HYDROLOGICAL AND WATER QUALITY MODELING OF AGRICULTURAL FIELDS IN QUEBEC

by

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ABSTRACT

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Hydrological and Water Quality Modeling of Agricultural Fields in Quebec

Two tile-drained agricultural fields in the Pike River watershed of Southern Quebec were instrumented in October 2000 to monitor phosphorus and nitrate concentrations in surface runoff and tile drainage. Data collected from these sites were used as the primary input to test a GIS-based hydrological and water quality simulation model (ArcView SWAT2000) at the field scale. Surface runoff, subsurface flow, sediment yield, nitrate loads and phosphorus loads were the principal parameters evaluated by the model. The SWAT model was calibrated using data collected in the year 2002 while 2003 data was used for validating the model. Particulate phosphorus and total dissolved phosphorus loads in streamflow were also simulated using SWAT and compared with field measurements.

A sensitivity analysis showed that curve number, available soil water content and soil evaporation factors significantly influenced water yield simulations while model performance for water quality parameters was governed mainly by the accuracy of simulating field operations such as fertilization and tillage. The monthly coefficients of performance after calibration ranged from being very good for some parameters (0.27 to 0.66 for total water yield; 0.38 to 0.67 for total phosphorus; and 0.23 to 0.89 for sediments) to being inconsistent for others (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). Overall, it was found that SWAT 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. Short-term impacts of implementing different best management practices for tillage, crop rotation and fertilization were also evaluated using the validated SWAT model. It was found that conservation tillage of corn coupled with pasture or soybean rotations can reduce total phosphorus loads in the range of 25-50% over conventional tillage with corn.

RÉSUMÉ

Maîtrise ès sciences Apurva Gollamudi **Génie des bioressources**

Modélisation hydrologique et de la qualité de l'eau de champs agricoles au Québec

Deux champs agricoles drainés artificiellement, situés dans le bassin versant de la rivière aux Brochets, dans le sud du Québec, ont été instrumentés en octobre 2000 pour évaluer les charges de phosphore et de nitrates dans le ruissellement de surface et le drainage souterrain. Les données colligées sur ces champs ont été utilisées pour tester un modèle basé sur un système d'information géographique (ArcView SWAT2000) qui simule les paramètres hydrologiques et de qualité de l'eau à l'échelle du champ. Les débits de ruissellement de surface et de drainage souterrain, ainsi que les charges de sédiments, de nitrates et de phosphore, étaient les principaux paramètres évalués par le modèle. Le modèle SWAT a été calibré avec les données recueillies en 2002-03, alors que les données de 2003-04 ont été utilisées pour la validation. Les charges de phosphore particulaire et de phosphore total dissous sortant des champs ont aussi été simulées avec le modèle et comparées avec les données mesurées sur le terrain.

Une analyse de sensibilité a démontré que le numéro de courbe, la quantité d'eau disponible dans le sol et l'évaporation de la surface du sol avaient une influence significative sur la simulation des débits d'eau. Au niveau des paramètres de qualité de l'eau, la performance du modèle était influencée par la précision de la simulation des opérations agricoles telles que la fertilisation et le travail du sol. Les coefficients de performance mensuels après la calibration étaient très bons pour certains paramètres (0,27 à 0,66 pour les débits totaux d'eau; 0,38 à 0,67 pour le phosphore total; et 0,23 à 0,89 pour les sédiments) et très variables pour d'autres (0,44 à 2,28 pour les débits de drainage souterrain; 0,63 à 4,36 pour le ruissellement de surface; et 0,66 à 1,35 pour les charges totales de nitrates).

De manière générale, les résultats du modèle SWAT étaient plus fiables à l'échelle saisonnière, alors que les simulations quotidiennes et mensuelles pourraient être améliorées en utilisant une période de calibration plus longue ou en incorporant

des changements dans le modèle. Les effets à court terme de l'utilisation de bonnes pratiques de gestion de travail du sol, de rotation des cultures et de fertilisation ont aussi été évalués avec le modèle validé. Il a été démontré que le travail de conservation du sol, utilisé avec une rotation maïs-pâturage ou maïs-soya, pouvait réduire les charges de phosphore de 25 à 50% par rapport au travail du sol conventionnel avec une culture de maïs.

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LIST OF ABBREVIATIONS

ALPHA_BF: baseflow recession factor
AMC: antecedent moisture condition
API: antecedent precipitation index
AVSWAT: ArcView SWAT model
BMP: best management practice
CN: SCS curve number (AMC II)
C_p: coefficient of performance
DEM: digital elevation model
DMU-93: Endress Hauser Prosonic flowmeter
EPCO: plant uptake compensation factor
ESCO: soil evaporation compensation factor
ET: evapotranspiration
GAML: Green-Ampt Mien Larson
GIS: geographical information system
GPS: geographical positioning system
GW_DELAY: groundwater delay time
GW_REVAP: groundwater revap coefficient
GW_Q: groundwater baseflow volume
GWQMN: groundwater threshold depth
HRU: hydrologic response unit
LATQ: lateral flow volume
NLATQ: simulated nitrate in lateral flow
NO3-N: total nitrate-nitrogen
NPERC: Nitrogen percolation coefficient
NS: Nash-Sutcliffe coefficient
NSURQ: simulated nitrate in surface runoff
PP: particulate phosphorus
PHOSKD: phosphorus partitioning coefficient
PRECIP: precipitation
OV_n: Manning's roughness coefficient
RevapMN: revap threshold depth
RR: rainfall runoff ratio
SCS: Soil Conservation Service
SED_P: simulated phosphorus in sediment
SFTMP: mean snowfall temperature
SLOPE: slope of sub-basin
SLSoil: slope for lateral flow
SMFMN: minimum snowmelt rate
SMFMX: maximum snowmelt rate
SMTMP: base snowmelt temperature
SNO50COV: 50% snow cover fraction
SNOCOVMX: 100% snow cover equivalent
SOL_AWC: available soil water content
SOL_P: simulated soluble phosphorus
SR50: Campbell Scientific ultrasonic sensor
SRO: measured surface runoff
SRO_NO3: nitrate in surface runoff
SS: measured subsurface tile drainage
SS_NO3: nitrate in subsurface flow
SURQ: simulated surface runoff volume
SWAT: soil and water assessment tool
SYLD: simulated sediment yield
TDP: total dissolved phosphorus
TLOSS: transmission losses
TP: total phosphorus
TSS: total suspended sediment
WYLD: total water yield

CONTRIBUTIONS OF AUTHORS

All the manuscripts in this thesis (Chapters 3, 4 and 5) have been authored by me, Dr. Chandra Madramootoo and Mr. Peter Enright. Professor Chandra Madramootoo, research supervisor, is the first co-author for all the manuscripts in this thesis. His role included supervisory guidance, funding and many constructive comments and inputs while reviewing the manuscripts. Mr. Peter Enright, professional associate and project engineer in the Department of Bioresource Engineering at McGill University, is the second co-author for all the manuscripts. His contribution includes site instrumentation and programming, field management supervision and assistance, analysis of field data, valuable technical guidance and manuscript review.

CHAPTER 1: Introduction

The agricultural sector in Canada and Quebec in particular has witnessed substantial growth over the past two decades. This manifold increase in agricultural production can be attributed to several factors: mechanization of farm operations, use of chemical fertilizers, and improved crop varieties – to name a few. At the same time, this has placed the region's water bodies under severe environmental stress. In Quebec alone, agriculture is responsible for over 70% of the total nonpoint source pollution. 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. The limiting nutrient in this process is phosphorus, and concentrations in excess of 0.03 mg l^{-1} are deemed dangerous for human consumption.

The implementation of effective farm management practices is seen as one of the primary ways in alleviating water quality. Several initiatives have been taken by the government and research teams to identify potential ways of balancing economic benefit and ecological risk. This thesis is a part of one such project conducted by McGill University, in collaboration with the *Ministère de l'Agriculture, des Pêcheries et de l'Alimentation du Québec* (MAPAQ), and the *Institut de Recherche et de Développement en Agroenvironnement* (IRDA), with funding from *Le Fonds Québécois de la Recherche sur la Nature et les Technologies* (FQRNT). Initiated in the year 2000, the overall aim of this project is to develop and validate agro-environmental indicators to minimize phosphorus losses from agricultural fields. The project involves watershed and field-scale studies, but this thesis mainly focuses on the field component.

The agriculture intensive Pike River watershed in Southern Quebec is the region where this study is being conducted. The water quality of this river is of significant environmental concern as it drains into the critically polluted Missisquoi Bay of Lake Champlain. High phosphorus concentrations from nonpoint sources have degraded the water quality of this shallow bay to an alarming degree, with recurring algal blooms forcing the closure of recreational beaches and depreciating real estate value. Field studies were conducted to identify the pathways for the movement of water and nutrients, especially phosphorus, from tile-drained agricultural fields. Sediments and nutrients in both surface runoff and subsurface flow (tile drainage) were also monitored from these fields. The hydrologic and water quality monitoring were essential in improving our current understanding of agricultural nonpoint source pollution, especially in the context of Quebec's climatic conditions. Most of the streamflow is distributed between two distinct periods, spring snowmelt and fall, and each of these periods are characterized by markedly different hydrology. The dynamics of nutrient transport under such varying conditions present a complex problem to simulate.

The data collected was used in calibrating and validating a water quality model, namely SWAT (Soil and Water Assessment Tool). With the advantages of being time and cost-efficient, computer simulation models are being increasingly recognized and adopted as a means to extend existing knowledge into developing predictive scenarios. Once validated using field data, a model has the potential to predict results and evaluate scenarios for best management practices over a wide range of conditions.

1.1. Objectives

The main objectives of this study were to:

i. Use field data to setup and calibrate AVSWAT 2000 at the field-scale for hydrology, sediment and nutrient movement (nitrates and phosphorus).

ii. Assess model performance over different time-scales (i.e. annual, seasonal, monthly and daily simulations) for the above parameters.

iii. Validate AVSWAT performance in simulating surface runoff and subsurface flow, and the consequent ratios of sediment and nutrient loads exiting the fields via each pathway, i.e. surface and subsurface flow.

iv. Determine AVSWAT performance in simulating the forms of P, namely dissolved phosphorus (DP) and particulate phosphorus (PP).

v. Create and test preliminary scenarios for different Best Management Practices (BMPs).

1.2. Scope

The field monitoring was carried out on two tile-drained agricultural fields in the Pike River watershed of Southern Quebec, and the SWAT model was calibrated for hydrology and water quality of these fields. Simulations were carried out over five years (October 2000 – September 2005), using climatic data being collected at the sites. Two years of hydrologic and water quality data served to calibrate and validate the model, with the year 2002 being used for calibration and 2003 for validation. Although the simulation results are limited to the two sites and their corresponding soil types and land use, SWAT was calibrated to simulate field hydrology for the region's climate. Thus, the model parameters could be easily adapted to develop agro-environmental indicators for other fields in the region.

1.3. 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 field hydrology, nutrient transport pathways, water quality models and best management practices is presented in Chapter 2. This chapter is followed by three sequentially connected manuscripts: the first manuscript (Chapter 3) details the methodology used in calibrating the hydrology component of SWAT; the second manuscript (Chapter 4) calibrates and validates the model performance for sediment and water quality. Chapter 5 presents an evaluation of BMPs for reducing nitrogen and phosphorus pollution, chiefly by varying crop rotation and tillage practices on the two fields. The sixth chapter of the thesis summarizes the important results of the study and Chapter 7 provides recommendations for further studies on the project and lists suggestions that need to be investigated to improve model performance, based on the conclusions drawn from this thesis.

CHAPTER 2: Literature Review

2.1. Water Quality and Nutrient Pollution

Agricultural water quality in Quebec has become a cause for growing environmental concern as a result of the intensification of production and mechanization of management practices (van Es et al, 2002). Non-point source pollution is the main reason for the transport of sediments, nitrates and phosphorus down from agricultural fields into watercourses (Bolinder et al, 2000; Painchaud, 1997). While the implementation of efficient management plans and the upgradation of water treatment systems have been successful in improving the quality of wastewater from point sources (Simard, 2000), non-point source pollution has contributed in hastening the natural processes of eutrophication and deoxygenating water bodies (Harker et al, 1998). Eutrophication is the normal aging process that controls the release of oxygen in lakes, and the critical nutrient in this process is phosphorus. An excess of phosphorus (> 0.03 mg l^{-1}) (MENV, 2005) stimulates the formation of algal blooms, which release toxic cyanobacteria on decay. Concentrations in excess of this limiting level are commonly found in the rivers of southern Quebec (Giroux and Tran, 1996).

The Missisquoi Bay of southern Quebec is one such receiving body that has been adversely affected by high phosphorus levels in the rivers that drain into the bay (Blais, 2002). The pathways for the transport of these nutrients and sediment are mainly through surface runoff and through subsurface drainage, on fields where artificial tile drains are installed. The watershed region surrounding the bay contains soils rich in phosphorus, extensively cultivated fields and high animal densities. All these factors contribute to high nutrient levels in the rivers of the region (MENV, 1999a)

In the past two decades, several studies have documented the problem of nonpoint source pollution in Quebec, at both the watershed and the field scale. These studies have reported high levels of nitrates (Wiyo, 1991; Asselin et al, 1992) and phosphorus (Beauchemin et al, 1998) in subsurface drainage. High concentrations of these nutrients in lakes and rivers are detrimental to human health; toxins from blue green algae can prove to be fatal (Health and Welfare Canada, 1992) while high nitrate concentrations can be specially harmful for infants and have been linked to the blue baby syndrome (Fewtrell, 2004).

Water quality guidelines have been stipulated depending on the water use requirements. The MENV (2004) has set maximum tolerable levels of 0.03 mg l^{-1} for phosphorus in fresh water sources and 10 mg l^{-1} for nitrate-nitrogen in drinking water. In the Pike River, one of the main tributaries draining into the Missisquoi bay, the median P concentrations between 1998 and 2001 was 0.05 mg l^{-1}. During the same period, median nitrate concentrations were 0.95 mg l^{-1} (CBVBM, 2003). Thus, while phosphorus concentrations exceeded recommended guidelines in the river, nitrate concentrations were within acceptable limits.

Phosphorus is considered to be the limiting agent in the eutrophication process ahead of nitrogen, with critical levels that promote growth of algal blooms being 0.02 mg l^{-1} and 0.3 mg l^{-1} respectively (Daniel et al, 1998). Also, phosphorus inputs can be limited more easily compared to nitrogen, due to the capacity of atmospheric nitrogen to be fixed on blue green algae (Sharpley 1995).

2.2. Field Hydrology and Nutrient Transport

The scale at which the water balance of a hydrologic cycle is applied is important to identify the significant parameters in the cycle. The watershed is generally preferred as the unit within which water quality research is carried out and policies are framed (Chesters and Schierow, 1985). The natural ecological boundary that a watershed provides makes it convenient to analyze its hydrology and water quality (Omernik and Griffith, 1991). At the same time, watersheds are often spread over large areas and cover a variety of land uses, topographies and soils. These factors have a direct relationship with each other and can significantly alter the hydrology of the basin (Kirby and Mehuys, 1987). In studies such as this where more specific requirements need to be met, namely the accurate estimation of nutrient loads from agricultural fields, the scale of research needs to be concentrated at a much smaller level.

2.2.1. The Hydrologic Cycle and Snowmelt

The principles of the hydrologic cycle and water balance remain the same regardless of the scale at which the study is carried out. 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).

The main means of nutrient transport from agricultural fields to watercourses are identified as surface runoff and subsurface flow. A precipitation event that is greater than the threshold capacity of the field to retain and intercept water initiates surface runoff, which carries sediment, phosphorus and nitrates in both their soluble and insoluble forms into the watercourse. Subsurface flow could be through natural lateral flow or artificial tile drains installed to maintain water table depth at a level that does not adversely affect crop yields. 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 pollutants, the accurate estimation and prediction of flows are necessary to quantify the magnitude of these pollutant loads from contributing sources.

2.2.2. Tile Drainage in Quebec

In eastern Canada, the installation of artificial tile drainage systems on agricultural fields is a common practice. Tile drains chiefly serve to reduce the depth of the water table to a level that is beneficial for crop growth in periods of excess rainfall. In a region that witnesses a short growing season, the presence of tile drainage is a boon that serves to prepare the field earlier in spring when the soils are saturated with water, giving the farmer a few more precious growing days. Artificial drainage also reduces surface runoff, and subsequently soil erosion and particulate pollutant transport (Culley et al, 1983). In Quebec, the total area of drained fields in

2002 was estimated at 735,000 hectares (Beaulieu, 2002). About 44% of the agricultural region in the Pike river watershed is artificially drained (CBVBM, 2003).

Fields with artificial drainage systems contribute much more water to streamflow 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 phosphorus in tile drains (Jamieson et al, 2001). With soils becoming richer in phosphorus due to continual fertilization, it is believed that P losses through tile drains cannot be ignored any longer (Enright and Madramootoo, 2004).

2.2.3. Preferential Flow

The movement of nutrients in solution in the soil profile can occur through different pathways. Soil structure influences the lateral movement of water, with the distribution of micro and macropores controlling the rate and extent of nutrient transport (Heathwaite et al, 2000). The main pathway for transporting nutrients to subsurface drains is not considered to be lateral flow but preferential flow through macropores. The large macropores effectively short-circuit the natural pathways and render ineffective the capacity of soil to act as a natural filter (Heathwaite et al, 2000). Although the phenomenon is difficult to model, some field and lab studies have been conducted to evaluate its importance in subsurface nutrient dynamics. High soil P absorption capacities were cited as the main reason for high concentrations of P because of preferential flow (Heckrath et al, 1995). Dye tracer studies by Stamm et al (1998) provided some evidence that preferential flow is an efficient mechanism for P transport into tile drains.

2.3. Water Quality Models

In order to carry out an assessment of water quality over a range of scenarios, the use of computer models has helped make predictions with limited user inputs, and improved our understanding of hydrologic processes and nutrient dynamics (Frere et al, 1982). It is important to bear in mind the needs of the water resource problem before developing, choosing or operating a model (Parsons et al, 2001). While a sensitive model can be useful in evaluating the impact of different parameters on corresponding outputs, it can sometimes be detrimental if the user has limited input information. Another factor to consider before choosing a model is the availability of data to calibrate and validate the model, without which an analysis of outputs would not be possible. The scale at which the modeling is carried out is a third criterion that needs to be addressed while choosing a model, with specific models being designed for the plot-scale, field-scale and watershed-scale. For instance, this is especially important if the modeler's objective is to assess spatial differences as a result of different soil types or management practices. The temporal scale of simulations also needs to be considered, with models being event-based or continuous in nature.

To meet the objectives of this study, the main requirements for the model were: to be able to simulate hydrologic and nutrient transport processes for individual agricultural fields with a single surface runoff output for each field. Thus, each field can be considered as a sub-basin or a sub-watershed. Additionally, the model should have a subsurface flow component that incorporates sediment and nutrient losses. Thirdly, the model should be able to incorporate the physical characteristics of each field, including soil type, topography, crop cover, etc. Fourthly, the model should be able to simulate snowmelt hydrology as accurately as rainfall hydrology since snowmelt is a significant event in a region such as Quebec. Finally, in order to evaluate the impact of management practices on the field, the model must be able to carry out continuous simulations and be sensitive to changes in crop cover, tillage or fertilization. The model interface should be convenient to create numerous scenarios for BMP simulations.

Some of the common hydrological and water quality models are briefly described in this section: DRAINMOD (Skaggs, 1980); Agricultural Non-Point Source Pollution Model, AGNPS (Yoon et al, 1993); Watershed Ecosystem Nutrient Dynamics, WEND (Cassell and Kort, 1998); Areal Non-point Source Watershed Environment Response Simulation, ANSWERS2000 (Bouraoui and Dillaha, 1996); and the Soil and Water Assessment Tool, SWAT (Arnold et al, 1993).

2.3.1. DRAINMOD

Specifically designed to simulate water management practices and their impacts on surface and subsurface flows, DRAINMOD (Skaggs, 1980; Fernandez et al, 1998) is a field-scale model appropriate for soils with high water tables or poor drainage conditions. Combinations of surface and subsurface drainage, controlled drainage and subirrigation can be simulated with this model. The model was improved to simulate nitrogen leaching and predict N concentrations in surface and subsurface waters (Breve et al, 1997).

Model inputs include climatic data, soil characteristics, and field management. Simulations are based on time-scales greater than 20 years, although outputs can be generated on daily, monthly or annual basis. Outputs are surface runoff, subsurface drainage, infiltration, evapotranspiration, water table depth and crop water stresses (Parsons et al, 2001).

DRAINMOD results for water table depth are accurate even without calibrating the model when specific field input data are available. However, the model is mainly used to assess water management and has limited scope with regard to nutrient management scenarios. The nitrogen submodel, DRAINMOD-N provides N concentrations based on a nitrate pool balance and accounts for mineralization, plant uptake, fertilizer addition and denitrification. Such a submodel has not been developed to measure P concentrations.

2.3.2. AGNPS

The AGNPS model (Yoon et al, 1993) is designed to simulate surface runoff, sediment, nutrients and pesticide movement within an agricultural watershed. It is an event-based model that accounts for spatial variability in the watershed through hydrologic response units (HRU). Each HRU constitutes a cell within which pollutant movement can be modeled on a daily time frame. However, AGNPS faces a limitation in being event-based (Bosch et al, 2001), and it has undergone changes to create an annualized continuous simulation model called AnnAGNPS (Bingner et al, 1998).

Geographic Information Systems (GIS) were used for developing inputs, with AGNPS 2001 also having the capability of evaluating management practices on a watershed scale. Bosh et al (2001) state that AnnAGNPS retains the basic principles of AGNPS by incorporating a multi-event modification that permits continuous modeling. More detailed inputs in AnnAGNPS have provided a better representation of nutrient movement. For instance, upto two layers of soil can be defined. Also, each cell contains unique information on soil type, land use and management practices and a daily mass balance of nutrients can be performed for each cell.

Perrone (1997) tested AGNPS on the St-Esprit watershed in Quebec and found that estimates of surface runoff and sediment yield were accurate after calibration. However, simulation accuracy was poor during the winter, and the authors suggested an investigation of seasonal parameters to improve the model (Perrone and Madramootoo, 1999). Other limitations of the model were the absence of mass balance calculations for inflow and outflow and an assumption of constant precipitation distribution across the watershed.

2.3.3. WEND

The Watershed Ecosystem Nutrient Dynamics model (Cassell and Kort, 1998) is based on a dynamic modeling framework to perform phosphorus mass balance calculations in a watershed. It is a long-term continuous simulation model, capable of running simulations over several decades (Cassell et al, 2000). It has been designed for agricultural watersheds, and has been customized to the requirements of three production categories, namely dairy, poultry and swine. A calibration procedure is required to match the appropriate model to the study watershed.

