nitrogen and phosphorus contamination of watercourses and lakes is largely attributed to non-point source pollution from agricultural fields (Enright and Madramootoo, 2004).

While long-term field-scale monitoring is necessary to establish a theoretical understanding of nutrient dynamics, only a limited number of studies are available due to the high cost of instrumentation and operation (Gollamudi, 2006). Additionally, collecting long-term data for a range of climatic, hydrologic and topographic conditions is a time-consuming and difficult process. Thus, complementing real-time field data with a validated hydrological and water quality simulation model is both cost-effective and time-efficient.

Hydrological and water quality simulation models have developed from the elementary to the complex algorithms in the past three decades (Gollamudi, 2006). A common starting point for all these models is the necessity to accurately simulate the movement of water through different components of the hydrologic cycle – precipitation, overland flow, infiltration, subsurface flow, deep seepage, evapotranspiration (ET) and stream flow. The ability of a model to accurately simulate hydrological processes such as surface runoff and subsurface drain flow are important for reliable predictions of nutrient losses. The key criteria in considering a model include the availability of reliable input data for the model parameters, spatial/temporal scale of use, and nature of output.

In this study, we used the WARMF model, Watershed Analysis Risk Management Framework (Chen et al., 1998), to prepare visual depictions of water quality in an agricultural watershed in Quebec, Canada. WARMF is a user-friendly tool, organized into five linked modules (Engineering, Data, Knowledge, Consensus, and TMDL) under one 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 (Chen et al., 1998). The model can simulate stream flow, lateral flow and sediment loadings. Furthermore, the fate and transport of nitrogen, phosphorus, heavy metals, and pesticides can also be simulated on a watershed scale. The scientific basis of the model has undergone several peer reviews by independent experts under US EPA guidelines (EPRI 2000).

WARMF has been applied to over 15 watersheds in the United States and internationally (Rambow et al., 2008; Geza and McCray, 2007; Keller et al., 2004; Weintraub et al., 2004, 2001b; Herr et al., 2002; Chen et al., 2001a;). 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. The size of river basin applications ranges from 28 to 42,000 km^2. There is no limit on the size or scale of a potential WARMF application as long as adequate topography data are available (USEPA, 2009b).

The main objective of this study was to evaluate the WARMF model for the flow and nitrate-nitrogen losses in an agricultural watershed in a cold region using three years of site data.

5.2. Materials and Methods

5.2.1. Site Description

The WARMF model was applied to the St. Esprit watershed, located approximately 50 km north of Montreal between 45^{o} 55'0" and 46^{o} 0'0'' N, and 73^{o} 41'32' and 73^{o} 36'0' W (Fig. 5.1) in south-western Quebec, Canada. It is a part of the 210 km^2 St. Esprit River Basin, a tributary of the L'Assomption Watershed (4220 km^2). The land in the watershed is predominantly used for agriculture. The human population of the watershed is about 700; however, there are no villages or towns within the watershed.

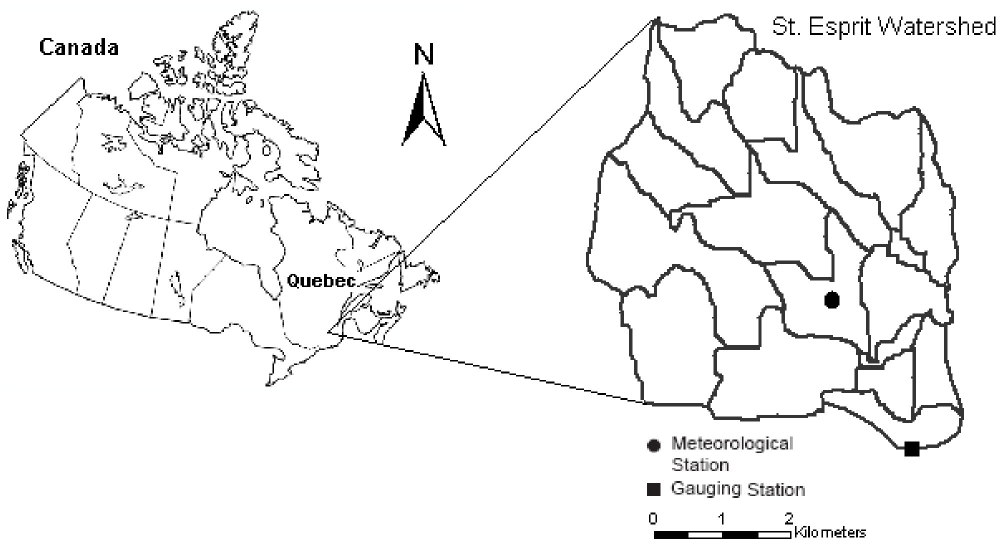

Figure 5.1. Location of St. Esprit watershed

The St. Esprit Watershed is comprised of a net drainage area of 24.3 km^2. During the study period (1994-1996), approximately 64% of the total area was under crop production with the majority of land use under corn crop, followed by cereals, soybeans, vegetables, hay, and pastures. The remaining 36% of the area was occupied by forested, bare, and residential lands (Table 5.1). Over 50% of the agricultural land has subsurface drainage. The difference in elevation from the outlet to the highest point of the watershed is 44 m and the principal watercourse is 8.5 km long. Topography can be described as flat to rolling, with most of cultivated land having slopes of less than 3%. The elevation data was obtained from GeoBase (GeoBase, 2007), Canadian Digital Elevation Data (CDED); the watershed boundary was created using GIS tools and DEM (Fig. 5.2). The streams map was taken from previous studies on St. Esprit watershed and also created using DEM and GIS tools (Enright et al., 1995; Mousavizadeh et al., 1995; Sarangi et al., 2005a,b).

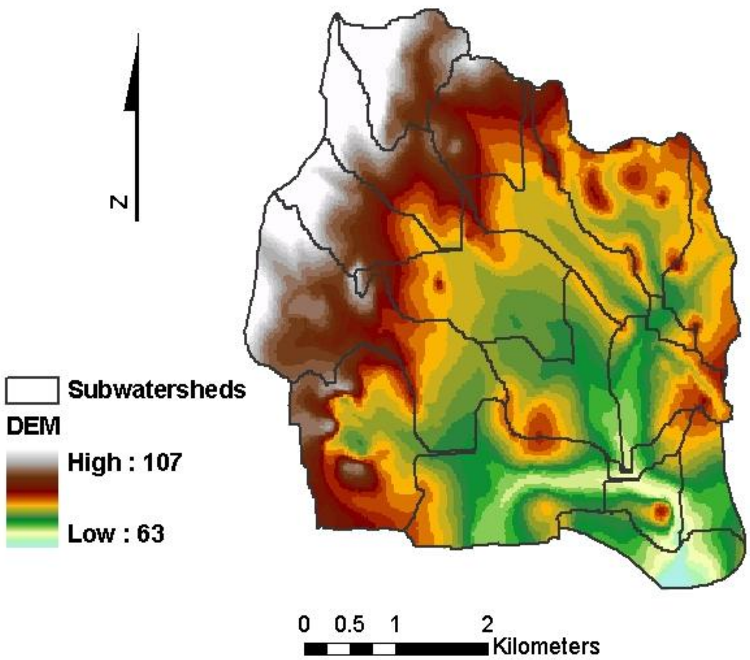

Figure 5.2. Topography map of St. Esprit watershed (DEM)

Table 5.1. Land use distribution on St. Esprit Watershed

Landuse	Area (m^2)	Area (%)
Corn	6272062.93	25.75
Cereal	2073508.21	8.51
Soya	1565615.35	6.43
Vegetable	1966098.15	8.07
Hay	2919677.45	11.99
Forest	6345533.46	26.05
Pasture	703183.30	2.89
Irrigation-pond	165435.29	0.68
Residential	1241620.58	5.10
Unused	1107938.69	4.55
Total	24360673.39	100

These maps, along with 1:63360 soil maps (Lajoie, 1965), 1:15000 field-level aerial photography, and information provided by the producers (Enright et al., 1995) identified approximately 16 soil series, and 10 different land use categories

(Fig. 5.3). Soil textures in the watershed are variable; in general, the largest proportion of the watershed is occupied by coarse-textured soils (sand and sandy loam 44%), followed by fine-textured soils (clay and clay loam 39%). The distribution of soil textural classes in the watershed is shown in Figure 5.4. The lower portion of the watershed is mostly composed of clays and clay loams, including the Ste. Rosaile and St. Laurent series (Lapp et al., 1998). Most of the annual crop production takes place on the heavier soils. The upper regions of the watershed are composed of loamy and sandy soils. Natural drainage on these soils is poor and the majority of these soils are subsurface drained (Enright et al., 1995).

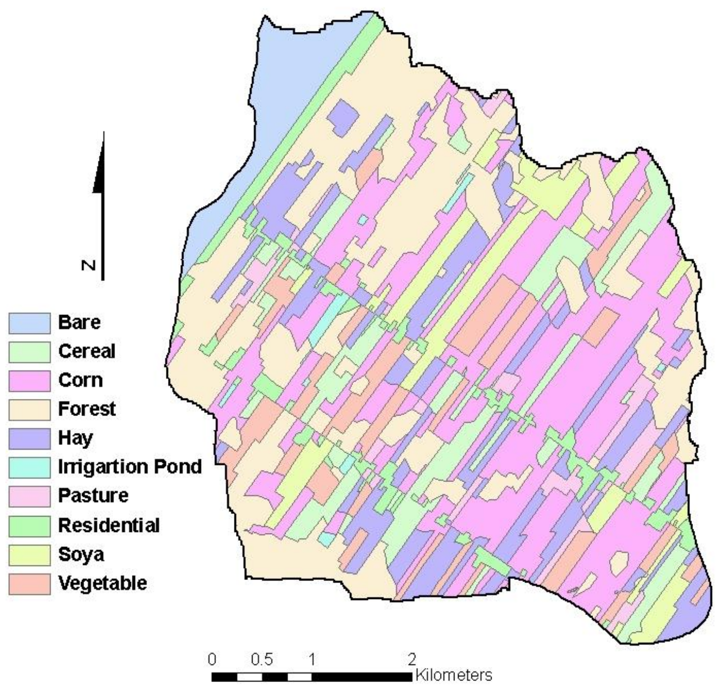

Figure 5.3. Land use map of St. Esprit watershed

The climate of the watershed is temperate. The period of frost varies from 122 to 138 days. Average annual precipitation varies between 860 and 1050 mm, with approximately 20 to 25% appearing as snow (Sarangi et al., 2005a,b). Average annual potential evapotranspiration is between 400 and 560 mm. The mean temperature in the month of July varies between 18 and 21 ^{o}C (MAPAQ, 1983).

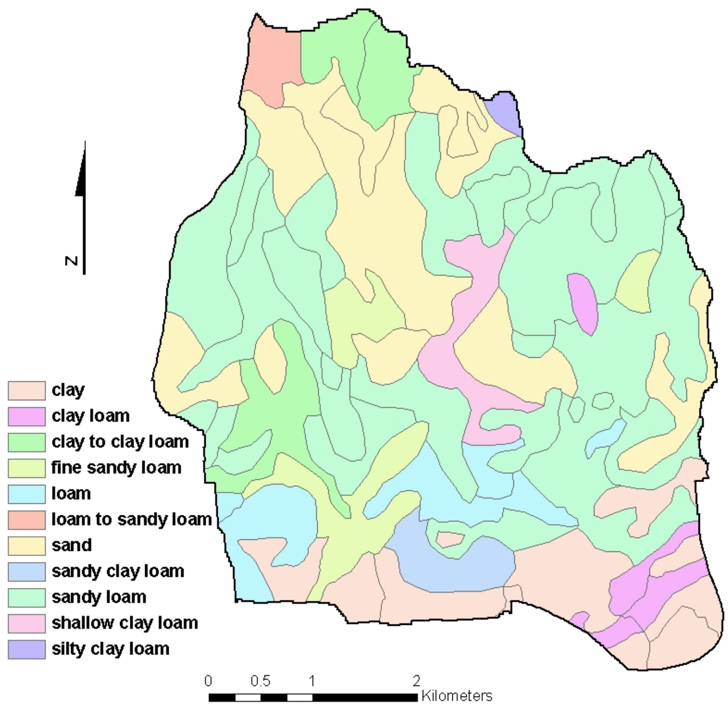

Figure 5.4. Soil texture map of St. Esprit watershed

5.2.2. Instrumentation and Monitoring

In the winter of 1993-1994, a stream gaging station was established at the watershed outlet, and a meteorological station was installed in the watershed (Fig. 5.1). The equipment installed at the watershed outlet included a water level sensor (Druck 950 submersible pressure transducer) installed on the stream bed bottom, a UDG01 ultrasonic level sensor mounted over the outlet culvert, and a data logger (Campbell CR10) located in the gauging station building to record and store the data. A backup system that independently measures water level and flow velocity and sends these data to the primary data logger was also installed The meteorological station was equipped with sensors for air and soil temperature, solar radiation, wind speed and direction, snow accumulation, as well as a tipping bucket rain gauge and a Campbell data logger (Perrone and Madramootoo, 1998). Table 5.2 shows monthly precipitation for 1994-1996 measured at the site and average 30 year monthly precipitation measured at the St. Jacques weather station, located about 6 km from the experimental site. The annual precipitation of 1994 and 1995 is 14 and 49 mm below the 30-year average, respectively; while, the annual precipitation in 1995 was 71 mm above the 30-year average (Table 5.2).

Land use and land management information were collected on St. Esprit as part of an integrated watershed monitoring and management project (Enright et al. 1995; Papineau and Enright, 1997). There were 25 farms, of which information from 18 of the farms was available. The participating producers account for approximately 67% of the agricultural land use of the watershed (Sarangi et al., 2005a,b). Water samples were collected on a flow-weighted basis. An automated water sampler was installed at the gauging station. A sampler intake line was suspended over the control section to be monitored. An automated sampling strategy was based on the flow volume calculation; the automated sampler was programmed for activation at a variable but predetermined threshold value of accumulated flow. The collected samples consisted of the automated type and the in-stream grab samples collected on the weekly or bi-weekly site visits. Details of the water sampling protocol are given in Enright et al. (1995).

Table 5.2. Monthly precipitation (mm)

	1994	1995	1996	30 year average
January	111.0	140.0	156.0	66.5
February	45.0	37.0	131.0	37.0
March	47.3	53.8	50.0	52.0
April	105.2	44.3	73.0	78.1
May	53.3	85.0	53.0	86.7
June	187.0	38.0	92.0	103.2
July	119.0	122.0	96.0	87.5
August	113.0	82.0	85.0	92.1
September	45.0	58.0	89.0	98.0
October	20.0	91.0	70.0	87.0
November	63.0	97.0	71.0	89.9
December	19.0	45.0	46.0	63.4
Total	927.8	893.1	1012.0	941.4

5.2.3. WARMF Model Description

WARMF (Chen et al., 1998) is classified as a watershed decision support system (DSS), sponsored by Electric Power Research Institute (EPRI). A DSS provides information and tools that help collaborative decision making among interested parties (Chen et al., 2001b). Typically, a DSS contains three basic components: database, model, and knowledge base (Guariso and Werthner, 1989) or in other words a watershed management DSS should meet three needs of the users (Neilson et al., 2003): the pre-processing (data and tools), modeling (receiving and watershed models), and post-processing (analysis of model results and facilitation of collaborative decision making). Figure 5.5 shows the modular design of WARMF. As shown, WARMF has all three basic components of a DSS.

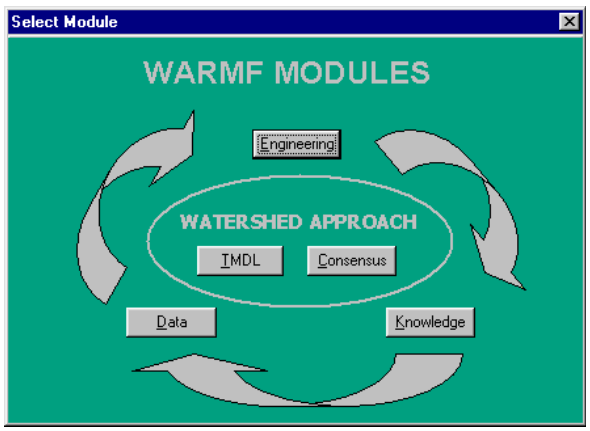

Figure 5.5. Modular Design of WARMF

WARMF was designed to assist in watershed management and TMDL development, and is available in the public domain. WARMF intended users are technical and non-technical stakeholders making watershed management decisions. As mentioned earlier, WARMF is organized into five linked modules (Engineering, Data, Consensus, TMDL, and Knowledge) under one, GIS-based graphical user interface (GUI). The Engineering module is the dynamic, simulation model that drives WARMF. The Data module shows time series input data (meteorological, point source) and calibration data. The Knowledge module is a utility to store important documents for the watershed. At the center of WARMF are the two watershed approach modules for Consensus building and TMDL calculations, which provide road maps for the step-by-step decision making process (Weintraub et al., 2001a). The model can be used to run simulations for certain management goals and objectives within a watershed that enables the user to see and compare the outcomes of alternative management plans. Output from the model is shown in GIS-based maps, graphs, and tables.

The algorithms of WARMF were derived from many well-established codes (Chen et al., 2001b). Algorithms for snow hydrology, groundwater hydrology, river hydrology, lake hydrodynamics, and mass balance for acid base chemistry were based on the Integrated Lake-Watershed Acidification Study (ILWAS) model (Chen et., al 1983). Algorithms for erosion, deposition, resuspension, and transport of sediment were adapted and modified from ANSWERS (Beasley et al., 1980; Beasley and Huggins, 1981). The pollutant accumulation and wash-off from urban areas was adapted from the Storm Water Management Model (SWMM) (Chen and Shubinski, 1971; USEPA, 1992). The sediment sorption-desorption of pesticides and phosphorus and the kinetics of nutrients and algal dynamics were adapted from WASP5 (Ambrose et al., 1991). A complete description of the WARMF formulations can be found in Chen et al. (1998).

5.2.3.1. Engineering Module

The Engineering Module is a GIS-based watershed model that calculates daily runoff, groundwater flow, stream flow, and water quality of river segments and reservoirs. The model divides the watershed into various components; including sub-watersheds, stream segments, and lake layers (Figure 5.6 shows the network of sub-watersheds and rivers for the St. Esprit watershed). Sub-watersheds are further divided into canopy and soil layers. Land surface is described by land use. In order to run water quality simulations, these components are connected into an integrated network allowing for the flow of pollutants between them. A hydrologic model within WARMF simulates canopy interception, snow pack accumulation and melt, infiltration through soil layers, evapotranspiration from soil, ex-filtration of groundwater to stream segments, and kinematic wave routing of stream flows. Figure 5.7 shows the conceptual model of hydrology for WARMF. A sub-watershed can have various land uses on the land surface. Below ground, the soils can have up to five layers (only 2 layers are shown in Fig. 5.7). The groundwater table can rise or fall depending on the balance between vertical percolation from above and lateral outflow to the river segment (Chen et al., 2001b). The potential evapotranspiration for each month is calculated as a function of latitude using Hargreaves equation (Hargreaves, 1974).

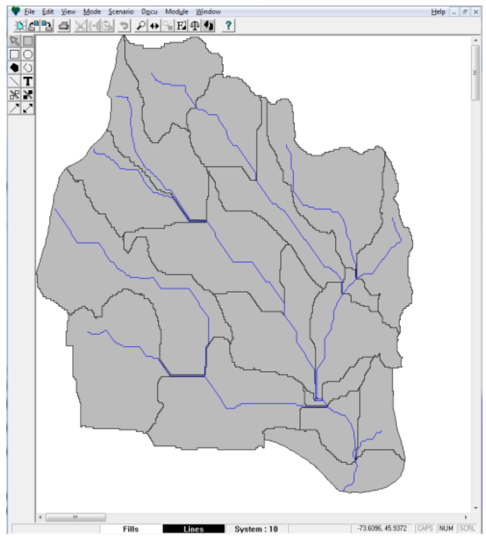

Figure 5.6. Network of land catchments and rivers for the St. Esprit watershed

In general, the hydrologic simulation is performed as follows (Chen et al., 2005): The rate of infiltration into the soil is limited by the vertical hydraulic conductivity of the top soil layer. If the soil is frozen (which occurs at the St. Esprit Watershed) or the groundwater table rises to the ground level, the water from precipitation and snowmelt is backed up to the ground surface. The water retained on the ground surface fills surface depression storage. When surface depression storage is filled, the excess water flows to a river segment by sheet flow, which is calculated by Manning’s equation. For each soil layer, percolation is calculated from the layer above and to the layer below. The soil layer has an allocation of evaporation according to the root distribution of plants. The model performs a flow balance in each time step to update soil moisture by accounting for the evaporation and the difference in percolation to and from the soil layer. The hydraulic conductivity of soil layers is a function of soil moisture. The available void space in the soil is filled with the water, which percolates downward. When the percolation reaches the groundwater table, it raises the groundwater level. Ground water can flow out to the river segment by lateral flow, which is calculated with Darcy's equation using horizontal hydraulic conductivity and slope. The unconfined aquifer is assumed to be watertight. Any known loss of groundwater to the deep confined aquifer must be specified as groundwater pumping for WARMF to extract water from the unconfined aquifer. Stream flow is routed by the kinematic wave method, and Manning's equation is used to calculate the outflow rate. Water depth is determined by performing a flow balance by accounting for inflow from the upstream river segment, inflow from land catchments on both sides of the river segment, outflow to the downstream river segment, and the change of storage. Such simulations track the flow paths of precipitation from land into different water bodies (Chen et al., 2005).

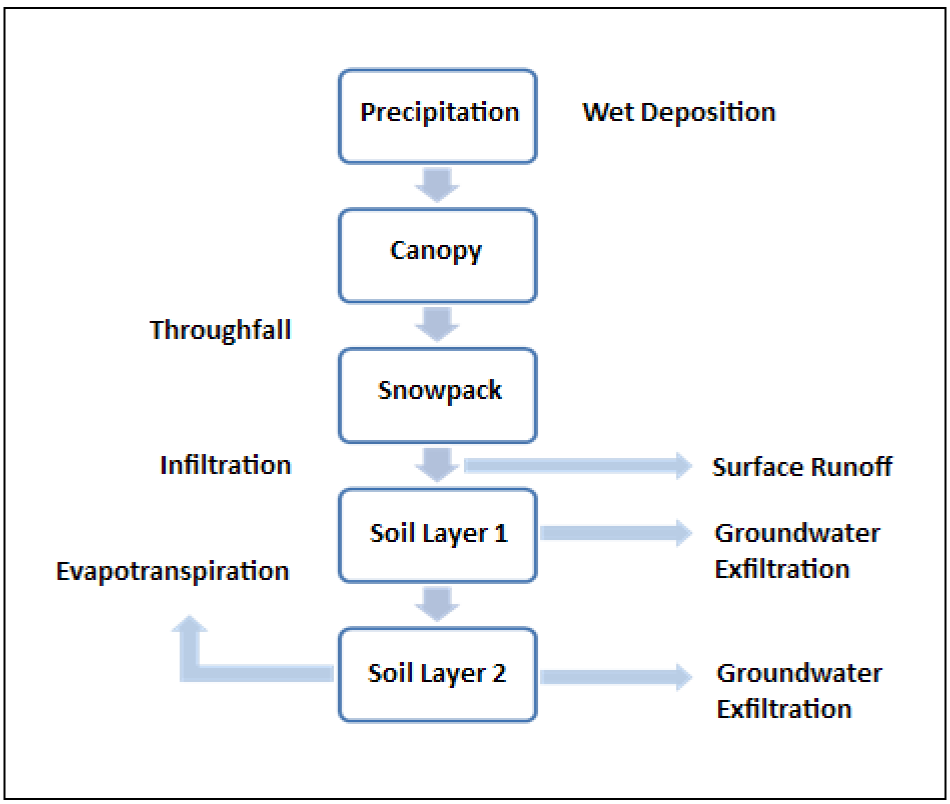

Figure 5.7. Definition Sketch for the Compartments of a watershed (Chen et al., 2001b)

Chemistry module performs various mass balance and chemical equilibrium calculations along each flow path (Weintraub et al., 2001b; Eisen-Hecht and

Kramer, 2002). A complete mass balance is performed, starting with atmospheric deposition and land application as boundary conditions. Pollutants are routed with water in throughfall, infiltration, soil adsorption, exfiltration, and overland flow. The sources of point and non-point loads are routed through the system with the mass so that the source of non-point loading can be tracked back to land use and location (Chen et al., 1998).

5.2.3.2. Data and Knowledge Modules

The data module contains meteorology, air quality, and point source data used to run the model. It also contains observed flow and water quality data used for model calibration purposes. The data is accessed using a map-based interface and can be viewed and edited in both graphical and tabular format. Supplemental watershed data, documents, case studies, or reports of past modeling activities are stored in the Knowledge Module for easy access by model users (Chen et al., 1998). On the watershed map, users can view the locations of point source dischargers, meteorology stations, stream gages, and water quality monitoring stations. All of this data can be viewed and updated through the data module.

5.2.3.3. Consensus and TMDL Modules

The last two watershed approach modules are roadmaps providing guidance for stakeholders during the decision making process. The Consensus Module provides information in a series of steps for stakeholders to learn about the issues, formulate and evaluate alternatives, and negotiate a consensus. It provides a simple menu for scenario generation that allows stakeholders, without extensive WARMF knowledge, to reduce point loads, non-point loads, atmospheric deposition, or diversion quantities by a percentage (Chen et al., 2001b). User requires knowledge of the models and interfaces to run more detailed scenarios (e.g., changes in land use distribution, changes in fertilizer application rates, etc.).

USEPA regulations require the calculation of total maximum daily loads (TMDLs) of pollutants when a water body's designated uses are impaired (USEPA, 2009a). A TMDL is the sum of point and non-point loads that can be discharged upstream of a water quality limited section without violating the water quality criteria of its designated use. Through the TMDL Module, calculations are made for a series of control points from upstream to the downstream of a watershed. Iterative sets of simulations can be performed to calculate various combinations of point and non-point loads that the water body can accept and meet the water quality criteria of the designated uses (Chen et al., 1998).

5.2.4. Model Inputs

WARMF inputs include meteorology data (daily precipitation and min/max temperature, cloud cover, dew point temperature, air pressure, and wind speed), soil properties (field and saturated moistures of soil, vertical and horizontal hydraulic conductivities, and bulk density), land use data, digital elevation (DEM) map, sub-watershed boundaries, ground slope and aspect, and fertilizer application data. WARMF's water quality related parameters are comprised of initial soil concentration of ammonia, soil nitrification rate, litter fall rate, productivity of land uses, and air quality data.