The model is composed of sectors within which the phosphorus processes and transformations are carried out – namely agricultural, forested and urban. The WEND model is capable of assessing long-term management strategies required to reduce P losses in an agriculturally intensive watershed. It is also capable of simulating phosphorus losses in drainage, which is one of the objectives of this study. It has been tested successfully at the field level in the Castor watershed of southern Quebec (Choquette, 2005), close to the study area of this thesis.

One of the biggest limitations of WEND is the necessity to adapt it to the watershed being considered through an extensive calibration or customization procedure. The model is also highly input-intensive, requiring a large range of information from the user. Novotney and Olem (1994) have stated that sediment load predictions could be improved by the insertion of sediment delivery ratio and precipitation intensity in the calculations. Yet, these limitations can be overcome in studies where such information is available, or in watersheds that need little or no customization.

2.3.4. ANSWERS 2000

The Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) model (Bouraoui and Dillaha, 1996) was developed to study management practice effects on sediment and nutrient transport. It is a flexible model allowing field-scale and watershed-scale, short-term and long-term simulations. Being a distributed parameter, continuous simulation model, ANSWERS works with an ArcInfo GIS interface for data input and processing. Variable time-step simulations and the use of breakpoint precipitation information add versatility to the model.

Nutrient dynamics for nitrogen and phosphorus are based on interactions between four pools of N and P each. The ANSWERS model can specifically address nitrogen leaching problems and assess nitrification risk with accuracy through the estimation of N percolation, Kjeldahl N and denitrification, as affected by soil, crop and hydrologic conditions. Phosphorus losses in surface runoff can be simulated as well (Dillaha et al, 2001).

The ANSWERS model has been applied extensively to assess surface runoff, nitrate pollution risk and sediment loads at the watershed scale. ANSWERS 2000 has also been used for predicting drainage below the root zone, by adding a groundwater component to it (Bouraoui et al, 1997). 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).

2.3.5. AVSWAT 2000

The 2000 version of the Soil and Water Assessment Tool, integrated with the ArcView 3.2 interface was chosen in this study. The model was developed by Arnold et al (1993) for the USDA Agricultural Research Service (ARS), chiefly aimed towards predicting the impact of management practices on water, chemical and sediment yields on large watersheds. The models that contributed to the development of SWAT were Chemicals, Runoff, and Erosion from Agricultural Management Systems - CREAMS (Knisel, 1980); Groundwater Loading Effects on Agricultural Management Systems – GLEAMS (Leonard et al, 1987) and Erosion Productivity Impact Calculator - EPIC (Williams et al, 1984).

The main features of the model are (Neitsch et al, 2002):

i) It is physically based, implying that it requires specific inputs to enable direct modeling of water movement, nutrient transport and crop growth. These inputs include climatic data, soil properties, topography, land use and management practices.

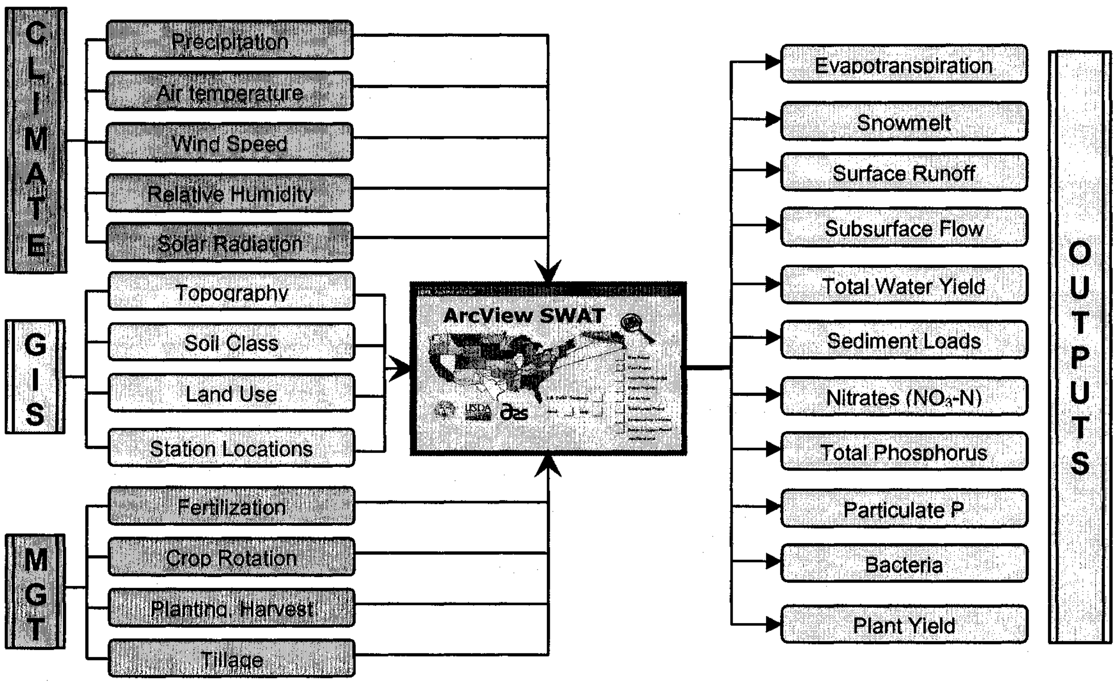
ii) It is a continuous time model and provides outputs over the long-term. It is not suited for event-based rainfall-runoff modeling.

iii) It is computationally efficient, enabling simulations of complex management practice scenarios as well as very large watersheds.

The range of inputs in the SWAT model and the chief outputs simulated by it are summarized in Figure 2.1.

Based on the review of these hydrological and water quality simulation models and the requirements of this study, the ArcView SWAT 2000 model was chosen to predict sediment, nitrate and phosphorus losses in surface runoff and tile drainage on agricultural fields. Although it is a watershed-scale model, the availability of extensive input data and the ability to treat the field as a sub-watershed were considered in making this choice. Moreover, its functionality as an assessment tool to evaluate the impact of management practices made it suitable to meet the objectives of this study. A more detailed description of the AVSWAT 2000 model is presented in the following sections.

Figure 2.1: Schematic showing inputs and outputs of the AVSWAT 2000 model



2.4. SWAT Hydrology

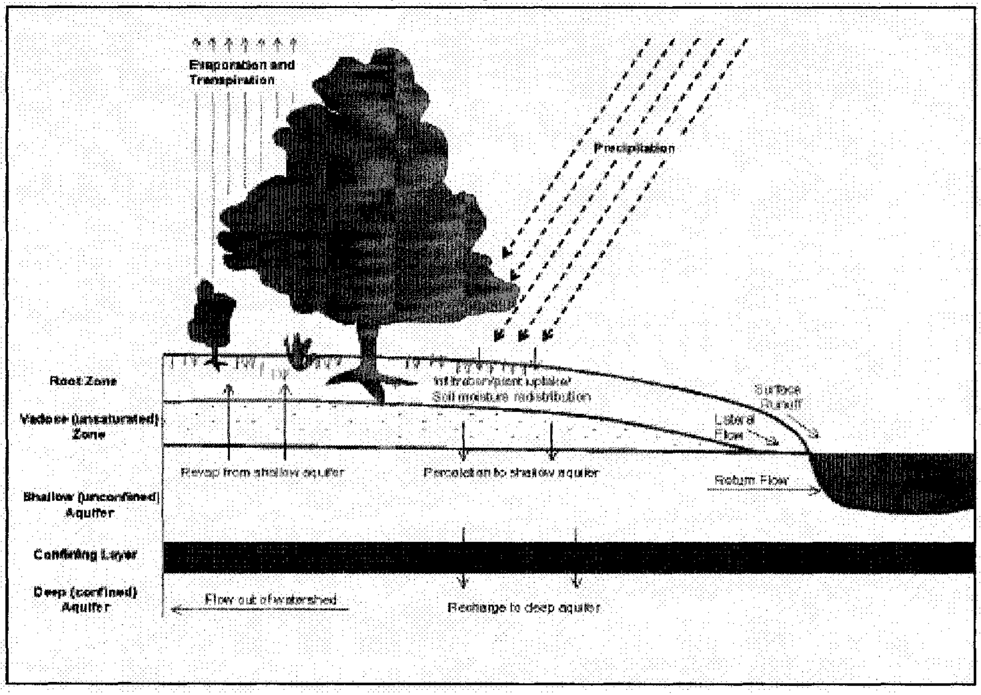
The AVSWAT 2000 model uses data from digital elevation models (DEM) as the basis from which the watershed is partitioned into sub-watersheds and sub-basins. In this study, the model will be applied at the field-scale, with each field being treated as a single sub-basin having a single output. Since the water balance is the main governing principle behind the simulations, the equations for simulating the hydrologic cycle constitute a very important part of the model structure.

The water balance equation as simulated by SWAT is:

[1] $$SW_t = SW_0 + \quad (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

where SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content (mm H_2O), *t* is the time (days), R_{day} is the amount of precipitation (mm H_2O), Q_{surf} is the amount of surface runoff (mm H_2O), E_a is the amount of evapotranspiration (mm H_2O), w_{seep} is the amount of water entering the vadose zone from the soil profile, and Q_{gw} is the amount of return flow (Figure 2.2).

Figure 2.2: Schematic of the hydrologic cycle in SWAT (Neitsch et al, 2002)



Precipitation, air temperature (maximum and minimum), solar radiation, wind speed and relative humidity are the climatic inputs required by the model. The model also comprises a weather generator to simulate daily data for each of these variables based on long-term monthly averages for the concerned region. Since precipitation and air temperature were the only two measured daily inputs available from the study sites, the other parameters were simulated by SWAT. Precipitation is classified as rain or snow based on the average daily temperature while snowmelt is controlled by snow pack temperature as well. Snow cover is defined based on a user-oriented input for threshold snow depth beyond which 100% cover exists for the basin. Non-linear areal depletion curves are plotted to determine snow cover below this value. The mass balance for snowpack in SWAT is governed by the following equation:

[2] $$SNO_{final} = SNO_{initial} + R_{day} - E_{sub} - SNO_{mlt}$$

where on a given day, SNO is the water content of the snowpack, R_{day} is the amount of precipitation, E_{sub} is the amount of sublimation and SNO_{mlt} is the amount of snowmelt, which is defined as

[3] $$SNO_{mlt} = b_{mlt} \cdot sno_{cov} \cdot \left[\frac{(T_{snow} + T_{mx})}{2} - T_{mlt}\right]$$

where b_{mlt} is melt factor, sno_{cov} is the fraction of the area covered by snow, T_{snow} is the snow pack temperature, T_{mx} is the maximum air temperature and T_{mlt} is the base temperature above which snowmelt is allowed.

Surface runoff can be calculated using a modification of the SCS curve number method (USDA Soil Conservation Service, 1972), with the curve number varying non-linearly with the moisture content of the soil. The Green-Ampt infiltration method (Green and Ampt, 1911) can also be used for estimating runoff but requires sub-hourly precipitation inputs. Water that enters the soil may be removed through plant uptake, may seep down into aquifer storage or move laterally and contribute to streamflow. Lateral subsurface flow is calculated using a kinematic storage model (Sloan et al, 1983) for each soil layer, accounting for variations in conductivity, slope and soil water content.

2.5. Nutrient Dynamics in SWAT

Sediment yield is calculated based on the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). The movement of nutrients, i.e. nitrogen and phosphorus is based on built in equations for their transformation from one form to the other. The total amounts of nitrates in runoff and subsurface flow is calculated the volume of water in each pathway with the average concentration. Phosphorus however is assumed to be a relatively less mobile nutrient, with only the top 10 mm of soil considered in estimating the amount of soluble P removed in runoff. A loading function is used to estimate the phosphorus load bound to sediments (McElroy et al, 1976). The nitrogen and phosphorus cycles used by SWAT are shown in Figure 2.3 and Figure 2.4 (Neitsch et al, 2002).

2.5.1. Nitrogen

Nitrogen is one of the most important nutrients for plant growth. In soil and water, it is extremely reactive and exists in a number of dynamic forms. It may be added to the soil through natural bacteriological fixation, rainfall or artificial application of fertilizers. It can be removed through plant consumption, soil erosion, leaching and denitrification to the atmosphere. In the SWAT model, there are five main pools of nitrogen in the soil (Figure 2.3). In the mineral form, the ammonium (NH_4^+) and the nitrate (NO_3^-) ions interact with each other, plants and atmosphere through nitrification, plant use and denitrification processes. Active organic forms of nitrogen can also be mineralized into the NO_3^- form. Plant residue and humic biomass constitute the fresh, active and stable organic pools (Figure 2.3).

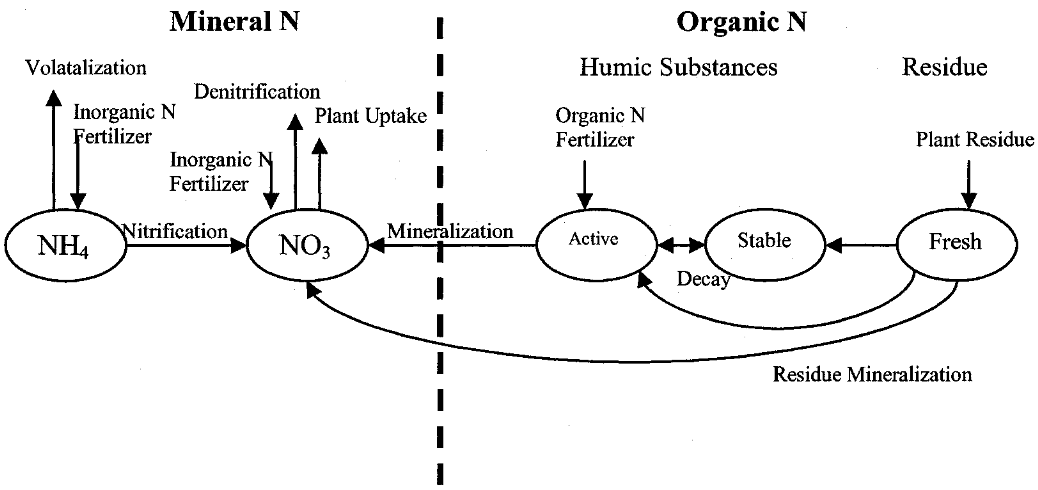


Figure 2.3: Nitrogen cycle as simulated by SWAT (Neitsch et al, 2002)

User-defined inputs include the amount of nitrogen contained in mineral and organic forms in the soil at the beginning of simulation. Also, the addition of organic and mineral nitrogen fertilizers can be specified by the user for each year of the simulation.

2.5.2. Phosphorus

Phosphorus exists in three major forms – organic (with humus), insoluble mineral and in soil solution, which is available to plants. It can be added to soil through fertilizers, manure and from biomass, while it can be removed by the plants, erosion and runoff. Since phosphorus is less reactive and relatively insoluble in most forms, it tends to accumulate at the surface of the soil, and is thus highly susceptible to surface runoff (Sharpley and Syers, 1979).

In the SWAT model, there are six main pools of P in soil (Figure 2.4). Fresh organic phosphorus is driven by plant residues, while the active and stable pools are linked to humus. Mineral P in solution can be formed through mineralization of the active organic phosphorus or from the active mineral pool, which is in a state of slow equilibrium with the stable pool.

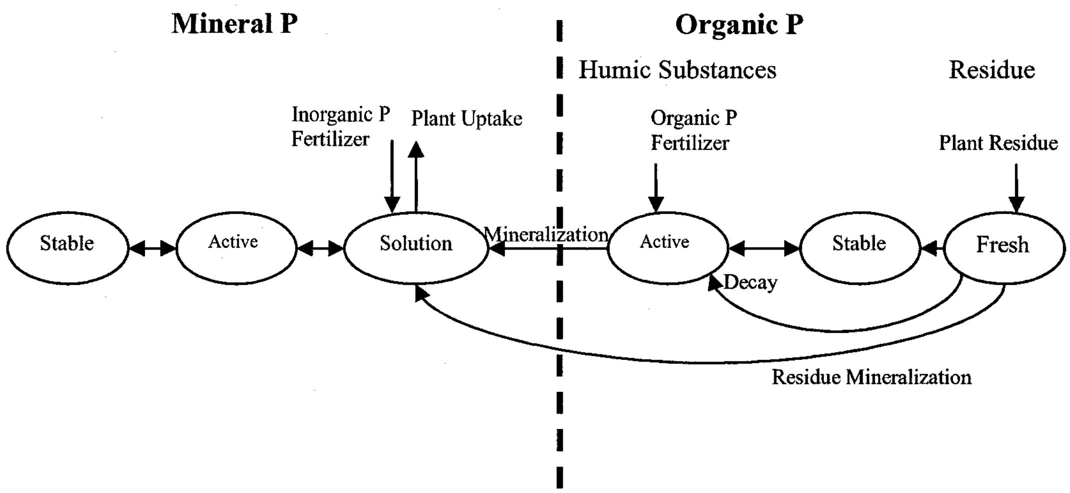


Figure 2.4: Phosphorus cycle as simulated by SWAT (Neitsch et al, 2002)

User inputs can define amounts of soluble and organic phosphorus in the soil layers, along with the amount of fertilization for every year, without which SWAT initializes its own values based on the phosphorus availability index (Jones et al, 1984).

[4] $minP_{act,ly} = P_{solution,ly} \cdot [(1 - pai)/pai]$

where $minP_{act,ly}$ is the amount of phosphorus in the active mineral pool (mg/kg), $P_{solution,ly}$ is the amount of phosphorus in solution (mg/kg) and *pai* is the phosphorus availability index.

All calculations in SWAT are performed on a mass basis, although user inputs may be given as concentrations. The conversion is based on the following formula

[5] $(conc \cdot \rho_b \cdot depth_{ly}) / 100 = \text{kg ha}^{-1}$

where *conc* is the concentration of nitrogen or phosphorus in a layer in mg/kg, ρ_b is the bulk density of the layer (Mg m^{-3}) and $depth_{ly}$ is the depth of the layer in mm.

2.6. Management Practice Simulations in SWAT

Management operations that can be simulated by SWAT include tillage, planting and harvest dates, timing and amount of fertilizers and pesticides, residue levels and filter strips. Water management operations such as irrigation can also be simulated by the model.

The plant growth and harvest operations may be input based on actual dates are through heat unit calculations. The user can vary the curve number throughout the year, depending on the operation concerned. A 'kill' operation is used to remove all plant cover. This operation is typically carried out at the end of the growing season, or sometimes before a new growing season.

The parameter inputs for a tillage operation are depth of tillage, curve number and timing of operation. SWAT has built in databases for standard tillage operations. A tillage operation redistributes soil, residue, nutrients, bacteria and pesticides with a specified mixing efficiency.

Fertilizer inputs require the date of application, the type of fertilizer or manure applied and the depth of distribution of the fertilizer. Since SWAT considers surface runoff contributions from the top 10 mm of the soil, the fraction of fertilizer in this layer can be varied by the user, in which case the remaining is applied to the next soil layer in the profile.

Filter strips at the edge of the field may be defined in the model. This results in reduced sediment, nutrient and pesticide loads in surface runoff, with the trapping efficiency being a direct function of the width of the filter strip.

CONNECTING TEXT TO CHAPTER 3

This chapter is a manuscript prepared for publication in the *Canadian Journal of Civil Engineering* in 2005. The manuscript is co-authored by my supervisor Dr. C.A. Madramootoo and Mr. Peter Enright, project engineer and professional associate. The format has been changed to be consistent within this thesis. All literature cited in this chapter is listed in the reference section at the end of this thesis.

Chapter 3 covers the various aspects of field-scale hydrological modeling using SWAT. A description of the site instrumentation and data collection methodology is provided along with calibration procedures and statistical analyses. Simulation results for water yield, surface runoff and subsurface drain flow on two agricultural fields have been presented.

CHAPTER 3: Hydrological Modeling of Two Agricultural Fields in the Pike River Watershed of Southern Quebec Using SWAT

Apurva Gollamudi, Chandra Madramootoo and Peter Enright

ABSTRACT

Two field sites in the Pike River watershed of Southern Quebec were instrumented to measure surface runoff and tile drainage volumes. The Soil and Water Assessment Tool (ArcView SWAT2000) was used to simulate the hydrological characteristics of these fields, representing each field as a sub-basin. A sensitivity analysis on model parameters showed that runoff curve number, available soil moisture content and baseflow recession factor significantly affected hydrological simulations. Climatic data (precipitation, air temperature) from the sites was used as the primary simulation input. The model was calibrated based on surface runoff and subsurface flow data over a 12-month period (2002-03), while an independent 12-month interval (2003-04) was used to validate results. An autocorrelation and cross-correlation analysis was also performed to assess model performance for daily streamflow. Coefficients of performance for sites #1 and #2 were 0.67, 0.62 for surface runoff; 2.21, 2.28 for subsurface drainage; and 0.32, 0.64 for total water yield during the validation year.

Keywords: SWAT, Hydrologic Modeling, Calibration, Surface Runoff, Subsurface Drainage, Coefficient of Performance, Correlation Analysis

3.1. INTRODUCTION

In Quebec, phosphorus contamination of water-courses and lakes is largely attributed to nonpoint source pollution from agricultural fields. Surface runoff and tile drainage are the two principal pathways by which sediment and nutrients are transported from field to watercourse (Mimeault, 2002). However, the understanding of phosphorus dynamics on typical fields in Southern Quebec, which often exhibit high soil test P values, is limited and finding an effective solution to the problem necessitates in-depth field studies. Studies have shown that tile drains can also be a significant pathway for phosphorus transport from agricultural fields, accounting for up to 40% of the total phosphorus losses in fields oversaturated with nutrients (Enright and Madramootoo, 2004). While long-term field-scale monitoring is essential to establish and corroborate a theoretical understanding of phosphorus dynamics, only a limited number of studies are available due to the high cost of instrumentation and operation. Additionally, collecting long-term data for a range of climatic, hydrologic and topographic conditions is a time-consuming process. Thus, complementing real-time field data with a validated hydrological and water quality simulation model is both economically beneficial and time-efficient.

The ability of a model to accurately simulate hydrological processes such as surface runoff and subsurface drain flow are important prerequisites for subsequent reliable predictions of sediment and nutrient losses. The key criteria in considering a model are: the availability of reliable input data for the required range of parameters, scale of use, and nature of output. Hydrological and water quality simulation models to estimate runoff, sediment loads and nutrient movement have developed from the elementary to the complex in the past three decades. A wide range of models are available, such as CREAMS (Knisel, 1980), EPIC (Williams *et al*, 1984) and GLEAMS (Leonard *et al*, 1987) for the field-scale; ANSWERS (Beasley *et al*, 1980), AGNPS (Young *et al*, 1987), SWAT (Arnold *et al*, 1998) and DWSM (Borah *et al*, 2002) for the watershed scale. A common starting point for all these models is the necessity to accurately reproduce the movement of water through different components of the hydrologic cycle – precipitation, overland flow, infiltration, subsurface flow, deep seepage, evapotranspiration (ET) and streamflow.