The climatic data was obtained from the meteorological station installed in the watershed. The DEM (Fig. 5.2) is developed using topographic data (contour lines and elevation point data). The natural drainage network is generated from the DEM of the watershed, using the Arc-Hydro tools of GIS. The sub-watershed boundary map (watershed delineation) is developed using DEM and by knowing where the watershed outlet is located. Using GIS tools, the watershed was discretized into 18 sub-watersheds ranging from several hundred m^2 to a few km^2 in size (Fig. 5.6). The slope and aspect maps are developed using DEM in GIS. The county-level soil maps are digitized and a soil database (Fig. 5.4) is developed and used to identify the different soil types across the watershed. Crop related data was taken from land use maps imported into GIS (Fig. 5.3). Fertilizer data was obtained from the GIS shape files developed for the watershed. WARMF aligns the polygons of land uses to the polygons of sub-watersheds to calculate the percentages of land use categories (e.g. urban, agriculture, deciduous forest, coniferous forest, open etc.). The van Genuchten equation (Van Genuchten,

1980) was used to determine the soil parameters (retention curve and hydraulic conductivity). The van Genuchten parameters were obtained from previous research performed in Quebec (Dayyani et al., 2009a, b; Mousavizadeh, 1998 and 1992; Perrone, 1997) and also using the Rosetta model (Schaap et al., 2001). Rosetta is a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions. Air and rain chemistry data was obtained from the National Atmospheric Deposition Program (NADP) website (NADP, 2009). The closest station to the watershed was HWF187, located approximately 220 km south of the watershed. Other parameters were set to the default values recommended in the model manual. Table 5.3 presents the range of values used for different input parameters.

Table 5.3. Selected WARMF input data

Model Input Parameter		
Watershed physical data		
Aspect, Slope, Width (degrees, m/m, m)	0 - 360, > 0, > 0	GIS maps
Detenstion storage (%)	0 - 100	
Surface roughness	0.1 - 0.3	
Land use		Land use map
Fertilizer data		
Function of land use, time (month), and chemical compositions		Land use and fertilizer maps, watershed reports
Soil properties		
Hydraulic conductivity (cm/d)	> 0	Rosetta software (using the soil texture based on the soil map), Sarangi et al., 2005a,b; Perrone 1997; Mousavizadeh et al., 1995; Mousavizadeh 1992 and 1998,
field capacity (m^3/m^3)	0 - 0.4	
Saturation mositure (m^3/m^3)	0.2 - 0.6	
bulk density (g/cm^3)	> 0	
Reaction rates		
Nitrification (day^{-1})	0.1 - 1.0	Elmi et al., 2004; Helwig et al., 2002
Denitrification (day^{-1})	1.08	Elmi et al., 2004; Helwig et al., 2002
snow/ice related parameters		
Snow formation temperature (^oC)	0 - 3	Wang et al., 2006; Luo et al., 2001
Melting temperature (^oC)	0 - 3	Wang et al., 2006; Luo et al., 2001
Evaporation coefficients		
Magnitude	0.6 - 1	Chen et al., 2001b
Skewness	0.6 - 1.4	Chen et al., 2001b

5.2.5. Methods of Evaluation

Three years of complete data set (1994-1996) was divided into two parts: 1994-1995 for calibration and 1996 for validation. Statistical tools such as, (AD) average deviation, root mean square error (RMSE), coefficient of determination (R^2), and Nash-Sutcliffe (E) coefficient (Nash and Sutcliffe, 1970), were used to analyze the results in order to evaluate model performance for both calibration and validation processes. The coefficient of determination is a measure of accuracy or the degree to which the measured and predicted values agree. The average deviation is used to determine whether the model made over- or under-predictions. The root mean square error measures the difference between predicted and observed values. It is sensitive to the extreme values and deals with both systematic and random errors. The Nash and Sutcliffe coefficient measures the goodness-of-fit between observed and simulated values. A value of 1 represents a perfect match, while a value of zero (0) shows a prediction no better than using the mean of the data. The negative efficiency indicates that the prediction is worse than simply taking the mean of the measured values.

The model performance was first qualitatively assessed with graphical displays of the results and then statistical measures were used for quantitative evaluation. The graphical comparison is made easily using the scenario manager of WARMF model. For example, Scenario 1 may be used to represent a set of numerical values of model coefficients used in the simulation. Scenario 2 may be used to represent a second set of modified model coefficients used in the simulation. Once the simulations are performed, WARMF can plot the observed data as well as the model predictions for both scenarios on the same graph. By visual inspection, it is relatively easy to see whether the changes to model coefficients improve the match.

5.3. Results and Discussion

5.3.1. Model Calibration and Validation

Model calibration is the procedure in which model parameters are adjusted to improve the match between the simulated and observed values. Only a few parameters are adjusted for each calibration. In this study, the model was calibrated by adjusting the evaporation coefficients (magnitude, skewness), snow/ice related parameters (melting rates, snow formation and melting temperature), field and saturated soil moisture, vertical/horizontal hydraulic conductivities, detention storage, initial soil concentration of nitrate, surface roughness (Manning's n), litter fall rate, and soil nitrification and denitrification rates. These parameters were selected for calibration based on literature (Weintraub et al., 2001b; Geza and McCray, 2007) and Herr (2008). The initial values of the calibration parameters were taken from studies conducted at the St-Esprit watershed (Sarangi et al., 2005a,b; Perrone 1997; Mousavizadeh et al., 1995; Mousavizadeh 1998) or studies performed in regions with the same soil and climatic conditions (Dayyani et al., 2009a, b).

Measured flow, nitrate-nitrogen, and climatic data are available from 1994 through 1996 for the gaging and weather stations installed in the watershed. The model initialization was important for model since WARMF assumes zero initial snowpack so it is recommended to start simulation before first of January. Thus, the calibration started on May 1, 1993 in order to initialize the model; the first 8 months of simulation (before January 1, 1994) were not considered in the evaluations of the calibration process. The climatic data for these extra 8 months was obtained from St. Jacques weather station, since it was not recorded at weather station installed in the watershed. Ideally, one may want to collect field data in a variety of wet and dry years. However, the field investigators have no control over the natural meteorological and hydrological variability. Model calibration/validation must be performed for the period that the field data were collected.

5.3.1.1. Hydrologic Simulations

Model calibration follows a logical sequence. Hydrological calibration is performed first, because an accurate flow simulation is a pre-requisite for accurate water quality simulation. Thus, generally the calibration for flow is performed before the calibration of nutrients, algae and dissolved oxygen concentrations. WARMF calculates daily flow and pollutant concentrations for all river segments. Since in this study the data is measured only at the outlet of the watershed, the simulated flow and NO_3^--N concentrations are compared to the observed values at the outlet of watershed.

Figure 5.8 compares simulated and observed daily hydrographs at the outlet of watershed for the entire simulation period of 1994–1996. The first part of the figure is for the calibration period of 1994–1995, in which the simulated and observed daily values show a correlation coefficient of 0.53 (Table 5.4); the second part shows results for the validation period with the R^2 of 0.58. The model seems to have performed reasonably well at simulating the number and timing of runoff events. WARMF underestimated some peaks during the snowmelt for both calibration and validation periods. The statistical indices calculated from the predicted and observed daily drainage outflows are given in Table 5.4. The positive mean deviation during the calibration and validation period between observed and simulated daily values indicates that the model slightly under-predicted flow. Mean deviation values, 0.50 and 0.29 mm, indicate that daily under-estimations were small.

In certain cases during winter/spring period, the model simulated greater flow than was observed which could be due to the fact that the model does not consider water freezing on the ground surface, eventually simulating greater runoff. For most of the events during the winter/spring period, simulated and observed timing of runoff peaks was found to differ by one day. This difference is thought to arise due to the quantity of accumulated snow on the soil surface resulting in differences in the roughness of bare and snow-covered land surfaces. The model considers the same surface roughness coefficient irrespective of the day of the year or the soil surface conditions. In reality, flow velocity is higher on snow-covered surfaces; thus, the time for the flow to reach the watershed outlet is faster.

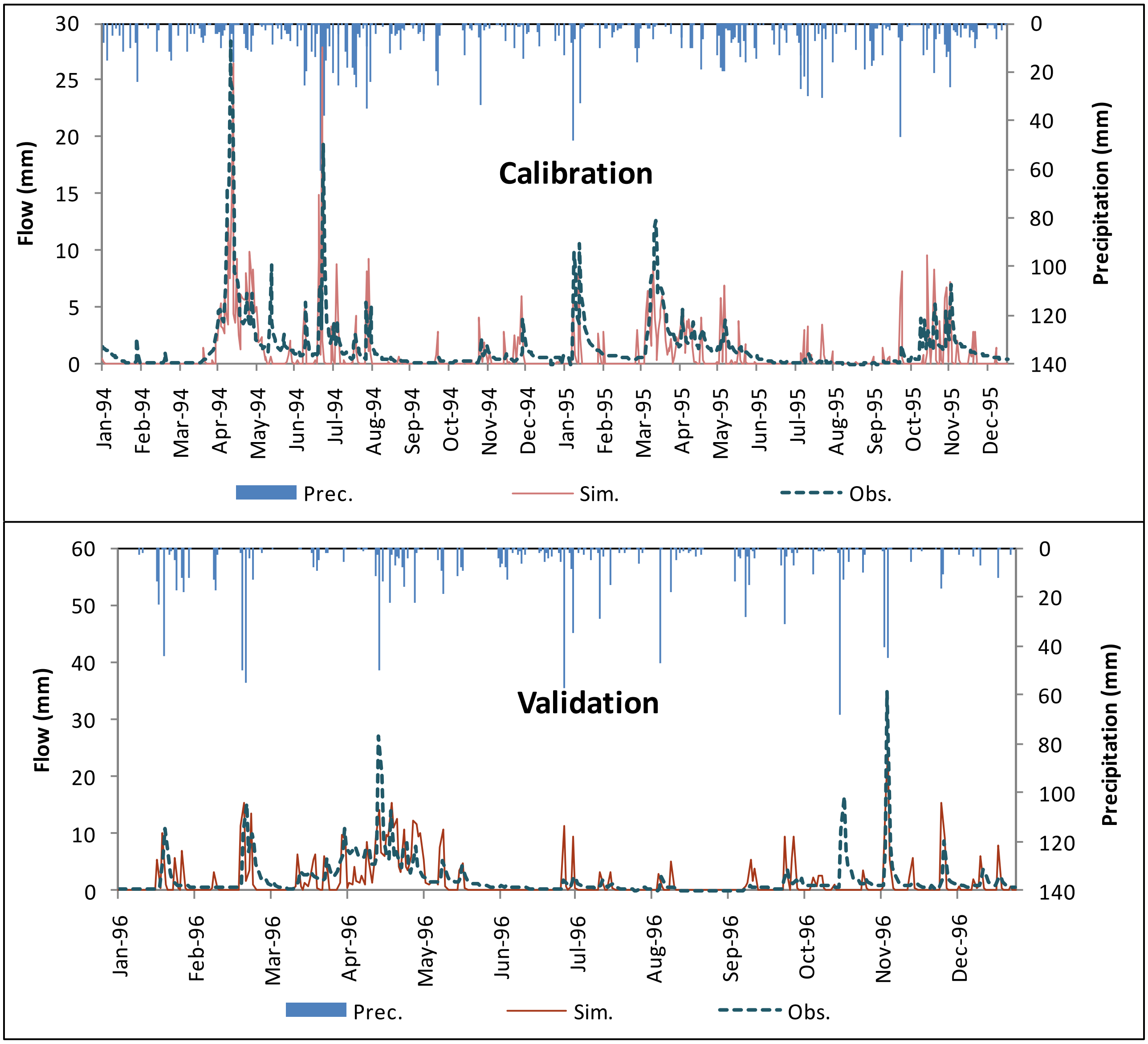

Figure 5.8. Daily hyetograph and hydrographs for calibration and validation period

Figure 5.9 presents WARMF's simulated monthly results and observed data. The WARMF calibration had a good statistical correlation between simulated and observed monthly flows (R^2= 0.92 and E= 0.89), although the model seemed to slightly overestimate flow during some months (AD > 0; Table 5.4). During the validation period the coefficient of determination and model performance were 0.94 and 0.91, respectively, showing good correspondence between the simulated and observed monthly values. The modeling errors (RMSE) during calibration and validation years were low, 17.1 and 17.6 mm, further indicating that model performed well in predicting monthly flow at the outlet of watershed.

Table 5.4: Model performance during calibration and validation

Statistical Parameter	Calibration (1994-1995)	Validation (1996)
Daily drain flow		
AD (mm)	0.5	0.29
RMSE (mm)	2.37	3.26
R^2	0.53	0.58
E	0.45	0.5
Monthly drain flow		
AD (mm)	7.27	4.16
RMSE (mm)	17.06	17.62
R^2	0.92	0.94
E	0.89	0.91
Monthly Nitrogen losses		
AD (kg/ha)	0.18	0.41
RMSE (kg/ha)	0.48	0.86
R^2	0.89	0.84
E	0.86	0.75

As mentioned earlier, overall the model seems to underestimate the flow during the winter and snowmelt period. Other researches in Quebec region have presented that there is considerable amount of flow coming out of tile drainage system during the winter and spring (Dayyani et al., 2009a, b; Gollamudi, 2006). Since WARMF does not take into account the tile drainage system, and almost half of the St. Esprit Watershed is subsurface drained, it does not simulate the base flow properly specially during the winter and snowmelt period, leading to underestimating the total flow during those months.

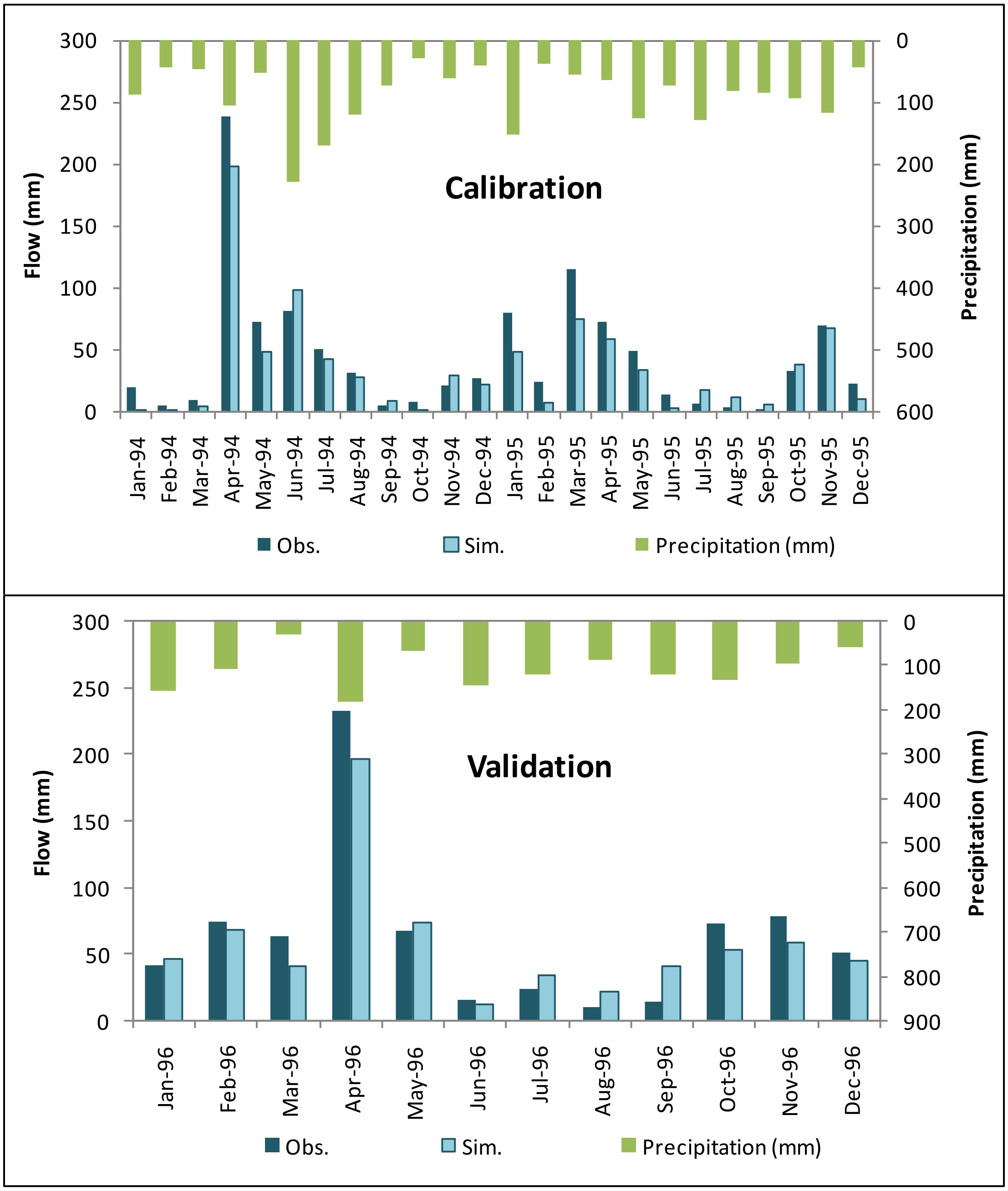

Figure 5.9. Monthly hyetograph and hydrographs for calibration and validation period

5.3.1.2. Nitrogen Simulations

Once the hydrology component of the model was calibrated and validated, nitrogen simulations were conducted to calibrate the nitrogen component of the model. Water-quality data collected during the flow calibration period, 1994-

1995, was used to guide the nitrogen calibration. Using parameters fine-tuned in the calibration process, the model was validated using 1996 data.

The fertilizer application rate and time data was taken from the GIS shape files and St. Esprit Watershed reports. The adjusted parameters used during calibration were soil nitrification and denitrification rate, litter fall rate, and initial NO_3^-–N concentrations in the soil. Initial runs of the model to simulate NO_3^-–N concentrations were conducted using the nitrogen input values, as per Dayyani et al. (2009b), Lapp (1996), and Elmi et al. (2000). Figure 5.10 compares the simulated and observed monthly NO_3^-–N losses at the outlet of St. Esprit watershed. The movement of NO_3–N has been closely associated with the movement of water in agricultural soils (Armstrong and Burt 1993). In this study, the NO_3^-–N losses were dependent on outflow rates (Fig. 5.10). The comparison between the observed and simulated monthly NO_3^-–N and cumulative losses (Figs. 5.10 and 5.11) shows that the model performed quite well with the R^2 value of 0.89 and 0.84 for calibration and validation periods, respectively (Table 5.4).

About 67% of the overall NO_3^-–N losses was recorded in April, May and June 1994; this is correlated to the intensive flow rates (72% of the annual flow) measured during this period (Fig. 5.10). In 1994, heavy rainfall events occurred soon after the second surface fertilizer application (early-June). June had 187 mm of rainfall, 1.8 times the 30-year average rainfall (Table 5.2). Although the flow is being underestimated over the snowmelt period in all three years, the NO_3^-–N losses were overestimated (Fig. 5.10), which might be because of time of 1st and 2nd fertilizer application, May and June. Overall, the comparison between the observed and simulated monthly and cumulative NO_3^-–N losses (Fig. 5.11) shows that the model performed quite well, although tended to slightly underestimate the total annual losses by 9% and 8% during calibration and validation periods, respectively. This could be due to the flow underestimation by the model.

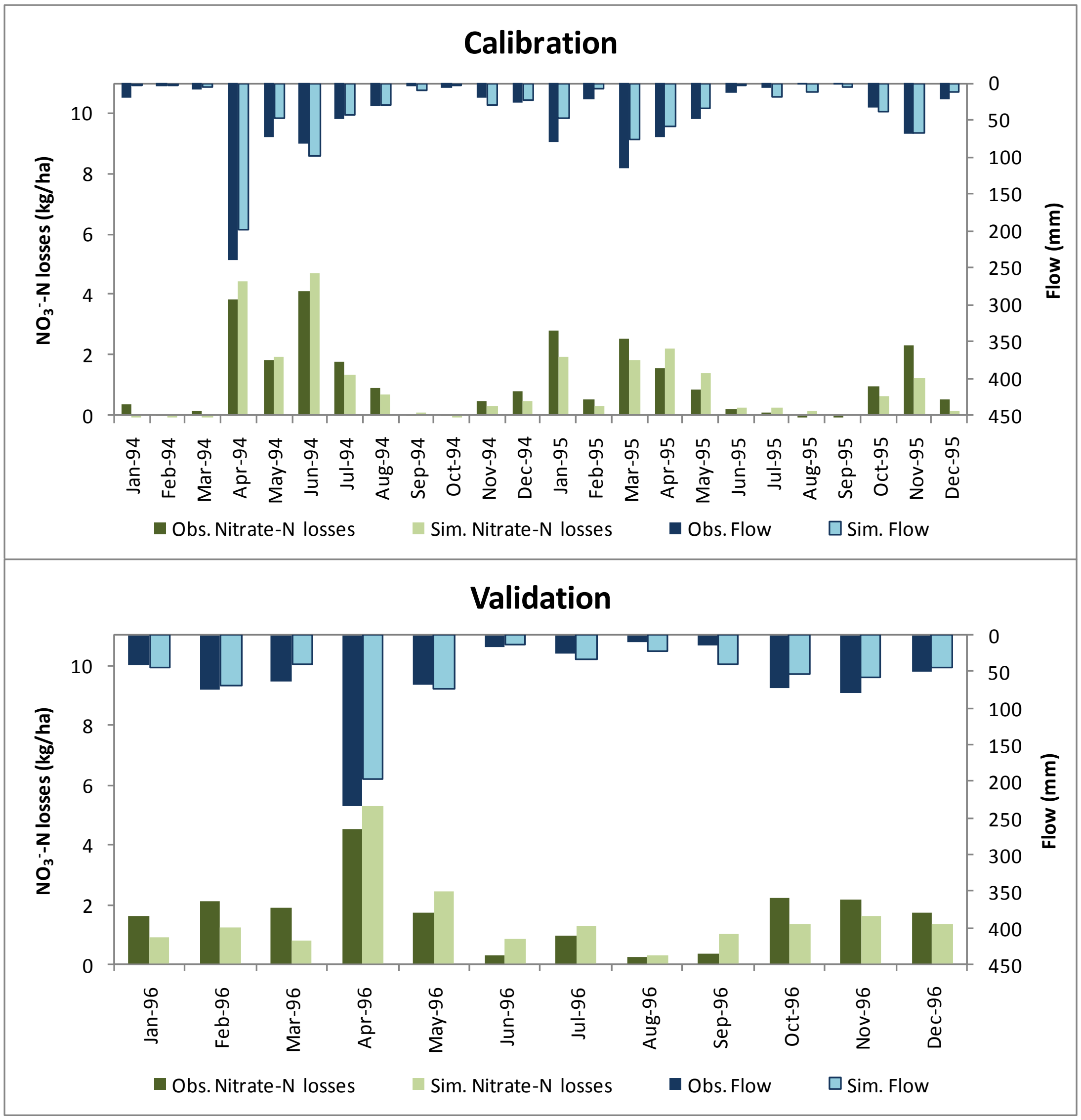

Figure 5.10. Simulated vs. observed monthly NO_3^--N losses at the outlet for calibration and validation period

The statistical comparison (Table 5.4) showed good agreement between simulated and measured monthly NO_3^-–N losses during the study period. The overall positive mean deviation (AD) value (0.18 and 0.41 kg ha^{-1}) indicates that the monthly N losses are slightly under-estimated (Table 5.4). The coefficient of determination was more than 0.84, indicating a good correspondence between simulated and observed NO_3^--N losses. Overall, the model performance was slightly better during the calibration period, with the modeling efficiency (E) being 0.86 as compared to 0.75 for validation.

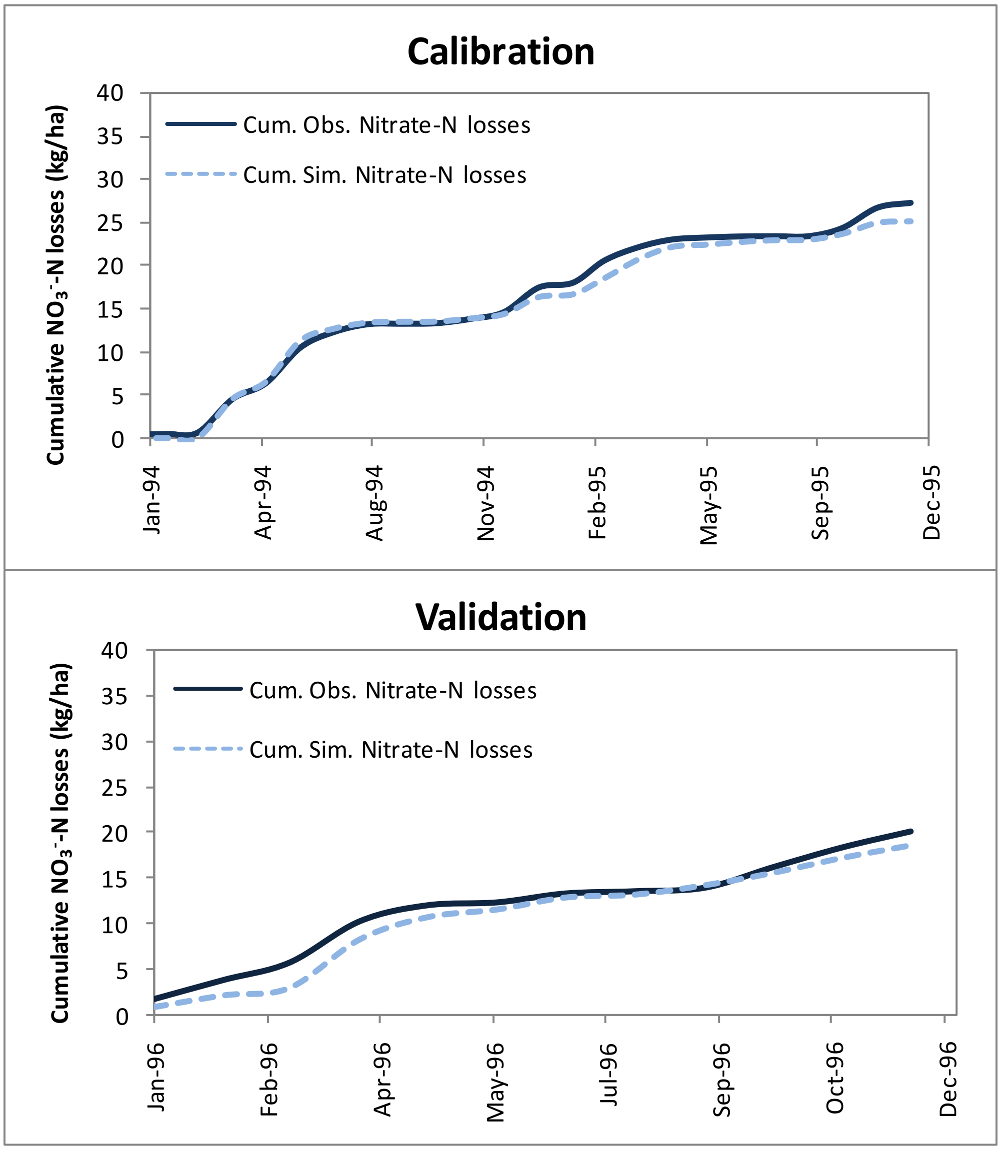

Figure 5.11. Simulated vs. observed cumulative NO_3^--N losses at the watershed outlet for calibration and validation periods

The comparison between the observed and simulated annual nitrate-nitrogen losses (Table 5.5) shows that the model performed quite well, although tended to slightly under-predict cumulative losses, which could be due to underestimation of flow.

Table 5.5. Observed and simulated cumulative flow and NO_3-N losses

	Obs		Sim	
	Flow (mm)	N (kg/ha)	Flow (mm)	N (kg/ha)
1994	563.8	14.6	478.3	14.4
1995	488.5	12.7	371.1	10.7
1996	742.4	20.1	692.5	18.6

The WARMF performed reasonably well in simulating the seasonal variation of flow (Fig. 5.12), although the spring flow is underestimated in all years. The dynamics of nutrient transport are different in the three seasons which experienced high flows (winter, spring, and fall), due to the changing hydrologic conditions between these seasons. WARMF was able to reproduce the conditions of all seasons satisfactorily for both the calibration and validation years, although the spring nitrate loads are overestimated (Fig. 5.12).

Mousavizadeh (1998) applied ANSWERS2000 to the St. Esprit Watershed. The model seemed to underestimate the flow; total simulated cumulative runoff values were 66.6%, 54.9%, and 71.7% of measured cumulative runoff values, for 1994, 1995, and 1996, respectively. Romero (2000) evaluated the performance of SLURP hydrological model at St. Esprit Watershed and reported R^2 values of 0.522 and 0.66 for calibration and validation periods, respectively. Geza and McCray (2007) applied WARMF model to a watershed in Colorado and reported E= 0.58 and R^2= 0.68 for simulation of monthly stream flow. SWAT model has been applied to different watersheds around the world; the range of reported R^2 and E values are: for daily flow R^2 = 0.04-0.78 (Wang et al., 2008; Wang and Melesse, 2005; Eckhardt and Arnold, 2001; Spruill et al., 2000; Peterson and Hamlett, 1998) and E= -0.04 to 0.84 (Bosch et al., 2004; Eckhardt and Arnold, 2001; Spruill et al., 2000); for monthly flow R^2= 0.35-0.92 (Wang et al., 2008; Jha et al., 2007; Gebremeskel et al., 2005; Chu and Shirmohammadi, 2004; Santhi et al., 2001; Spruill et al., 2000; Bingner, 1996) and E= 0.48- 0.94 (Jha et al., 2007; Gebremeskel et al., 2005; Bosch et al., 2004; Di Luzio et al., 2002; Saleh et al., 2000; Peterson and Hamlett, 1998); for monthly simulation of nitrate-nitrogen R^2= 0.72- 0.89 (Jha et al., 2007; Santhi et al., 2001) and E= 0.27- 0.73 (Jha et al., 2007; Di Luzio, 2002; Saleh et al., 2000). Comparing the results of this study (Table 5.4) with mentioned applications of different watershed models indicates that the WARMF models performed well in simulating flow and N loads at the outlet of watershed.

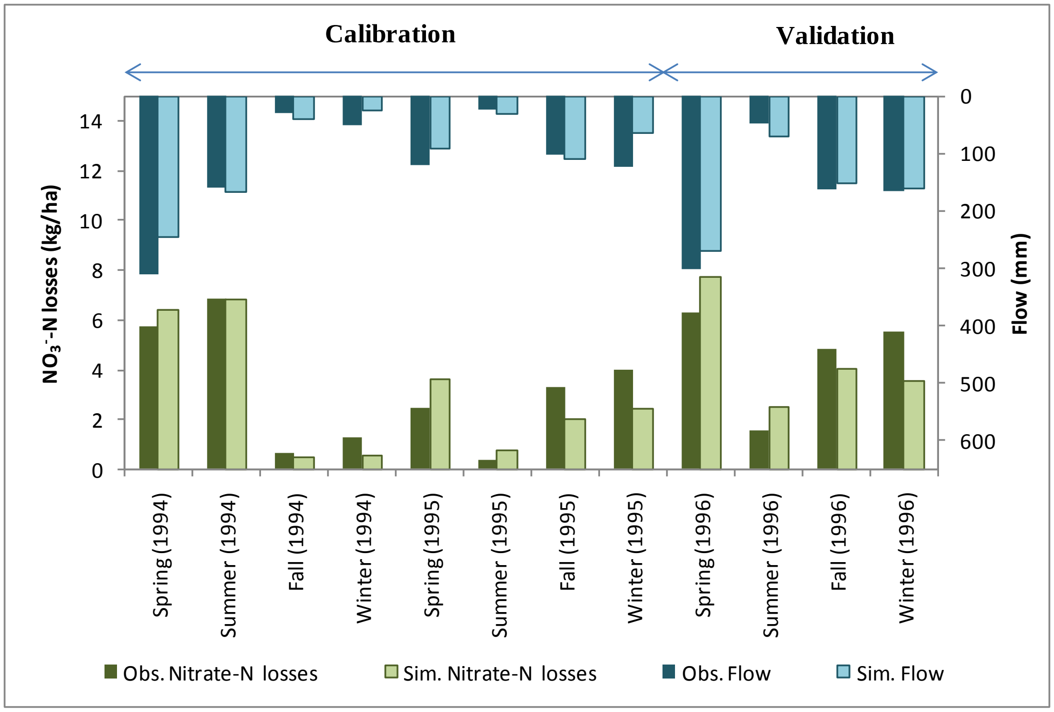

Figure 5.12. Simulated vs. observed seasonal flow and NO_3^--N losses at the watershed outlet for calibration (1994-1995) and validation (1996) periods

5.4. Conclusions

WARMF is a powerful decision support system consisting of several integrated modules. The engineering and data modules drive a dynamic simulation model that predicts flow, water quality, and point and non-point source loading throughout the watershed. The WARMF model was applied to predict daily flow from a 24 km^2 St. Esprit watershed in southwestern Quebec, Canada. The hydrologic response of the watershed was simulated for a three-year period from 1994 to 1996. The model simulated the pattern of monthly flow with a good degree of accuracy; the R^2 for calibration was 0.92, and that for validation was 0.94. The corresponding coefficients of efficiency (E) were 0.89 and 0.91. The model also performed well in simulating the flow during the snowmelt period with the error of 26%, 33%, and 11% in 1994, 1995, and 1996, respectively. The model also performed well in simulating nitrate loads at the outlet of watershed (Nash and Sutcliffe coefficient $\geq$ 0.75). These values are indicative of an acceptable model performance in a cold region.

CONNECTING TEXT TO CHAPTER 6

This chapter addresses the third objective of the thesis. In the chapters 4 and 5 DRAINMOD and WARMF models are evaluated individually, and proved to be good candidates in simulating flow and nitrogen transport in cold regions. Thus, this chapter discusses the development of the DRAIN-WARMF model developed by linking DRAINMOD and WARMF models to simulate flow and the transport of nitrogen in the surface and subsurface flows. As stated in Chapter 1, the proposed model aims at covering the limitations of other models; hence, improving the prediction of N in the soil-water environment. A complete description of the development of DRAIN-WARMF model and its evaluation for an agricultural watershed under Quebec climatic and soil conditions is presented.

This chapter is a manuscript accepted for publication in the Journal of Agricultural Water Management. The manuscript is co-authored by my supervisors Drs. S. O. Prasher and C.A. Madramootoo; Dr. A. Madani, Professor in the Engineering Department of Nova Scotia Agriculture College. 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: Development of DRAIN-WARMF Model to Simulate Flow and Nitrogen Transport in an Agricultural Watershed in Cold Climates

Shadi Dayyani, Shiv O. Prasher, Chandra A. Madramootoo, and Ali Madani

Abstract:

A new watershed model, DRAIN-WARMF, was developed to simulate the hydrologic processes and the nitrogen fate and transport that occur in small, predominantly subsurface-drained, agricultural watersheds that experience periodic freezing and thawing conditions. In this modeling approach, surface flow is simulated using a watershed-scale model, WARMF, and subsurface flow is estimated using a field-scale model for subsurface-drained shallow water table fields, DRAINMOD 5.1. For subsurface flow calculations, the watershed is subdivided into uniform cells, and DRAINMOD is run on each cell with inputs based on the individual hydrologic characteristics of the cell. The coupling results in a distributed parameter model that calculates the total flow at the outlet of a watershed as well as the nitrogen losses. The model was evaluated for the St. Esprit watershed, located approximately 50 km northeast of Montreal. Simulations were carried out from 1994 to 1996; data from 1994 and 1995 was used for model calibration and data from 1996 was used for model validation. The new model was able to adequately simulate the hydrologic response and nitrate losses at the outlet of the watershed. Comparing the observed daily-flow/monthly-nitrogen with the model's outputs over the validation period returned an R^2 value of 0.74/0.86 and modeling efficiency of 0.72/0.83. This clearly demonstrates the model's ability to simulate hydrology and nitrogen losses occurring in small agricultural watersheds in cold climates.

Key Terms: WARMF, DRAINMOD, Hydrology, Nitrogen, Watershed scale, Cold climate

6.1.Introduction

Across North America, particularly in humid regions with fine-textured soils, subsurface drainage systems are used effectively to enhance crop production by alleviating crop-water stresses, caused by shallow water tables. Approximately 2 million ha of cropland, used mostly for corn and soybean production, in the provinces of Ontario and Quebec are subsurface-drained (Helwig et al. 2002). However, while subsurface drainage removes excess water and improves crop productivity, it also increases the leaching of agro-chemicals from agricultural fields. Studies by the Quebec Ministry of the Environment (MENV) have reported that most rivers draining from agricultural lands have elevated nitrate and phosphorous concentrations (Enright and Madramootoo 2004). Surface runoff and tile drainage are the two principal pathways by which nutrients and sediment are transported from agricultural lands to waterways. Subsurface drainage acts as a conduit for leached nitrate–nitrogen to move rapidly into surface water supplies (Northcott et al. 2002).

Use of computer models has greatly increased our ability to model hydrologic and non-point source (NPS) pollution effects on field and watershed scales. Incorporation of real-time field data into a watershed model is economical and time-efficient since collecting long-term hydrologic and water quality data for a range of agro-climatic conditions is an expensive and time-consuming process. Several computer simulation models are currently available that can simulate hydrology as well as chemical transport through soil on a watershed scale [ANSWERS (Bouraoui et al., 2002), AnnAGNPS (Bingner et al, 1998), MIKE SHE (Refsgaard and Storm, 1995), SWAT (Arnold et al., 1998), and WARMF (Chen et al., 1998)]. However, only a few of these models can effectively simulate the dynamics of heat and water flow in soils that undergo periodic freezing and thawing cycles (Stahli et al. 1999). DRAINMOD 5.1 (Skaggs 1980), a subsurface flow model, includes freezing, thawing, and snowmelt components and thus, it is capable of simulating drainage phenomenon in cold regions. DRAINMOD has been tested worldwide and proven to be an efficient model in simulating subsurface flows from poorly drained, high water table soils experiencing freeze-thaw cycles (Luo et al. 2000; Luo et al. 2001; Sands et al. 2003; Dayyani et al. 2009a, b).

Watershed Analysis Risk Management Framework, WARMF (Chen et al., 1998), is a decision support system that can be used to evaluate water quality management alternatives in watersheds located in cold regions. WARMF has undergone several peer reviews by independent experts under EPA (Environment Protection Agency) guidelines, and is now available in the public domain via USEPA. The algorithms used in WARMF were derived from many well-established models. It has been applied to many watersheds and proven to be an effective tool in simulating surface flows on a watershed scale (Chen et al., 2001b).

Although WARMF can simulate subsurface flow/chemical transport, tile drainage systems are not taken into consideration by the model. Moreover, the subsurface flow component of the model tends to be somewhat simplistic. WARMF calculates the moisture of soil layers (up to 5 layers of soil) for every time step. If the moisture of a soil layer is below field capacity, the hydraulic conductivity of the said layer is zero. If the soil moisture is at saturation, the infiltration rate is the hydraulic conductivity. In between, WARMF interpolates the infiltration rate. A good approach to modeling the hydrology and water quality issues in agricultural watersheds in colder regions is to use a model that can adequately address the hydrology of both undrained and subsurface drained areas. DRAINMOD is a subsurface flow model which takes into account details of tile drainage system and simulates drain outflow, water table depth, and nitrogen losses, and appears to be a good candidate for subsurface flow calculation.

In this study, a new computer model was developed by combining the best features of two current models – surface hydrology simulations using WARMF and subsurface hydrology modeling with DRAINMOD, with the hope that the sum would be better than the parts. The linked model could offer an effective decision-making system for predominantly subsurface drained agricultural watersheds in cold regions. The new model would also allow for the evaluation of different management scenarios on a watershed scale.

Therefore, the overall goal of this study was to link DRAINMOD with WARMF to improve water flow and NPS pollution estimations from watersheds that are drained/partially-drained under frozen/unfrozen soil conditions. The first step in developing the linkage was to develop a computer program, written in Visual Basic programming language, to exploit the functionalities of Arc/GIS; this would prepare the input files for DRAINMOD, using local soil and hydrologic conditions on a watershed scale. Next, DRAINMOD was to be used for both drained and un-drained areas of the watershed to simulate subsurface flow and nitrogen fate and transport in unsaturated zone. Whereas the model can easily handle subsurface drainage conditions, the hydrology of un-drained areas was simulated using very wide drain spacing and making use of Darcy's law for computing flow from un-drained areas. Lastly, DRANMOD and WARMF were linked to simulate collectively the hydrology and NPS pollution on a watershed scale. The new linked model was evaluated using independently measured data from a small agricultural watershed.

6.1.1. WARMF Model (Watershed Analysis Risk Management Framework)

WARMF is classified as a watershed decision support system (DSS); it provides information and tools that facilitate collaborative decision making among interested parties (EPRI, 2001). WARMF is a user-friendly tool, organized into five linked modules (Engineering, Data, Knowledge, Consensus, and TMDL) under one, 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. The model can simulate stream flow/groundwater and sediment loadings. Furthermore, the fate and transport of nitrogen, phosphorus, heavy metals, and pesticides can also be simulated on a watershed scale. The scientific basis of the model has undergone several peer reviews by independent experts under US EPA guidelines (EPRI 2000). The algorithms for the model were derived from many well-established codes (Chen et al. 2001b). For example, the computing engine is taken from the Integrated Lake-Watershed Acidification Study (ILWAS) model (Chen et al., 1983). Algorithms for sediment erosion and pollutant transport from farm lands were adapted from ANSWERS (Beasley and Huggins, 1981), the universal soil loss equation. The sediment sorption-desorption of pesticides and phosphorus and the kinetics of nutrients and algal dynamics were adapted from WASP5 (Ambrose et al., 1991). The pollutant accumulation and wash-off from urban areas was adapted from the Storm Water Management Model (SWMM) (Agency, 1992).

The Engineering Module is a GIS-based watershed model that calculates daily runoff, ground water flow, and water quality of a watershed. A watershed is divided into a network of land catchments (including canopy and soil layers), stream segments, and lake layers for hydrologic and water quality simulations. Land surface is described by land use. The snow and soil hydrology is calculated using the precipitation on the land catchments; these results in surface runoff and groundwater entering the river segments. Water is then routed from one river segment to the next, from river segments to reservoirs, and from reservoirs to river segments until the watershed outlet. Along each flow path, the chemistry module calculates the mass balance and chemical equilibrium. A complete mass balance is performed, starting with atmospheric deposition and fertilizer application as boundary conditions. Pollutants are routed with water in throughfall, infiltration, soil adsorption, exfiltration, and overland flow. The sources of point and non-point loads are routed through the system with the mass in order for the source of non-point loading to be tracked back to land use and location (Chen et al., 1998). The potential evapotranspiration for each month is calculated as a function of latitude using Hargreaves equation (Hargreaves, 1974). The Data Module contains meteorology, air quality, point sources, and flow diversion data used to run the model. It also contains observed flow and water quality data used for model calibration purposes. The data is accessed using a map-based interface and can be viewed and edited in both graphical and tabular format. Supplemental watershed data, documents, case studies, or reports of past modeling activities are stored in the Knowledge Module for easy access by model users (Chen et al., 1998). The last two watershed approach modules are for Consensus building and TMDL calculation, which are roadmaps providing guidance for stakeholders during the decision making process. The Consensus Module provides information in a series of steps for stakeholders to learn about the issues, formulate and evaluate alternatives, and negotiate a consensus. Outputs can be displayed in color maps and graphs. Through the TMDL Module, calculations are made for a series of control points from upstream to the downstream of a watershed. Iterative sets of simulations can be performed to calculate various combinations of point and non-point loads that the water body can accept and meet the water quality criteria of the designated uses (Chen et al. 1998).

WARMF was evaluated for St. Esprit Watershed in Quebec (Dayyani et al., 2009c). The model was tested to simulate stream flow and nitrogen losses at the outlet of the watershed. The simulated daily/monthly flow and monthly $NO_3^{-}N$ were in good agreement with the measured values. The R^2 values were in the range of 0.53-0.94 and 0.84-0.89 for flow and nitrate-N losses, respectively. The coefficient of efficiency, E, was in the range of 0.45-0.91 and 0.75-0.86 for stream flow and $NO_3^{-}N$ losses, respectively. Thus, the performance of the model was deemed satisfactory (Dayyani et al., 2009c).

6.1.2. DRAINMOD Model

DRAINMOD (Skaggs, 1980) is a deterministic, hydrologic model that began as a tool for the design and evaluation of agricultural drainage and related water management systems of poorly drained soils. The model simulates the performance of a given shallow water table management system over a long period of climatological record. The water management systems can be a combination of subsurface drainage, controlled drainage, and sub-irrigation. The model uses approximate methods to compute a water balance for a vertical soil column of unit surface area at drain mid-spacing. Water balance is conducted on an hour-by-hour basis and predicts surface and subsurface drainage, infiltration and evapotranspiration. The rates of infiltration, evapotranspiration, drainage, and distribution of soil water in the profile are calculated by various methods, which have been tested and validated for a range of soil and boundary conditions (Skaggs, 1980). The Green-Ampt equation is used to describe the infiltration component in DRAINMOD. The model calculates daily potential ET using the Thornthwaite method (Thornthwaite, 1948), although ET can be computed by the method of the user's choice (e.g., Penman–Monteith or Hargreaves) and read by the model as input data. 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 ponded surface using Kirkham's steady state flow equation (Kirkham, 1957). Deep seepage rates are calculated with an application of Darcy's law (Darcy, 1856).

In DRAINMOD, the calculation of evapotranspiration and subsurface drainage depends on the position of the water table depth and the soil water distribution in the unsaturated zone. Soil water is assumed to be in two zones - the wet zone extending from the water table up to the root zone, or possibly through the root zone to the surface, and the dry zone. The water content distribution in the wet zone is assumed to have been drained to equilibrium. When the maximum rate of upward water movement, determined as a function of the water table depth, is not sufficient to supply the ET demand, water is removed from root zone storage creating a dry zone. The rooting depth in the model defines the zone from which water can be removed to supply ET. The dry zone, therefore, can extend equally to the root zone. When the dry zone depth becomes equal to the rooting depth, ET is limited by soil water conditions and is set equal to the upward water movement. The sum of wet and dry zone depths gives the water table depth at a time step. Further detailed descriptions of the hydrologic processes in DRAINMOD are given in Skaggs (1980).

The DRAINMOD model, version 5.1, includes freezing, thawing, and snowmelt components and is capable of simulating the drainage phenomena in cold regions. The model simultaneously solves the water flow equation and heat flow equation based on the principles of mass and energy conservation. It predicts soil temperature to simulate processes controlling field hydrology under cold conditions such as freezing, thawing, and snowmelt (Luo et al., 2000).

DRAINMOD 5.1 also includes a one-dimensional nitrogen cycling model (Breve et al., 1992). This version of the model uses the water balances and fluxes from DRAINMOD as inputs to a one-dimensional advective-dispersive-reactive equation for nitrogen fate and transport. The model considers a simplified version of the nitrogen cycle using nitrate as the main pool. The nitrogen balance considers fertilizer dissolution, mineralization of organic nitrogen, denitrification, and plant uptake using first order rate equations. At each daily time step, first order rate equations are used to balance transformations to and from the nitrate pool. The DRAINMOD simulated hydrology provides the necessary water contents, soil water contents and fluxes for simulating the nitrate transport. The nitrogen sub-model uses the daily outputs from DRAINMOD as the hydrology inputs. Crop potential yield, nitrogen content of the crop, and nitrogen fertilizer application amounts and dates are specified. Other inputs include nitrate concentration in the rain and the dispersivity and reaction rate coefficients for the nitrogen transformations.

Over the past two 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).

We have evaluated the hydrology and nitrogen components of DRAINMOD 5.1 for two sites in the province of Quebec where artificial drainage is a common practice in cold climates. The model was tested to simulate water table fluctuations and drain outflows under different water table management practices and also nitrogen fate and transport through the tile drainage in soils typical of Quebec (Dayyani et al., 2009a, b). The simulated daily WTD and drainage outflows were in good agreement with the measured values. The R^2 values were in the range of 0.48-0.95 and 0.78-0.93 for drainage outflow and WTD, respectively. The model also gave good results for drain outflow in cold months given its ability to address frozen soil conditions. The coefficient of efficiency, E, was in the range of 0.5-0.7 and 0.3-0.7 for subsurface flow and WTD, respectively. For the subsurface flow results, the E values were 0.72 for calibration years and 0.48 for validation years (2002 - 2003). These values are indicative of an acceptable model performance in a colder region of North America. Moreover, DRAINMOD 5.1 was calibrated and validated for WTD, tile drainage volume and NO_3^-–N losses in southern Quebec (cold climate) under water table management practices, such as free drainage and sub-irrigation (Dayyani et al., 2009b). The model predicted the daily WTDs, daily drainage outflows, and monthly nitrate-nitrogen losses with an acceptable degree of accuracy for both FD and SI water table management practices. The R^2 values were in the range of 0.84-0.88 for daily drainage outflow. The nitrogen component provided good results for both sub-irrigation and free drainage [R^2 (FD and SI) $\geq$ 0.91]. Thus, the performance of the model was deemed satisfactory. It may be concluded that the DRAINMOD 5.1 model can be effectively used to simulate WTD depth, drainage outflows and NO_3^-–N losses in cold regions (Dayyani et al., 2009a, b).

6.2.DRAIN-WARMF Modeling Procedure

DRAINMOD is a field-scale model and it needs to be up-scaled in order to simulate the hydrology of a watershed. This study uses a distributed parameter approach in which watershed is subdivided into field–sized units (cells), and

DRAINMOD is run with inputs based on the individual soil type, land use and subsurface drainage system of each cell. DRAINMOD results for individual cells are routed and summed to calculate the total daily/monthly subsurface flow at the watershed outlet. To implement this process, a computer program written in the Visual Basic programming language was combined with the functionality of GIS to manage the large amount of data needed to run the model on numerous cells, prepare and store input data, create DRAINMOD input files, develop the supplementary modules, and manage output files.

The DRAIN-WARMF modeling interface contains 11 modules. As can be seen in Figure 6.1, the modules are: 1- GIS module; 2- WARMF output processor; 3- DRAINMOD parameter generation and input file creator; 4- DRAINMOD cell simulation; 5- DRAINMOD output processor; 6- Subsurface flow calculator for un-drained cells; 7- Subsurface flow calculator at the outlet (routed/not routed); 8- Total flow calculator at the watershed outlet; 9- Surface nitrogen processor; 10- Subsurface nitrogen processor; and 11- Total nitrogen calculator. Each of these modules is described briefly.

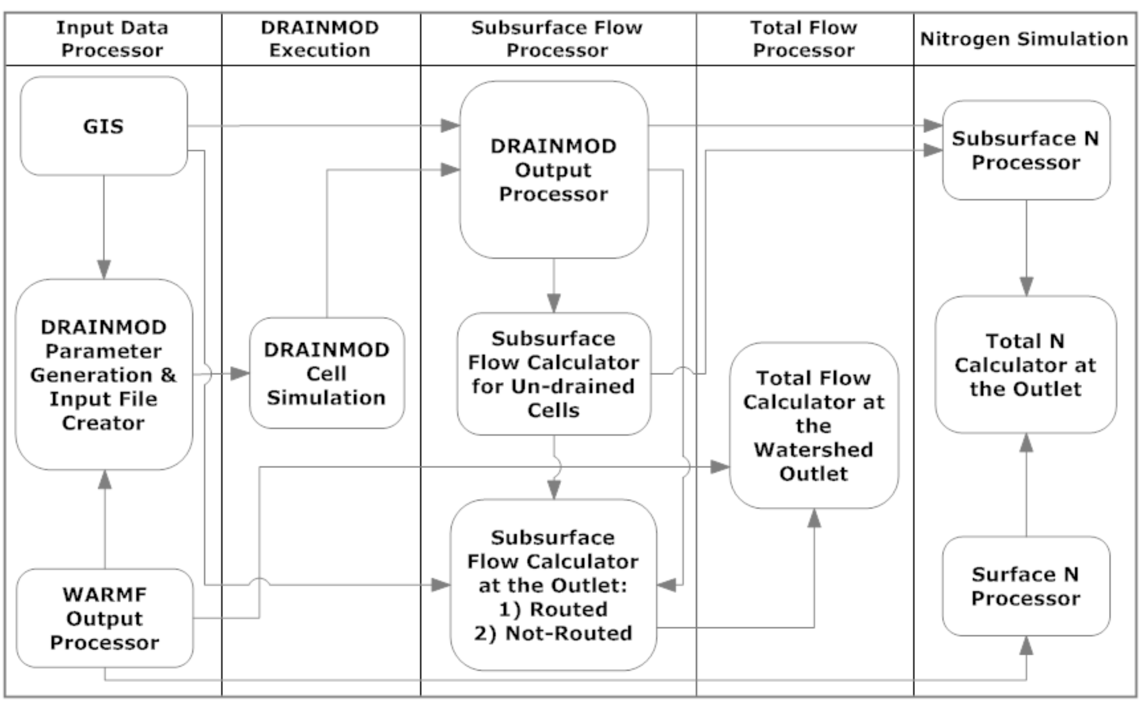

Figure 6.1. DRAIN-WARMF modeling interface flowchart

6.2.1. The GIS Module

The basic GIS database requirements for the DRAIN–WARMF interface include a sub-watershed boundary map (polygon), land use map (polygon), drainage map (polygon), soil map (polygon), stream network map (line), nitrogen application map (polygon), and DEM or digital elevation model (grid). All of these layers are ArcGIS shape files (vector), with the exception of the digital elevation map, which is in ArcGIS ‘grid’ format (raster).