SWAT, a watershed-scale, physically based, continuous model developed by Arnold *et al* (1993) for the USDA Agricultural Research Service (ARS) has been used effectively all around the world to predict daily and monthly stream discharge from watersheds of varying size (Spruill *et al*, 2000; Tripathi *et al*, 2004). Borah and Bera (2003) reviewed eleven hydrologic and non-point source pollution models and inferred that SWAT was the most promising for long-term simulation in predominantly agricultural watersheds. Van Liew *et al* (2003) tested HSPF and SWAT on experimental watersheds and showed that SWAT was better suited for assessing long-term impact of management practices on hydrologic response, nutrient and sediment yield. The success of SWAT is making it a preferred application to develop the US-based Total Maximum Daily Load (TMDL) programs for small watersheds (Kang *et al*, 2005; DiLuzio and Arnold, 2004). SWAT has been used successfully at the watershed (630 km^2) and sub-basin scale (11 km^2) in the Pike River watershed of Quebec (Beaudin *et al*, 2004) to develop agro-environmental indicators for nutrient transport. Although SWAT has not been tested extensively at the field-scale, it was selected for this study since exhaustive field data was available for most parameters required and the Geographical Information System (GIS) interface (ArcView SWAT 2000) facilitated easy integration of spatial and temporal datasets. In addition, the computational efficiency of SWAT enables convenient parametric adjustment and multiple simulations to be carried out in minimal time (Arnold and Fohrer, 2005).

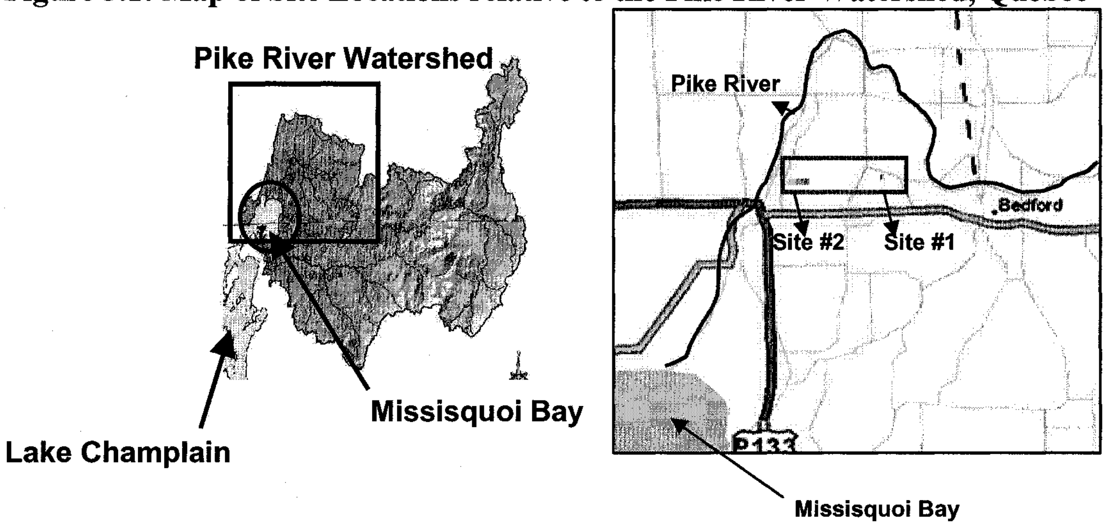
Therefore, the main objectives of this study were: (i) to apply the SWAT model to two agricultural field sites in the Pike River watershed; (ii) to perform a sensitivity analysis, calibrate and validate the model using four-site years of data; (iii) to evaluate the performance of SWAT in simulating total water yield, surface runoff and subsurface flow on agricultural fields at the monthly and seasonal scale, and (iv) to test its ability to simulate snowmelt and runoff in frozen soil conditions.

3.2. MATERIALS AND METHODS

3.2.1. Site Description

The two agricultural fields for this study are located near the town of Bedford in the Pike River watershed of Southern Quebec, about 70 km from Montreal. Figure 3.1 provides a map of the region, indicating the location of the two sites. The first site (# 1) is located on a dairy farm with a surface and subsurface drainage area of 6 ha. The second site (# 2) belongs to a swine and cash crop producer, with a surface drainage area of 7 ha and a subsurface drainage area of 7.8 ha. Instrumentation on the sites was installed in the fall of 2000, and hydrologic and meteorological data are being collected continuously since October 2000.

Figure 3.1: Map of Site Locations relative to the Pike River Watershed, Quebec



The soil on site # 1 is a Rubicon sandy loam; site # 2 has three soil types – Suffield clay loam (9.4%), Ste. Rosalie clay loam (69.9%) and Bedford sandy clay loam (20.7%). During the study period (2001-2004), the principle crop grown on both sites was corn, with the exception of alfalfa (2004) at site # 1; and barley (2002), and soybean (2001) at site # 2. Site summaries are presented in Table 3.1.

Table 3.1: Site Description

	Site # 1	*Site # 2*
Surface drainage area	6 ha	7 ha
Subsurface drainage area	6 ha	7.8 ha
Soil type(s)	Rubicon sandy loam	Suffield clay loam (9.4%)
		Ste Rosalie clay loam (69.9%)
		Bedford sandy clay loam (20.7%)
Average land slope	1.5%	0.8%
Elevation	40 m	36 m
Land use	2000 – Corn	2000 – Corn
	2001 – Corn	2001 – Soybean
	2002 – Corn	2002 – Barley
	2003 – Corn	2003 – Corn
	2004 – Alfalfa	2004 – Corn
Tillage	Conventional	Conventional

3.2.2. Instrumentation and Monitoring

Precipitation, air temperature, surface runoff and subsurface drain flow are the main inputs that are continuously monitored at the two sites. Precipitation is measured with tipping bucket rain gauges. Precipitation data are also obtained from the Quebec Ministry of Sustainable Development, Environment and Parks (DEDD) Philipsburg weather station (45°02' N and 73°0 45' W), located about 9 km from the sites. The 30 yr climatic normal for precipitation at Philipsburg is 1095.6 mm yr^{-1}, with snowfall accounting for 203.9 mm. The total annual potential evapotranspiration is 602 mm yr^{-1} (Jamieson, 2001). Snowfall is not measured on the field sites, as this data is obtained from the Philipsburg station.

Surface runoff is measured using an H-flume located at the surface outlet of each field. An ultrasonic depth sensor (Campbell Scientific SR50) is used to measure water level in the flume, and a Keller 173 submersible pressure transducer is used as a secondary sensor. Surface flows are calculated using a rating curve for the H-flumes. To measure subsurface flow, the tile drainage collector was modified and fitted with an ultrasonic flow meter (Endress & Hauser Prosonic Flow DMU-93), which serves as the primary measurement device. An insertion flow meter (Global Water IF-200) serves as the back-up sensor. In the initial phases of the field monitoring, only the IF-200 meter was installed. The DMU-93 is a retrofit and was installed in February 2002. Meteorological and hydrologic data are measured on 5 s intervals and stored as means (or totals) over 15 min periods onto a Campbell Scientific 21X datalogger. (Jamieson *et al*, 2003). Refinements have been made to surface flow and precipitation data as newer information on drainage areas and meteorology became available. A more detailed and complete description of site locations, instrumentation, monitoring procedures and water quality sampling strategies is presented by Enright and Madramootoo (2004).

3.2.3. Model Inputs

Inputs required by SWAT to model movement of water are: topography, stream paths, soil physical properties, land use, crop rotation and meteorological data. In order to model water quality and sediment and nutrient movement, additional inputs such as fertilization and soil chemical properties are required. For topographic data, a survey was carried out on the two field sites using a Sokkia SET 610 total station and a differential GPS on a 20 m X 20 m grid. The data was modeled using ArcGIS 8.3 to generate a Digital Elevation Model (DEM), which was integrated into the ArcView SWAT interface (DiLuzio *et al*, 1998). The stream network and sub-basins were delineated using the SWAT automatic delineation tool. Digital soil maps were used to overlay the soil type boundaries on both field sites and soil characteristics from the map were verified with results from a physicochemical analysis carried out in 2002-03. Bulk density, saturated hydraulic conductivity, organic matter content and soil texture properties were obtained from the regional soil quality inventory (MAPAQ, 1990). Land use, cultural practices and crop rotation data were obtained from the field owners (Table 3.1). The hydrological response units (HRU) were based on soil types: site #1 had a single HRU while site #2 had three HRUs. Meteorological data inputs were based on daily precipitation data from the tipping bucket rain gauges at the two sites, while snowfall data was obtained from the Philipsburg weather station. Solar radiation, wind speed and relative humidity are simulated based on historical data from Plattsburg, NY which is about 60 km south-west of the field sites.

Once all input files are integrated into the Geographical Information System (GIS), methods used for calculating surface runoff, evapotranspiration and precipitation distribution need to be specified. The options available are: duration of simulation (start, end date); time-step for which output is desired (daily, monthly or yearly); mathematical model for surface run-off (SCS Curve Number, Green-Ampt Infiltration Model); and method for calculating evapotranspiration (Penman - Monteith, Hargreaves or Priestley - Taylor). For both sites, simulations were run on a daily precipitation input and daily output was obtained. Daily output was summed to get monthly, seasonal and yearly totals. Precipitation was simulated as a skewed normal distribution and runoff was routed by the variable storage method. The Penman-Monteith method was chosen to calculate evapotranspiration.

The Penman-Monteith method requires solar radiation, wind speed, relative humidity and air temperature data to calculate potential evapotranspiration. The equation for this method is given as

[1]
$$\lambda E = \frac{\Delta \cdot (H_{net} - G) + \rho_{air} \cdot c_p \cdot [e_z^o - e_z]/r_a}{\Delta + \gamma \cdot (1 + r_c/r_a)}$$

where λE is the latent heat flux density (MJ m^{-2} d^{-1}), E is the depth rate evaporation (mm d^{-1}), is the slope of the saturation vapor pressure-temperature curve, de/dT (kPa $^oC^{-1}$), H_{net} is the net radiation (MJ m^{-2} d^{-1}), G is the heat flux density to the ground (MJ m^{-2} d^{-1}), ρ_{air} is the air density (kg m^{-3}), c_p is the specific heat at constant pressure (MJ kg^{-1} $^oC^{-1}$), e_z^o is the saturation vapor pressure of air at height z (kPa), e_z is the water vapor pressure of air at height z (kPa), γ is the psychrometric constant (kPa $^oC^{-1}$), r_c is the plant canopy resistance (s m^{-1}), and r_a is the diffusion resistance of the air layer (aerodynamic resistance) (s m^{-1}). The methodology used by SWAT in estimating these variables is detailed in Neitsch et al (2002).

King *et al* (1999) compared the Green-Ampt Mien-Larson (GAML) and SCS curve number (CN) methods using SWAT. While GAML was found to simulate annual surface runoff better, CN gave better results for monthly totals. For daily comparison however, no significant difference was found between the models. Due to the robustness of the CN method and the need for breakpoint rainfall data and parameterization for GAML, the curve number method was preferred over GAML to simulate runoff.

The SCS curve number equation (Soil Conservation Service, 1972) is an empirical formula to calculate surface runoff, and is given by:

[2] $$Q = (P - 0.2S)^2 / (P + 0.8S)$$

where Q is surface runoff (mm), P is rainfall (mm) and S is a retention parameter (U.S. Department of Agriculture, 1972). The retention parameter is defined as

[3] $S = 25400 / CN - 254$, where CN is the daily SCS Curve Number.

3.2.4. Simulation

The duration of simulation was divided into three stages – testing, calibration and validation. The initial testing period was used to perform a water balance to check accuracy of model setup. The water balance equations used in the SWAT model for every time-step are (Neitsch *et al*, 2002a):

[3] PRECIP = WYLD + ET + ΔSW + Deep Seepage (in mm H_2O)

[4] WYLD = SURQ + LATQ + GW_Q – TLOSS – pond abstractions (in mm H_2O)

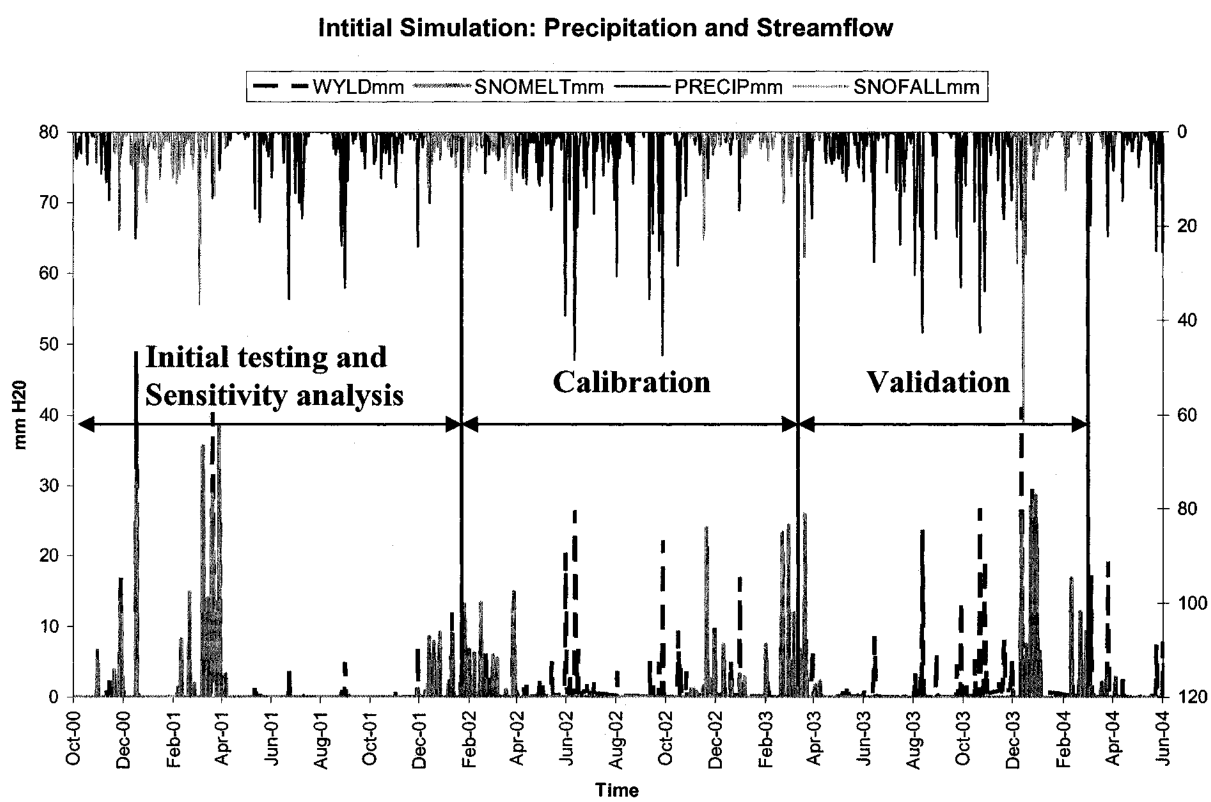
where PRECIP is the total precipitation, WYLD is the total water yield at the outlet of the sub-basin, ET is the evapotranspiration, ΔSW is the change in soil water content, SURQ is the surface runoff contribution to streamflow, LATQ is the lateral flow contribution to streamflow, GW_Q is the groundwater contribution to streamflow and TLOSS are transmission losses from tributary channels. SWAT simulates tile drainage as lateral flow, with drainage occurring when the soil water content exceeds field capacity in the soil layer where the tile drains are installed.

A sensitivity analysis was conducted to assess the quantitative impact of SWAT parameter inputs on hydrologic outputs, viz. evapotranspiration, snowmelt, total water yield, surface runoff and subsurface flow. Sensitivity was also assessed qualitatively for temporal variations such as sub-basin response time and hydrograph shape. The most sensitive parameters were then adjusted to calibrate the model using measured flow data from the sites. The results were corroborated by other sensitivity analyses conducted on SWAT parameters in Canadian conditions (Goel *et al*, 2004). To assess SWAT-predicted ET, studies by Barnett *et al* (1998) and Romero *et al* (2002) on the St. Esprit watershed, about 90 km north-west of the sites were used as a reference. Preliminary assessment of the model was done using default parameters assigned by SWAT. Sub-basin characteristics were assigned values based on pre-defined soil hydrologic characteristics and built-in land use classification tables. Errors in precipitation and climate input, weather station locations, etc. were identified and resolved in this step. Management practices, i.e. planting, fertilization, tillage and harvesting dates, were initially determined based on heat units.

Calibration and Validation

Although SWAT has been designed for use in ungauged basins as an uncalibrated model, results have known to significantly improve after a calibration procedure is adopted (King *et al*, 1999; Spruill *et al*, 2000). The simulation period for this study was from October 2000, but a complete dataset of flow measurements was not available until the hydrologic year February 2002 due to instrumentation problems with the insertion flow meter. Moreover, the more accurate ultrasonic DMU-93 flowmeter was installed in February 2002. Thus, the hydrologic year 2000/01 was excluded from the analysis for calibration and validation. Two full years of flow data were available for calibration and validation, from March 2002 to February 2004. This was split into two 12 month intervals: the first being used for calibration and the second for validation (Figure 3.2).

Figure 3.2: Intervals for model testing and evaluation



3.2.5. Assessment of Model Performance

Coffey *et al* (2004) evaluated different statistical procedures for daily and monthly SWAT hydrologic streamflow predictions, the methods tested being linear regression, Nash-Sutcliffe efficiency, non-parametric tests, t-tests, objective functions, and autocorrelation and cross-correlation analysis. The best estimator for daily data sets, which are often non-normal and dependent, was autocorrelation and cross-correlation analysis. Only these statistics address dependent data explicitly. Monthly totals usually meet the assumptions of normality and independence required by most statistical tests better than daily data does. Hence the t-tests, regression coefficients (R^2) and Nash Sutcliffe coefficient (NS) are suggested to judge model efficiency, with the advantage of the latter two being a fixed reference of unity to judge perfect model fit.

For this study, the mean and standard deviation of measured and simulated daily surface runoff, subsurface flow and total water yield was calculated. Predicted values for monthly totals of surface runoff, subsurface flow and total water yield were evaluated using the coefficient of performance, C_p, which is defined as:

[5] $$C_p = \Sigma (P_i - O_i)^2 / \Sigma (O_i - O_{avg})^2$$

where O_i is the i^{th} observed value, P_i is the i^{th} predicted value, O_{avg} is the mean observed value for the total number of events 'n', which is the total number of months. (James and Burgess, 1982) As the difference between observed and predicted values decreases, the coefficient of performance C_p approaches zero. 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. The Nash-Sutcliffe coefficient, which is equivalent to the coefficient of performance, and the R^2 regression coefficient have also been presented for comparison; these being the preferred performance evaluation statistics in a majority of SWAT case studies (Spruill *et al*, 2000; Qi and Grunwald, 2005).

An autocorrelation and cross-correlation analysis between observed and simulated daily water yield was conducted. The investigation of sequential properties of a series to determine linear dependence among successive values separated by a given lag is the underlying concept of autocorrelation analysis. The datasets were checked for the condition of stationarity and pre-whitened to remove interdependence (Haan, 2002), by subtracting the moving average process from the autoregressive part of the hydrologic time series. Because of large differences between peak and low discharge values, streamflow data was log transformed before correlation analysis.

In the following equations, Cov (x, y) is the covariance between x and y, and Var (x) is the variance of x. The autocorrelation coefficient 'ρ_τ' is defined as:

[6] $\rho_\tau = \mathrm{Cov}\,(x_\tau, x_{t+\tau}) / \mathrm{Var}\,(x_t)$

where 'x_t' is the water yield at time 't'; '$x_{t+\tau}$' is the water yield at time '$t + \tau$'.

Cross-correlation analysis is used to obtain the dependence between the values of two time-series, with or without a lag 'k'. It shows the agreement between simulated and observed series, and can be calculated for a given lag. The lagged cross correlation function 'ρ_k' between two series x and y is defined as

[7] $\rho_k(x,y) = \mathrm{Cov}\,(x_t, y_{t-k}) / (\mathrm{Var}\, x_t * \mathrm{Var}\, y_t)^{1/2}$

where 'x_t' is the observed water yield at time 't', 'y_{t-k}' is the simulated water yield at time 't-k' and 'y_t' is the simulated water yield at time 't'. For a perfect model fit, the auto-correlograms for observed and simulated hydrographs should be identical, while the cross-correlation at lag zero should have a symmetric plot.

3.3. RESULTS AND DISCUSSION

3.3.1. Initial Simulations

<u>Annual water yield</u>

For the hydrologic year 2002-03, the simulated water yields were 355.1 mm and 335.1 mm, which were lower than the observed values of 453.8 and 417.2 mm for sites #1 and #2 respectively. Average errors in simulated water yield were -20.4 % for site #1 and -11.5% for site #2. The annual water balance for initial simulations and a comparison with measured water yield is presented in Table 3.2. Hydrologic and climatic factors were identified to improve water yield: the soil evaporation compensation factor needed modification to correct ET estimates, soil moisture content was too high and snowmelt occurred as a series of small events instead of being simulated as a single large event (Table 3.2).

Table 3.2: Water balance and annual water yield comparison: initial simulation

Year [a]	*Observed*				*Simulated*			
	Precipitation (mm H_2O)		**Yield (mm H_2O)**		**WYLD (mm H_2O)**		**ET (mm H_2O)**	
Site	# 1	# 2	# 1	# 2	# 1	# 2	# 1	# 2
2000/01	875.6	852.1	--- [b]	--- [b]	265.9	361.4	451.3	435.9
2001/02	1029.3	952.5	400.0 [c]	362.8 [c]	388.9	340.9	556.7	558.3
2002/03	889.5	864.3	453.8	417.2	355.1	335.1	533.2	511.9
2003/04	1087.2	1008	563.6 [d]	408.9 [d]	507.2	506.5	579.0	504.8

[a] Based on hydrologic year (October to September) unless otherwise mentioned

[b] Data not available from October 2000 to September 2001

[c] Total in mm from March 2001 to September 2002

[d] Total in mm from October 2003 to June 2004

Surface and subsurface flows

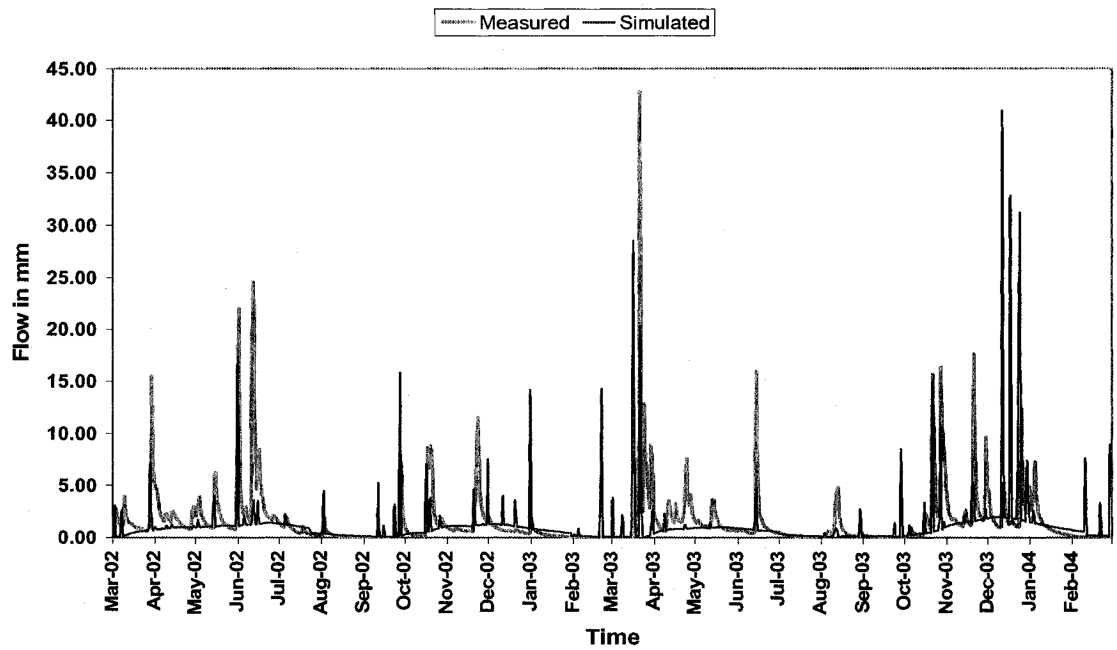
The initial simulations failed on several counts in reproducing the observed surface and subsurface flows. At both sites, surface runoff was highly overestimated indicating high curve number assumptions within the model. It has been shown that the SCS curve numbers based on the antecedent moisture conditions (AMC) are not always appropriate in Canadian conditions (Madramootoo and Enright, 1988). SWAT curve numbers were reduced to correct surface runoff. Simulated subsurface flow was almost negligible, with the result that the total annual water yield was underestimated. A majority of the average annual simulated water yield for site # 2 constituted surface runoff (87%) whereas the observed percentage was only 17%. In comparison, the average annual simulated water yield for site # 1 divided equally (50%) between surface and subsurface flow compared to the measured ratio of 10% in surface runoff and 90% in subsurface flow. In the uncalibrated hydrographs (Figure 3.3a, 3.3b), the peaks tended to fall suddenly indicating a need to modify the streamflow response to changes in groundwater recharge. This can be achieved by altering either the baseflow recession constant or the groundwater delay period factor.

Snowmelt

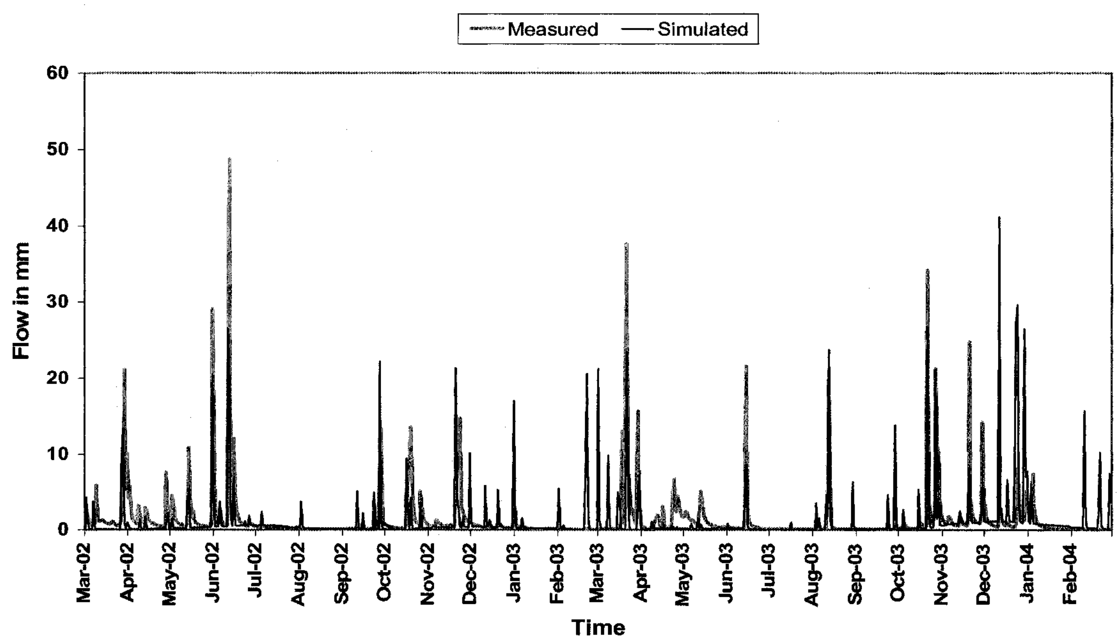
Snowfall accounts for nearly one-fifth of the annual precipitation and the spring snowmelt is usually the biggest surface runoff event of the year (Jamieson *et al*, 2003). The accuracy of simulated snowfall, timing of snowmelt and volume of runoff are critical in modeling this crucial event. From winter leading to spring snowmelt, the soil is frozen and the ground is covered with snow. In these months, the key model parameters that govern water movement are maximum and minimum melt rates for snow; minimum temperature for snowmelt; and maximum snow cover. The uncalibrated hydrograph shows a scattering of small snowmelt induced events opposed to the observed single large event in late March 2003 (Figure 3.3a, 3.3b). The above parameters were varied to calibrate the model for snowmelt.

Figure 3.3: Comparison of observed and simulated hydrographs before calibration: (a) Site # 1; (b) Site # 2

(a) Uncalibrated – site # 1



(b) Uncalibrated – site # 2



Site Comparison

It is important to note that precipitation recorded on site # 2 is consistently lower than site # 1, which might explain the lower yield at this site. Moreover, the rain gauge at site # 2 is exposed to more wind, which might have underpredicted the actual rainfall at the site. The sandy loam soil on site # 1 has a high water retention capacity, and this traditionally results in fewer surface runoff events compared to site # 2. However, physical characteristics such as the clay loam soil and HRU characteristics such as slope contribute to a quicker response time on site # 2. The subsurface component on site # 1 is considerably larger, accounting for about 90% of total water yield. As a result of this, the hydrograph for site # 1 has a characteristically slow recession towards the end of each event, while that for site # 2 is 'sharper' with smaller time to peak flow and steeper recessions.

3.3.2. Sensitivity Analysis

SWAT sub-basin parameters were varied between their minimum and maximum value one at a time and the resultant changes in streamflow, surface runoff and subsurface flow were assessed to derive sensitivity ranks. The range chosen for sensitivity analysis differed from the maximum range permissible in SWAT. For instance, the runoff curve number range was 61-81 whereas SWAT permits values from 35-98. The rationale behind this was that it is vital to judge parameter sensitivity within the purview of existing physical conditions, viz. agricultural fields with row crop cultivation, loamy soils and cold climate. The sensitivity analysis showed CN to be the most sensitive parameter for surface runoff. The total yield was almost unaffected by changes in the curve number, making it the ideal parameter to work with to partition streamflow. The available soil moisture content plays an important role in determining surface and subsurface flows: near wilting point conditions (0.05-0.10 cm^3/cm^3) simulated water yield that matched observed annual totals while field capacity conditions (0.25 cm^3/cm^3) lowered subsurface flows by almost half (48%).

The groundwater "revap" coefficient, which controls movement of water from the shallow aquifer to the root zone, notably influences subsurface flow volume. Along with ESCO and EPCO, this factor needs to be adjusted to control plant water uptake and evapotranspiration. The baseflow recession factor and groundwater delay time strongly influenced hydrograph shape, but did not change total water yield. As the basin areas are very small, the quick watershed response time required high recession factors (0.7, 0.8). Results for the most sensitive sub-basin parameters are presented in Table 3.3, with sensitivity ranks for total water yield, surface runoff and subsurface flow. These parameters were refined to improve the quality of the simulations.

Table 3.3: Results of sensitivity analysis

Site	*Parameter*	*Sensitivity Rank* [a]			*Range* [b]		*Water yield* [c]		*Surface Runoff* [c]		*Subsurface Flow* [c]	
		Yield	**SRO**	**SS**	**Min**	**Max**	**Low**	**High**	**Low**	**High**	**Low**	**High**
# 1	CN	5	1	2	61	81	505.6	532.0	68.2	258.9	438.1	274.9
# 2							427.6	443.3	87.0	244.2	341.5	200.7
# 1	SOL_AWC	1	2	1	0	0.25	643.1	356.5	155.8	112.5	488.4	245.0
# 2							619.6	413.7	167.1	127.3	453.4	243.6
# 1	GW_REVAP	2	-	3	0.02	0.2	515.0	334.1	141.9	141.9	374.1	193.5
# 2							434.4	352.6	143.6	143.6	290.8	208.9
# 1	ESCO	3	3	5	0.01	1	313.6	522.1	106.4	142.4	208.2	381.1
# 2							262.8	437.6	91.5	145.9	170.6	290.9
# 1	REVAPMN	4	-	4	0	500	377.5	515.0	141.9	141.9	237.2	374.1
# 2							389.7	434.4	143.6	143.6	246.9	291.6

[a] Relative variation between water yield, runoff and subsurface flow with respect to parameter range indicates parameter sensitivity

[b] The range chosen for CN and SOL_AWC based on soil and land use characteristics of field sites

[c] 'Low' and 'High' columns represent the simulated output corresponding to the 'Min' and 'Max' parameter range. Units in mm H_2O

3.3.3. Calibration

Annual water yield

The first objective of the calibration procedure is to match total annual water yield. (Neitsch *et al,* 2002b) Based on the sensitivity analysis, runoff curve number, available soil water content and soil evaporation coefficient were varied to try and match surface runoff. Runoff curve numbers were calculated based on the antecedent precipitation index (API), which takes into account rainfall occurring over a number of days before the event (Perrone and Madramootoo, 1998). For both sites, these modified curve number ranges were used as a reference in calibrating the model. The final calibrated curve numbers (Table 3.4) fell within the recommended range of the API-based estimation (71 for site # 1 and 68 for site # 2). 2002-03 was a relatively dry year (precipitation being 16% and 18.5% below normal at the 2 sites) and simulated ET estimates were 533.2 mm for site # 1 and 511.9 mm for site # 2 during this period. In Southern Quebec, a cool, humid region, the soil evaporation losses are minimal; the ESCO parameter was thus altered from 0.95 to 0.85 to increase total water yield. The soil moisture contents had to be reduced to near wilting point values to match annual water yield (0.05 cm^3/cm^3 on site # 1; 0.08-0.10 cm^3/cm^3 on site # 2).

Surface and subsurface flows

Once the total water yield and surface runoff were within an acceptable range, partitioning of flow between surface runoff and subsurface drainage was addressed. The streamflow partitioning ratio was adjusted by varying a number of parameters one at a time – CN, ESCO, SOL_AWC, EPCO, as well as HRU parameters such like SLOPE, SLSOIL and Manning's n. After flow was partitioned satisfactorily, movement of water within the soil profile was calibrated. The volume of flow appearing as lateral flow (tile drainage), base flow, return flow, recharge and percolation into the aquifer are calibrated with GW_REVAP, GWQMN and REVAPMN. After calibration, total water yield was simulated accurately although SWAT was inconsistent in evaluating surface and subsurface components of streamflow. SWAT produced site-averaged errors of -0.56 % for total water yield, 161.6 % for the surface runoff and -23.6 % for subsurface drainage after calibration.

Table 3.4: Parameter values before and after calibration

			Site # 1		*Site # 2*	
Parameter	**Range**	**Units**	**Uncalibrated**	**Calibrated**	**Uncalibrated**	**Calibrated**
CN	35 to 98	---	72	71	85	68
SOL_AWC	0 to 1	cm^3/cm^3	0.21	0.05	0.1/0.18/0.14	0.08/0.1/0.08
GW_REVAP	0.02 to 0.2	---	0.02	0.15	0.02	0.15
REVAPMN	0 to 500	days	1.0	100	1.0	250
GWQMN	0 to 5000	mm	0.0	50	0.0	500
ALPHA_BF	0 to 1	days	0.048	0.7	0.048	0.8
GW_DELAY	0 to 500	days	31	10	31	15
ESCO	0 to 1	---	0.95	0.85	0.95	0.85
EPCO	0 to 1	---	0.95	0.20	0.95	0.10
OV_n	0.01 to 30	---	0.14	0.15	0.14	0.18
SLOPE	0 to 0.6	m/m	0.027	0.04	0.008	0.02
SLSoil	0 to 0.6	m	0.0	0.4	0.0	0.02
SFTMP	-5 to 5	^0C	1.0	2.5	1.0	2.5 ^0C
SMTMP	-5 to 5	^0C	0.5	2.0	0.5	2.0
SMFMX	1.4 to 6.9	mmC^-day^{-1}	4.5	6	4.5	6
SMFMN	1.4 to 6.9	mmC^-day^{-1}	4.5	1.5	4.5	1.5
SNOCOVMX	0 to 500	mm	1	250	1	250
SNO50COV	0 to 1	---	0.5	0.99	0.5	0.99

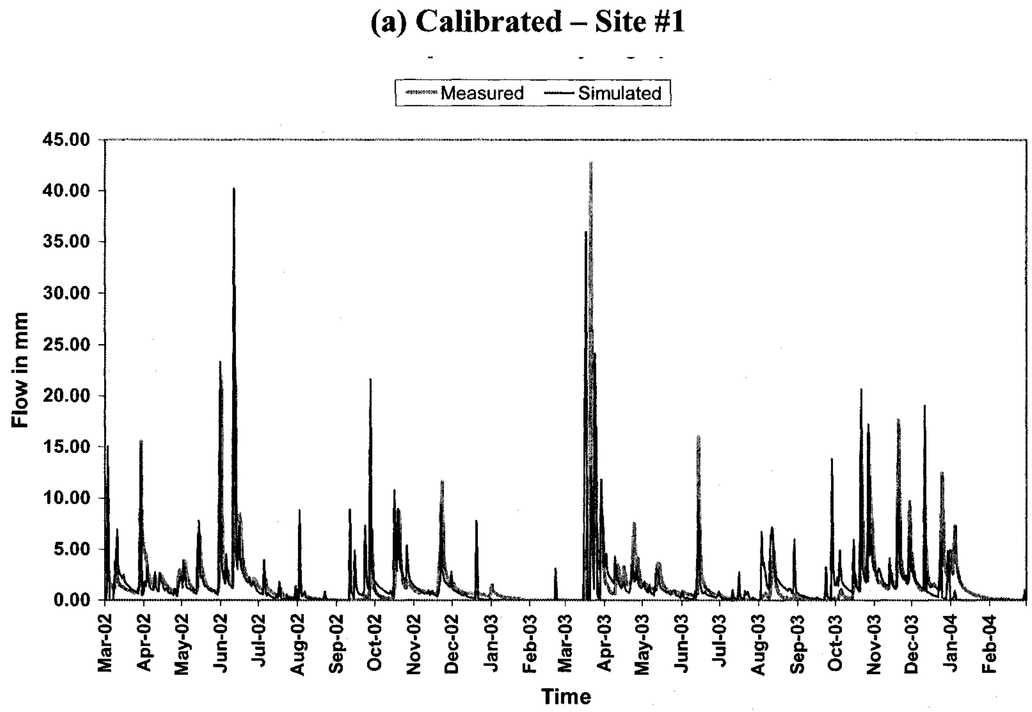
Although errors in surface runoff prediction are very high, their impact on water yield was minimal since runoff comprises a minor percentage of total water yield (10% at site # 1; 17% at site # 2). Improvements in streamflow partitioning ratios were moderate, and mainly due to better representation of sub-basin characteristics post-calibration (Table 3.4).

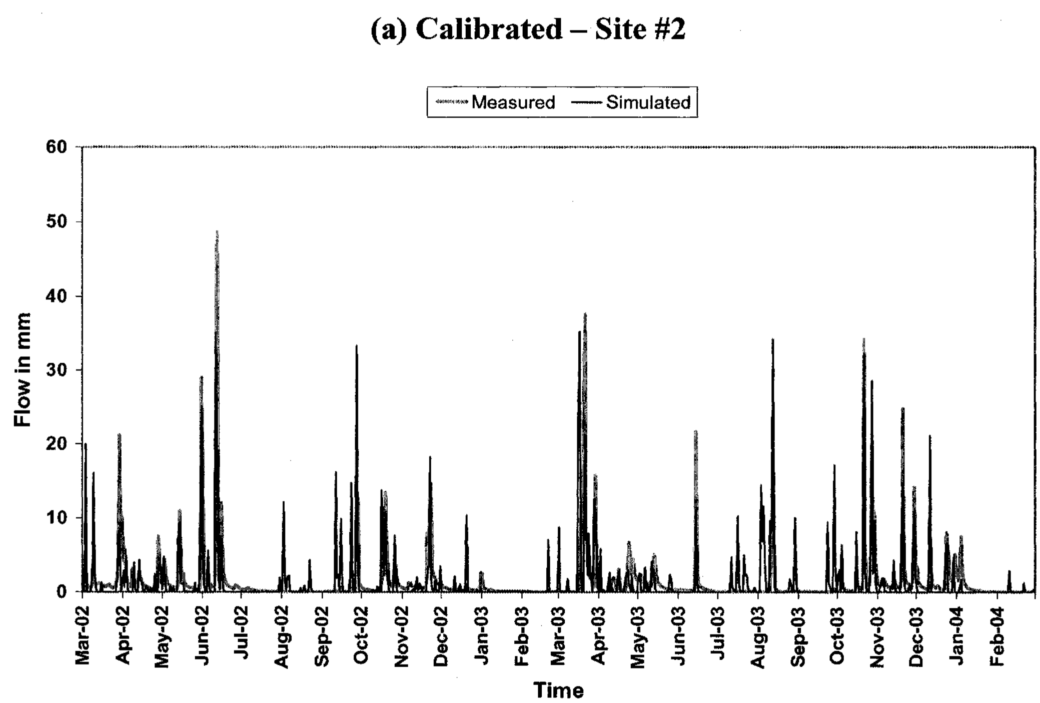
Growing and non-growing season

To minimize seasonal variations and inaccuracies, sub-basin and climatic parameters were varied to improve model performance. The non-growing season (October – April) is dominated by snowmelt as the single largest event. The model was calibrated to aid snow accumulation by increasing snowmelt base temperature and decreasing snowmelt rates. The minimum snow water content corresponding to 100% snow cover was increased (from 1mm to 250 mm); melt factor was decreased (from 4.5 to 1.5 mm $^{0}C^{-1}$ day^{-1}); and mean daily temperature for snowmelt was increased (from 0.5 to 2 ^{0}C). After calibration, snowmelt matched observed amounts for all four site-years, with the average error for total water yield in the months of February to April being only - 3.7 %. Also, the calibrated hydrographs (Figure 3.4a, 3.3b) demonstrate the improvement in the late March 2003 snowmelt event.

During the growing season (May – September), the dominant runoff and drainage determinants are CN, SOL_AWC, GW_REVAP and ESCO. SWAT tended to overpredict water yield and surface runoff during the latter part of the growing season. The number of rainfall events in this period was significant but largely intermittent and ranged from low to medium intensity storms for the four-site years on record – circumstances ideal for infiltration. The preceding dry spells could have led to macropore formation, which is a complex phenomenon to model. Also, the development of considerable canopy storage before harvest often reduced observed surface runoff. These conditions, combined with the inadequacy of high-intensity rainstorms for calibration resulted in a poorer performance than expected. Increasing the calibration period to represent a wider range of rainfall distribution patterns may help resolve this problem

Figure 3.4: Comparison of observed and simulated hydrographs after calibration: (a) Site # 1; (b) Site # 2





Management practices such as planting, tillage and harvest can significantly alter runoff volumes: actual dates for these operations were input into the model to replace simulation based on plant heat units. This resulted in moderate improvement in simulations.

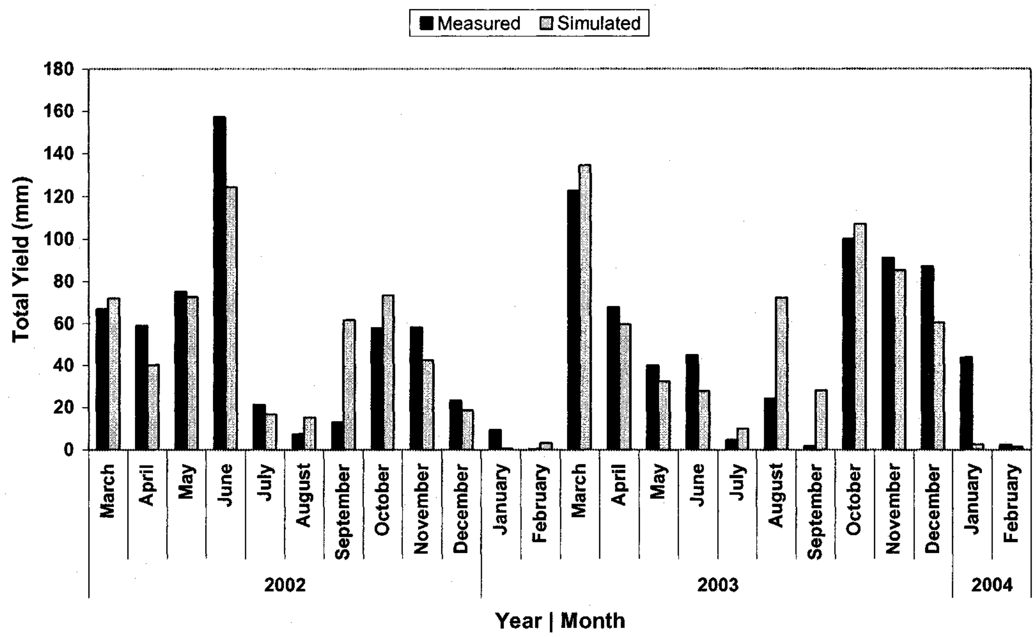
3.3.4. Model Evaluation

SWAT was validated over the period March 2003-February 2004. A comparison of model performance during the calibration and validation periods for monthly water yield and streamflow partitioning was conducted. SWAT simulated monthly water yield accurately (< 20% error) for most of the year except the months of August and September (Figure 3.5). SWAT performed best during the non-growing season (October-April). During the calibration year 2002-03, surface runoff was recorded only during the months of May-June on site # 1 and May, June, August, September and November on site # 2 (Figure 3.6). During the validation year 2003-04, the surface runoff pattern was significantly different, with a large snowmelt event in March on both sites, followed only by small events in the fall on site # 1 whereas site # 2 had events in June and August. For the validation period, SWAT simulated water yields to excellent accuracy – 620.5 mm and 531.0 mm against observed values of 629.9 mm and 587.4 mm for sites # 1 and # 2 respectively.