Using GIS tools and the watershed boundary map, the entire watershed is subdivided into units/cells (same size, here 200 m); the user is queried for the desired cell size and then a cell layer is created. A digital elevation map with the corresponding cell size is required for determining flow direction for subsurface flow routing. A digital elevation map, a grid with elevation value for each cell, is developed using topographic data (contour lines and elevation point data). The natural drainage network is generated from the digital elevation model (DEM) of the watershed, using the ArcHydro tools of GIS. This stream network map is required to determine the distance that water travels from each cell to the watershed outlet for the purpose of subsurface flow routing. The sub-watershed boundary map is developed using DEM and by knowing where the watershed outlet is located. GIS develops the flow direction and flow accumulation maps from DEM and then delineates the sub-watershed boundaries. The county-level soil maps are digitized and a soil database is developed and used to identify the soil type for each cell of the watershed. The drainage area maps are used to determine if a cell is tile-drained or not, and if it is drained, the drainage parameters are derived.

6.2.2. WARMF Output Processor Module

One of the main outputs of the WARMF model, the depth of surface flow for each sub-watershed, is used in this module. On a daily basis, surface flow depth is subtracted from precipitation. The difference is referred to herein by the term “net rainfall” for DRAINMOD simulations. To prevent DRAINMOD from simulating surface runoff, the surface storage value is set to a large value to force all the net rainfall to infiltrate into the soil. Also, the monthly evapotranspiration factors are set close to zero in DRAINMOD in order for the simulated ET by DRAINMOD to be close to zero. This has been done since evapotranspiration is already simulated using WARMF.

6.2.3. DRAINMOD Parameter Generation and Input File Creator Module

For each soil type in the watershed (based on the soil map), DRAINMOD soil input files ('.sin', '.mis', and '.wdv') are required. For all types of land uses, a DRAINMOD '.cin' file is required. The land use information is taken from the land use map. DRAINMOD also requires several drainage system design parameters, such as: drain spacing and depth, effective drain radius, drainage coefficient, impermeable layer depth, and surface storage. Drain depth, effective drain radius, impermeable layer depth, and drainage coefficient are set to average values for the watershed. Drain spacing varies over the watershed and surface storage is set to a large value in order to prevent surface runoff. Using the cell layer, DRAINMOD input parameters for each cell are extracted from land use, soil, drainage, and sub-watershed layers of the GIS. Based on the soil type and land use of the cell, the following files are created: '.sin', '.mis', '.wdv', and '.cin'. Lateral saturated hydraulic conductivity is soil-specific and input into the model by the soil file used for each cell. According to the drainage layer, each cell is either tile-drained or not. In cells with no drain tubes, the simulation set up consists of increasing the spacing of the drains (wide spacing) and effectively shutting off the drainage system. This allows for water balance to be calculated without a subsurface drainage component.

The input file creator module creates the .gen and .prj files for each cell. These files store DRAINMOD input parameters for each cell and identify accompanying files (weather, cropping, soils, and hydrology). This module results in a full set of DRAINMOD input files for each cell in the watershed.

6.2.4. DRAINMOD Cell Simulation and DRAINMOD Output Processor

The cell simulation module reads the input files for each cell and runs DRAINMOD simulations for all of the cells in the watershed, drained or un-drained. The output processor model reads the results. The module reads the daily subsurface flow depth and water table depth (WTD) from the DRAINMOD '.plt' output file for each of the drained cells; and only the water table depth values for the un-drained cells. The daily subsurface flow volume for drained cells is calculated by multiplying the daily subsurface flow depth by the drainage area of each cell.

6.2.5. Subsurface Flow Calculator for Un-Drained Cells

To calculate the subsurface flow from un-drained cells, Darcy's law is used. The Darcy equation can be written as:

$$Q = CKA\frac{H_A - H_X}{L} \qquad 6.1$$

Where Q is flow rate (m^3/s), K is the hydraulic conductivity (cm/day), A is the flow cross sectional area (m^2), $\frac{H_A - H_X}{L}$ is the hydraulic gradient, H_A and H_X are the hydraulic heads at point A and X (m), L is length between point A and X (m), C is a unit conversion factor. In Figure 6.2, X could be the centroid of any cell from 1 through 8.

In order to calculate the flow coming out of cell "A" (un-drained cell), the receiving cell needs to be determined (Figure 6.2). Following steps illustrate the method used to determine the flow direction from cell A:

Using GIS tools and DEM layer, the elevation of cell A and all adjacent cells are known. The water table depth (WTD) of each cell is also known (from the DRAINMOD output processor module).

Water table height (WTH) of each cell is calculated as,

$$WTH_{cell} = Elevation_{cell} - WTD_{cell} \qquad 6.2$$

The distance (D) between cell A and its 8 neighbour cells is calculated using GIS tools. The ΔWTH is calculated between cell A and adjacent cells:

$$\Delta WTH_{A,i} = WTH_A - WTH_i \qquad (\mathrm{i} = 1\ \mathrm{to}\ 8) \tag{6.3}$$

$\Delta WTH_{A,i}$ is divided by the distance between two corresponding cells to compute the hydraulic gradient:

$$\frac{\Delta WTH_{A,i}}{D_{A,i}} \tag{6.4}$$

The maximum hydraulic gradient is determined; cell A drains to the cell with maximum hydraulic gradient.

Once the flow direction is determined (Figure 6.3), the amount of flow leaving cell A is calculated using Darcy's equation (Eq. 6.1).

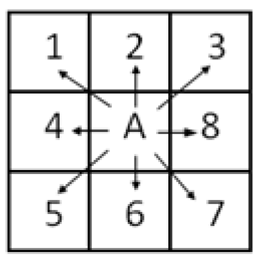

Figure 6.2. Determination of receiving cell for each un-drained cell

Therefore, equation 6.1 can be re-written as follow:

$$Q = CK(H_6 X)\frac{\Delta WTD}{D} \tag{6.5}$$

where X is the cell dimension, and K, the hydraulic conductivity, is the lesser of hydraulic conductivity of cell A and cell 6. This module results in daily subsurface flow rates from all un-drained cells in the watershed.

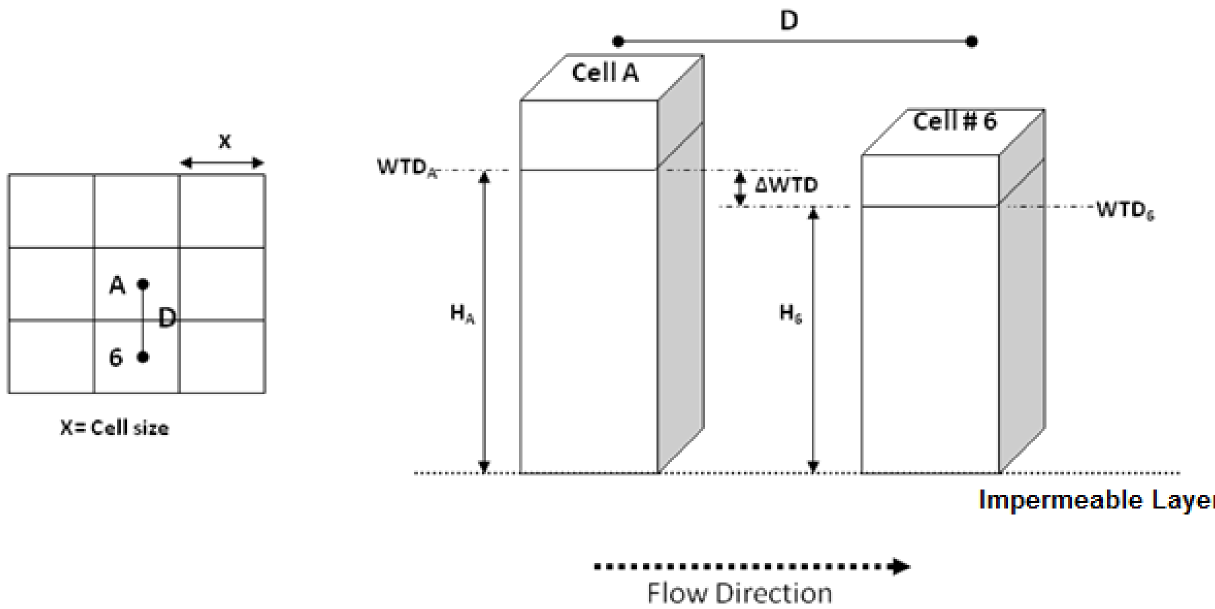

Figure 6.3. Flow calculation using Darcy's law

6.2.6. Subsurface Flow Calculator at the Outlet

Two methods are used to calculate the total subsurface flow at the outlet of the watershed: un-routed and routed methods.

6.2.6.1. Un-Routed Method

In this method, the results from each cell are summed to provide the subsurface drainage flow component for the entire watershed on a daily basis. Flow from all of the cells reaches the outlet at the same day, assuming the time of concentration for the watershed to be less than a day (valid for small watersheds).

6.2.6.2. Routed Method

In the second method, flow from each cell is routed to the watershed outlet through the streams. In this module, using GIS tools, distance from each cell (L_i) to the outlet is calculated through the streams (streams considered as routes). Knowing the average time of concentration for the watershed and the longest path

(L_{max}) for water to travel to the watershed outlet, the time delay for each cell is calculated as follows:

$$(\text{Time Delay})_i = \frac{(\text{Average Time of Concentration}) * (L_i)}{L_{max}} \qquad 6.6$$

If the time delay of a cell is more than a day, the flow is delayed according to the time delay.

6.2.7. Total Flow Calculator at the Watershed Outlet

This module develops a daily hydrograph at the watershed outlet. The outflow hydrograph is a combination of subsurface flow from each cell (routed or un-routed), and surface flow (from WARMF).

6.2.8. Surface/Subsurface Nitrogen Processor

The total nitrogen load in surface flow at the watershed outlet is determined by multiplying the daily surface flow volumes by nitrogen concentration taken from WARMF output files.

In subsurface flows, the nitrogen load at the edge of each cell is calculated by multiplying the daily subsurface flow volumes by nitrogen concentration, using DRAINMOD output files for each cell.

6.2.9. Total Nitrogen Calculator

Total daily nitrogen load at the watershed outlet is calculated by adding the total daily nitrogen loads in surface and subsurface flows (results of surface/subsurface nitrogen processor)

6.3. Model Application

The DRAIN–WARMF model was applied to the St. Esprit watershed, located approximately 50 km north of Montreal between 45^o 55’0” and 46^o 0’0’’ N, and 73^o 41’32’ and 73^o 36’0’ W (Figure 6.4) in south-western Quebec, Canada. It is a part of the 210 km^2 St. Esprit River Basin, a tributary of the L'Assomption Watershed (4220 km^2). The land in the watershed is predominantly used for agriculture. The human population of the watershed is about 700; however, there are no villages or towns within the watershed. The St. Esprit Watershed is comprised of a net drainage area of 24.4 km^2. During the study period (1994-1996), approximately 64% of the total area was under crop production with the majority of land use under corn crop, followed by cereals, soybeans, vegetables, hay, and pastures. The remaining 36% of the area was occupied by forested, bare, and residential lands. Table 6.1 shows the distribution of land use in St. Esprit watershed. Over 50% of the agricultural land has subsurface drainage.

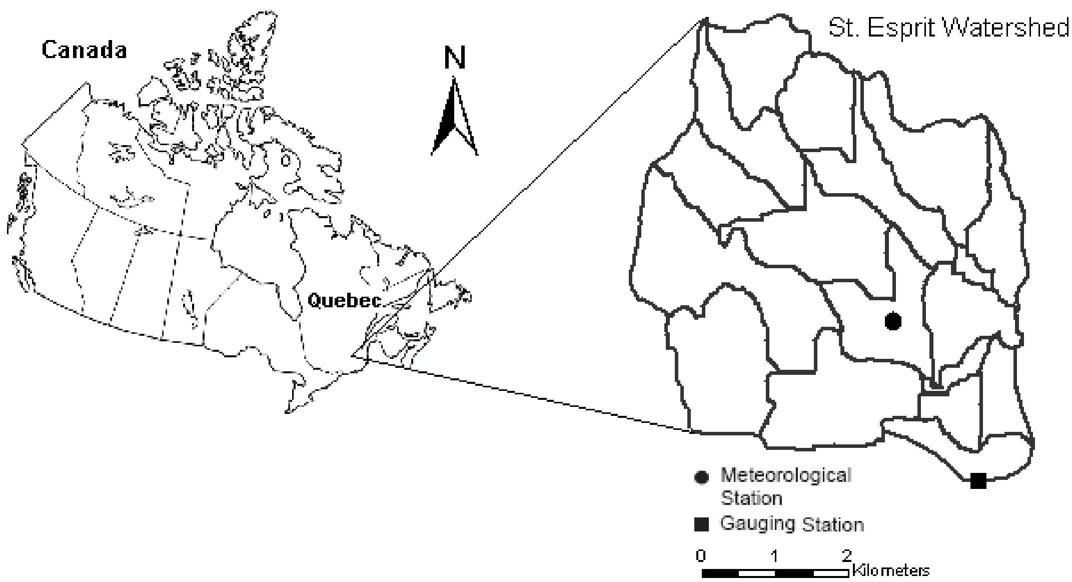

Figure 6.4. Location of St. Esprit watershed

The difference in elevation from the outlet to the highest point of the watershed is 44 m and the principal watercourse is 8.5 km long. Topography can be described as flat to rolling, with most of cultivated land having slopes of less than 3%. The elevation data was obtained from GeoBase (GeoBase, 2007), Canadian Digital Elevation Data (CDED); the watershed boundary was created using GIS tools and DEM (Figure 6.5). The streams map was taken from previous studies on St. Esprit watershed and also created using DEM and GIS tools (Enright et al., 1995; Mousavizadeh et al., 1995; Sarangi et al., 2005a,b). These maps, along with

1:63360 soil maps (Lajoie, 1965), 1:15000 field-level aerial photography, and information provided by the producers (Enright et al., 1995) identified approximately 16 soil series, and 10 different land use categories (Figure 6.6). Soil textures in the watershed are variable; in general, the largest proportion of the watershed is occupied by coarse-textured soils (sand and sandy loam 44%), followed by fine-textured soils (clay and clay loam 39%). The distribution of soil textural classes in the watershed is shown in Figure 6.7. The lower portion of the watershed is mostly composed of clays and clay loams, including the Ste. Rosaile and St. Laurent series (Lapp et al., 1998). Most of the annual crop production takes place on the heavier soils. The upper regions of the watershed are composed of loamy and sandy soils. Natural drainage on these soils is poor and the majority of these soils are subsurface drained. (Enright et al., 1995).

Table 6.1. Land use distribution on St. Esprit Watershed

Landuse	Area (m^2)	Area (%)
Corn	6272062.93	25.75
Cereal	2073508.21	8.51
Soya	1565615.35	6.43
Vegetable	1966098.15	8.07
Hay	2919677.45	11.99
Forest	6345533.46	26.05
Pasture	703183.30	2.89
Irrigation-pond	165435.29	0.68
Residential	1241620.58	5.10
Unused	1107938.69	4.55
Total	24360673.39	100

The climate of the watershed is temperate. The period of frost varies from 122 to 138 days. Average annual precipitation varies between 860 and 1050 mm, with approximately 20 to 25% appearing as snow (Sarangi et al., 2005a,b). Average annual potential evapotranspiration is between 400 and 560 mm. The mean temperature in the month of July varies between 18 and 21 °C (MAPAQ, 1983).

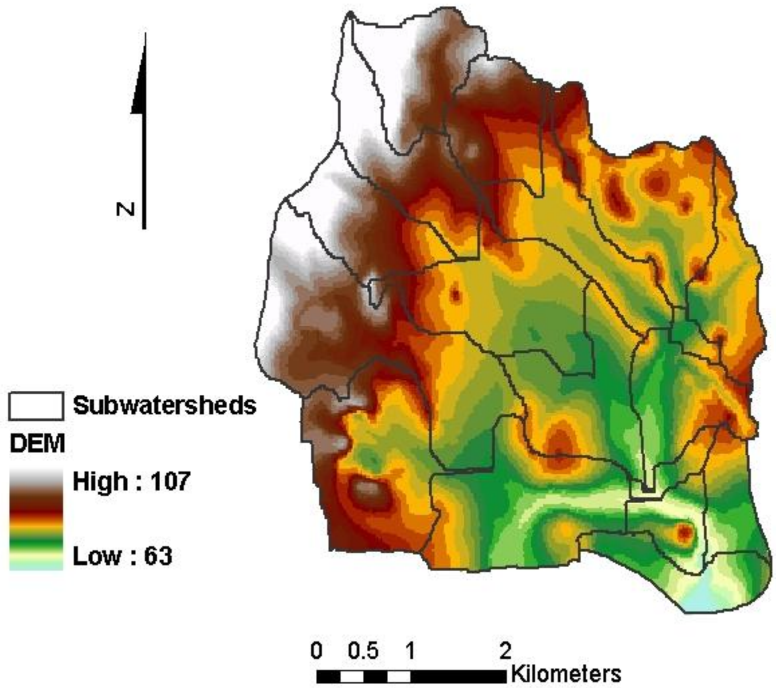

Figure 6.5. Topography map of St. Esprit watershed (DEM)

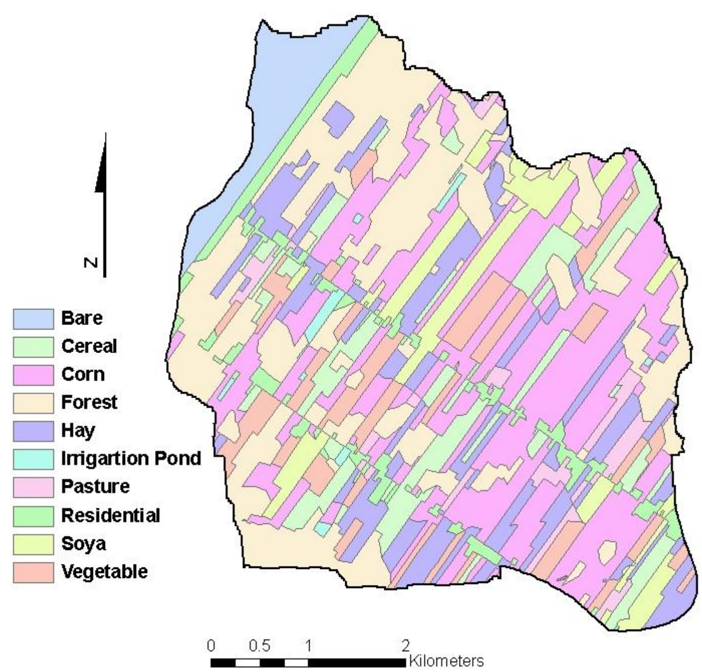

Figure 6.6. Land use map of St. Esprit watershed

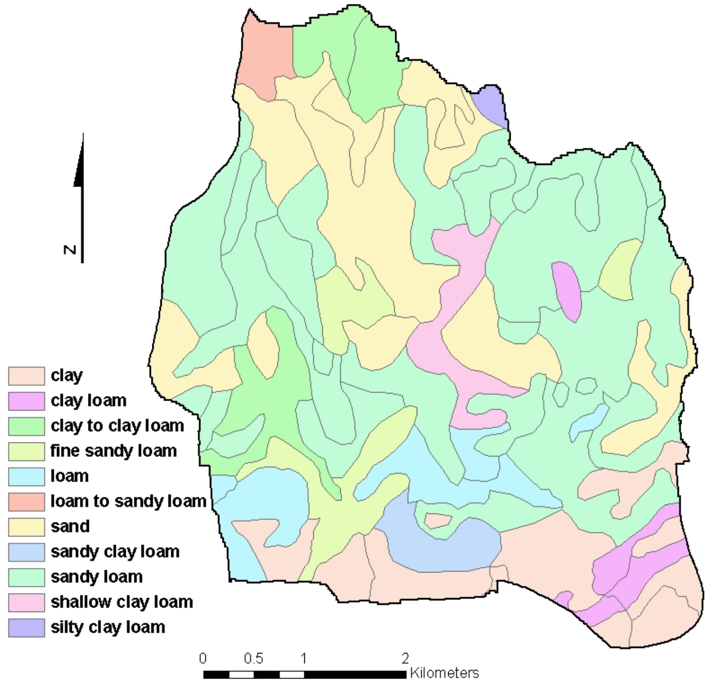

Figure 6.7. Soil texture map of St. Esprit watershed

6.3.1. Instrumentation and Monitoring

In the winter of 1993-1994, a stream gauging station was established at the watershed outlet, and a meteorological station was installed in the watershed (Figure 6.4). The equipment installed at the watershed outlet included a water level sensor (Druck 950 submersible pressure transducer) installed on the stream bed bottom, a UDG01 ultrasonic level sensor mounted over the outlet culvert, and a data logger (Campbell CR10) located in the gauging station building to record and store the data. A backup system that independently measures water level and flow velocity and sends these data to the primary data logger was also installed The meteorological station was equipped with sensors for air and soil temperature, solar radiation, wind speed and direction, snow accumulation, as well as a tipping bucket rain gauge and a Campbell data logger (Perrone and Madramootoo, 1998). Table 6.2 shows monthly precipitation for 1994-1996 measured at the site and average 30 year monthly precipitation measured at the St. Jacques weather station, located about 6 km from the experimental site. The annual precipitation of 1994 and 1995 is 14 and 49 mm below the 30-year average, respectively; while, the annual precipitation in 1995 was 71 mm above the 30-year average (Table 6.2).

Land use and land management information were collected on St. Esprit as part of an integrated watershed monitoring and management project (Enright et al., 1995; Papineau and Enright, 1997). There were 25 farms, of which information from 18 of the farms was available. The participating producers account for approximately 67% of the agricultural land use of the watershed (Sarangi et al., 2005a,b). Water samples were collected on a flow-weighted basis. An automated water sampler was installed at the gauging station. A sampler intake line was suspended over the control section to be monitored. An automated sampling strategy was based on the flow volume calculation; the automated sampler was programmed for activation at a variable but predetermined threshold value of accumulated flow. The collected samples consisted of the automated type and the in-stream grab samples collected on the weekly or bi-weekly site visits. Details of the water sampling protocol are given in Enright et al. (1995).

Table 6.2. Monthly precipitation (mm)

	1994	1995	1996	30 year average
January	111.0	140.0	156.0	66.5
February	45.0	37.0	131.0	37.0
March	47.3	53.8	50.0	52.0
April	105.2	44.3	73.0	78.1
May	53.3	85.0	53.0	86.7
June	187.0	38.0	92.0	103.2
July	119.0	122.0	96.0	87.5
August	113.0	82.0	85.0	92.1
September	45.0	58.0	89.0	98.0
October	20.0	91.0	70.0	87.0
November	63.0	97.0	71.0	89.9
December	19.0	45.0	46.0	63.4
Total	927.8	893.1	1012.0	941.4

6.3.2. Executing the Model

DRAINMOD inputs include soil and crop properties, drainage system parameters, and climatic data (daily max/min air temperature and hourly precipitation). DRAINMOD requires additional inputs in order to reflect the freezing and thawing phenomenon. These include the two constants relating soil thermal conductivity to soil water content, the rain/snow-dividing temperature, the snow melt base temperature and degree–day coefficient for snowmelt, the critical ice content above which infiltration stops, the initial soil temperature distribution and a base temperature as the lower boundary condition, the phase lag for daily air temperature sine wave, the initial snow depth and density, and soil freezing characteristics which indicate the relationship between unfrozen water content and soil temperature. Nitrogen-related parameters, required in DRAINMOD, include standard rate coefficients for denitrification and net mineralization, soil dispersivity, and the nitrogen content in rain and crops. Soil temperature and nitrogen-related parameter values were taken from Dayyani et al. (2009a, b) for two experimental sites located within the same climate area with similar soil conditions in south-western Quebec.

WARMF inputs include meteorology data (daily precipitation and min/max temperature, cloud cover, dew point temperature, air pressure, and wind speed), soil properties (field and saturated moistures of soil, vertical and horizontal hydraulic conductivities, and bulk density), land use data, digital elevation (DEM) map, and fertilizer application data. WARMF's water quality related parameters are comprised of initial soil concentration of ammonia, soil nitrification rate, litter fall rate, productivity of land uses, and air quality data. Air quality data was obtained from the National Atmospheric Deposition Program (NADP, 2009). The closest station to the watershed was HWF187, located approximately 220 km south of the watershed. Other parameters were set to the default values recommended in the model manual.

Climatic data were obtained from the meteorological station installed in the watershed. Soil maps and previous research done in Quebec were used to define soil parameters (Dayyani et al., 2009a, b, c; Mousavizadeh 1998 and 1992; Perrone 1997). Crop related data was taken from land use maps. Fertilizer data was obtained from the GIS shape files developed for the watershed. The van Genuchten equation was used to determine the soil parameters (retention curve and hydraulic conductivity). The van Genuchten parameters were obtained from the Rosetta model (Schaap et al. 2001), using the soil textural classes as primary input data. Rosetta is a computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions.

To begin modeling, the field–scale simulation of DRAINMOD was performed on a single cell within the watershed to establish template files for the watershed simulation. Template files consist of the general (.gen) and project (.prj) files, which store DRAINMOD input parameter values and identify accompanying files (weather, cropping, soils, and hydrology) that will be used in the model. These template files act as master DRAINMOD input files for the rest of the cells in the watershed. The model loads WARMF outputs and reads depth of surface runoff values for each sub-watershed. Rainfall values are modified and “net rainfall” files are created for each cell. DRAINMOD’s template files are loaded, the model creates copies of the files for each cell in the watershed and simultaneously substitutes site–specific cell parameters derived from the GIS into each corresponding file. Site-specific parameters taken from the GIS include: soil, crop, nitrogen application, net rainfall, and drainage information which indicates if a cell is drained or un-drained and provides drainage system information. This results in a full set of DRAINMOD input files for each cell in the watershed. DRAINMOD cell simulations are run and subsurface flow depth and water table depth values are read from the DRAINMOD’s *.plt output files. Daily subsurface flow for un-drained cells is calculated using a subsurface flow calculator module. The model calculates the total daily flow at the outlet and the daily nitrate-nitrogen load using the Surface/Subsurface nitrogen module.

6.4. Methods of Evaluation

Three years of complete data (1994-1996) was split into two parts: 1994-1995 for calibration and 1996 for validation. Statistical tools were used to analyze the results in order to evaluate model performance for both calibration and validation processes.