The coefficient of performance (C_p) was computed for monthly totals of surface runoff, subsurface flow and total water yield for the calibration year 2002-03 and the validation year 2003-04. Monthly totals for simulated and observed total water yield are compared in Figure 3.5. For the calibration year (2002-03), SWAT simulated total monthly water yield with a very good degree of accuracy, with a C_p of 0.21 and 0.45 for sites # 1 and # 2 respectively. Subsurface flow was simulated with a C_P of 0.35 for site # 1 and 0.76 for site # 2. Surface runoff predictions for both sites during this year were highly inaccurate – C_p was 4.49 for site # 1 and 1.35 for site # 2. The number of surface runoff events was not adequate to calibrate the model accurately for surface runoff. Another feature is that, because of low surface runoff volumes, even a small error in prediction results in a large percentage error and adversely affects coefficient of performance.

Figure 3.5: Monthly water yields: comparison of simulated and observed values: (a) Site # 1; (b) Site # 2

(a) Site # 1



(b) Site # 2

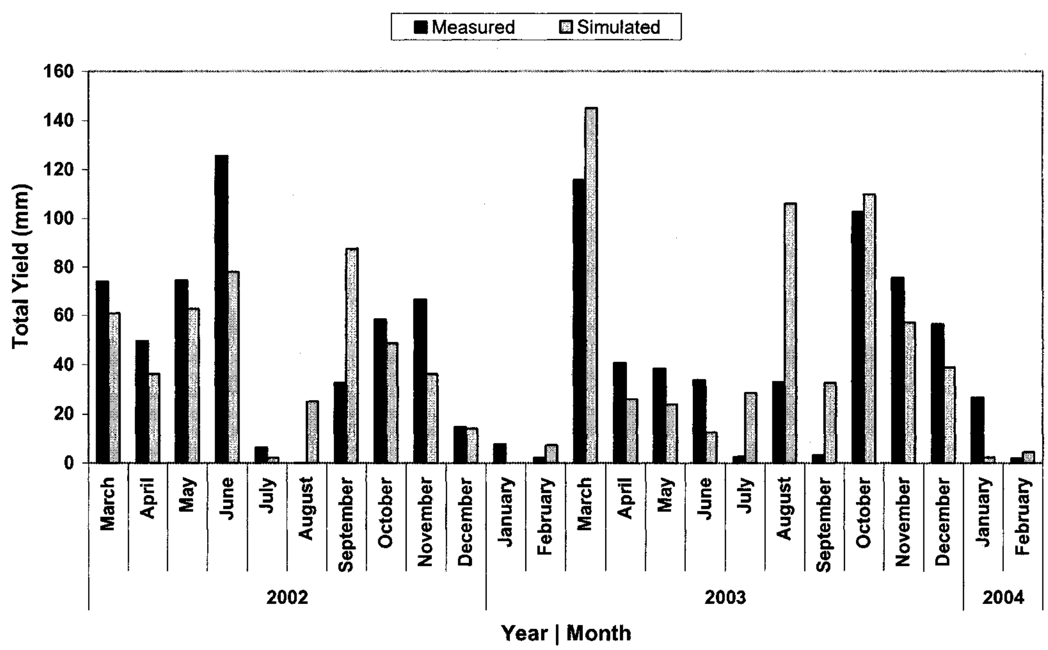
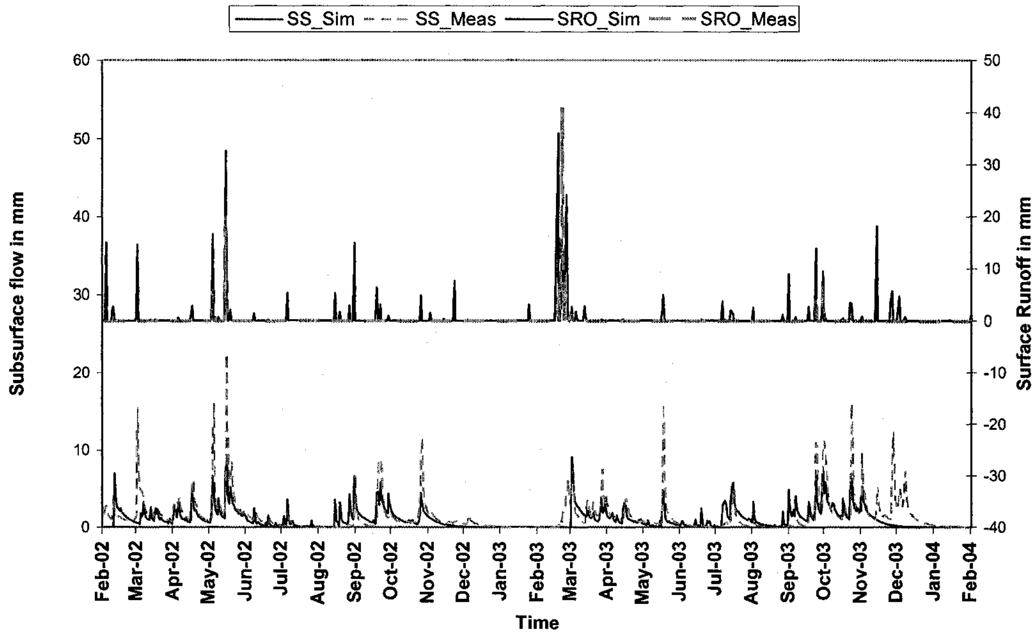
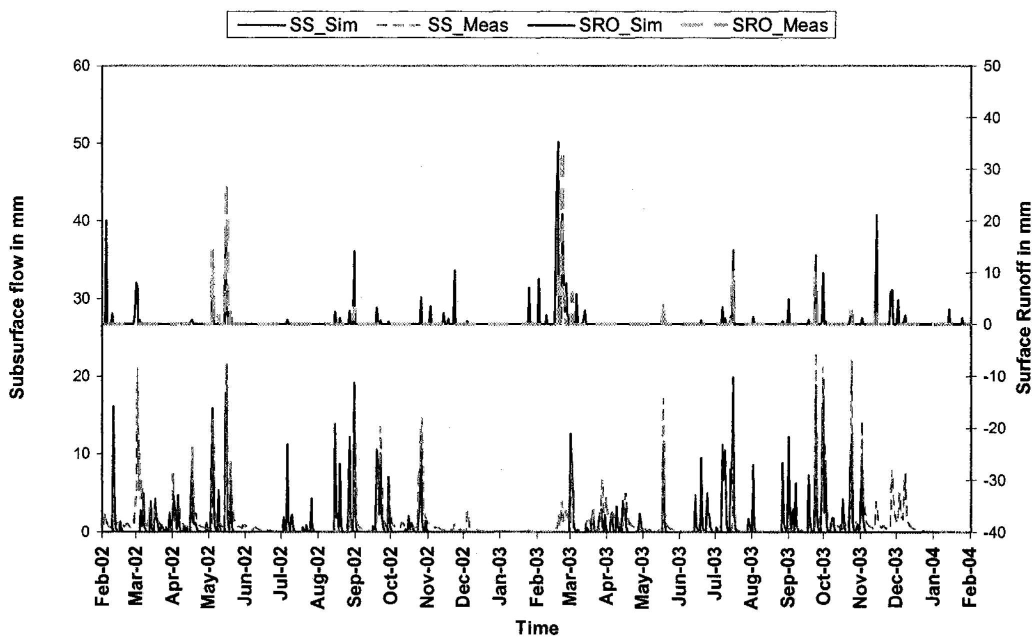


Figure 3.6: Comparison of surface and subsurface runoff in daily observed and simulated values: (a) Daily flow – site # 1; (b) Daily flow – site # 2

(a) Daily flow – site # 1



(b) Daily flow – site # 2

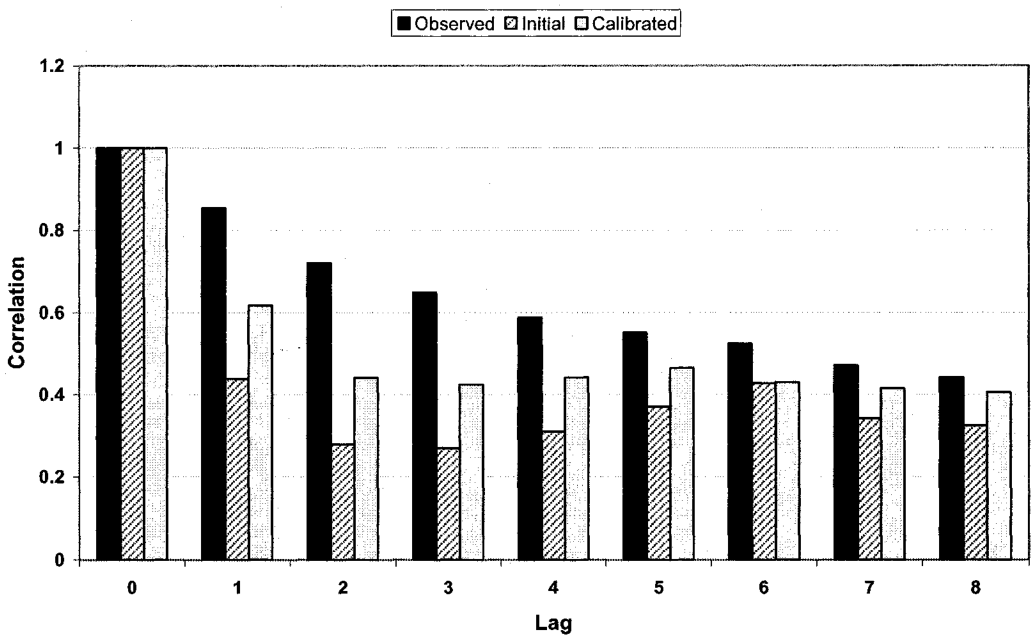


Similar results were obtained for monthly total water yields for the validation year (2003-04) with the coefficient of performance being 0.32 for site # 1 and 0.64 for site # 2. Subsurface runoff simulations during the validation period were inaccurate; the C_p for the sites being 2.21 and 2.28 respectively. The model simulated surface runoff with a much better degree of accuracy, with a C_p of 0.67 (site # 1) and 0.62 (site # 2). Apart from the coefficient of performance, the R^2 regression coefficient and the Nash-Sutcliffe coefficient (NS) were calculated. The results from these statistics pointed towards similar conclusions. For total water yield, the R^2 regression coefficient improved from 0.29 to 0.79 at site # 1, and from 0.49 to 0.56 for site # 2; the NS coefficient improved from 0.16 to 0.78 for site # 1, and from 0.36 to 0.55 for site # 2. Although the performance of both sites is acceptable, the performance statistics for site # 2 were not as good as site # 1. Daily streamflow data was examined through autocorrelation and cross-correlation analysis to rationalize these results.

Autocorrelation and cross-correlation analysis of daily simulated streamflow showed varying results for the two sites. Autocorrelations for observed and simulated flow showed marked improvement after calibrating SWAT for site # 1. The strength of the autocorrelation at a lag 'k' indicates the influence of streamflow after 'k' days. The error in autocorrelation at lag 1 reduced from 0.31 to 0.11 after calibrating site # 1. This analysis also showed that calibration did not significantly alter daily water yield predictions for site # 2 (Figure 3.7a, 3.7b). The error in autocorrelation only decreased marginally from 0.32 to 0.28 on site # 2. This could be explained by the fact that surface runoff was excessively high before calibration. The cross-correlograms in Figure 3.7c are nearly symmetric about lag zero, indicating good model fit. Moreover, the cross-correlations for site # 1 are, in general, stronger than site # 2 confirming that SWAT performs better on site # 1. The inherent characteristic of site # 2 to respond to storm events quicker necessitates model accuracy on a daily time-step. However, this is difficult to achieve in practice due to a number of reasons. Daily simulation results for both sites may have been affected by high intensity evening storms, since hourly or sub-daily precipitation input data were not used. The temporal variability of rainstorms is therefore a factor unaccounted for in simulation.

Figure 3.7: Auto and cross-correlation analysis (observed and simulated daily water yield)): (a) Autocorrelogram – site # 1; (b) Autocorrelogram – site # 2; (c) Cross-correlograms for both sites.

(a) Autocorrelogram – site # 1



(b) Autocorrelogram – site # 2

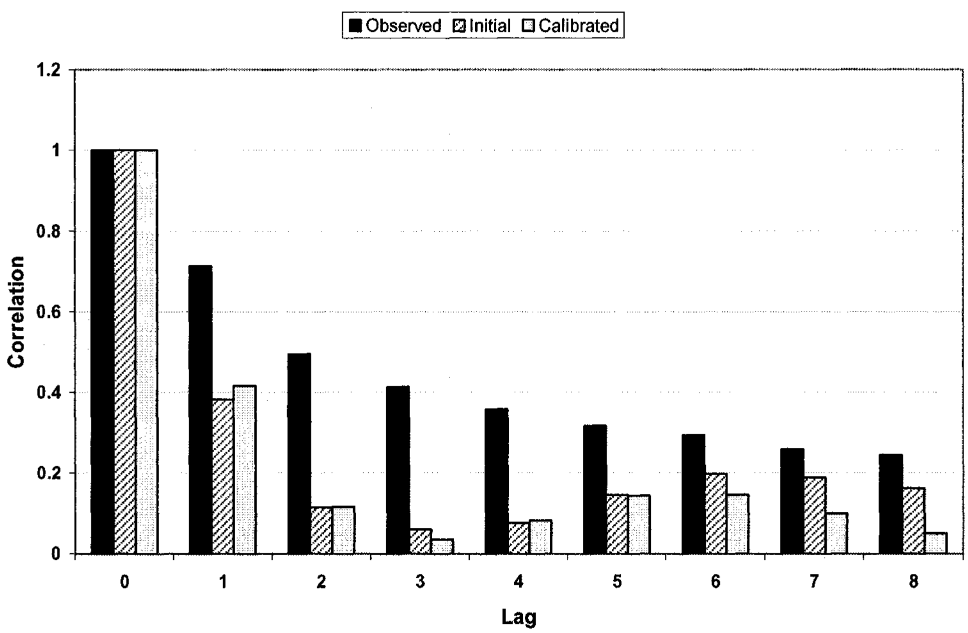
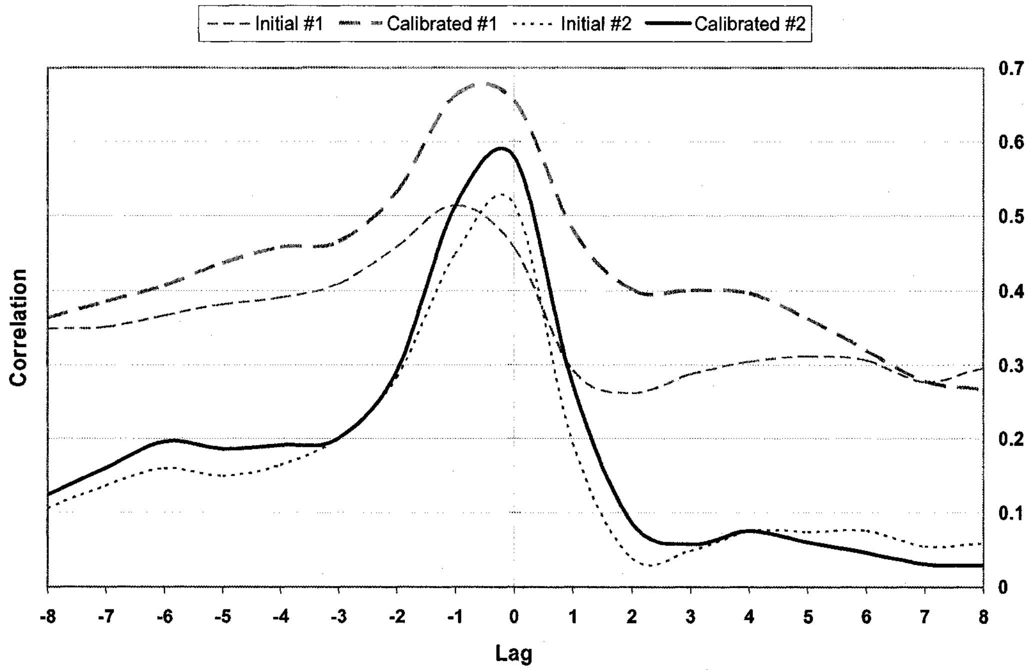


Figure 3.7 (c) ***(continued)*****: Auto and cross-correlation analysis (observed and simulated daily water yield**

(c) Cross-correlograms for both sites



3.4. CONCLUSIONS

Hydrological and meteorological data collected from two agricultural field sites were integrated into the AVSWAT interface to predict surface runoff and subsurface flow. Four years of meteorological data constituted the input, from which two years of measured flow data were used for calibrating and validating the model. Initial simulations were used to evaluate the sensitivity of model output to changes in sub-basin, soil and HRU parameters. Coefficient of performance and autocorrelation and cross-correlation analysis were used to judge model performance across monthly totals and daily values respectively.

Initial simulations overpredicted surface runoff and underpredicted total water yield in general. Monthly totals showed that the uncalibrated model failed to simulate snowmelt. Based on the sensitivity analysis, the model was calibrated. A reduction in curve numbers resolved problems with excessive runoff volume to a considerable degree. Modified curve numbers based on empirical equations using the antecedent precipitation index were selected.

Calibrating the model showed significant improvement on all counts. The coefficients of performance for water yield, surface runoff and subsurface flow for the calibration year 2002-03 were 0.21, 4.49 and 0.35 for site # 1; 0.45, 1.35 and 0.76 for site # 2. For the validation year 2003-04, the coefficients of performance for sites # 1, 2 were 0.32, 0.64 for total water yield; 0.67, 0.62 for surface runoff; and 2.21, 2.28 for subsurface flow respectively.

Autocorrelograms and cross-correlograms obtained for daily results demonstrated varying results between sites. For site # 1, daily total water yield improved after calibrating the model whereas correlations weakened for site # 2 due to the small time to peak and quick response time on this site. This characteristic resulted in poorer model performance for site # 2, especially when daily output was obtained. However, accurate model performance on a monthly or seasonal basis was of primary importance within the objectives of this study and SWAT performs creditably in this domain. The use of sub-hourly rainfall data is suggested to improve performance on sub-basins that have a short response time.

Overall, SWAT performed satisfactorily in simulating monthly and daily total water yields. The drainage and surface runoff components of streamflow have scope for improvement, which could be achieved by increasing the calibration period and incorporating more surface runoff events. The model performed best during the late fall and early spring (snowmelt), demonstrating that SWAT has potential to adapt well to cold climates with frozen soil conditions and snowfall. Its ability to simulate water yield at the field-scale accurately allows for further investigation into its performance on sediment and nutrient transport from the field to the water-course.

CONNECTING TEXT TO CHAPTER 4

This chapter is a manuscript prepared for publication in the *Transactions of the ASAE* in 2005. The manuscript is co-authored by my supervisor Dr. C.A. Madramootoo and Mr. Peter Enright, project engineer and professional associate. 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.

Once validated for field hydrology on the two fields, SWAT was calibrated for sediment and water quality. In this chapter, a comparative evaluation of field monitoring and simulation results are presented for total suspended sediment, nitrate loads in surface runoff and subsurface drainage, and phosphorus loads in streamflow (both dissolved and particulate P).

CHAPTER 4: Water Quality Modeling of Two Agricultural Fields in the Pike River Watershed of Southern Quebec using SWAT

Apurva Gollamudi, Chandra Madramootoo and Peter Enright

ABSTRACT

To study the dynamics of nutrient transport at the field-scale, data were collected from two tile-drained agricultural fields in the region's Pike River watershed. A two year data set was used to calibrate and validate the Soil and Water Assessment Tool (SWAT) for sediment, nitrate and phosphorus loads exiting the field through surface runoff and tile drainage. It was found that SWAT output on water quality required an accurate estimation of the timing and form of field management practices employed. After calibration, the monthly coefficients of performance (C_p) over four site-years varied from 0.23 to 0.89 for sediment loads; 0.48 to 1.35 for nitrate loads; and 0.38 to 0.67 for total phosphorus loads. Subsurface nitrate loads accounted for 97.7% and 86.7% of the total nitrate yield while particulate phosphorus accounted for 61.2% and 87.7% of total phosphorus load on sites #1 and #2, respectively. SWAT underestimated nitrate loads in subsurface drainage during spring snowmelt and large storms. Sediments and particulate phosphorus predictions were most accurate of all simulated parameters whereas dissolved phosphorus was marginally overestimated year-round. Overall, SWAT satisfactorily reproduced field observations for sediment and nutrient transport and could be used to compare the impacts of implementing different best management practices (BMP) on individual fields.

Keywords: SWAT, Water quality, Phosphorus, Sediment, Nitrate, Tile drainage, Model validation, Nonpoint source pollution

4.1. INTRODUCTION

Runoff from agricultural fields is the major source of non-point phosphorus pollution in Southern Quebec. Concentrations in excess of the environmental guideline for water quality (0.03 mg l^{-1}) have been consistently found in the rivers and lakes in Southern Quebec, a region that practices intensive conventional agriculture. Such high concentrations of P causes eutrophication, a phenomenon that is linked to the decay of algal blooms that release cyanobacteria and produce toxins harmful to aquatic life as well as human health (Daniel et al., 1994; Sharpley et al., 1994).

The pathways for sediment and nutrient movement could be through surface transport or through subsurface flow in fields equipped with tile drainage, depending on hydrological conditions such as the flow route discharge capacity, rainfall distribution, soil macropores and drainage systems (Heathwaite and Dils, 2000). Phosphorus (P) is considered to be relatively less mobile, with sediments in surface runoff being the major carrier of P as particulates sorbed to the soil (Sims et al., 1998). However, studies have reported significant amounts of particulate phosphorus (PP) and soluble phosphorus in subsurface drainage waters, mainly due to preferential flow (Beauchemin and Simard, 2000; Enright and Madramootoo, 2004; Laubel et al., 1999). Although PP has been reported as the major component transported in tile drainage in few studies (Andraski and Bundy, 2003), the percentage of dissolved phosphorus (TDP) on tile-drained fields containing high soil phosphorus has been shown to be as high as 71% by others (Novak et al., 2003; Turtola and Jaakkola, 1995). Djodjic et al. (2002) reported that TDP transport increased under no-till and conservation tillage as compared to conventional practices because of better contact between soil particles and fertilizer.

The benefits of tile drainage in terms of increased agricultural productivity are evident but its consequences on water quality are constantly debated. Sediment and nutrient losses have been shown to decrease with drainage because of lower surface runoff loads (Bottcher et al., 1981). However, recent studies have shown that nitrate-nitrogen (NO_3-N) leaching increases in drained systems (Baker et al., 2004). Similarly, the results for phosphorus transport do not have a consensus with increases in total P in subsurface flow reported in various studies (Stamm et al., 1998; Uusitalo et al., 2001). The reasons for these dissimilarities between study results are attributed to a combination of variable factors, such as fertilization (Baker and Johnson, 1981; Tarkalson and Mikkelsen, 2004), soil type (Schroeder et al., 2004), soil phosphorus content (Djodjic et al., 2004), cropping systems , tillage, and drainage conditions.

The use of hydrological and water quality simulation models that are capable of physically representing these multiple factors can help improve the understanding of nutrient dynamics, especially on drained fields. With this objective, the Soil and Water Assessment Tool (SWAT) developed by Arnold et al. (1998) was chosen to simulate sediment and nutrient transport at the field-scale. SWAT is a physically-based model and its GIS interface permits an accurate representation of field conditions. Data from two fully instrumented tile-drained fields was used in validating the model. Thus, the main objective of this study is to validate SWAT at the field scale for sediment and nutrient movement in surface runoff and subsurface flow so as to be able to carry out short-term simulations of different best management practices (BMP). These short-term predictions using simulated climatic conditions and management scenarios present a valuable indicator towards future trends of the environmental impacts of agricultural practices.

4.2. MATERIALS AND METHODS

4.2.1. Instrumentation, Sampling and Water Quality Analyses

Two agricultural fields in the Pike River watershed of Southern Quebec were instrumented in October 2000 to monitor water quality in surface runoff and tile drainage. Site #1 is a 6 ha drained field owned by a dairy farmer while site #2 is a field cultivated by a cash-crop producer. Site #2 has a surface drained area of 7 ha while the tile drained area is 7.8 ha. Automatic water samplers were installed to trigger samples during storm events. The threshold runoff depths for triggering samples are seasonally dependent, with high thresholds set during snowmelt (implying fewer samples for a given flow volume) and lower thresholds over the summer and fall. These samples were analyzed in an external lab (IRDA, *Institute of*

Research and Development for the Agro-environment) for pH, ammonium ions (NH_4^+), nitrates (NO_3-N), total suspended solids (TSS), orthophosphates (Ortho-P), particulate phosphorus (PP), total dissolved phosphorus (TDP) and bio-available phosphorus (Bio-P). Standard procedures were followed for wastewater analyses (Standard Methods, 1992; Standard Methods, 1995; Technicon Industrial Systems, 1973).

The installation also includes rain gauges, air and soil temperature thermocouples, water table level loggers, barometric pressure loggers and remote data access capabilities, enabling year-round functionality. While subsurface drainage samples are flow-pulsed composites from multiple time periods during storm events, a discrete sampling strategy was employed for surface runoff until March 2005. Surface runoff sampling was switched to composite before the 2005 snowmelt, mainly to reduce sampling costs. Complete information on site locations, soil types, instrumentation and water sampling protocol are available in Jamieson (2001); Jamieson et al. (2003) and Simard (2005).

4.2.2. Management Practices

The farmers practice conventional tillage using moldboard plow, a common mode of operation in the region. Fields are tilled in the fall after harvest, usually during the month of October or early November. During the study period, both chemical fertilizers and manure were applied on the sites. On site #1, high nitrogen content fertilizers were coupled with a starter application in May. Dairy manure was also applied during the fall either as a solid or liquid spread. On site #2, the first chemical application in May was usually followed up with a secondary nitrogen solution. Occasionally, pig manure was applied as a liquid spread at the end of the growing season. Although the fields are mainly cultivated in corn and do not practice a set crop rotation, alfalfa was grown on site #1 during the study period while soybean and cereals were grown on site #2. Soil phosphorus levels, cropping patterns and fertilization information are presented in Table 4.1.

Table 4.1: Soil test results, fertilization, tillage and crop rotation practices

	Site #1 [a]			*Site #2* [a]		
Soil test P	373 kg ha^{-1}			114 kg ha^{-1}		
P saturation	22 %			5.3 %		
Tillage	Moldboard plow in the fall (except in 2004)			Moldboard plow in the fall		
Crop Rotation						
2001	Corn (*Zea mays L.)*			Soybean *(Glycine max L.)*		
2002	Corn (*Zea mays L.)*			Barley *(Hordeum vulgare L.)*		
2003	Corn (*Zea mays L.)*			Corn *(Zea mays L.)*		
2004	Alfalfa *(Medicago sativa L.)*			Corn *(Zea mays L.)*		
Fertilization	**Mth.**	**Qty.** [b]	**Ratio**	**Mth.**	**Qty.** [b]	**Ratio**
2001	May	196.1	18-29-8	---	---	No Fertilization
	May	448.1	46-0-0			
2002	May	196.1	18-29-8	May	250	25-14-14
	May	448.1	46-0-0	June	100	34-0-0
				Sept	4000	Pig manure
2003	May	196.1	18-29-8	May	100.0	18-46-0
	May	448.1	46-0-0	May	60.0	32% N_2
	Oct	--- [c]	Solid	June	200.0	46-0-0
2004	May	168.0	46-0-0	May	100.0	18-46-0
	July	168.0	5-12-42.6	May	100.0	0-0-60
	Oct	2500 [d]	Liquid	June	315.0	46-0-0

[a] Soil tests conducted in 2001 on site #1 and in 1998 on site #2.

[b] All values in kilogram per hectare unless otherwise mentioned

[c] Dairy manure shredded with spreader and applied uniformly on corn (N: 4.4 kg Mg^{-1}, P_2O_5: 2.8 kg Mg^{-1}, K_2O: 4.6 kg Mg^{-1})

[d] In gallons per hectare (N: 4.3 kg Mg^{-1}, P_2O_5: 0.7 kg Mg^{-1}, K_2O: 5.0 kg Mg^{-1})

4.2.3. Model Input Parameters

SWAT was setup using spatial and temporal datasets from the fields. Topography, soil classes, cropping patterns, planting, fertilization, and tillage and harvest dates comprised one part of model input. The following meteorological data: precipitation, air temperature, wind speed, solar radiation and relative humidity constituted the second part. A sensitivity analysis on model parameters was performed and the model was calibrated over 12 months (March 2002 – February 2003) to simulate field hydrologic conditions. The calibration procedure utilized monthly depths of surface runoff, subsurface drainflow and total water exiting the field. In calibrating the model for sediment and nutrient transport, monthly totals from water quality analyses over the same duration were used. While sample analysis results give concentrations for individual events, these are converted into loads by using surface runoff and subsurface flow data.

SWAT faces some limitations with regard to simulating the movement of sediments and nutrients, especially phosphorus in tile drainage. Although nutrients and sediment concentrations in tile drainage and surface runoff were measured separately, these data could not always be compared with simulated results. SWAT simulates the different forms of phosphorus and computes loads in total streamflow, but does not calculate the ratio between surface runoff and subsurface drainage. The 'crack flow' feature in SWAT simulates preferential or bypass flow, but it is still under development and thus was not activated for this study. SWAT was initially calibrated based on total sediment yield, total phosphorus and total nitrates in streamflow. Subsequently, sub-basin parameters and management practices were varied to improve performance.

The main parameters that influence model performance on sediment yield are: field slope, timing and type of tillage, harvest efficiency and crop residue coefficient. For nutrient transport, the main factors affecting model output are: timing and extent of fertilization, soil chemical concentrations, crop rotation, and nutrient percolation coefficients. SWAT-simulated sediment loads (SYLD) are obtained in tons ha^{-1} and nutrient loads are obtained in kg ha^{-1} over daily, monthly and yearly intervals. For nitrates, there are four main contributing sources into the main stream – leaching through the soil (NO3L), direct export from surface runoff (NSURQ), lateral flow (NLATQ) and from groundwater as return flow (NO3_GW). For phosphorus, SWAT does not simulate loads in tile drainage and surface runoff independently. However, the different forms of phosphorus exiting the field are simulated: namely soluble phosphorus (SOL_P), phosphorus in sediments (SED_P) and phosphorus in groundwater (P_GW). The parameters for SWAT output and their corresponding field parameters used for calibration are summarized in Table 4.2 (Neitsch et al, 2002).

Table 4.2: Water quality parameters used in model calibration

Parameter	*SWAT*	*Field Analysis*
Dissolved Phosphorus	SOL_P	TDP
Particulate Phosphorus	SED_P	PP
Total Phosphorus	-	TP
Nitrates in Subsurface Flow	NLATQ	NO3_SS
	NO3_GW	
	NO3_L	
Nitrates in Surface Runoff	NSURQ	NO3_SRO
Sediment	SYLD	TSS
Total Nitrates	-	NO3-N

4.2.4. Assessment of Model Performance

The coefficient of performance (C_p) and the R^2 coefficient of regression were used to evaluate model performance on a monthly basis. The annual and seasonal means were calculated for field and simulated results over the calibration and validation periods. Percentage differences between annual measured and simulated values are also estimated for the two fields. The partitioning of streamflow between surface runoff and tile drainage was compared with measured percentages. Visual comparisons between monthly loads of sediments, phosphorus and nitrates were also drawn.

4.3. RESULTS AND DISCUSSION

4.3.1. Field Observations

Hydrologic characteristics of the fields play a major role in determining the water quality of surface runoff and subsurface drainage. Organic matter content, water storage capacity, soil class, slope, and crop cover are some of the factors that influence the processes governing nutrient movement in soil and water. Low field slopes on both fields keep sediment transport to a minimum, with site #1 having almost negligible sediment losses (0.32 tons ha^{-1} yr^{-1}) due to minimal surface runoff. Site #2, with higher clay content and less organic matter has higher soil loss potential and contains more suspended sediments. Average losses of 1.96 tons ha^{-1} yr^{-1} were observed during the study period. Sediment losses occurred mostly through surface transport on site #1 (82%) but were equally distributed between surface runoff (53%) and subsurface drainage (47%) on site #2, possibly due to macropore flow. Compared to the maximum tolerable soil loss levels of 3.5 tons ha^{-1} yr^{-1} in Quebec, erosion losses on both sites are within acceptable limits.

High nutrient concentrations have been observed immediately succeeding fertilizer applications and this phenomenon is particularly accentuated by coincident rainfall events. The Rubicon sandy loam soil on site #1 has a capacity to absorb and store large volumes of water, which are discharged gradually. This characteristic coupled with higher organic matter content and the use of high nitrogen-content fertilizers augmented nitrate transport on this site. The average annual nitrate load in subsurface drainage was 165 kg ha^{-1} yr^{-1} on site #1 against 59 kg ha^{-1} yr^{-1} on site #2. Although nitrate loads in subsurface flow are significantly high on site #2 as well, they are considerably smaller than site #1 – a characteristic attributed to lower fertilization loads. Nitrate concentrations in surface runoff were notable only during the months when fertilizers were applied, and accounted for only 2.3% of total nitrate load on site #1 and 13.27% on site #2.

Phosphorus loads on site #2 (3.26 kg ha^{-1} yr^{-1}) were consistently higher than site #1 (1.12 kg ha^{-1} yr^{-1}) over the study period, although the second field has lower soil P level and percent P saturation (Table 4.1). Minimal surface runoff on site #1 decreases erosion and reduces particulate phosphorus losses, which accounts for a bulk of the phosphorus leaving the fields. For this reason, sediment movement on fields with high soil phosphorus levels must be limited to the maximum extent possible. Moreover, conventional erosion norms for tolerable soil losses may not be an appropriate guideline for water quality. Dissolved phosphorus losses, though minor, are significant accounting for 38.8% of total phosphorus on site #1 and 12.3% on site #2. Although orthophosphates and bio-available phosphorus were also analyzed in the lab, these parameters are not simulated by SWAT and hence were excluded from the calibration and validation data sets.

4.3.2. Model Calibration and Validation

The hydrology component of SWAT was validated using streamflow data from the two sites over two years. It was found that SWAT performed well in simulating total monthly and annual water yields on both sites, with coefficients of performance being 0.27 and 0.45 respectively. For surface runoff predictions, the low number of events did not permit efficient model calibration for monthly flows. The streamflow hydrograph showed that subsurface flows were matched during low flows but peak flows and dominant subsurface events were consistently underestimated.

I. Sediment Calibration

Sediment transport was calibrated by altering the depth and timing of tillage, sub-basin slope and crop residue coefficients. During the calibration year, total simulated sediment yield was 0.60 tons ha^{-1} on site #1 and 1.77 tons ha^{-1} on site #2, corresponding to percentage errors of 87.8% and 1.2% respectively. Results during the validation year showed contrasting results, with site #1 having a -2.0% error (i.e. -0.01 tons ha^{-1}) compared with a -46.6% error (i.e. -1.01 tons ha^{-1}) on site #2. Results are summarized in Table 4.3.

Since exact tillage and harvesting dates were not available, fall season erosion was better simulated only after calibrating the model. This included adjusting tillage and harvest dates to match sediment yield.

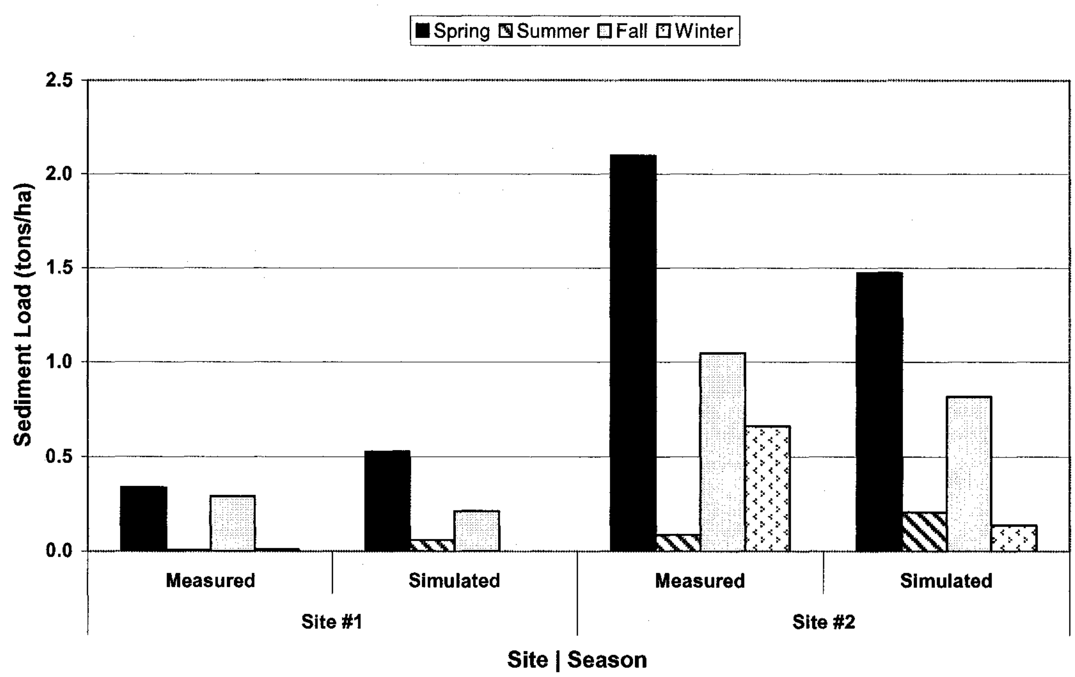
Table 4.3: Comparison of annual sediment, nitrate and phosphorus loads

	Site #1			*Site #2*		
	Measured	**Simulated**	**Error**	**Measured**	**Simulated**	**Error**
Sediment	*(In tons ha^{-1})*		*%*	*(In tons ha^{-1})*		*%*
Uncalibrated	0.36	9.96	2666.7	1.80	1.87	4.0
Calibration	0.32	0.60	87.8	1.75	1.77	1.2
Validation	0.31	0.31	-2.0	2.18	1.17	-46.6
NO3-N	*(In kg ha^{-1})*		*%*	*(In kg ha^{-1})*		*%*
Uncalibrated	189.74	14.39	-92.4	69.53	30.18	-56.6
Calibration	189.74	121.31	-36.1	69.53	42.91	-38.3
Validation	148.00	132.36	-10.6	66.63	58.68	-11.9
NO3_SRO						
Uncalibrated	4.68	3.06	-34.6	8.14	1.46	-82.0
Calibration	4.67	0.79	-83.1	8.13	1.81	-77.8
Validation	3.06	0.43	-86.1	9.94	2.30	-76.9
NO3_SS						
Uncalibrated	185.04	11.33	-93.9	61.44	28.72	-53.3
Calibration	185.07	120.53	-34.9	61.39	41.10	-33.1
Validation	144.93	131.93	-9.0	56.70	56.38	-0.5
TP						
Uncalibrated	0.88	1.24	41.1	2.40	0.59	-75.5
Calibration	0.88	1.16	32.2	2.44	3.42	40.2
Validation	1.35	1.00	-26.2	4.07	2.88	-29.2
PP						
Uncalibrated	0.72	0.83	15.0	2.14	0.44	-79.2
Calibration	0.67	0.78	17.7	2.14	2.87	34.2
Validation	0.70	0.41	-41.9	3.58	1.94	-45.8
TDP						
Uncalibrated	0.24	0.41	70.0	0.30	0.16	-48.0
Calibration	0.21	0.38	77.5	0.30	0.55	82.3
Validation	0.65	0.59	-9.3	0.50	0.95	90.6

In terms of seasonal loads, the sediment yield was significant only during the spring snowmelt and fall seasons. Spring snowmelt simulations produced errors of 56.2% and -29.7% compared with fall season errors of -26.2% and -21.8%, on sites #1 and #2 respectively. This corresponds to mean absolute errors of 0.09 and -0.31 tons ha^{-1} in spring and -0.04 to -0.11 tons ha^{-1} in the fall. A comparison of measured and simulated seasonal sediment yield is shown in Figure 4.1

In addition to simulating sediment yield based on Modified USLE – a function of rainfall distribution, soil erodibility, slope length and gradient, crop cover, and support practices – erosion calculated using the USLE soil loss equation was also compared with simulated and measured results. There was no difference between MUSLE and USLE erosion predictions on site #1; the difference between measured and USLE-derived losses being just 0.01 tons ha^{-1} yr^{-1}. In contrast, USLE-derived values were much closer to field observations on site #2, with spring and fall season errors being 2.7% and 5.6%, respectively.

Figure 4.1: Comparison of measured and simulated seasonal sediment loads on sites #1 and #2

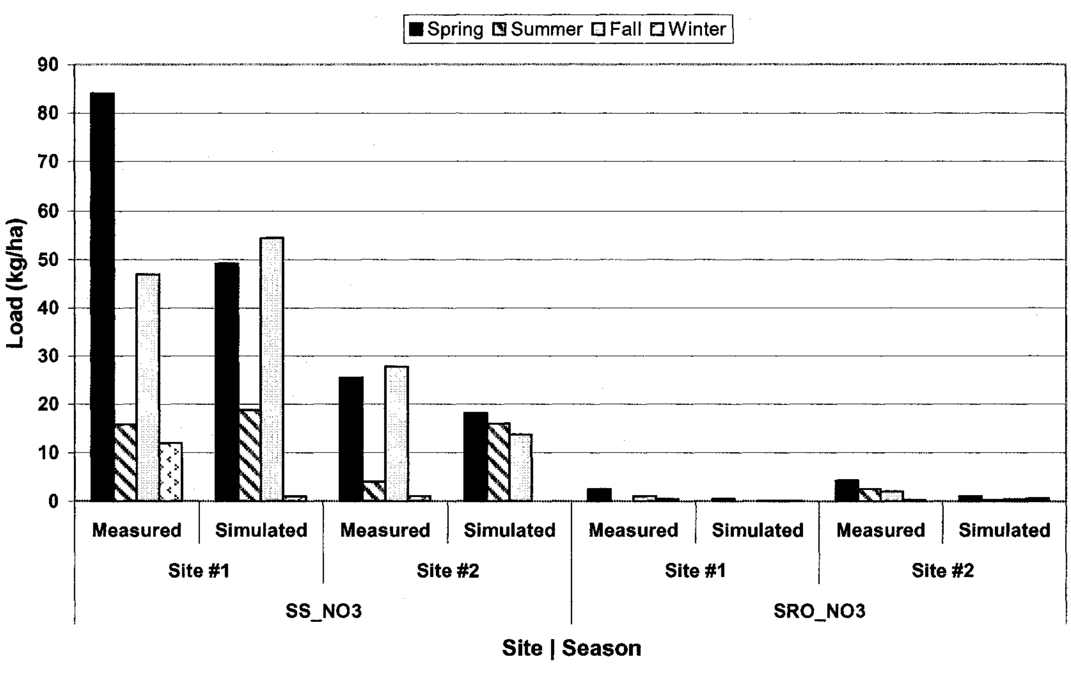


II. Nitrates Calibration

Field observations have reported annual loads between 1.26 and 8.36 kg ha^{-1} in surface runoff and between 40.76 to 166.13 kg ha^{-1} in subsurface drainage (Simard, 2005). While site #1 has high concentrations in surface runoff, the volume is minor and thus the loads of both sites are comparable. However, the first site had much larger subsurface nitrate loads due to high fertilizer application (Table 4.1). This is confirmed through notable peaks in nitrate loads in May, June and October, a phenomenon closely linked to fertilization during these months.

Before calibration, nitrate loads were generally underestimated due to incorrect estimates of soil nitrogen levels and fertilization timing, since exact dates were unavailable. Measured nitrate loads during calibration were 189.7 kg ha^{-1} and 69.5 kg ha^{-1}, compared with simulated loads of 14.4 kg ha^{-1} on site #1 and 30.2 kg ha^{-1} on site #2. Figure 4.2 illustrates the difference between surface and subsurface nitrate loads across both sites and over all seasons.

Figure 4.2: A comparison of measured and simulated nitrate loads in surface runoff and subsurface drainage on sites #1 and #2



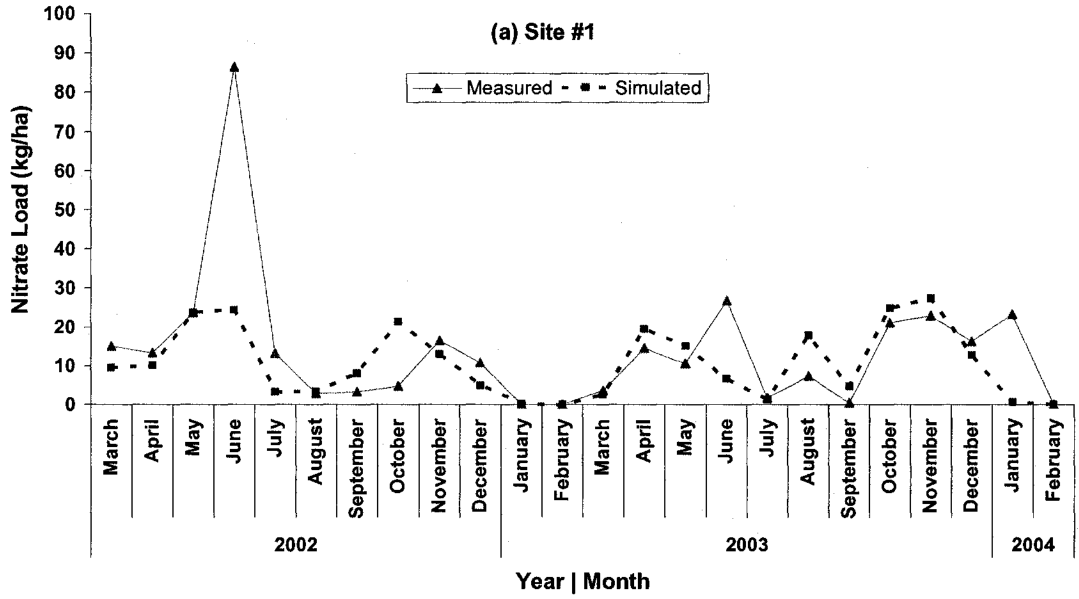
Once the magnitudes of annual loads were acceptable, the efficiency of nitrogen movement through the soil into subsurface drains was addressed. The nitrogen percolation coefficient (NPERC), which controls the percentage of nitrates in surface and subsurface flow, was set at 0.2 after model calibration. Surface runoff accounted for 2.3% and 13.3% of total nitrate load during the study period, whereas the percentages simulated in SWAT were 0.5% and 4.0% (Table 4.4).