The model performance was first qualitatively assessed with graphical displays of the results and then statistical measures were used for quantitative evaluation. Statistical parameters such as average deviation (AD), root mean square error (RMSE), coefficient of determination (R^2), and Nash-Sutcliffe coefficient (E) were used (Nash and Sutcliffe, 1970). The coefficient of determination is a measure of accuracy or the degree to which the measured and predicted values agree. The average deviation is used to determine whether the model made over- or under-predictions. The root mean square error measures the difference between predicted and observed values. It is sensitive to the extreme values and deals with both systematic and random errors. The Nash and Sutcliffe coefficient measures the goodness-of-fit between observed and simulated values. A value of 1 represents a perfect match, while a value of zero (0) shows a prediction no better than using the mean of the data. The negative efficiency indicates that the prediction is worse than simply taking the mean of the measured values.

6.5.Results and Discussion

6.5.1.Model Calibration

Calibration started on May 1st, 1993 in order to initialize the model; the first 8 months of simulation (May 1st, 1993 to January 1st, 1994) were not considered in the calibration process. The model initialization was important for both models; WARMF assumes zero initial snowpack so it is recommended to start simulation before January 1st; moreover, while evaluating DRAINMOD, the authors obtained better results using an initialization period during model calibration (Dayyani et al., 2009a, b).

Model calibration was performed to evaluate the differences between the simulated and observed values from the gage station located at the outlet of St. Esprit Watershed. To adequately represent the system being modeled, the calibration parameters were varied, one at a time, with an appropriate range, using a trial-and-error approach.

Calibration parameters for the linked model were chosen based on the studies by Dayyani et al. (2009a, b, c). DRAINMOD was calibrated for two experimental sites in Quebec under similar conditions, based on lateral saturated hydraulic conductivities of the three layers, vertical hydraulic conductivity of the restrictive layer, soil surface storage, monthly ET factors, soil freezing characteristics (soil thermal conductivity parameters), snowmelt constants (degree-day factor and threshold melting temperature), denitrification rate, and initial NO_3^- concentration in the soil. Parameters adjusted in the WARMF evaluation study (Dayyani et al., 2009c) included evaporation coefficients, snow/ice related parameters (melting rates, snow formation and melting temperature), field and saturated soil moisture, vertical/horizontal hydraulic conductivities, detention storage, initial soil concentration of ammonia, and soil nitrification rate. In this study, the model was calibrated by adjusting the hydraulic conductivity of soil layers, detention storage, evaporation coefficients, snow/ice related parameters (melting rates, snow formation and melting temperature), and surface roughness (Manning's n), litter fall rate, denitrification rate, soil dispersivity, and initial nitrate concentrations in the soil. The initial values of the calibration parameters were taken from studies conducted by the authors (Dayyani et al., 2009a, b, and c). A formal sensitivity analysis was not performed during this study due to the long execution time required by the linked model. Nevertheless, it was found during the calibration process that the model was sensitive to hydraulic conductivity of soil layers, ET coefficient, surface storage, Manning's n, the threshold melting temperature, initial soil concentrations, and nitrification/denitrification rates. The values of the above-mentioned parameters used in this study are listed in Table 6.3.

Table 6.3. Model parameters subjected to calibration

Calibration Parameter	Range	Final Value
Lateral hydraulic conductivity of soil layers, cm/hr (for different soil types)	0.1 - 7.4	varies for different soil types
Surface roughness (for different land uses)	0.01 - 0.1	Urban (0.011), Agriculture (0.04), Pasture (0.03), Forest (0.013), Barren (0.025), Streams (0.04)
Soil Thermal Conductivity functions (a, b)	0.4 - 1.6, 1.3 - 2.3	1.55, 1.5
Detention storage, %	0 - 30	15
Evaporation coefficients:		
Magnitude	0.6 - 1	0.9
Skewness	0.6 – 1.4	1
Snow/ice related parameters:		
Open area melting rates, cm / °C / day	0.05 - 0.1	0.05
Snow formation temperature, ^{o}C	0 - 3	0
Snow melting temperature, ^{o}C	0 - 3	0
Litter fall rate, Kg /m^2/month	0 - 0.2	Varies for different months
Denitrification rate, 1/day	0.9 - 1.9	1.08
Soil dispersivity	6-Mar	5
Initial nitrate concentration in the soil, mg/l	0.01 - 10	0.1

6.5.1.1. Hydrologic Simulation

As stated earlier, WARMF was calibrated and validated for the same study area (Dayyani et al., 2009c), and DRAINMOD was evaluated for two experimental sites in Quebec with the same soil and climatic conditions. The initial input parameters for the first run of the DRAIN-WARMF model were set equal to the calibrated values of WARMF and DRAINMOD.

DRAIN-WARMF's simulated values were compared with the observed data. The results of routed and un-routed methods were almost the same since it is a small watershed. The routed results are presented here. The model seemed to overestimate surface flow before calibration (pre-calibration results are not presented here). This was corrected by adjusting the values of hydraulic conductivity, detention storage, evaporation coefficients, and surface roughness. The evaporation magnitude and detention storage used in the calibrated model were 0.9 and 0.15 (Table 6.3). In spite of these adjustments, there remained some mismatch between the magnitudes of the peaks; it appears as if the simulated peaks generally exceed the observed ones.

Daily:

Time series of daily observed and model predicted flows are shown in Figure 6.8. The model seems to have performed well at simulating the number and timing of runoff events in both snowmelt and later–season periods.

Summer/Fall season (June - November):

Over the calibration years, most simulated flow peaks matched their observed counterparts, both in terms of timing and quantity although some under- and over-estimations occurred for certain events. Some events were slightly overestimated (27/06/1994, 24/07/1994, and early-August 1994; Figure 6.8). The hydraulic conductivity was estimated from the soil textural classes using the Rosetta software, since the field data was not available. Furthermore, soil hydraulic conductivity was considered to be uniform throughout the year. In reality, the soil’s conductivity may be altered by cultivation operations. Similarly, root development and the enhanced activities of earthworms and other organisms could result in preferential flow through macropores. Therefore, the hydraulic conductivity of the soil might actually have been greater than the values used in the simulations. Conversely, the 16/11/1995 simulated peak was found to be smaller than the observed value (Figure 6.8). Greater observed runoff peak for this event is possibly due to the high intensity, short-duration storm that happened the day before (26.6 mm) where the temperature was above the freezing point.

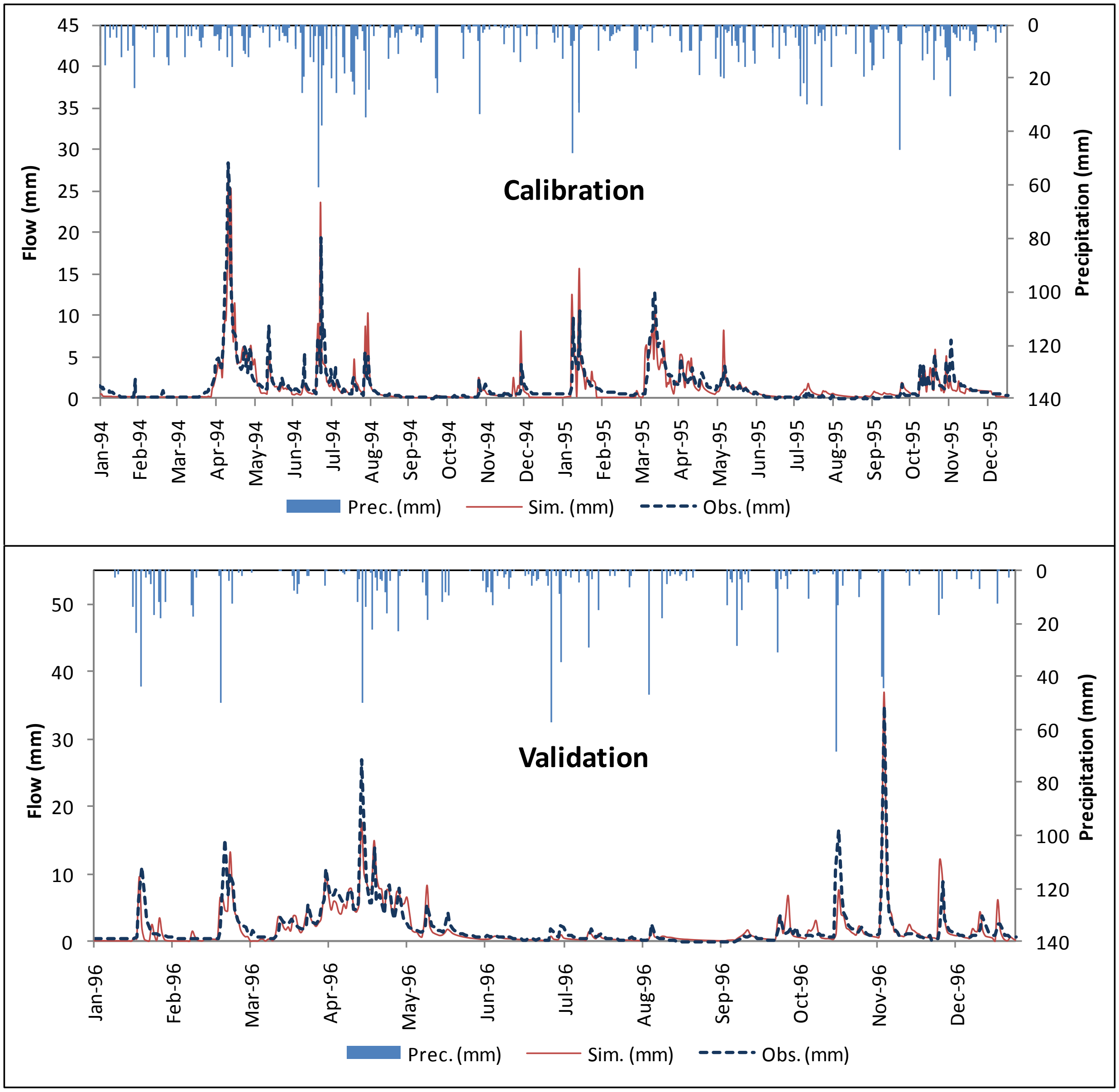

Figure 6.8. Daily hyetograph and hydrographs for calibration and validation period

During the validation period, simulated and observed hydrographs (Figure 6.8) show that the simulated flow generally matched its respective observed flow although, some over- and under-estimations occurred. For example, in early-October 1996 flow was over estimated. The high value for the simulated runoff (11 mm) on 1st and 2nd of October 1996 is justified by the important rainfall events on the preceding days (31.3 mm). Despite large rainfall events, observed runoffs were low as a result of greater actual evapotranspiration and infiltration than was predicted. Given greater hydraulic conductivity during the growing season, the actual runoff decreased. On 22/10/1996 (Figure 6.8), the observed runoff (16.4 mm) was almost two times that simulated (7.6 mm) due to a rainfall depth of 68 mm on the preceding days. Possibly, this could be due to the high intensity and short duration of the storm events already described. Such events can be compared with that which occurred on 16/11/1995 during the calibration period.

In spite of the over- and under-prediction, the model performed well for the following events: 2/11/1994, 22/10/1995, 9/08/1996, and 9/11/1996. These predicted events matched extremely well with the observed runoff. For example, on 9/11/1996 (Figure 6.8), the simulated and observed flows were 36.8 mm and 34.9 mm, respectively, arising from a 44.8 mm rainfall event on the same day and 40.4 mm on the previous day. Also on 9/08/1996, the simulated and observed runoff values were 2.0 mm and 2.6 mm, caused by a rainfall event of 47 mm on the previous day. Although for the same periods, such phenomena were not observed for all years; this could be explained by the spatial and temporal variability in the soil properties and the growth of vegetation. In addition, the time to peaks for the simulated and observed runoff events were very well matched during both the calibration and validation periods (e.g. 13/06/1994, 1/08/1994, 25/10/1995, and 20/10/1996), possibly because the adjusted Mannings' n was able to represent adequately the watershed surface roughness coefficient.

Winter/Spring season (December - May):

As was the case in the summer/fall season, the model under- or over-estimated the flow for certain events through the winter/spring period (Figure 6.8). During the calibration period, on 22/03/1995 the observed flow (12.6 mm) was almost twice the simulated flow (6.13 mm). The minimum temperature for that day was zero (0^{o}C) while the temperature was below the freezing point for the preceding and the following day. Although the temperature was 0^{o}C on the 22^{nd}, the precipitation was in the form of rainfall (verified with data from environment Canada (ENV CAN, 2007)). The observed runoff occurred as a result of the rainfall on the same day as well as the frozen soil conditions and the melting of the previously accumulated snow on the surface; the model, on the other hand, considered the precipitation as snow on the 22nd and, therefore, simulated less runoff.

In certain cases, the model simulated greater flow than was observed (5/12/1994, mid-January (15th & 21st) 1995, and 17/05/1995). On 5/12/1994, the temperature dropped below 0^{o}C, causing the rainfall from the previous day to freeze on the ground. However, the model does not consider water freezing on the ground surface, thus simulating greater runoff. Furthermore, in the following days, there would be less simulated accumulated snow on the ground surface, resulting in less subsequent runoff on 6/12/1994 (Figure 6.8). On 15/01/1995 the minimum temperature increased from -16 (on previous day) to 1^{o}C causing the model to simulate more flow, while the observed data shows that the ground surface was still frozen and the rainfall froze when it reached the ground (same reasoning for 21/01/1995).

For most of the events during the winter/spring period, simulated and observed timing of runoff peaks was found to differ by one day (e.g. 4/12/1994 and 14/01/1995). This difference is thought to arise due to the quantity of accumulated snow on the soil surface resulting in differences in the roughness of bare and snow-covered land surfaces. The model considers the same surface roughness coefficient irrespective of the day of the year or the soil surface conditions. In reality, flow velocity is higher on snow-covered surfaces; thus, the time for the flow to reach the watershed outlet is faster.

Over the validation period, the model underestimated the flow on 16/04/1996; the observed flow was 26.9 mm while the simulated value was 17.6 mm. On the runoff day, maximum and minimum temperatures were 2^{o}C and 7^{o}C, respectively. The 25 mm precipitation on the previous day was in the form of rainfall (verified with data from environment Canada (ENV CAN, 2007)), although the temperature was below the freezing point. The model considered the rainfall (25 mm) on the previous day as snow and this resulted in a lower simulated runoff.

On the other hand, some simulated runoff events were greater than those observed (21/02/1996, early May 1996, and 1 & 24 December 1996). For example on 21/02/1996, the observed runoff (10.34 mm) from 55.2 mm of rainfall was almost half of the simulated value (20.62 mm). The minimum temperature increased from -28^{o} (on the previous day) to 2^{o}C (on 21st) causing the model to simulate more flow, while the observed data shows that the soil surface was still frozen.

There was no precipitation on 1st and 24th of December 1996; thus, the simulated runoff could be due to the fact that the minimum temperature rose to above freezing point on both days, while on the preceding days there were negative minimum temperatures. In reality the soil surface is still frozen and the observed runoff is lower than the simulated values.

Although some under- and over estimations occurred for certain events, most simulated flow peaks matched well with the corresponding observed values, both in terms of timing and quantity, especially in the cold months. The model performed reasonably well for certain events in this period (e.g. 16/04/1994, 16/05/1994, 13/04/1995, 19/01/1996, 2/04/1996, 21/04/1996, and 18/12/1996). On 16/04/1994, the observed and simulated runoff was 24.1 mm and 25.3 mm, respectively, from a rainfall event of 16.1 mm on the same day and 11.9 mm on the previous day. Peaks' timing matched perfectly for some events (e.g. 27/01/94, 18/05/1995, 21/01/1996, 15/04/1996, and 1/12/1996).

Statistical Analysis:

The statistical analysis is presented in Table 6.4. The positive mean deviation during the calibration and validation period between observed and simulated values indicates that the model slightly under-predicted flow (Table 6.4). Mean deviation values, 0.14 and 0.16 mm, indicate that daily under-estimations were small. The coefficient of determination was above 0.69 for the calibration/validation years, showing good correspondance between the simulated and observed values. The modeling errors were low: the RMSE 1.50 and 1.70 mm, further indicating a good simulation. Finally, the model performance tested by the E (≥ 0.66), again corroborated that the observed and predicted runoff volume matched quite well.

Table 6.4. Model performance during calibration and validation

Statistical Parameter	Calibration (1994-1995)	Validation (1996)
Daily drain flow		
AD (mm)	0.14	0.16
RMSE (mm)	1.5	1.7
R^2	0.69	0.76
E	0.66	0.75
Monthly drain flow		
AD (mm)	4.44	3.6
RMSE (mm)	9.86	10.62
R^2	0.98	0.97
E	0.96	0.97
Monthly Nitrogen losses		
AD (kg/ha)	0.15	0.16
RMSE (kg/ha)	0.25	0.46
R^2	0.98	0.86
E	0.96	0.83

Monthly:

Figure 6.9 presents the comparison of monthly simulated and observed stream flow. The predictions matched well for both the calibration and validation years. The model appears to simulate monthly runoff quite well. The average deviation was 4.44 mm and 3.6 mm for calibration and validation years, respectively (Table 6.4). The coefficient of determination (R^2) and modeling efficiency were above 0.96 for both periods. This indicates that the model is capable of simulating flow accurately in cold regions.

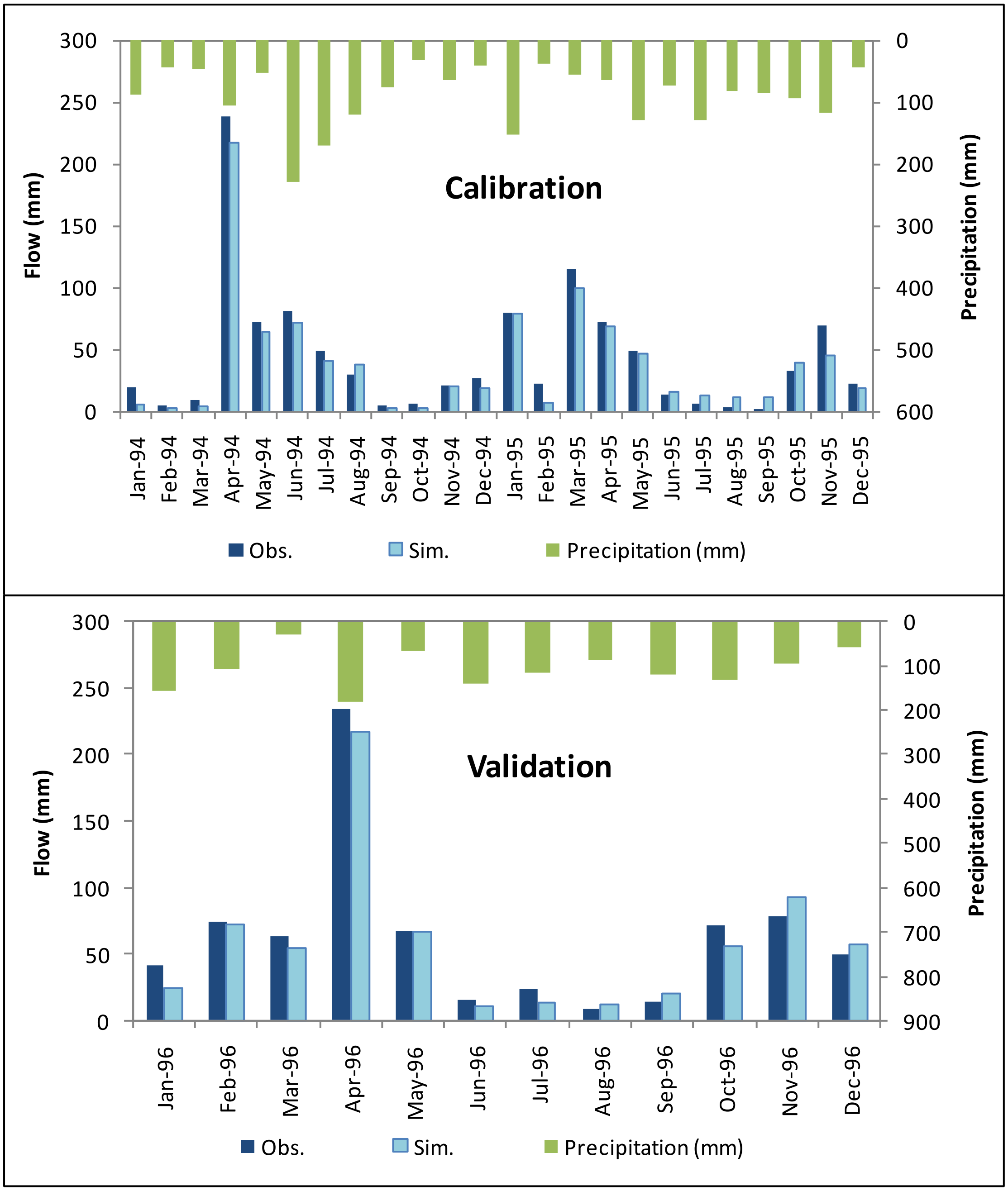

Figure 6.9. Monthly hyetograph and hydrographs for calibration and validation period

6.5.1.2. Water Balance Analysis

As part of the hydrologic calibration, the overall water balance was calculated for each water year (for 1994 the water balance is calculated from the beginning of January). For the total simulation period from 1994 to 1996, total water diverted from the watershed into the stream at the outlet was 3.68 x10^7 m^3. The annual water balance summaries for the three hydrological years of simulation are presented in Table 6.5.

Table 6.5. Annual water balance for the simulation period

Water Year	PPT (mm)	ET (mm)	Flow (mm)	Change in Storage (mm)	Error in mm (%)
Oct 1993- Sept 1994	1083.8	566.1	535.6	17.4	-35.3 (3)
Oct 1994- Sept 1995	762.1	531.2	396.0	-93.2	-71.9 (9)
Oct 1995- Sept 1996	1058.0	548.7	581.1	25.7	-97.5 (9)

PPT – precipitation; ET – evapotranspiration

From 51 to 69% (mean = 57%) of the annual precipitation was simulated as being lost in evapotranspiration across the watershed (Table 6.5). Since the model simulated the water table depth for each cell, a mean water table is calculated by averaging that of all the model‘s grids. The water balance error was obtained by balancing all the major hydrologic components simulated in the model (precipitation, evapotranspiration, stream flow, and changes in storage). This error was then divided by the precipitation and presented as a percent error. The change in storage simulated by the model indicated an increase in water table depths over a given year. For example, the decrease in storage for the hydrologic year 1994-95 implies that the water stored in the soil contributed to other components of water balance and this resulted in an overall drop in the water table level. For 1996, there was a positive change in the storage, leading to a shallower water table at the end of the year.

6.5.1.3. Nitrogen Simulation

Once the hydrology component of the model was calibrated and validated, nitrogen simulations were conducted to calibrate the nitrogen component of the model. Water quality data collected during the flow calibration period, 1994-1995, was used to guide the nitrogen calibration. Using parameters fine-tuned in the calibration process, the model was validated using 1996 data.

Initial runs of the model to simulate NO_3^--N at the watershed outlet were conducted using the nitrogen input values, as per Dayyani et al. (2009b,c). As mentioned earlier, the adjusted parameters used during calibration were denitrification rate (DRAINMOD and WARMF), litter fall rate (WARMF), soil dispersivity (DRAINMOD), and initial nitrate concentrations in the soil (DRAINMOD and WARMF). Figure 6.10 compares the simulated and observed monthly NO_3^-–N losses at the outlet of St. Esprit watershed.

The movement of NO_3–N has been closely associated with the movement of water in agricultural soils in several studies (Armstrong and Burt 1993). In this study, the NO_3^-–N losses in surface/subsurface flows were strongly dependent on outflow rates (Fig. 6.10). The comparison between the observed and simulated monthly nitrate-nitrogen losses shows that the model performed quite well, although tended to slightly under-predict cumulative losses (Table 6.6, Fig. 6.11), which could be due to underestimation of flows.

Table 6.6. Observed and simulated cumulative flow and NO_3-N losses

	Obs		Sim	
	Flow (mm)	N (kg/ha)	Flow (mm)	N (kg/ha)
1994	563.8	14.6	466.9	12.5
1995	488.5	12.7	456.1	11.2
1996	742.4	20.1	708.1	18.1

In 1994, 67% of the overall NO_3^--N losses was recorded in April, May and June; this is correlated to the intensive flow rates (72% of the annual flow) measured during this period (Fig. 6.10). In 1994, heavy rainfall events occurred soon after the second surface fertilizer application (early-June). June had 187 mm of rainfall, 1.8 times the 30-year average rainfall (Table 6.2). The model might have overestimated denitrification between January and March in both calibration and validation periods (shallow water table might have favoured high N denitrification), leaving less mineral N susceptible to leaching in the profile (Fig. 6.10). Similarly, cumulative NO_3^--N losses in surface and subsurface flows (Fig. 6.11) showed that DRAIN-WARMF underestimated the total annual losses by 12% and 7% during calibration and validation periods, respectively.