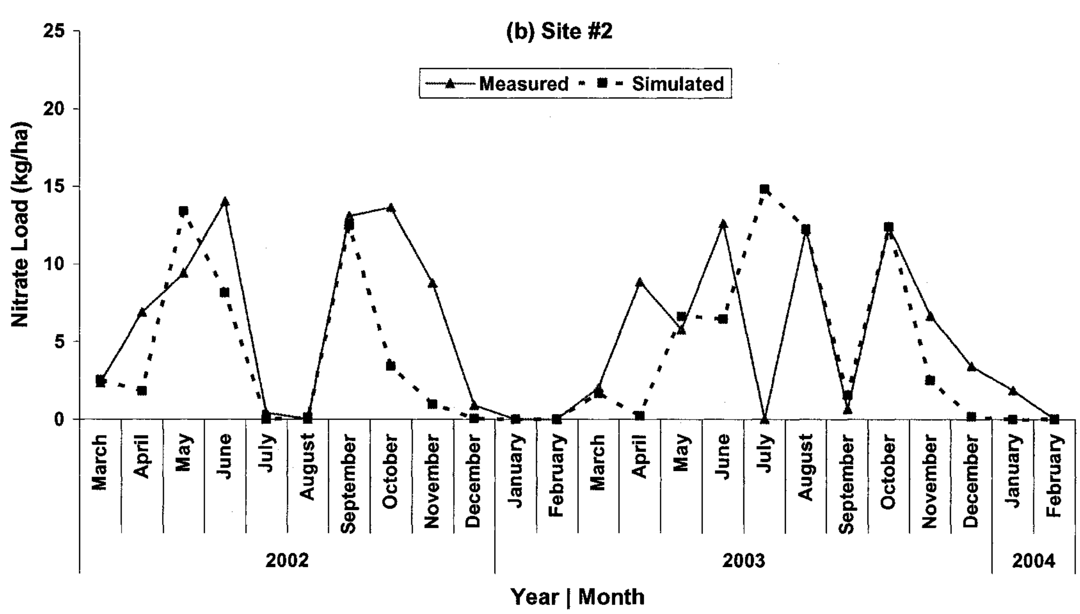
Table 4.4: Measured and simulated loads in surface runoff (SRO) and subsurface flow (SS) on sites #1 and #2: (a) Sediment; (b) Nitrate-nitrogen; (c) Particulate and dissolved phosphorus as a percentage of total P

	Site #1		*Site #2*	
	Measured	**Simulated**	**Measured**	**Simulated**
(a) Sediment	%	%	%	%
SRO	82.0	--	53.0	--
SS	18.0	--	46.0	--
(b) Nitrate-N				
SRO-N	2.3	0.5	13.27	4.0
SS-N	97.7	99.5	86.73	96.0
(c) Phosphorus				
PP	61.2	55.1	87.7	76.3
TDP	38.8	44.9	12.3	23.7

The model consistently underestimated nitrate loads on both sites, in surface and subsurface transport, and over all study years. During the calibration year, total nitrate loads were 36.1% and 38.3% less than observed; these percentages during validation were 10.6% and 11.9% on sites #1 and #2 respectively. Moreover, the amount of nitrates being leached from the soil were minor in simulation, with the result that soil-water interactions are probably not represented adequately. It is observed that the general trend is reproduced well across months (Figure 4.3) with the exception of few extreme events, which were highly underestimated (June 2002, Site #1; Oct 2002; Site #2). This can be attributed to the inability of SWAT to match water yield for that month or to errors in fertilization load. Due to a high intensity storm in June 2002, there was almost 160 mm of runoff on both sites while simulated values fell short by about 50 mm on both sites.

Figure 4.3: Measured and simulated monthly nitrate loads (a) Site #1 (b) Site #2



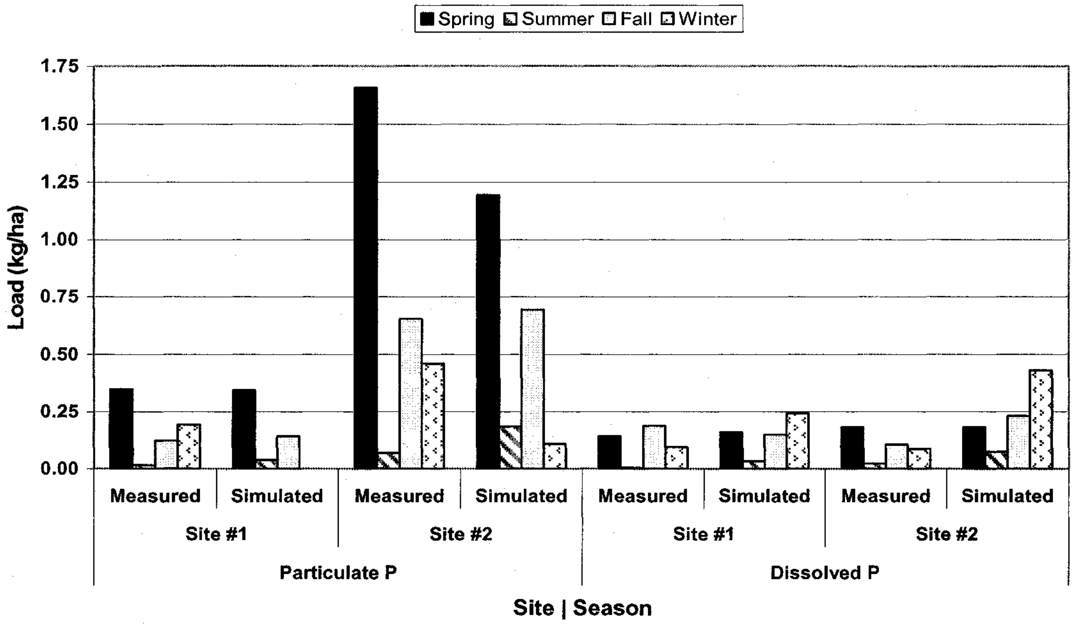


III. Phosphorus Calibration

Measured particulate phosphorus (PP) loads were compared with simulated phosphorus attached to sediment (SED_P); total dissolved phosphorus (TDP) loads were compared with simulated soluble phosphorus in total streamflow (SOL_P). Analysis of total phosphorus gave annual loads of 0.88 kg ha^{-1} for site #1 and 2.40 kg ha^{-1} for site #2. In contrast, the annual simulated loads were 1.24 kg ha^{-1} and 0.59 kg ha^{-1} before calibration. The calibration procedure involved altering soil phosphorus concentrations at the start of simulation; timing, method and extent of fertilization; tillage; phosphorus percolation coefficient (PPERC) and soil phosphorus partitioning coefficient (PHOSKD). It was observed that simulated phosphorus transport was most sensitive to fertilization, with soil phosphorus content being least sensitive. Since sediment yield was already calibrated at this stage, some parameters that could potentially influence PP loads – namely tillage and residue coefficients were not varied minimally. Soil phosphorus levels were entered based on the results of soil analysis (Table 4.1). During model calibration, the PHOSKD was set at 200 on site #1 and 175 on site #2. The PPERC on both sites was set at 10 through the simulations.

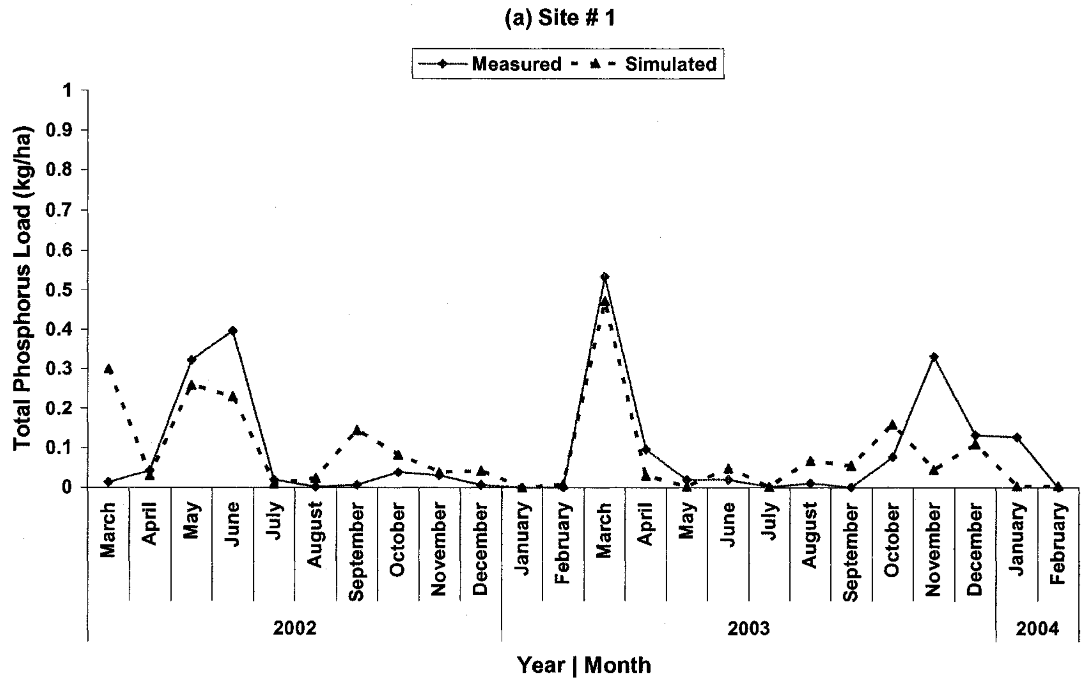
Particulate Phosphorus simulations were accurate on site #1 and did not require further calibration. However, the measured PP load of 2.14 kg ha^{-1} was simulated as 0.44 kg ha^{-1} on site #2 and this improved to 2.87 kg ha^{-1} after calibration. Dissolved P accounted for 0.24 kg ha^{-1} and 0.30 kg ha^{-1} on the sites whereas SWAT-simulated loads were 0.41 kg ha^{-1} and 0.16 kg ha^{-1} before calibration. After calibration, this improved to 0.38 kg ha^{-1} and 0.55 kg ha^{-1}. Results during the validation year were similar, with percentage errors being in the order of 30% for total phosphorus (Table 4.3). A majority of P transport occurs via sediment, with 61.2% and 87.7% of total phosphorus exiting the fields #1 and #2 in the particulate form. In comparison, these percentages were 55.1% and 76.3% using SWAT (Table 4.4). The implementation of simple practices to minimize erosion and trap sediments at the edge of the field could be effective in minimizing phosphorus contamination of watercourses. On the other hand, total dissolved phosphorus is minor but forms a significant portion of total phosphorus, especially on fields that are equipped with tile drainage. Moreover, the ratio of reactive phosphorus is higher in dissolved phosphorus than in particulate phosphorus. Thus it is equally important to address this pathway of P export, which has been increasing with constant fertilization and oversaturation of soils with nutrients. Figure 4.4 shows the seasonal variation in soluble and particulate phosphorus.

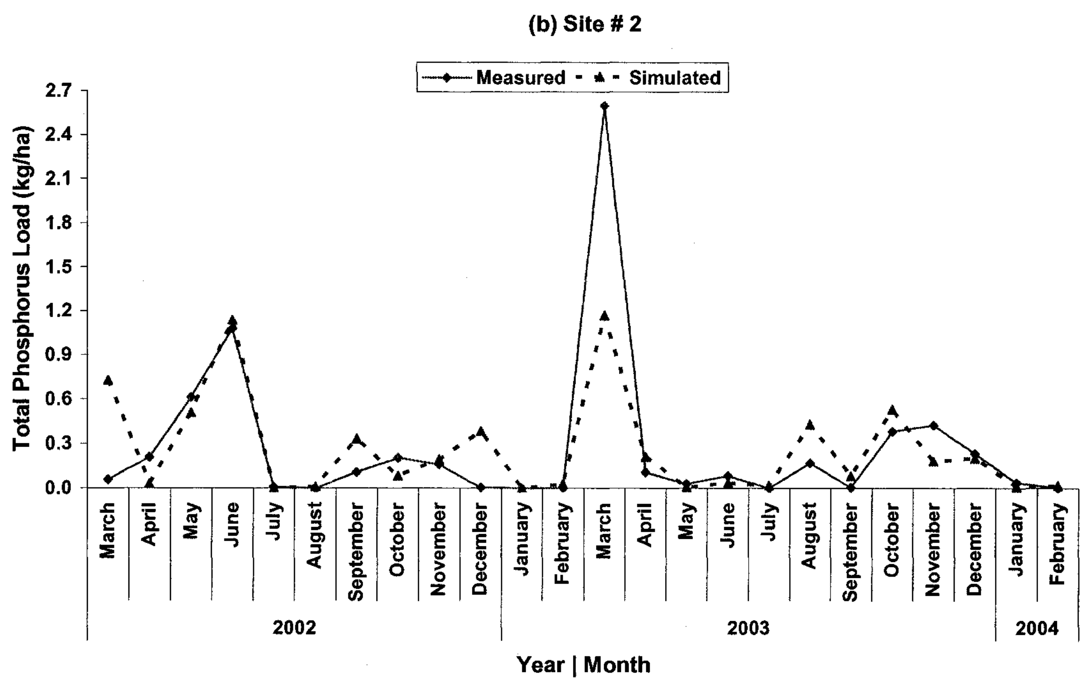
Figure 4.4: A comparison of measured and simulated particulate and dissolved phosphorus loads on sites #1 and #2



SWAT performed well on monthly scale as well, with notable exceptions during three occasions in the snowmelt period over the 48 site-months. Two occasions were during the March 2002 snowmelt on both sites and the third being the March 2003 snowmelt on site #2 (Figure 4.5). In 2002, the simulated phosphorus load was highly overestimated although total water yields were matched. The reason for this is that SWAT routed most of the snowmelt through surface runoff whereas a majority of snowmelt exited through tile drainage that year. In 2003, a majority of the snowmelt was through surface runoff and SWAT simulations were a closer representation of the existing field hydrology, with the result being that phosphorus loads simulated were accurate on site #1 but underestimated on site #2. P loads are underestimated in November 2003 as well, possibly reflecting that the model was underestimating soil P losses after harvest.

Figure 4.5: Measured and simulated total phosphorus loads after calibration for: (a) Site #1 (b) Site #2





4.3.3. Model Evaluation

Monthly loads were compared using coefficient of performance and the coefficient of regression. A C_p of zero indicates perfect model fit, while a C_p of one implies that the model estimate is as good as the sample mean itself. For the coefficient of regression, an R^2 value of 1 is obtained for a perfect model. After calibrating SWAT for sediments, the monthly coefficient of performance improved from 635.6 to 0.89 on site #1 and from 0.89 to 0.41 on site #2. The corresponding R^2 regression coefficients during this period were 0.44 and 0.58 respectively, indicating an average model fit on monthly loads. Coefficients of performance during the validation year were 0.23 and 0.49, indicating excellent model fit. The R^2 coefficient of regression also improved simultaneously to 0.85 on both sites. For total nitrate load, C_p estimated an average to poor model performance with a range between 0.66 and 1.35. The R^2 values were consistent with this, with the corresponding range being from 0.16 to 0.52. Although nitrate simulation was not reliable at a monthly time-scale, seasonal and annual loads gave acceptable values. Thus, SWAT may be used for seasonal-scale or long-term simulations for nitrate transport at the field scale.

For phosphorus, the monthly coefficients of performance on sites #1 and #2 during the calibration year are: 0.67 and 0.60 for total phosphorus; 1.60 and 2.01 for TDP; 0.56 and 0.50 for PP. In the validation year, the corresponding values were: 0.41 and 0.38 for TP; 1.54 and 1.85 for TDP; 0.42 and 0.56 for PP. The R^2 coefficient of regression during validation was consistent with these values, estimating a good model fit for particulate (#1: 0.79; #2: 0.78) and total phosphorus (#1: 0.63; #2: 0.84); R^2 for dissolved phosphorus was 0.15 and 0.85 for sites #1 and #2 respectively. Table 4.5 summarizes these statistics for all simulated parameters. Although the C_p values for dissolved phosphorus values were poor, this is because of the unavailability of data points with high loads. Thus for dissolved phosphorus, seasonal or annual differences are a better indicator of model performance than C_p or R^2. Overall, the performance statistics obtained for particulate and total phosphorus loads demonstrate that SWAT can be used for monthly predictions of phosphorus loads.

Table 4.5: SWAT performance evaluation statistics

	Coefficient of Performance		*R^2 Coefficient of Regression*	
	Site #1	**Site #2**	**Site #1**	**Site #2**
Sediment				
Uncalibrated	635.6	0.89		
Calibration	0.89	0.41	0.44	0.59
Validation	0.23	0.49	0.85	0.85
Nitrates - Surface				
Uncalibrated	1.27	1.18		
Calibration	1.07	0.97	0.02	0.60
Validation	1.13	1.09	0.09	0.19
Nitrates - Subsurface				
Uncalibrated	1.43	1.14		
Calibration	0.70	0.84	0.43	0.39
Validation	1.11	1.99	0.20	0.08
Nitrates - Total NO3-N				
Uncalibrated	0.94	1.00		
Calibration	0.72	0.66	0.45	0.52
Validation	1.09	1.35	0.22	0.16
Particulate Phosphorus				
Uncalibrated	0.59	0.94		
Calibration	0.56	0.50	0.45	0.63
Validation	0.42	0.56	0.79	0.78
Dissolved Phosphorus				
Uncalibrated	1.89	0.70		
Calibration	1.60	2.01	0.21	0.19
Validation	1.54	1.85	0.15	0.85
Total Phosphorus				
Uncalibrated	0.73	0.90		
Calibration	0.67	0.60	0.39	0.58
Validation	0.41	0.38	0.63	0.84

4.4. CONCLUSIONS

I. **Seasonal Performance**: The two seasons which witness high flows are fall and spring and the dynamics of nutrient transport are markedly different due to changing hydrologic conditions between these seasons. SWAT was able to reproduce the conditions of both seasons adequately but with contrasting results. Spring snowmelt was generally underestimated, and this error was carried over when estimating sediment, phosphorus and nitrate loads. On the other hand, surface runoff was overestimated in the fall and this led to sediment and particulate phosphorus predictions being higher than observed. Nitrates, which are mainly transported through the tile drains, were underestimated because of smaller subsurface flow volumes.

II. **Site Comparison:** Although the magnitudes of nutrient loads were significantly different on the sites, the general trends across months were similar. Site #1 had much lower particulate phosphorus exiting the field but dissolved phosphorus loads were identical on both fields. The soil phosphorus levels and percent P saturation did not have a direct correlation with P loads. SWAT was able to simulate these site characteristics satisfactorily, demonstrating its applicability at the field-scale.

III. **Pathway Comparison**: A comparison of phosphorus loads in surface runoff and subsurface drainage was not possible with SWAT. Simulated water, sediment and nutrient volumes tended to be lower than observed in subsurface flow and overestimated in surface transport. It was observed that preferential flow conditions enhanced sediment and phosphorus movement down the soil profile and SWAT currently does not address these conditions adequately. However, the percentages of nitrate loads in surface runoff and subsurface flow were much closer to measured values despite their magnitudes being underestimated. The significant contribution of subsurface drainage in phosphorus transport advocates the need to develop this component of SWAT further.

The statistical coefficients of performance and regression coefficients were consistent in evaluating model efficiency, and demonstrate that SWAT results are reliable at a monthly time-scale for total sediments and total particulate phosphorus. However, seasonal or annual totals give a fair representation of nitrate transport via both pathways. Overall, the validation of SWAT at the field-scale demonstrates its effectiveness and facilitates the creation of different management practice scenarios for longer term phosphorus loss predictions.

CONNECTING TEXT TO CHAPTER 5

The manuscript is co-authored by my supervisor Dr. C.A. Madramootoo and Mr. Peter Enright, project engineer and professional associate. All literature cited in this chapter is listed in the reference section at the end of this thesis.

The previous two chapters described the methodology for validating SWAT for hydrological and water quality processes, and evaluated its applicability in Quebec's climatic conditions at the field-scale. Chapter 5 now uses the validated model for testing different types of tillage and crop rotations as Best Management Practices for minimizing nutrient transport.

CHAPTER 5: Evaluation of BMP Scenarios for Minimizing Nutrient and Sediment Transport from Agricultural Fields

Apurva Gollamudi, Chandra Madramootoo and Peter Enright

ABSTRACT

The validated SWAT model was used to create different Best Management Practice (BMP) scenarios and evaluate their impact on runoff volumes, sediment loads and water quality over the short term. Average annual nitrate-nitrogen (NO3-N) and total phosphorus (TP) load reductions were obtained by comparing the existing baseline scenario to combinations of nine different crop rotations and three types of tillage practices. BMP simulations were carried out over five years using measured climatic data from October 2000 – September 2005. The simulation results suggest that the implementation of conservation or no till practices alone are not a sufficient BMP to minimize sediment and phosphorus losses when compared to conventional tillage and load reductions were in the range of 0.7 – 3.5% for nitrates and 2.5 – 6.1% for phosphorus. Moreover, no significant difference was found for runoff volumes with tillage. The best BMP options were obtained when soybean or pasture were cropped in rotation with corn under conservation tillage. The soybean BMP scenarios gave load reductions in the range of 25% for sediments, 22% for nitrates and 31% for phosphorus, when compared with continuous corn. Pasture gave load reductions of around 50% for sediments and phosphorus but only 9% for nitrates.