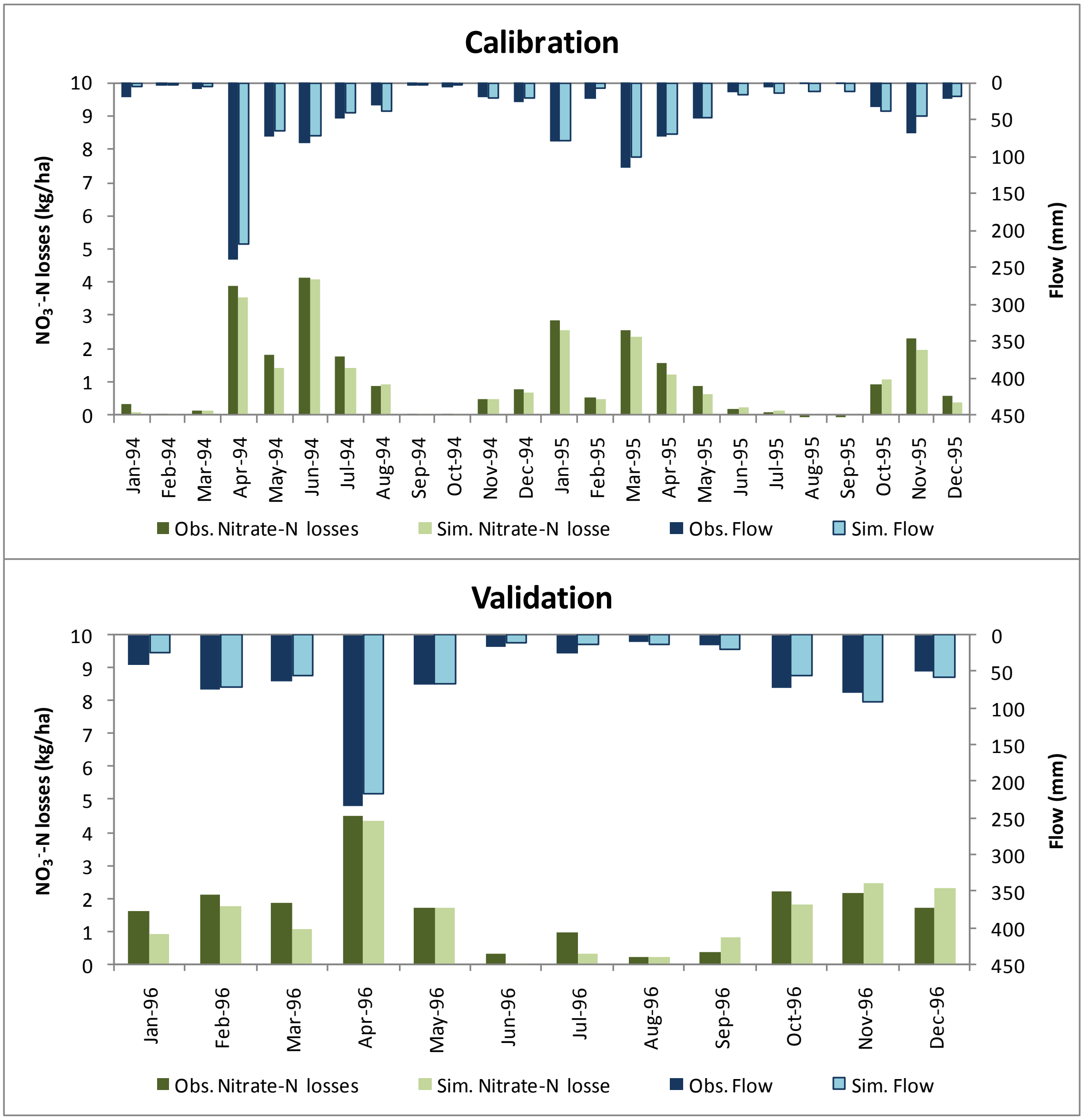

Figure 6.10. Simulated vs. observed monthly NO_3^--N losses at the outlet for calibration and validation period

The NO_3^--N losses were overestimated between November-December 1996 (Fig. 6.10). The average monthly minimum temperature for these months was much higher in 1996 compared to 1994 and 1995 (temperature data not presented here). Thus, it is possible that the model overestimated N mineralization rates, which partly contributed to the errors in predicting NO_3^--N losses during these periods. Unfortunately, neither denitrification nor N mineralization was measured and, therefore, it was not possible to directly test the accuracy of the model prediction for these quantities. Furthermore, model parameterization based mainly on the literature rather than field and laboratory measurements can cause some errors in predicting NO_3^{-}-N losses.

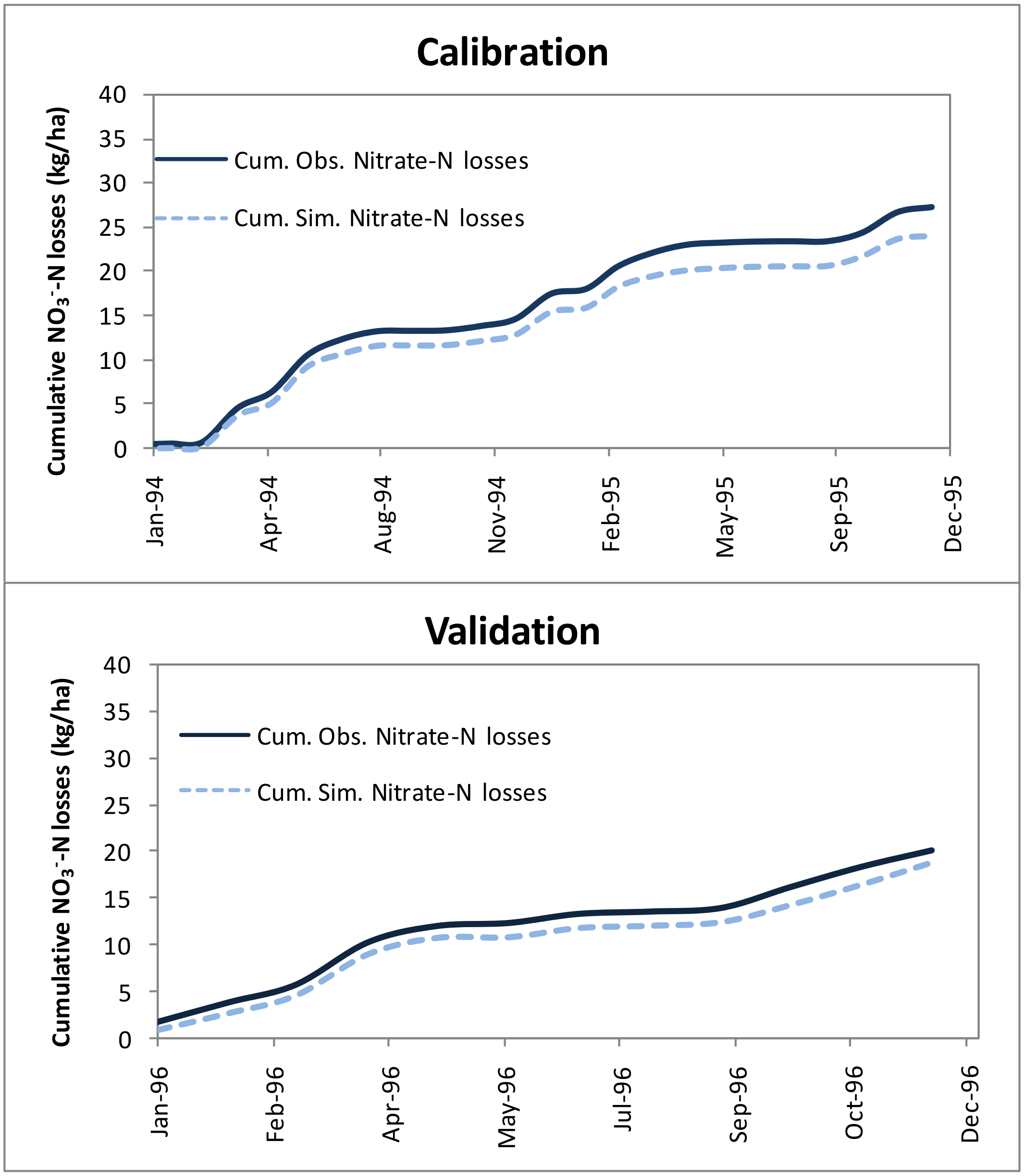

Figure 6.11. Simulated vs. observed cumulative NO_3–N losses at the watershed outlet for calibration and validation periods

Overall, the comparison between the observed and simulated monthly and cumulative nitrate-nitrogen losses (Figs. 6.10, 6.11; Table 6.6) shows that the model performed quite well, although tended to slightly under-predict cumulative losses. This could be due to the flow underestimation by the model.

The statistical indices calculated from the observed and simulated NO_3^--N losses for the calibration and validation periods are presented in Table 6.4. In the calibration and validation periods, simulated NO_3^-–N losses are more or less in agreement with the observed values. The overall mean deviation (AD) value of 0.15 kg ha^{-1} indicates that the model slightly under-predicted monthly N losses (Table 6.4). The coefficient of determination was high for both calibration and validation years ($\geq$ 0.86) indicating a close match between observed and simulated NO_3^--N losses. Overall, the model performance was slightly better during the calibration period, with the modeling efficiency (E) being 0.96 as compared to 0.83 for validation.

In the three seasons which experienced high flows (winter, spring, and fall), the dynamics of nutrient transport are markedly different due to the changing hydrologic conditions between these seasons. DRAIN-WARMF was able to reproduce the conditions of all seasons adequately for both the calibration and validation years, although the spring and winter flow was slightly underestimated, and this error was carried over when estimating nitrate loads (Fig. 6.12).

Mousavizadeh (1998) applied ANSWERS2000 to the St. Esprit Watershed. The model seemed to underestimate the flow; total simulated cumulative runoff values were 66.6%, 54.9%, and 71.7% of measured cumulative runoff values, for 1994, 1995, and 1996, respectively. Romero (2000) evaluated the performance of SLURP hydrological model at St. Esprit Watershed and reported R^2 values of 0.522 and 0.66 for calibration and validation periods, respectively. Northcott et al. (2002) used a GIS-integrated DRAINMOD model to simulate the flow on a tile-drained watershed in Illinois, and reported R^2 values ranging from 0.29 to 0.78 for daily stream flow. Fernandez et al. (2002) evaluated the performance of WHATGIS watershed model in simulating the monthly flow and nitrate-N loads. They reported Nash-Sutcliffe coefficient of 0.85 and 0.83 for flow and nitrate-nitrogen monthly simulations. Geza and McCray (2007) applied WARMF model to a watershed in Colorado and reported E= 0.58 and R^2= 0.68 for simulation of monthly stream flow. SWAT model has been applied to different watersheds around the world; the range of reported R^2 and E values are: for daily flow R^2 = 0.04-0.78 (Wang et al., 2008; Wang et al., 2005; Eckhardt and Arnold, 2001; Spruill et al., 2000; Peterson and Hamlett, 1998) and E= -0.04 to 0.84 (Bosch et al., 2004; Eckhardt and Arnold, 2001; Spruill et al., 2000); for monthly flow R^2= 0.35-0.92 (Wang et al., 2008; Jha et al., 2007; Gebremeskel et al., 2005; Chu and Shirmohammadi, 2004; Santhi et al., 2001; Spruill et al., 2000; Bingner, 1996) and E= 0.48- 0.94 (Jha et al., 2007; Gebremeskel et al., 2005; Bosch et al., 2004; Di Luzio et al., 2002; Saleh et al., 2000; Peterson and Hamlett, 1998); for monthly simulation of nitrate-nitrogen R^2= 0.72- 0.89 (Jha et al., 2007; Santhi et al., 2001) and E= 0.27- 0.73 (Jha et al., 2007; Di Luzio, 2002; Saleh et al., 2000). Comparing the results of this study (Table 6.4) with mentioned applications of different watershed models indicates that the DRAIN-WARMF models performed well in simulating flow and N loads at the outlet of the watershed.

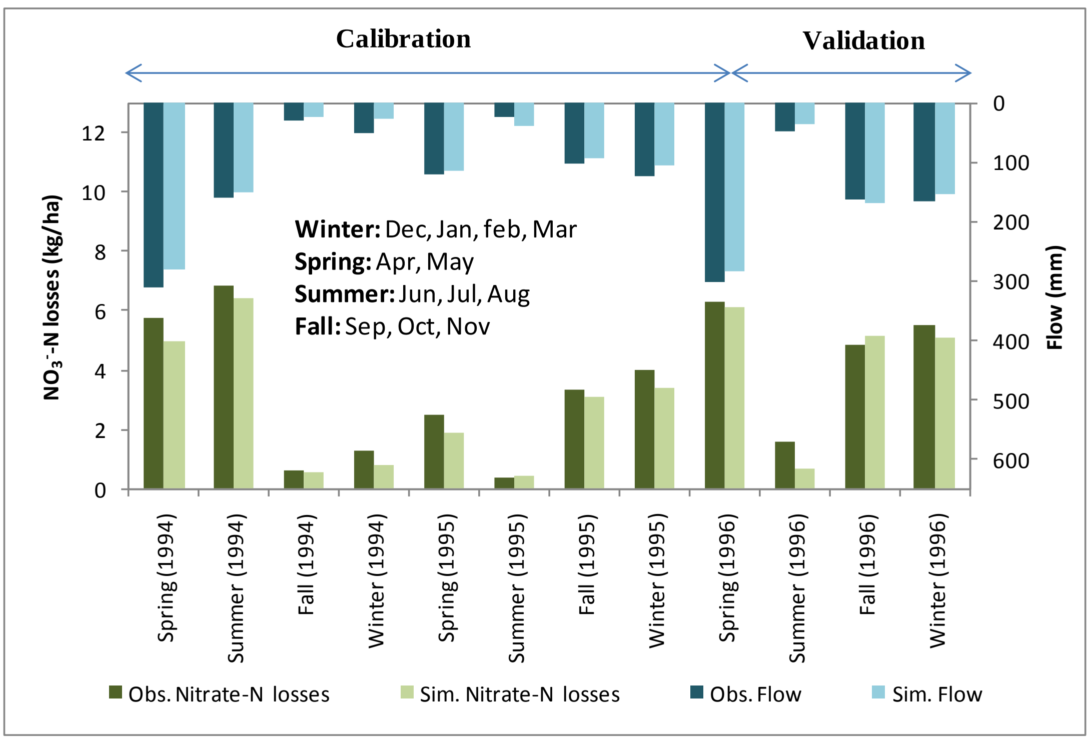

Figure 6.12. Simulated vs. observed seasonal flow and NO_3^--N losses at the watershed outlet for calibration (1994-1995) and validation (1996) periods

6.6.Conclusions

A new watershed model, DRAIN-WARMF, was developed; it combined WARMF, a watershed model developed primarily for simulating surface runoff, and DRAINMOD, a subsurface flow model for subsurface-drained fields. The primary goal behind model integration was to improve the accuracy, reliability, and predictive ability of the combined surface and subsurface flow simulations for small tile-drained agricultural watersheds that experience periodic freeze/thaw conditions. By linking WARMF and DRAINMOD models, the strong surface flow modeling capabilities of the former were combined with the higher accuracy of subsurface modeling of the latter. The final model is superior performance-wise to both of the models and allows for simulations to be carried out under different scenario analyses and management practices, which were not possible using the models individually.

The new model uses a distributed parameter approach by subdividing the watershed into cells and performing DRAINMOD simulations on each cell. Cell simulations return subsurface drainage flow and nitrogen losses from each cell. Cell results are routed and summed to simulate flow and determine the total NO_3-N losses at the outlet of the watershed. The lateral flow between adjacent cells is calculated using Darcy's Law and it is added to the cells' flow results.

The DRAIN-WARMF model was applied to predict daily surface/subsurface flow and nitrogen losses from a 24 km^2 St. Esprit watershed in south-western Quebec, Canada. The hydrologic response of the watershed was simulated for a three-year period from 1994 to 1996. There was good agreement between the observed and the predicted flow with R^2, average daily deviation, and Nash and Sutcliffe coefficient of 0.76, 0.16 mm, 0.75, respectively. The model also performed well in simulating the flow during the snowmelt period with the error of 10%, 4%, and 6% in 1994, 1995, and 1996, respectively. The model also performed well in simulating nitrate loads at the outlet of watershed (Nash and Sutcliffe coefficient ≥ 0.83). The new model provides a method for simulating the hydrology of tile-drained watersheds where subsurface drainage systems are the main mechanisms for removing excess water from the root zone. Once tested, the model could be used to evaluate environmentally sound management practices in cold regions.

CONNECTING TEXT TO CHAPTER 7

This chapter addresses the forth objective of this thesis. It presents the results of an application of DRAIN-WAMRF model in evaluating the effects of potential climate change on surface and subsurface flow and nitrogen transport at an agricultural watershed. The simulations were performed using the projected climate change conditions developed by CRCM4.2.0 model for 1961 to 2100, provided by OURANOS organization.

This chapter is a manuscript in review for publication in the Journal of Environmental Quality in 2009. The manuscript is co-authored by my supervisors Drs. S. O. Prasher and C.A. Madramootoo; Dr. A. Madani, Professor in the Engineering Department of Nova Scotia Agriculture College. 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 development and evaluation of DRAIN-WARMF model for hydrology and nitrate loads for an agricultural watershed in Quebec’s climatic conditions.

CHAPTER 7: Impact of Climate Change on the Hydrology and Nitrogen Pollution in a Tile-Drained Agricultural Watershed in Eastern Canada

Shadi Dayyani, Shiv O. Prasher, Chandra A. Madramootoo, and Ali Madani

Abstract:

The potential effects of climate change on the hydrology and nitrogen pollution of an agricultural watershed are predicted using the DRAIN-WARMF model. Newly-developed, physically-based hydrological model (DRAIN-WARMF) is applied on the St. Esprit watershed in southwestern Quebec, Canada. Under the assumption of no change in land use and land management, the model is applied in order to simulate annual, seasonal and monthly changes in surface and subsurface flows and NO_3-N loads at the outlet of the watershed under current and future climate conditions. The climate scenario under consideration in this study for 1961 to 2100 is based on projections from the Canadian Regional Climate Model (CRCM). The simulation results from the CRCM model suggest an increase in temperature and precipitation in the region being studied. Those changes result in a significant increase in simulated mean annual and seasonal flow in the watershed. Moreover, water quality simulations under future climatic conditions show a significant increase in annual and seasonal NO_3-N losses.

Key Terms: Modeling, Climate Change, Hydrology, Nitrogen, Drainage, Cold Climate

7.1. Introduction

Global warming due to the enhanced greenhouse effect is likely to have significant effects on local hydrologic regimes. The hydrological cycle would be affected with more evaporation and more precipitation; however, the extra precipitation would be unequally distributed around the globe. Some parts of the world may see significant reductions in precipitation, or major alterations in the timing of wet and dry seasons. The changes in the hydrological behaviour of watersheds caused by climate change will also affect nutrient transformation and transport characteristics (Bouraoui et al. 2004). An increase in diffuse-source pollutant loads and in nutrient cycling is among the effects to be expected. Research is needed to understand the impact of potential climate change on the environment. Indeed, if climate change occurs, it will have a significant impact not only on the quantity but also on the quality of surface and subsurface waters, impacting the ecosystem beyond the tolerable threshold, leading potentially to a constant degradation of water quality (Murdoch et al. 2000). The Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 1996) warned that climate change will lead to increases in both floods and droughts. Many aspects of the environment, economy and society are dependent upon water resources, and changes in the hydrological resource base have the potential to impact environmental quality, economic development and social well-being (Arnell, 1999). These potential changes caused by climate variations need to be addressed, or at the very least, taken into consideration by policy makers and decision makers when managing water resources in the future.

Since hydrologic conditions vary from region to region, the influences of climatic change on local hydrological processes will differ within localities, even under the same climate scenarios (Zhang et al., 2007). Studies in recent years have shown that important regional water resources are vulnerable to changes in both temperature and precipitation patterns (Lahmer et al., 2001). It is primarily at the local and regional level that policy and technical measures could be taken to prevent, or reduce, the negative effects of climate change on the natural environment and society.

Predictions have been made that the Canadian climate, in general, will become warmer, and more variable (Hengeveld, 2000). Some recent examples of climate change impacts on water resources include melting of the permafrost in Northern Quebec, rising sea levels in Atlantic Canada, glacial retreat in British Columbia, and prolonged drought in the Prairies (Mehdi et al., 2006). The impact on water resources in Canada as a result of climate change has been investigated by several institutional and government agencies (Mehdi et al., 2006). Overall, increased water volume in a wetter climate will affect water quality. Warmer and wetter conditions will influence the hydrologic cycle, with implications for precipitation and runoff, and consequently, the point and non-point source (NPS) pollutions that are flushed by runoff. During high runoff, erosion and sediment transport will increase, and biological and chemical transformations within surface waters will decrease because of reduced residence times (Murdoch et al., 2000). Higher flows can mobilize the organic matter stored within stream banks, lakes, and wetlands, causing an increase in dissolved organic carbon concentrations and a decrease in water clarity (Mulholland et al., 1997). A wetter climate will enlarge the spatial extent of direct runoff to surface waters, thus considerably increasing pollutant loads from point sources and NPS pollution that are hydrologically isolated or filtered through groundwater aquifers under current flow conditions (Jacoby, 1990; Lins and Slack, 1999; Mulholland et al., 1997). Increased sea level and expanded watershed source areas for runoff could result in leaching of contaminants from the numerous hazardous waste dumps located in the coastal region (Jacoby, 1990). These are dependent on local geology and human resource use, and therefore, will be highly location-specific.

Analyzing the climate-change impact on hydrology and nutrients in watersheds requires the use of models that integrate the most important hydrological, chemical and ecological processes. Although it is widely recognized that climate variability and climate change can affect water quality, there have been few research studies on small watersheds. In comparison to studies undertaken in larger river watersheds, small watershed scale studies are better able to capture local vulnerabilities to rapid and intense changes in climate (Chang et al., 2001). To the best of our knowledge, no studies have been conducted using a complex, physically-based, distributed hydrologic model that addresses both surface and subsurface flows to predict future hydrologic and water quality as a response to climate change at the regional level under the cold climatic conditions found in Canada.

The Soil and Water Assessment Tool (SWAT) model has been applied to several projects in the USA dealing with the impact of climate change on water supplies and reservoir operations (Arnold and Fohrer 2005), including: regional impacts of climate change on the recharge of groundwater to the an aquifer (Rosenberg et al., 1999); impact of climate change on water yields in a high-elevation, mountainous watershed (Stonefelt et al., 2000); impact of climate change on the Missouri River reservoir operation and water supply (Hotchkiss et al., 2000); and surface water irrigation and riparian management influenced by climate change (Wollmuth and Eheart, 2000). DRAINWAT, a watershed-scale forest hydrology model, has been applied to evaluate the potential effects of climate change on the hydrology of a 3,000 ha managed pine forest in coastal North Carolina (Amatya et al., 2006). Quilbé et al. (2008) used the GIBSI model (Gestion Intégrée des Bassins Versants a l'aide d'un Systéme Informatisé), which is a surface flow model based on the distributed hydrological model HYDROTEL (Fortin et al., 1995), to assess the effect of climate change on river flow in Quebec, Canada. The simulations were performed for a reference period of 1970-1999 and a short-term future period of 2010-2039. They found out that between 2010 and 2039 the studied watershed exhibits a statistically significant decrease in annual runoff, an increase in runoff during winter, a decrease in spring peak flow, and no obvious effect of climate change on summer low flows, under the modeled conditions (Quilbé et al., 2008). To the best of the authors' knowledge, no study has been conducted evaluating the effect of climate change on the hydrology and nitrogen losses in agricultural watersheds in a cold climate; considering both surface and subsurface (shallow groundwater) flows.

The authors have developed a new model, DRAIN-WARMF, by integrating a field scale subsurface flow model, DRAINMOD (Skaggs, 1980), with a watershed scale surface flow model, WARMF (Watershed Analysis Risk Management Framework; Chen et al., 1998), to simulate the hydrology and water quality of agricultural watersheds (Dayyani et al., 2009d). In this modeling approach, surface flow and nitrate-N transport is simulated using WARMF; while DRAINMOD is used to model subsurface flow and the fate and transport of NO_3^--

N in subsoil. The integrated model was calibrated and validated for an agricultural watershed in Quebec using daily stream flow and nitrogen data measured from 1994 to 1996 (Dayyani et al., 2009d). The calibration and validation results showed that the model was able to simulate the monthly stream flow and nitrate-N loads well, with a coefficient of determination and Nash-Sutcliffe efficiency greater than 0.86 for both calibration and validation periods (Dayyani et al., 2009d). The model also is capable of simulating hydrology and nitrate loading under different agricultural management and climatic scenarios.

The objective of this study was to evaluate the effect of climate change (under an assumption of no change in land use and land management), based on projections from the Canadian Regional Climate Model (CRCM), on the hydrology (surface and subsurface flows) and nitrogen pollution at the outlet of a 24.3 km^2 agricultural watershed in Quebec, using the DRAIN-WARMF model. The DRAIN-WARMF model, which was validated at the same study area (Dayyani et al., 2009d), is run for the historical and future climate data (1961 to 2100), and the potential impact of climate change on monthly, seasonal, and annual surface/subsurface flow and nitrogen losses is evaluated.

7.2. Materials and Methods

7.2.1. Site Description

The study site is the St. Esprit Watershed located approximately 50 km north of Montreal in southwestern Quebec, Canada (Figure 7.1). It is part of the 210 km^2 St. Esprit River Basin, a tributary of the L'Assomption Watershed (4220 km^2), and is mainly devoted to agriculture. The St. Esprit Watershed is located between 45^o 55'0" and 46^o 0'0'' N, and 73^o 41'32' and 73^o 36'0' W. The Saint Esprit watershed comprises of a net drainage area of 24.3 km^2. During the study period (1994-1996), approximately 64% of the total area was under crop production, with the majority of land used for corn, followed by cereals, soybeans, vegetables, hay, and pastures (Table 7.1); the remaining 36% of the area was comprised of forested, bare, and residential lands (Enright et al., 1995). Natural drainage on these soils is poor; consequently, a majority of these soils are tile-drained (Enright et al., 1995). The difference in elevation from the highest point to the outlet of the watershed is about 44 m, and the principal watercourse is 8.5 km long. Topography can be described as flat to rolling with mainly cultivated land with slopes of less than 3%.

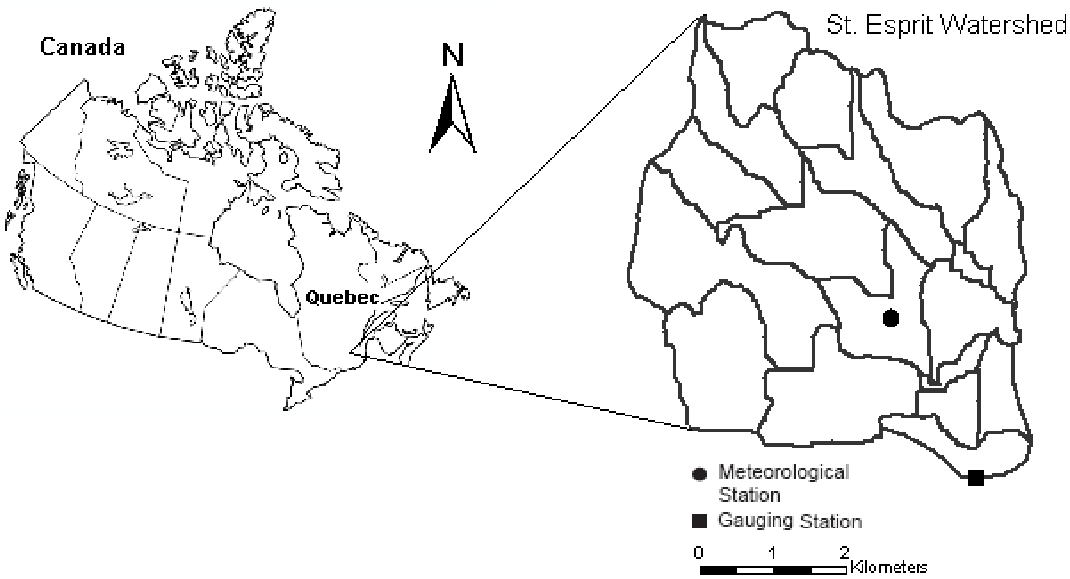

Figure 7.1. Location of St. Esprit watershed

Soil textures in the watershed are variable (16 soil series); in general, the largest proportion of the watershed is occupied by coarse-textured soils (sand and sandy loam 44%), followed by fine-textured soils (clay and clay loam 39%). The lower portion of the watershed is mostly composed of clays and clay loams, including the Ste. Rosalie and St. Laurent series (Lapp et al., 1998).

The climate of the watershed is temperate. The period of frost varies from 122 to 138 days (Sarangi et al., 2005a,b). Average annual precipitation varies between 860 and 1050 mm, with approximately 20 to 25% appearing as snow (Sarangi et al., 2005a,b). Average annual potential evapotranspiration is between 400 and 560 mm (Sarangi et al., 2005a,b). The mean temperature in the month of July varies between 18 and 21°C (MAPAQ, 1983).

Table 7.1. Land use distribution on St. Esprit Watershed

Landuse	Area (m^2)	Area (%)
Corn	6272062.93	25.75
Cereal	2073508.21	8.51
Soya	1565615.35	6.43
Vegetable	1966098.15	8.07
Hay	2919677.45	11.99
Forest	6345533.46	26.05
Pasture	703183.30	2.89
Irrigation-pond	165435.29	0.68
Residential	1241620.58	5.10
Unused	1107938.69	4.55
Total	24360673.39	100

7.3. DRAIN-WARMF Model Description

The DRAIN-WARMF model was developed by linking the WARMF and DRAINMOD models to improve the accuracy and efficiency of the simulation. In this modeling approach, in order to better understand the hydrologic response of tile–drained watersheds, subsurface flow is monitored using DRAINMOD and surface flow is simulated using watershed-scale WARMF model. Such a method offers effective decision tools leading to improved watershed management. Although WARMF can simulate subsurface flow/chemical transport, tile drainage systems are not taken into consideration by the model. Moreover, the subsurface flow component of the model tends to be somewhat simplistic. WARMF calculates the moisture of soil layers (up to 5 layers of soil) for every time step. If the moisture of a soil layer is below field capacity, the hydraulic conductivity of the said layer is zero. If the soil moisture is at saturation, the infiltration rate is the hydraulic conductivity. In between, WARMF interpolates the infiltration rate. A good approach to model the hydrology and water quality of watersheds with subsurface drainage systems is to use a model that addresses the hydrology and water quality parameters of both surface and subsurface drainage systems. Given that widely used subsurface flow models are available, the weak subsurface flow component of WARMF was replaced by an efficient subsurface flow model. By linking the WARMF and DRAINMOD (Skaggs, 1980) models, the strong surface flow modeling capabilities of WARMF are combined with the powerful subsurface modeling abilities of DRAINMOD. The resulting model is performance-wise superior to both. Moreover, different scenario analysis and management practices can be carried out using the linked model, such as an application of tile drain system in the watershed, or the use of water table management systems. Thus, the newly developed model improves water flow and nitrogen loss estimation from watersheds that are drained or partially drained by subsurface tile drainage under frozen/unfrozen soil conditions. Detailed information on the DRAIN-WARMF modeling procedure can be found in Dayyani et al. (2009d).

7.4. Climate Data

The climate data used in this paper is provided by Ouranos consortium, and the climate change modeling is not part of this study. Ouranos's mission is to acquire and develop knowledge on climate change, its impact and related socioeconomic and environmental vulnerabilities, in order to inform decision makers about probable climate trends and advise them on identifying, assessing, promoting and implementing local and regional adaptation strategies. The climatic parameters used to run DRAIN-WARMF model are: precipitation, min/max temperature, wind speed, air pressure, relative humidity, and cloud cover; all provided by Ouranos for the period of 1961 to 2100. The simulation used in this study has the following specifications: CRCM4.2.0 time-slice simulation for 1961-2100 ('adj' run) driven by CGCM3 (The Third Generation Coupled Global Climate Model), following IPCC "observed 20th century" scenario for years 1961-2000 and SRES (Special Report on Emission Scenarios) A2 scenario for years 2001-2100 over the North-American domain (201x193) with a 45-km horizontal grid-size mesh, 29 vertical levels and spectral nudging of large-scale winds. The CRCM is a limited-area nested model, originally developed at Université du Québec à Montréal, based on the fully elastic nonhydrostatic Euler equations. These equations are solved using a noncentered semi-implicit and semi-Lagrangian numerical algorithm (Caya, 1996; Laprise et al., 1998; Caya and Laprise, 1999). The CRCM horizontal grid is uniform in a polar stereographic projection, with a typical 45-km grid mesh (true at 60°N), and its vertical resolution is variable using a Gal-Chen scaled height terrain-following coordinate. The model characteristics are described in (Music and Caya, 2007). The CRCM_V4.2 is mostly based on CCCma GCM3 package (Scinocca and McFarlane, 2004). The values obtained from Ouranos were in raw format and there were 4 values per day for each parameter. A FORTRAN program was written to calculate the daily value of each parameter for the entire simulation period (1961-2100) and to convert the data format to the format which is readable by WARMF and DRAINMOD models.

The results obtained in this study are expected to provide more insight into the characteristics of future flow and nitrogen pollution, and to provide local water management authorities with a planning tool.

7.5. Time Series Analysis

An important issue is to identify the temporal changes in hydrological regimes of watersheds because of the potential impact of climate change on river flow regimes (Khaliq et al., 2009).

7.5.1. Moving Average

If the time series shows considerable variations then smoothing of data is required. A common method used for smoothing is moving average method. The moving average, also known as running mean, is an effective tool to identify the trends. The moving averages indicate an apparent trend and shows oscillatory movement of the series. Usually, a simple moving average of order 3 or 5 is used (Patra, 2001). If the moving average is rising, the trend is considered up. If the moving average is declining, the trend is considered down. For example if x_1, x_2, ..., x_7 are annual precipitation values at a station and a 5 year moving average is applied to the series, then the followings are computed (Patra, 2001):

$$X_1 = \frac{(x_1 + x_2 + x_3 + x_4 + x_5)}{5} \tag{7.1}$$

$$X_2 = \frac{(x_2 + x_3 + x_4 + x_5 + x_6)}{5} \tag{7.2}$$

$$X_3 = \frac{(x_3 + x_4 + x_5 + x_6 + x_7)}{5} \tag{7.3}$$

If the data is available from 1961 to 2100, then a 5 year moving average can be represented from 1963 to 2098. The first two years and the last two years of data are lost in the moving average process. In hydrology a moving average of more than 5 is not applied as some of the cyclic trends associated with the data are smoothened out (Patra, 2001). In this study, the moving average method (order 5) is used to investigate the clear trend on the time series by reducing the effects of peaks on data; the trend is further confirmed using Mann–Kendall test.

7.5.2. Test of Significance of the Trend: Mann-Kendall (MK) Test

Parametric or non-parametric tests have been employed to detect whether there is a statistically significant trend. In this study, a test of significance (either increasing or decreasing or non-significant) of the trend was performed using the Mann–Kendall (Kendall, 1975) test static. MK tests are non-parametric tests for the detection of trends in a time series, and are widely used in environmental science because they are simple, robust and can handle missing values and values below a detection limit (Adamowski et al., 2009). The MK rank statistic is considered to be the most appropriate for the analysis of trends in climatological time series (Goossens and Berger, 1986), and it has been used in a variety of climate and stream flow studies in Canada (e.g. Gan, 1995, 1998; Gobena and Gan, 2006). Two different approaches proposed by Sneyers (1990) and Onoz and Bayazit (2003) are used here in order to detect the trend of time series. Using Sneyers (1990) approach, the following equations are solved to test the significance of the trend:

$$E(d_n) = \frac{n(n-1)}{4} \tag{7.4}$$

$$\mathrm{var}(d_n) = \frac{n(n-1)(2n+5)}{72} \qquad 7.5$$

$$U(d_n) = \frac{d_n - E(d_n)}{\sqrt{\mathrm{var}(d_n)}} \qquad 7.6$$

Where, d_n is sum of number of observations, for which difference between the observations and reference observation is positive, $E(d_n)$ is the expected value of d_n and $U(d_n)$ is the measure of the trend (increasing, decreasing or no trend).

The equations for the approach proposed by Onoz and Bayazit (2003) are:

$$U = \frac{S-1}{\sigma_s}, \quad \text{for S} > 0 \qquad 7.7$$

Where, S is the difference between the “sum of number of observations for which the values are greater than starting value” and the “sum of number of observations for which the values are smaller than starting value”, U is the standard normal distribution, and σs is the standard deviation as follow,

$$\sigma_s = \sqrt{\frac{n(n-1)(2n+5)}{18}} \qquad 7.8$$

Where n is number of observations.

The trend is either increasing or decreasing, which can be identified by the value of $U(d_n)$. If $U(d_n) > 0$, the trend is increasing and if it is negative, the trend is decreasing. The test is carried out for 95% and 99% levels of significance using both methods. The trend is significant at 95% (or 99%) level of significance when the $U(d_n)$ is greater than 1.65 (or 2.33).

7.6. Results and Discussion

CRCM climate-change projections indicate an increase in the average annual precipitation and temperature (Fig. 7.2) for the St. Esprit watershed, while annual actual evapotranspiration (ET) decreases. ET almost remains the same during all seasons except that it is decreasing drastically over the summer due to the decrease in precipitation and the increase in temperature (Figs. 7.2, 7.3). Precipitation is increasing in all the seasons except in summer. The MK test results (Table 7.2) show a non-significant increasing trend for precipitation over the historical period (1961-2008), but a significant increase over the future period (2009-2100) ($P > 0.99$). A significant increase is also noted in the annual temperature for both historical and future data ($P > 0.99$; Table 7.2). The MK test results also indicate that seasonal max/min/average temperatures are increasing significantly except in fall, which is showing a decreasing trend although it is non-significant (Table 7.2).

The minimum temperature is increasing significantly in all seasons except fall (Table 7.2). The average annual temperature for the watershed for the future period is 3.4 ^{o}C warmer relative to the historical climate. Similarly, the average annual precipitation is also expected to be 9% higher for the future climate.

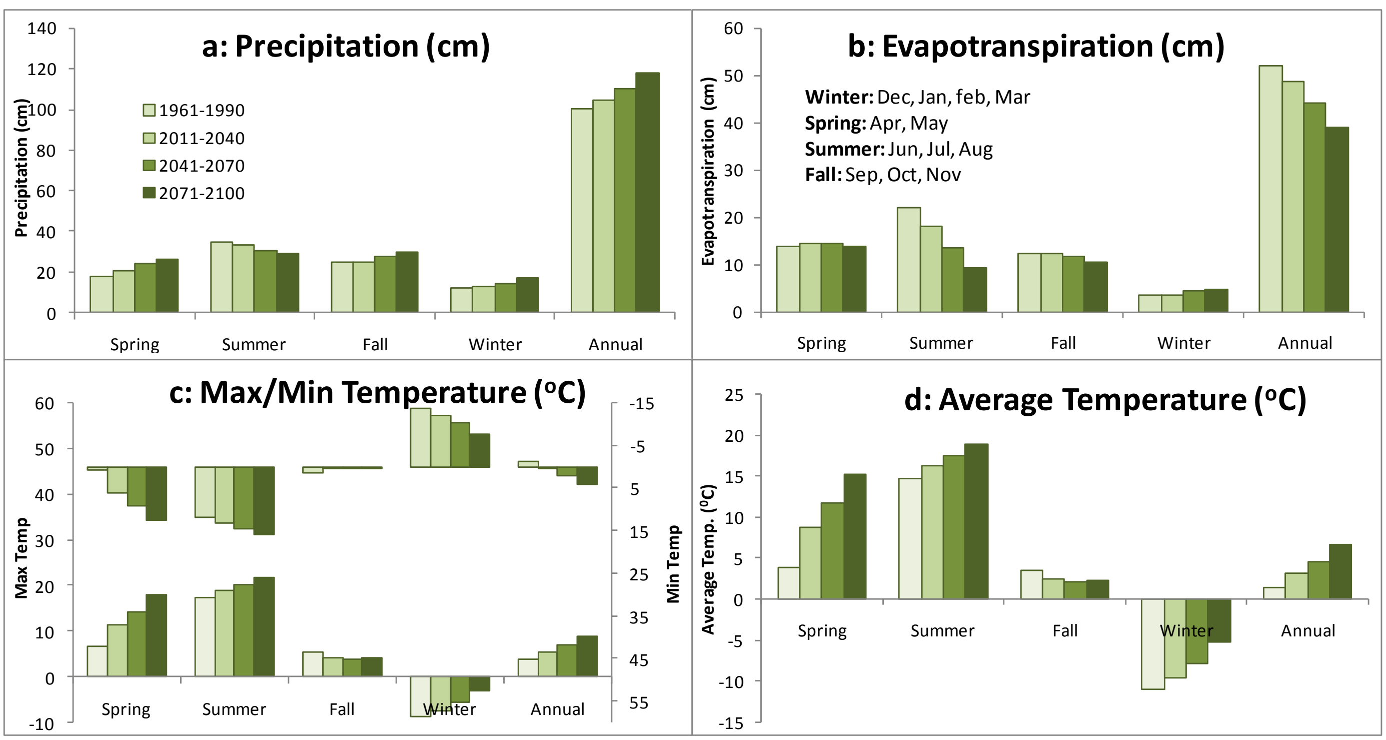

Figure 7.2. The historical (1961-1990) and future (2011-2100) predicted annual and seasonal average precipitation, evapotranspiration, and max/min/average temperature

Figure 7.4 shows the scatter plot of measured and CRCM predicted precipitation values for a part of historical period (1971-2000). The observed data is taken from St.Jacques weather station located about 6 km from the experimental site.

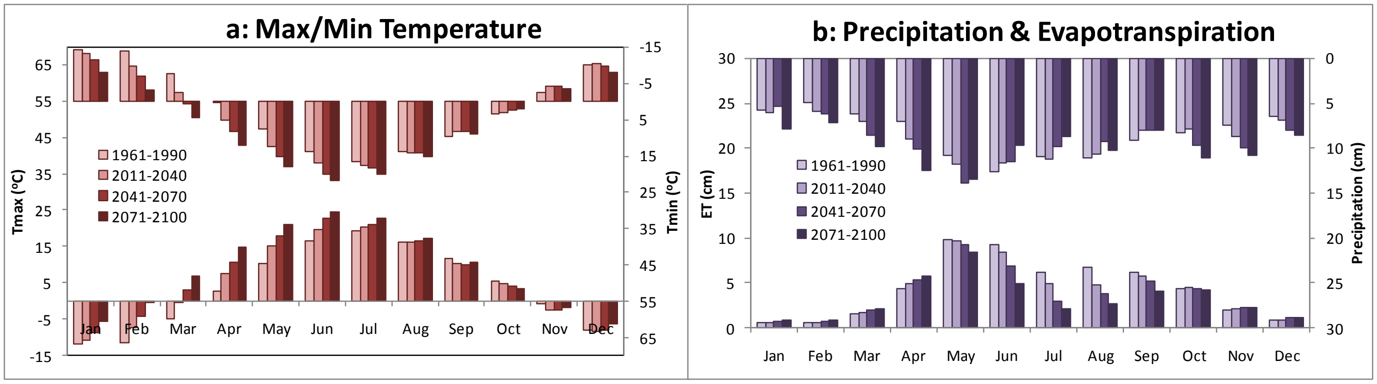

Figure 7.3. The historical (1961-1990) and future (2011-2100) predicted monthly average precipitation, Max/Min temperature and evapotranspiration

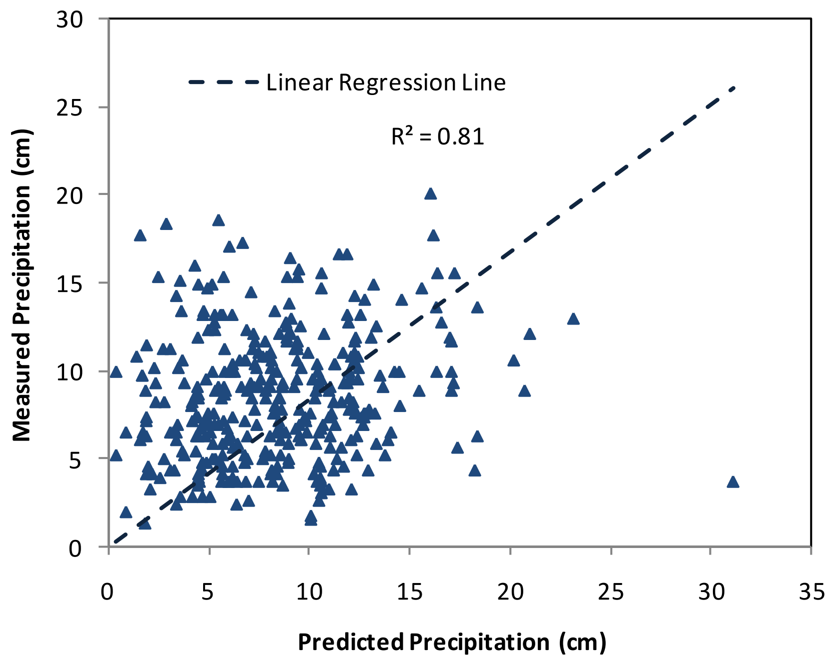

Figure 7.4. A scatter plot of measured and CRCM-predicted precipitation values for 1971-2000

A coefficient of determination of 0.81 (Fig. 7.4) indicates a good correspondence between predicted and measured precipitation values. In this study, simulations over the historical period were performed using the data predicted by the CRCM climate-change projections, since measured data was not available for all the climatic parameters (wind speed, air pressure, relative humidity, and cloud cover) required by the model.

7.6.1. Hydrologic Simulation

The climate-change impact on hydrology of the St. Esprit watershed was estimated by running the DRAIN-WARMF model (Dayyani et al., 2009d) using climate data from 1961 to 2100. DRAIN-WARMF was calibrated and validated for 1994-1996 at the same watershed (Dayyani et al., 2009d).

Simulation results demonstrate that annual precipitation in the driest year (2052) over the future period (2009-2100) increased by 5% relative to the driest year (1999) over the historical period (1961- 2008), while annual flow increased by 31.4%. Figure 7.5 shows the annual trend of the precipitation and simulated flow for both historical and future data. Here, the increasing trend was determined simply by looking at a plot of the moving average, which was confirmed by Mann-Kendall results (Table 7.2). The increasing trend of annual precipitation and flow were not significant over the historical period, whereas they were significant during the future period (Table 7.2, Fig. 7.5). Figure 7.6 presents the 30-year-annual and seasonal average of surface, subsurface, and total flow for 4 different 30 year periods. The model simulations show a significant increase in annual flow (Table 7.2, Fig. 7.6a), which is mainly due to the increase during April (Fig. 7.7a) and winter (December–March) in terms of both surface and subsurface flows (Fig. 7.7b). The increase in winter is mainly during March. Although precipitation is increasing during March, the flow is increasing at a higher rate. The min/max temperatures are increasing in winter, causing more rainfall dominated regimes and less snow accumulation. The rainfall intensity is increasing during the summer and fall (Table 7.3), that might lead to a decrease in infiltration rate and increase in runoff volume causing a rise in surface flow and a decline in subsurface flow during the period. Increased precipitation intensity also explains the increase in flow in June and July despite the decrease in precipitation (Fig. 7.7a). Moreover, the increase in flow in June and July might be due to a decrease in evapotranspiration (Fig. 7.3b).

Total flow is increasing significantly during March and April over the future period. Although precipitation increased in these months, flow increased to a greater extent as compared to precipitation. This is because the snowmelt is occurring earlier (in March and April) as compared to historical period, which causes an increase in flow during March and April (Fig. 7.7a). As a result, flow decreases in May. It is clear from Figure 7.7b that the decrease in flow during May is mainly the result of a decline in surface flow, which supports the hypothesis of snowmelt before May. The decline in subsurface flow during May might be due to the fact that warming is occurring earlier; the groundwater flow would also take place earlier. The simulations also showed almost no change during late summer and early fall both in terms of monthly flow and precipitation (Fig. 7.7a). As stated before, the increase in min/max temperatures in winter causes more rainfall dominated regimes and less snow accumulation. This might lengthen the growing season. It is an important finding that climate change seems to alter both the magnitude and the seasonality of flow. Overall, climate change affects more winter and spring hydrology; the watershed is expected to shift from a combined rainfall-snowmelt regime to more of a rainfall dominated regime.

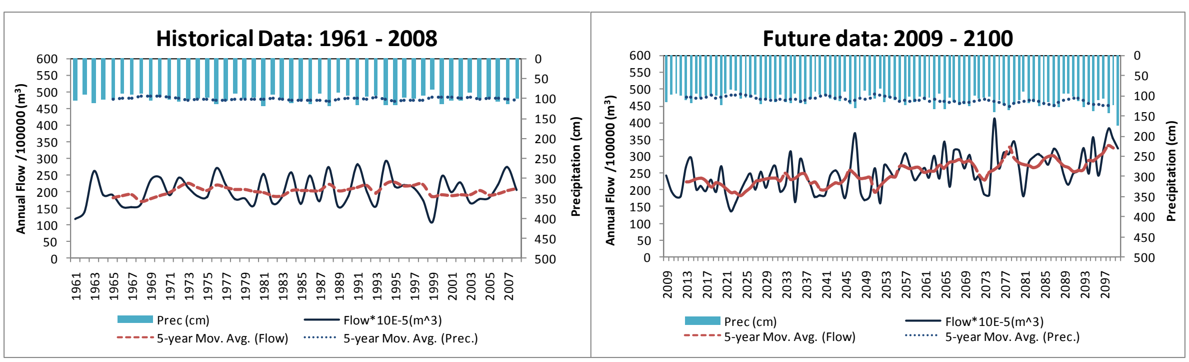

Figure 7.5: Annual comparison of the historical (1961-2008) and future (2009-2100) predicted precipitation and simulated flow

Table 7.2. Trend on annual/seasonal flow, nitrate-N, precipitation, and temperature (max/min/avg) time series for historical (1961-2008) and Future (2009-2100) data (I=Increasing trend, D=Decreasing trend, S=Significant, NS=Non-significant)

Parameter			U or Z rank (Mann-Kendall)		Trend		Significant/Non-significant	
			Sneyers (1990)	Onoz & Bayazit (2003)	Sneyers (1990)	Onoz & Bayazit (2003)	95% level, Sneyers/Onoz	99% level, Sneyers/Onoz
Annual Flow	Historical Data		1.15	1.14	I	I	NS/NS	NS/NS
	Future Data		5.06	5.06	I	I	S/S	S/S
Annual Nitrate-N Losses	Historical Data		5.27	5.27	I	I	S/S	S/S
	Future Data		5.86	5.86	I	I	S/S	S/S
Annual Precipitation	Historical Data		0.35	0.38	I	I	NS/NS	NS/NS
	Future Data		4.03	4.07	I	I	S/S	S/S
Annual Tmax	Historical Data		4.01	4	I	I	S/S	S/S
	Future Data		10.45	10.45	I	I	S/S	S/S
Annual Tmin	Historical Data		4.63	4.63	I	I	S/S	S/S
	Future Data		10.42	10.41	I	I	S/S	S/S
Annual Tavg	Historical Data		4.42	4.41	I	I	S/S	S/S
	Future Data		10.44	10.43	I	I	S/S	S/S
Seasonal Flow	Historical Data	Spring	1.19	1.18	I	I	NS/NS	NS/NS
		Summer	0.51	0.5	I	I	NS/NS	NS/NS
		Fall	-1.08	-1.09	D	D	NS/NS	NS/NS
		Winter	1.92	1.91	I	I	SS	NS/NS
	Future Data	Spring	1.92	1.91	I	I	SS	NS/NS
		Summer	1.49	1.49	I	I	NS/NS	NS/NS
		Fall	1.86	1.85	I	I	S/S	NS/NS
		Winter	6.73	6.73	I	I	S/S	S/S
Seasonal Nitrate-N Losses	Historical Data	Spring	4.03	4.02	I	I	S/S	S/S
		Summer	2.77	2.76	I	I	S/S	S/S
		Fall	2.91	2.9	I	I	S/S	S/S
		Winter	2.36	2.36	I	I	SS	SS
	Future Data	Spring	0.67	0.67	I	I	NS/NS	NS/NS
		Summer	1.9	1.89	I	I	S/S	NS/NS
		Fall	4	4	I	I	S/S	S/S
		Winter	7.29	7.29	I	I	S/S	S/S
Seasonal Precipitation	Historical Data	Spring	2	2.1	I	I	S/S	NS/NS
		Summer	-2.09	-2	D	D	S/S	NS/NS
		Fall	-1.35	-1.25	D	D	NS/NS	NS/NS
		Winter	0.8	0.87	I	I	NS/NS	NS/NS
	Future Data	Spring	3.7	3.8	I	I	S/S	S/S
		Summer	-2.7	-2.68	D	D	S/S	S/S
		Fall	3.66	3.71	I	I	S/S	S/S
		Winter	4.93	4.96	I	I	S/S	S/S
Seasonal Tmax	Historical Data	Spring	5.36	5.35	I	I	S/S	S/S
		Summer	3.25	3.24	I	I	SS	SS
		Fall	-0.88	-0.9	D	D	NS/NS	NS/NS
		Winter	2.48	2.48	I	I	S/S	S/S
	Future Data	Spring	10.5	10.5	I	I	S/S	S/S
		Summer	8.35	8.34	I	I	S/S	S/S
		Fall	-1.18	-1.18	D	D	NS/NS	NS/NS
		Winter	8.5	8.5	I	I	S/S	S/S

Table 7.2 (continue). Trend on annual/seasonal flow, nitrate-N, precipitation, and temperature (max/min/avg) time series for historical (1961-2008) and Future (2009-2100) data (I=Increasing trend, D=Decreasing trend, S=Significant, NS=Non-significant)

Parameter			U or Z rank (Mann-Kendall)		Trend		Significant/Non-significant	
			Sneyers (1990)	Onoz & Bayazit (2003)	Sneyers (1990)	Onoz & Bayazit (2003)	95% level, Sneyers/Onoz	99% level, Sneyers/Onoz
Seasonal Tmin	Historical Data	Spring	5.58	5.57	I	I	S/S	S/S
		Summer	3.8	3.79	I	I	S/S	S/S
		Fall	-0.2	-0.29	D	D	NS/NS	NS/NS
		Winter	2.47	2.46	I	I	S/S	S/S
	Future Data	Spring	10.8	10.8	I	I	S/S	S/S
		Summer	8.5	8.5	I	I	S/S	S/S
		Fall	-0.46	-0.46	D	D	NS/NS	NS/NS
		Winter	8.12	8.11	I	I	S/S	S/S
Seasonal Tavg	Historical Data	Spring	5.56	5.55	I	I	S/S	S/S
		Summer	3.55	3.54	I	I	S/S	S/S
		Fall	-0.74	-0.76	D	D	NS/NS	NS/NS
		Winter	2.5	2.5	I	I	S/S	S/S
	Future Data	Spring	10.6	10.6	I	I	S/S	S/S
		Summer	8.58	8.58	I	I	S/S	S/S
		Fall	-0.59	-0.59	D	D	NS/NS	NS/NS
		Winter	8.33	8.33	I	I	S/S	S/S

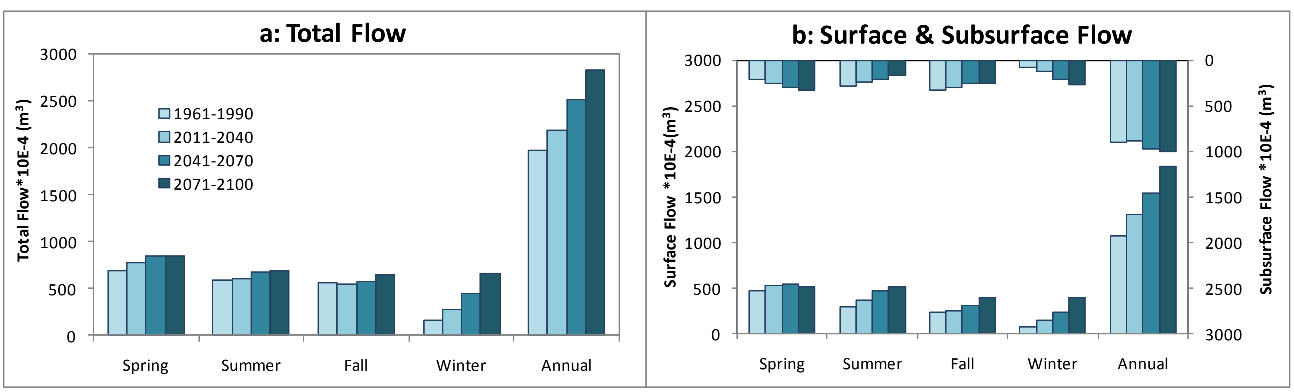

Figure 7.6. The historical (1961-1990) and future (2011-2100) simulated annual and seasonal average total/surface/subsurface flows

Results of the frequency analysis of extreme events are presented in Table 7.3. Annual and summer peak flow rates are higher for longer return periods, while the opposite is valid for spring. This indicates that climate change causes an increase in the magnitude of the extreme events (annual and summer) in the future as compared to historical data; the magnitude of extreme event decreased in spring.

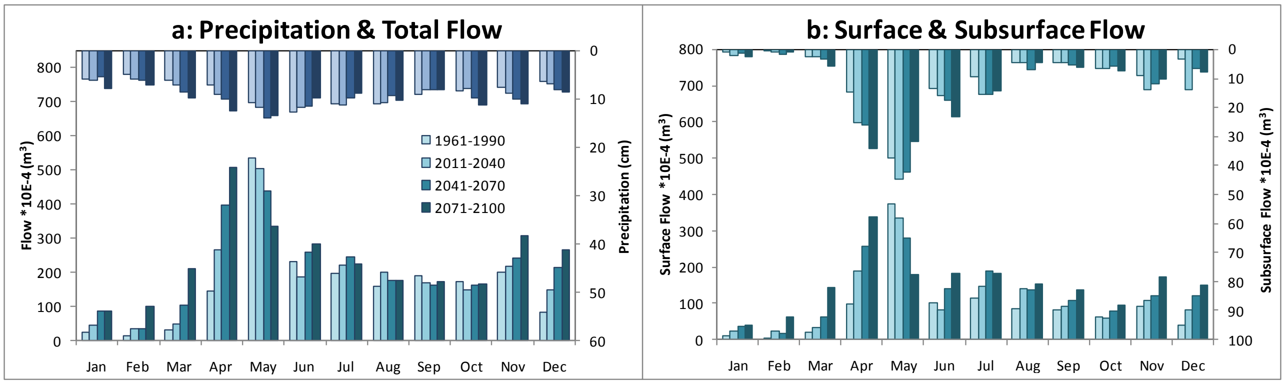

Figure 7.7. The historical (1961-1990) and future (2011-2100) predicted monthly average precipitation and simulated total/surface/subsurface flows

Table 7. 3. Frequency analysis results for peak flows (extreme events) and maximum precipitation

Return Period (year)	10		25		50		75		100	
	Historical	Future	Historical	Future	Historical	Future	Historical	Future	Historical	Future
Annual peak flow	13.08	14.2	15.12	16.14	16.6	17.54	17.47	18.36	18.07	18.92
Summer peak flow	9.77	10.74	11.96	13.04	13.64	14.80	14.65	15.85	15.36	16.60
Summer max precipitation	3.82	4.74	4.30	5.55	4.65	6.15	4.85	6.51	4.99	6.76
Spring peak flow	10.70	9.32	11.89	10.13	12.66	10.65	13.09	10.93	13.37	11.12
Spring max precipitation	3.75	3.65	4.45	4.21	4.97	4.62	5.28	4.86	5.49	5.03
Fall peak flow	4.71	6.37	5.61	7.73	6.29	8.76	6.70	9.38	6.98	9.82
Fall max precipitation	3.81	4.93	4.34	5.78	4.72	6.42	4.94	6.79	5.10	7.05

It should be noted that future flow conditions could not be projected exactly due to the uncertainty in climate change scenarios and the outputs from global climate change models. However, the results of this analysis could serve as a guideline for planning water resource management in order to promote more sustainable water use in the study area.

7.6.2. Nitrogen Simulations

The impact of changed hydrology on NO_3^--N losses in the St. Esprit watershed was assessed using the DRAIN-WARMF model. The annual, seasonal, and monthly results of model prediction are presented in Figures 7.8 through 7.10, respectively. Figure 7.8 shows the annual trend of the NO_3^--N losses for both historical and future data. The increasing trend is evident from the plot of the moving average and was confirmed by Mann-Kendall results (Table 7.2). The MK results indicate that the annual NO_3^--N losses are increasing for both historical and future data (P> 0.99).

The results show that annual flow is expected to increase significantly for future data. As a result, annual NO_3^--N loss also increased at the outlet (Table 7.2, Fig. 7.9a). The monthly NO_3^--N losses increased during the winter months both in surface and subsurface flows (Figs. 7.9b, 7.10). The MK results indicate that the NO_3^--N losses are increasing significantly in all seasons except spring (Table 7.2). Although the flow is not increasing significantly during the summer, the losses are increasing significantly, because the concentration of NO_3^--N is increasing while the volume is almost the same (Figs. 7.6a, 7.9a). Nitrogen loading decreased in May and increased in summer as a result of early snowmelt and decreasing evapotranspiration, respectively.

During the spring months total surface flow is almost unchanged (Fig. 7.6b), since it is increasing in April and decreasing in May (Fig. 7.7b). The subsurface flow increased by 7% in the last 30-year periods (2071-2100) as compared to the earlier 30 year period (2011-2040), while corresponding increases of 35% were observed for N concentration in subsurface flow. Considering the time of first fertilizer application in the watershed (normally in early May) and a significant decrease in the flow during May (Fig. 7.7b), less fertilizer is lost in surface runoff and this leads to a greater amount of fertilizer retained in the soil profile. On the other hand, the subsurface flow volume is also decreasing during May, while the concentration is increasing (by 35%, results not presented for concentration); this results in higher amounts of NO_3^--N loads at the outlet.

Subsurface flow contribution to annual nitrate loads was 14% of total load in 1961-1990, whereas it increased to 39.3% during 2071-2100. Results from this study demonstrate that the increase in NO_3^--N losses are higher than the increase in flow (Figs. 7.5b, 7.8b), which might be due to progressively higher N saturation in the watershed soils.

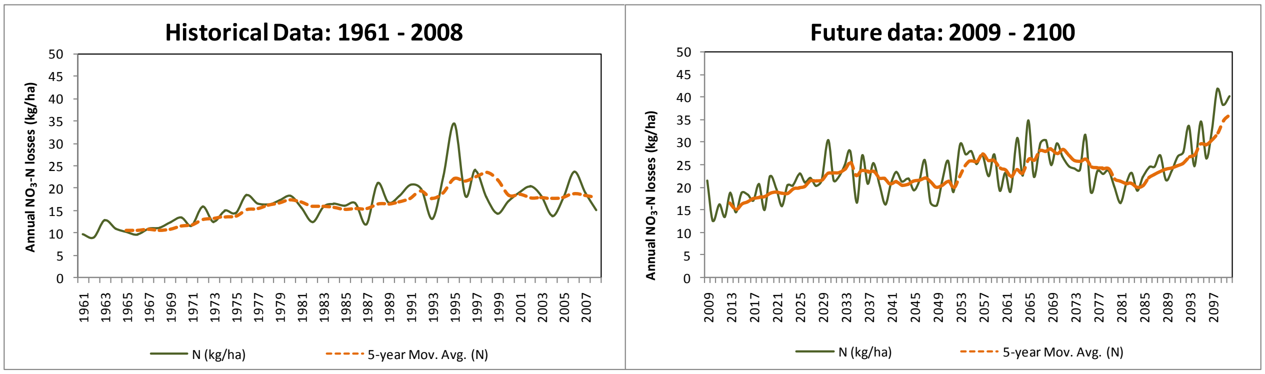

Figure 7.8. Annual comparison of the historical (1961-2008) and future (2009-2100) simulated nitrate-N losses

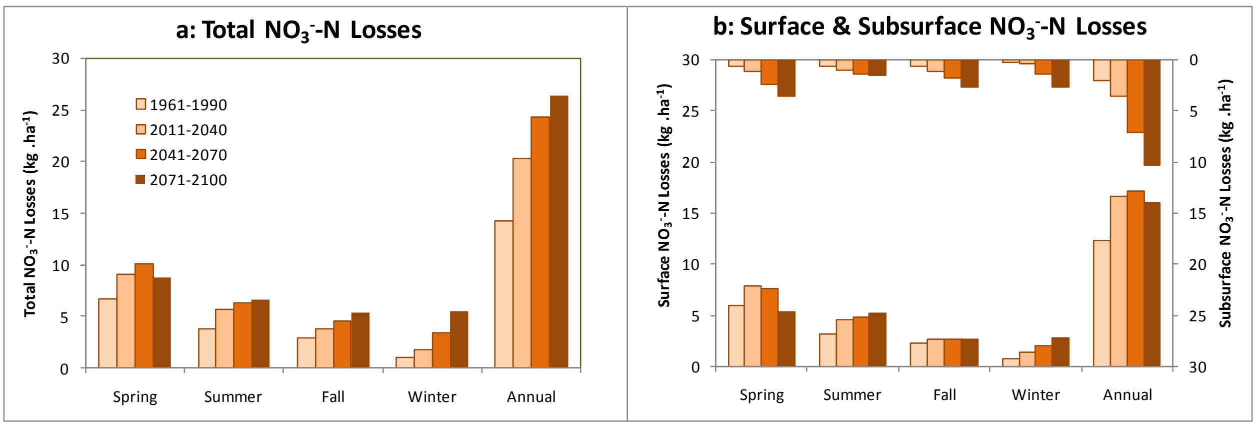

Figure 7.9. The historical (1961-1990) and future (2011-2100) simulated annual and seasonal average total/surface/subsurface nitrate-N losses.

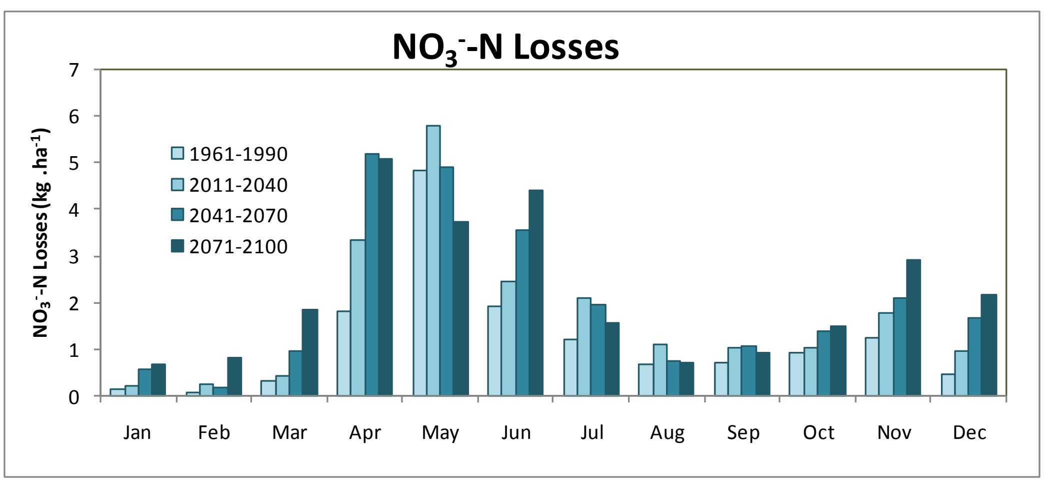

Figure 7.10. The historical (1961-1990) and future (2011-2100) simulated monthly average nitrate-N losses

7.6.3. Water Balance Analysis

Water balance components of the 48-year (1961-2008) historical and 92-year (2009-2100) future simulations, including precipitation, evapotranspiration, surface and subsurface flows are presented in Figure 7.11. As can be seen from the figure, all the components produce a increasing annual trend, except ET. The higher rate of increase is noted for surface flow as compared to subsurface flow. The graph shows a wetter and warmer climate for the future, lower amount of ET and higher surface/subsurface flows.

Figure 7.12 describes changes of the water balance components in 1961, 2050 and 2100. The results of 2100 as compared to 1990 show that the precipitation, surface and subsurface flows will increase by 46%, 52% and 26% in 2100, respectively (Figure 7.12).

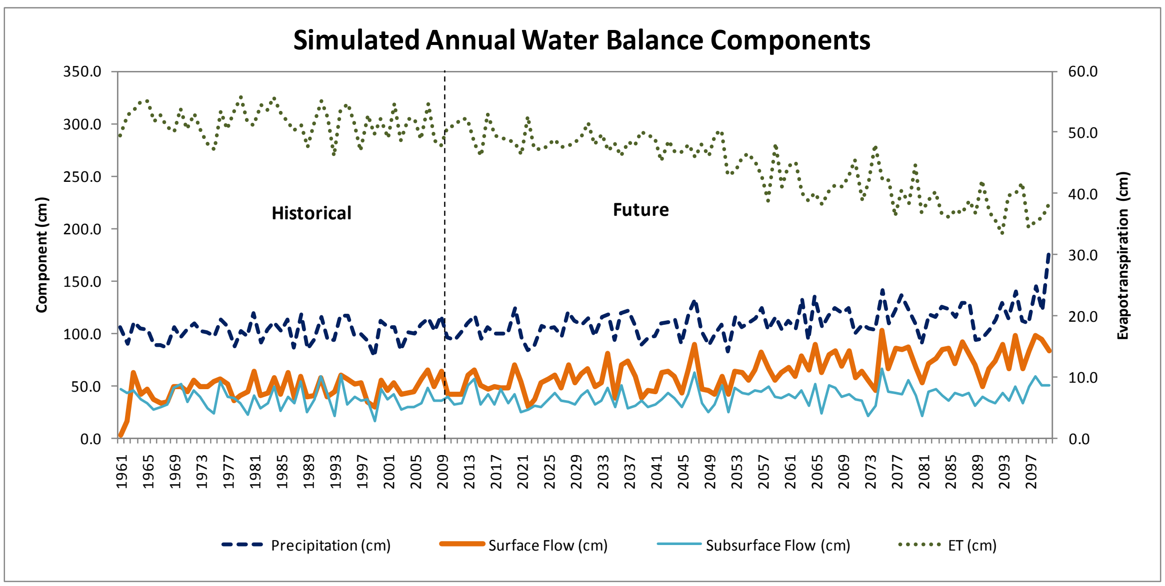

Figure 7.11. DRAIN-WARMF simulated water balance components (precipitation, ET, surface and subsurface flows) for 1961-2100

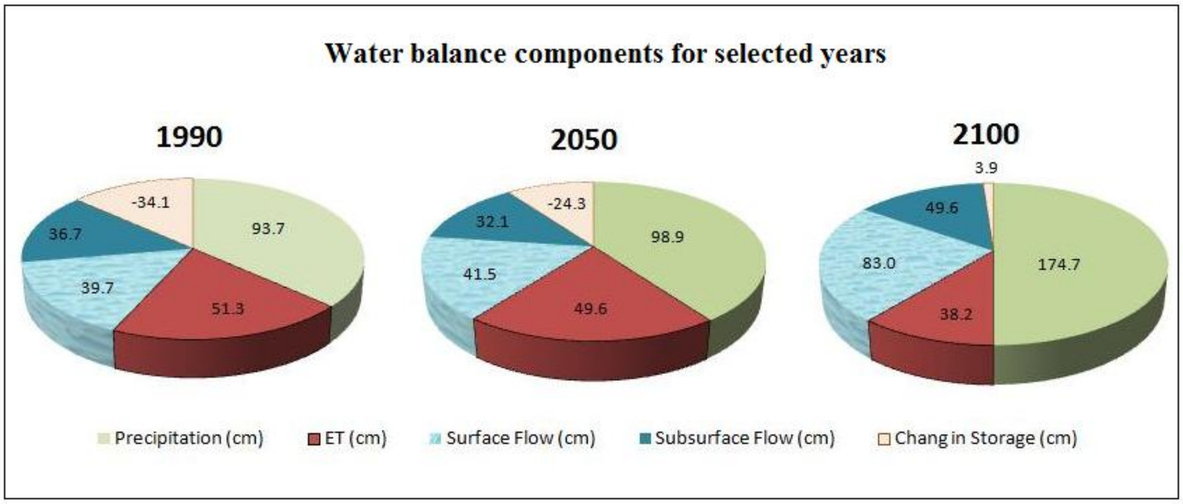

Figure 7.12. DRAIN-WARMF simulated water balance components (precipitation, ET, surface and subsurface flows, and change in storage) for 1961, 2050, and 2050

7.7. Conclusions

This study presents the results of an application of the DRAIN-WAMRF model in evaluating the effects of potential climate change on surface and subsurface flow and nitrogen transport at the St. Esprit watershed in Quebec, Canada. The simulations were performed based on projected climate change conditions developed by the CRCM4.2.0 model for 1961 to 2100. The projected annual temperature and precipitation changes indicate that the climate in the study area would generally become warmer and wetter. Warmer temperatures would alter the hydrologic cycle, with uncertain implications for precipitation, runoff, and the intensity and frequency of floods and droughts, especially at the watershed levels of most interest to planners. For the future hydrological assessment and NO_3-N losses, the DRAIN-WAMRF model was adopted. The DRAIN-WARMF simulation results show an increase in the average annual surface and drainage outflows, based on climatic data projected by Canadian CRCM4.2.0. It appears that the effects of increased annual precipitation are less pronounced in the annual subsurface flow (10% increase) as compared to the annual surface flow (41% increase), whereas the increased precipitation would have less impact on annual NO_3-N losses in surface flow (23% increase) as compared to losses in subsurface flow (80%

increase). In general, flow and nitrogen loads in the study area would experience significant changes in the future.

7.8. Acknowledgements

The authors wish to thank OURANOS (Quebec Consortium on Regional Climate and Adaptation to Climate Change, www.ouranos.ca) for providing the climatic data.

CHAPTER 8: General Summary and Conclusions

A new model, DRAIN-WARMF, has been developed in this study by integrating WARMF and DRAINMOD models, and evaluated for a small agricultural watershed in Quebec. DRAIN-WARMF model can be applied to any watershed. WARMF 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 under humid regions on 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, DRAIN-WARMF, can simulate surface/subsurface flow and transport processes in a rational way for small agricultural watersheds in humid regions.

The WARMF model incorporates algorithms derived from many well-established codes. It can simulate stream flow and groundwater, sediment loadings, fate and transport of nitrogen, phosphorus, heavy metals, and pesticides on a watershed scale. It was designed to take stakeholders through a series of steps to develop and evaluate water quality management alternatives for a watershed. The model also provides a procedure to calculate the total maximum daily load (TMDL) of pollutants. The Model's applicability was tested for a watershed in southwestern Quebec.

DRAINMOD is a deterministic, field-scale, hydrologic model for the design and evaluation of agricultural drainage and related water table management systems. The management systems can be a combination of subsurface drainage, controlled drainage, and sub-irrigation. The model was successfully tested for two field sites in southwestern Quebec.

The new model, DRAIN-WARMF, was developed by linking WARMF 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. The new model uses a distributed parameter approach by subdividing the watershed into cells and performing DRAINMOD simulations on each cell. Cell simulations return subsurface drainage flow and nitrogen losses from each cell. Cell results are routed and summed to simulate flow and determine the total NO_3-N losses at the outlet of the watershed. The lateral flow between adjacent cells is calculated using Darcy's Law and it is added to the cells' flow results.

The performance of the new model was tested on the St. Esprit watershed in Quebec. Physical properties of soil and land use, meteorological data (such as rainfall, air temperature, and evapotranspiration etc.), and observed runoff were collected for a 3-year period from 1994 to 1996. The data were divided into two sets, one for calibration (1994 to 1995) and the other for validation (1996). Using the calibration data set, the DRAIN-WARMF model was run and calibrated by adjusting various parameters. Calibration of these parameters improved the model simulation of total flow and nitrogen losses as compared to the single application of the WARMF model alone. It was found that the DRAIN-WARMF model was capable of simulating well hydrological and nitrate-N loads at the watershed-scale. The model was also able to simulate snowfall and snowmelt satisfactorily, demonstrating its potential to be adapted to Quebec's climatic conditions. Annual water balance errors were less than 10%. The maximum actual evapotranspiration was obtained in the summer months whereas the maximum recharge and runoff were observed for the snowmelt period. These observations are consistent with the climatic conditions in Quebec. On a daily basis, the model was also able to simulate all the hydrological components quite well. Although for certain events, the simulated number of runoff events and timing of peaks did not match well with the observed values, overall the model simulated the hydrology adequately. Regarding nitrogen simulations, monthly or seasonal nitrate-N load predictions were more reliable as compared to the daily values. By integrating these two models, the new model was able to adequately address issues related to tile drainage simulations and the movement of nitrate-N down the soil profile. The baseflow simulated by the model represented about 39% of the total runoff, which is also close to the value obtained by an independent baseflow separation technique.

Based on the results obtained in this study, it can be concluded that the new model provides a novel and innovative method for 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 drawn from the study are as follows:

i) DRAINMOD 5.1 was evaluated to predict WTD and subsurface drain outflows from an agricultural field in southern Quebec. The model performed well in simulating the daily drain outflows and peak flows in all four seasons. The model also gave good results for drain outflow in colder months, owing to its ability to address frozen soil conditions. For WTD, the coefficient of efficiency, E, was 0.77 and 0.74 for calibration years (2004 - 2005) and 0.31 for the validation year (2006). These values are indicative of acceptable model performance.

ii) DRAINMOD 5.1 was also evaluated for simulation of WTD, tile drainage volume and NO_3^-–N losses in another field in southern Quebec undergoing two water table management practices, namely free drainage and sub-irrigation. The hydrologic component of the model performed well for water table and flow predictions. The R^2 values were in the range of 0.84-0.88 for the daily drainage outflow. The leached NO_3^-–N simulations gave good results for both sub-irrigation and free drainage [R^2 (FD and SI) $\geq$ 0.91], although underestimating cumulative losses to some extent under both treatments. The performance of the model was deemed satisfactory and it appears that DRAINMOD 5.1 can be effectively used to simulate WTD depth, drainage outflows and NO_3^-–N losses in cold humid regions.

iii) WARMF was used to predict daily/monthly/seasonal flows from a 24 km^2 St. Esprit watershed in south-western Quebec. The model simulated the pattern of monthly flow with a good degree of accuracy; the R^2 for calibration was 0.92, and that for validation was 0.94. The corresponding coefficients of efficiency (E) were, respectively, 0.89 and 0.91. The model also performed well in simulating flows during the snowmelt period with the average error of 23%. In addition, the model performed well in simulating nitrate loads at the outlet of the watershed ($E \geq 0.75$). These values are indicative of an acceptable model performance.

iv) The newly developed watershed model, DRAIN-WARMF, was also used to predict daily surface/subsurface flow and nitrogen losses from the St. Esprit watershed. There was good agreement between the observed and the predicted flow with R^2, average daily deviation, and Nash and Sutcliffe coefficient of 0.76, 0.16 mm, 0.75, respectively. DRAIN-WARMF also simulated nitrate-N loads with a good degree of accuracy ($E \geq 0.83$). The model simulated the flow during the snowmelt period with the average error of 7%. Thus, the model can be used to evaluate environmentally sound management practices in cold humid regions.

v) Effects of climate change on surface and subsurface flow and nitrogen transport were evaluated with DRAIN-WAMRF for the St. Esprit watershed in Quebec. The simulations were performed based on projected climate change conditions, generated by the CRCM4.2.0 model, for 1961 to 2100. The projected annual temperature and precipitation changes indicate that the climate in the study area would generally become warmer and wetter. The simulation results show an increase in the average annual surface and drainage outflows. It appears that the effects of increased annual precipitation are less pronounced in annual subsurface flows (10% increase) as compared to the annual surface flows (41% increase) and lesser impact on the annual NO_3-N losses in surface flows (23% increase) as compared to the losses in subsurface flows (80% increase). In general, flow and nitrogen loads in the study area would experience dramatic changes in the future. The results of this analysis could serve as a guideline for planning water resource management on watershed scale in order to promote more sustainable water use in the study area.

CHAPTER 9: Claims of Originality and Recommendations for Further Research

9.1. Claims of Originality

The work presented here provides original contribution to the body of knowledge concerning watershed modeling of surface and subsurface flows and NO_3^--N fate and transport, especially in watersheds with tile drainage in cold humid regions. The main contributions of this dissertation are as follows:

1. A new model, DRAIN-WARMF, has been developed and successfully validated to improve predictions of flow and NO_3^--N losses in tile-drained agricultural watersheds with or without water table management systems.

2. DRAIN-WARMF makes it possible to study the effects of climate change on flow and nitrogen transport in tile drained agricultural watersheds. The results could serve as a guideline for planning water resource management on a watershed scale for cold humid regions.

3. As part of this research, year-round validation of DRAINMOD 5.1 was performed for flow and nitrogen transport in a cold region under water table management systems.

9.2. Recommendations for Further Research

1. Apply the DRAIN-WARMF model to evaluate the impacts of best management practices (BMPs) and carryout a detailed scenario analysis. For example, tile drainage for the whole watershed, implementation of different water table management systems, impact of shallower drainage depths on watershed hydrology, buffer strips, time/application rates of N fertilizer, urbanization, deforestation, conversion of pastureland into mono-crop agriculture, and turning conventional agriculture into cash crops.

2. Investigate the ability of the new model to simulate nitrogen losses from farmlands receiving inorganic and organic fertilizers

3. Add phosphorus component to DRAINMOD model, so the linked model is capable of simulating both nitrogen and phosphorus transport.

4. Performing TMDL analysis and set pollution reduction goals to improve the quality of impaired waters in a watershed.

5. To assess the impact of cell size on flow and nitrogen results (watershed is divided into uniform cells to run DRAIN-WARMF model).

6. It would be interesting to compare the forecasting ability of the DRAIN-WARMF model with a data based model, for example artificial neural networks.

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