Keywords: SWAT model, Best Management Practices (BMP), Water Quality, Simulation, Tillage, Crop Rotation, Nutrient Pollution

5.1. INTRODUCTION

Best Management Practices are defined as field measures that reduce the adverse impact of an activity on the environment. In relation to agriculture and water quality, a BMP could be a change in farm operations or land management to improve the quality of the water exiting agricultural fields. One of the main factors that need to be accounted for while evaluating a BMP is the physical characteristic of the field in which it is being implemented. The hydrological behavior of each field implies that the 'best' option for one field isn't necessarily the best for another. Many studies have been carried out in the past for testing different management practices (Djodjic et al, 2002; Burgess et al, 2002; Hansen et al, 2000; Logan et al, 1994; Van Es et al, 2002; Yoo et al, 1988; Laflen and Tabatabai, 1983).

Field studies are generally the best method to evaluate the effectiveness of a proposed BMP but they involve practical difficulties in implementation, in addition to larger investment of time and funds. Hence, a number of simulation models such as AGNPS (Young et al, 1987), WEND (Cassell and Kort, 1998), DWSM (Borah et al, 2002), ANSWERS (Beasley et al, 1980), and SWAT (Arnold et al, 1993), have been designed to evaluate best management practices. At the same time, it is essential to conduct field studies and collect sufficient data to be able to validate these models. Since farming practices are highly individualized, the validation of models at the field-scale allow them to be used as environmental assessment tools for water quality predictions and in developing efficient agricultural management plans.

Past studies have suggested the implementation of controlled drainage (Evans et al, 1995) and subirrigation (Elmi et al, 2001) as management practices to minimize nitrate losses. Different tillage practices have been tested at the plot-scale, which have shown that conservation tillage significantly reduces sediment yields and phosphorus loads (Zhao et al, 2001). At the same time, studies have also shown that the absence of tillage can lead to the accumulation of nutrients at the surface, which leads to enhanced nutrient loads in surface runoff (Djodjic et al, 2002). However, this effect is minimized on tile-drained fields, where most of the water exits through subsurface pathways (Logan et al, 1994; Enright and Madramootoo, 2004). On such fields, the gradual leaching of nutrients down the soil profile is of primary concern and steps need to be developed to control these losses. Hansen et al (2000) studied snowmelt runoff and phosphorus losses under three tillage systems and concluded that increased snow cover under conservation tillage resulted in increased phosphorus losses when compared to conventional tillage with less residue cover. Determining fertilizer applications according to soil chemical levels and crop type, the timing and method of fertilizer application, and the kind of fertilizer used (manure or chemical) are other factors that influence nutrient losses.

In this study, the ArcView SWAT 2000 model was used. The main objectives of this study were to create and test BMP scenarios related to crop rotations and tillage practices, and to determine their impact on water quality in terms of: (i) Total water yield, (ii) Sediment losses, (iii) Nitrate loads and (iv) Phosphorus loads.

5.2. MATERIALS AND METHODS

As described in the previous chapters, SWAT was calibrated for the transport of water, sediments, nitrate and phosphorus on two agricultural fields in the Pike River watershed of Southern Quebec. Model evaluation statistics demonstrated that SWAT could be used reliably for seasonal scale predictions of nutrient loads in surface runoff and subsurface drainage. BMP scenarios were developed for three types of tillage and ten different crop rotations, spread over three to five years. Many possible combinations of tillage and crop rotation were simulated, giving a total of thirty scenarios. Even though some combinations of tillage and crop rotation may not be realistic, they were still simulated to provide baseline references or to make comparative analyses.

5.2.1. Fertilization

Fertilization patterns involved a combination of manure and chemical fertilizers, used with or without starters and either broadcast or incorporated into the soil. The timing and magnitude of fertilization was not varied across scenarios, although they were varied across years of simulation and depending on the crop being cultivated. Fertilization was not considered as a BMP option in this study; application times for each year were kept constant based on actual field data to enable a comparison between rotations and tillage practices. The type of fertilizer used and amount applied were unique to the crop cultivated and its position in the rotation sequence.

5.2.2. Tillage Systems

The three systems employed were conventional tillage, conservation tillage and no till. Conventional tillage comprised a moldboard plow operation after harvesting, typically in late October. This is the predominant form of tillage practiced on agricultural fields in the region. The tillage depth for this operation was set at 150 mm and the residue mixing efficiency at 95%. Conservation tillage or mulch tillage employs the use of the chisel plow or the disc tiller. The amount of residue left behind after a generic conservation tillage operation is between 65% and 75%. The depth of tillage in these simulations was set at 100 mm. A no till mixing operation involves minimal disturbance of the soil to maintain the residue level after harvest. Up to 95% of the residue is assumed to have been left on the surface after no till mixing. The tillage depth during no till was set at 25 mm (Table 5.1).

Table 5.1: Tillage depth, timing of tillage and crop residue coefficients

Tillage Category	Depth of Tillage	Residue Cover
Conventional (moldboard plow)	150 mm	5 %
Conservation (generic)	100 mm	75%
No Till	25 mm	95%

5.2.3. Crop Rotations

Ten different crop rotation scenarios were simulated for each site, including a baseline scenario with the actual crops cultivated from 2000 through 2005. All other BMP scenarios are compared against this baseline scenario. The scenarios can broadly be divided into four categories: continuous pasture; corn and pasture based rotations (including grasslands); corn and soybean based rotations (including grains); and continuous corn. Since corn is the predominant crop cultivated in the region, it featured in most crop rotation scenarios. However, forages *(pasture)* and grasslands *(alfalfa)* were simulated at one end of the land use spectrum. Combinations of corn and pasture included four year rotations with two years each of corn and pasture *(corn2past2)*, and three years of corn with one year of pasture *(corn3past)*. Similarly, a four year rotation with two years each of corn and alfalfa was also simulated *(corn2alfalfa2)*. Corn soybean rotations included a four year rotation with two years each in corn and soybean *(corn2soy2)*; a four year rotation of corn, soybean, grain and pasture *(cornsoygrnpast)*; a four year rotation with two years of corn and one year each of soybean and grain *(corn2soygrn)*. At the other end of the spectrum, corn monoculture *(cornmono)* was simulated. The actual crops cultivated from 2000 through 2005 on each field comprised the tenth crop rotation scenario simulated in SWAT. This was done to enable a comparison of BMP scenarios with the current practice

5.2.4. BMP Simulations

Climatic data (precipitation, maximum and minimum air temperature) spanning October 2000 to September 2005 from the rain and temperature gauges on the sites were used as the main model input. SWAT was simulated to generate daily outputs which were summed to obtain seasonal totals for streamflow (WYLD), sediment losses (SYLD), nitrate-nitrogen (NO3-N) and total phosphorus (TP). Table 5.2 shows the rainfall runoff ratio for the actual field measurements for each year of the simulation period.

Table 5.2: Runoff to rainfall ratios across 5 years of simulation

Site/ Year	2000/01	2001/02	2002/03	2003/04	2004/05	Average
Site #1	0.55	0.51	0.56	0.62	0.45	0.54
Site #2	0.61	0.53	0.56	0.59	0.52	0.56

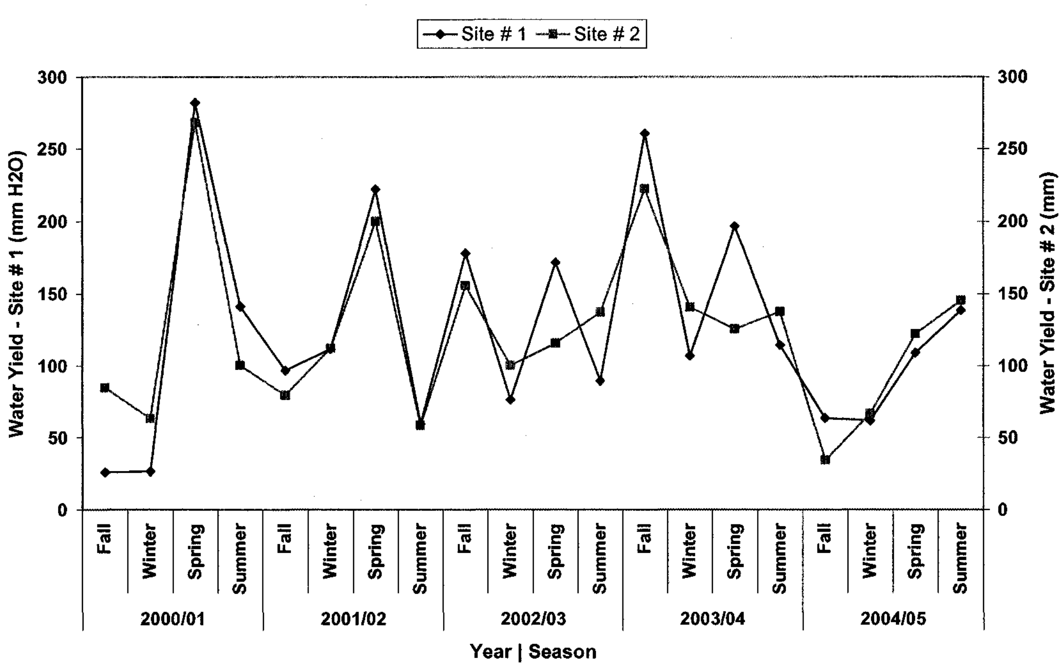
Rainfall runoff ratios (RR) were calculated for each BMP-year of simulation and plotted as five-year averages. In addition to a comparative analysis of annual and seasonal loads for each of the output parameters, 'radar' maps showing five-year mean loads were plotted to provide complementary information.

5.3. RESULTS AND DISCUSSION

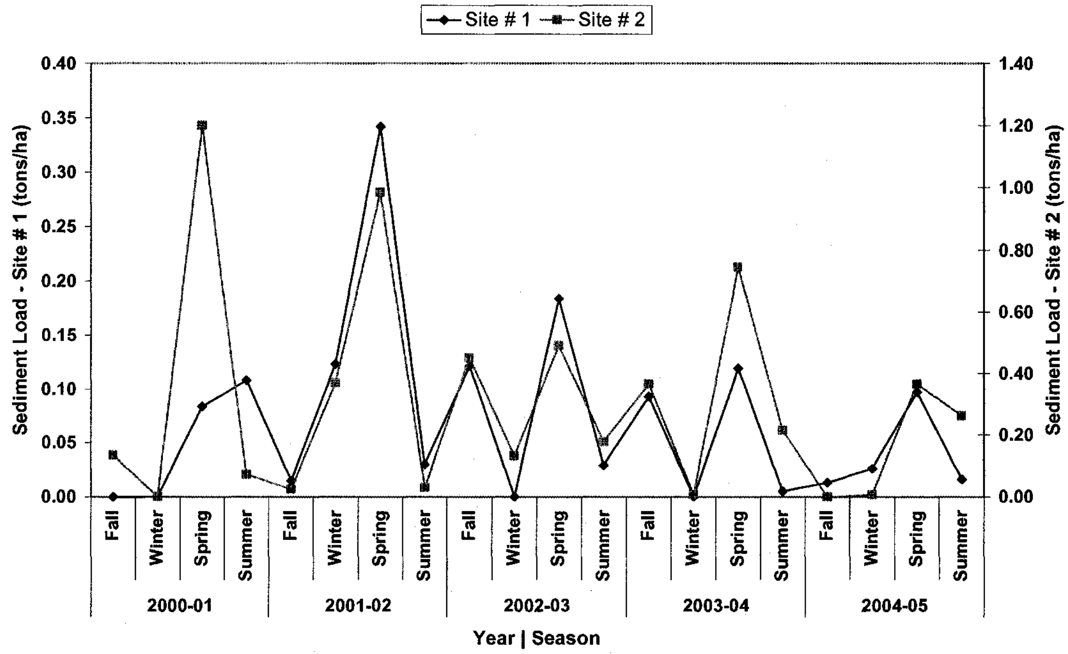
Comparisons of simulation results over the hydrologic years 2000 through 2005 for the two fields are plotted in Figure 5.1. As seen in these figures, the general trend in both the sites is similar over the years for all parameters with one or two exceptions. In the case of streamflow (Figure 5.1a), even the magnitudes are comparable. In the case of sediment losses (Figure 5.1b) and phosphorus loads (Figure 5.1d), site #2 has almost 2.5 to 3 times higher values compared to site #1 but both fields have similar trends. On the other hand, nitrate loads on site #1 are about three times higher than site #2 on a consistent basis (Figure 5.1c). Because of this similarity in response of both sites, graphical results for the different management practice scenarios evaluated have been presented only for site #2. Similar trends were obtained for site #1 but with correspondingly lower or higher magnitudes.

Figure 5.1: Comparison of seasonal streamflow, sediment, nitrate and phosphorus movement on sites #1 and #2 as simulated by SWAT

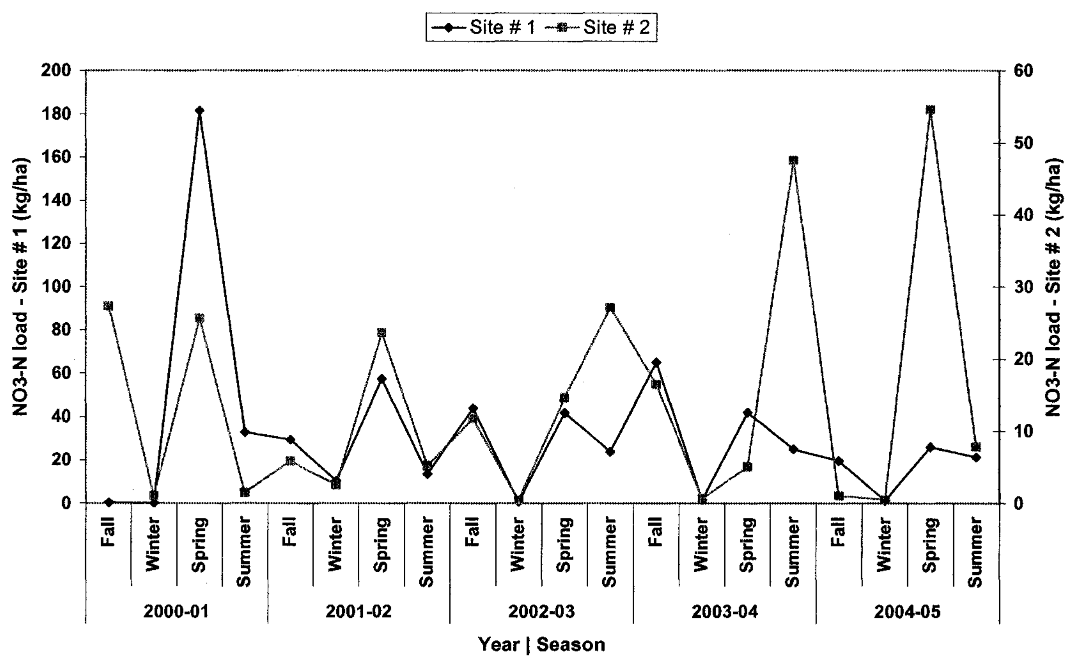
(a) Simulated water yield

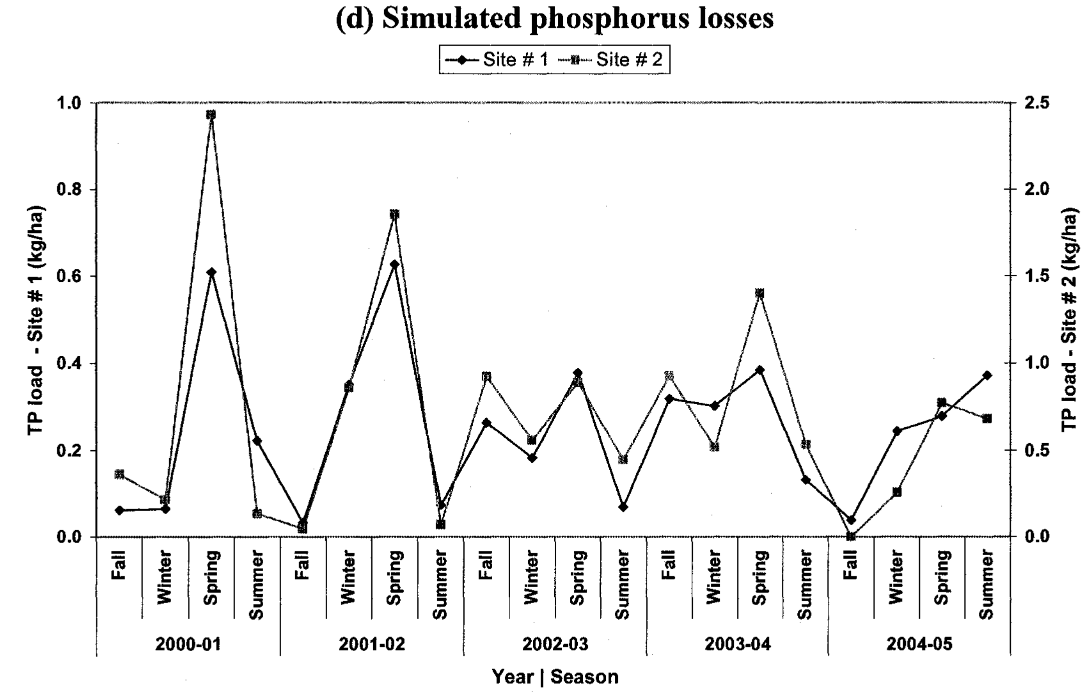


(b) Simulated sediment losses



(c) Simulated nitrate losses



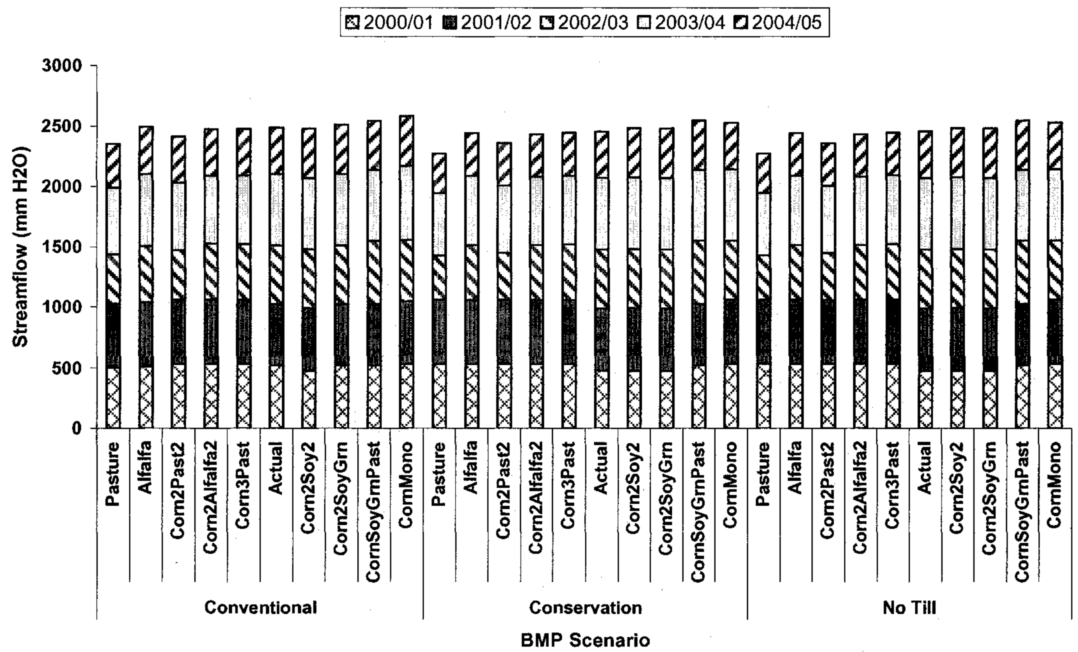


5.3.1. Impact on Streamflow

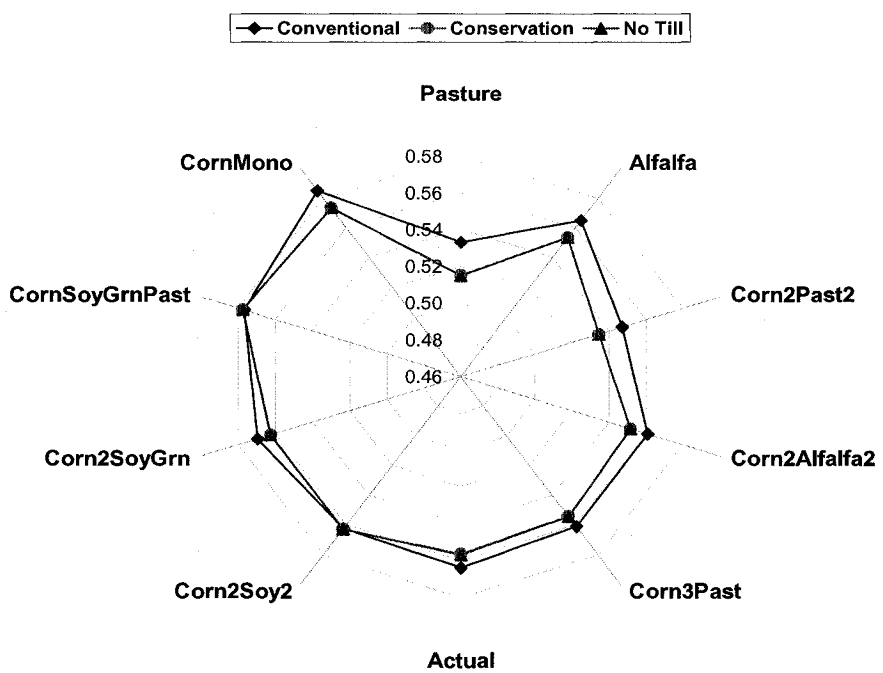
The average annual streamflow for the baseline scenario (*actual*) was 511 mm yr^{-1} for site #1 and 497 mm yr^{-1} for site #2. As shown in Figure 5.2a, the overall difference in streamflow cannot be differentiated clearly between scenarios over the five year simulation cycle. However, the differences are accentuated when the results are plotted as a mean of the runoff to rainfall ratios over the entire simulation period (Figure 5.2b). The 'radar' plot shows three polygons corresponding to the three tillage practices, and the ten vertices correspond to each crop rotation scenario. While monoculture in corn (*cornmono)* with conventional tillage had the greatest runoff to rainfall ratio of 0.59, conservation and no till practices with continuous pasture had the lowest ratios of 0.52 and 0.51 respectively. The baseline scenario on site #2 had a ratio of 0.56, and most scenarios with conventional tillage returned similar values, including soybean and alfalfa in rotation with corn. A shift to conservation or no till practices showed only a 1.5 – 2% decrease in runoff within a rotation. This reduction is not significant in the context of BMPs and shows that changing the tillage practices alone will not impact water yield. Thus, the best options to reduce runoff according to SWAT were to couple corn with pasture for at least two years in a 5 year rotation or move to continuous pasture for an extended duration before returning to corn or grain.

Figure 5.2: Comparison of runoff and streamflow under different BMP scenarios (shown for site #2)

(a) Annual streamflow



(b) Mean runoff to rainfall ratio



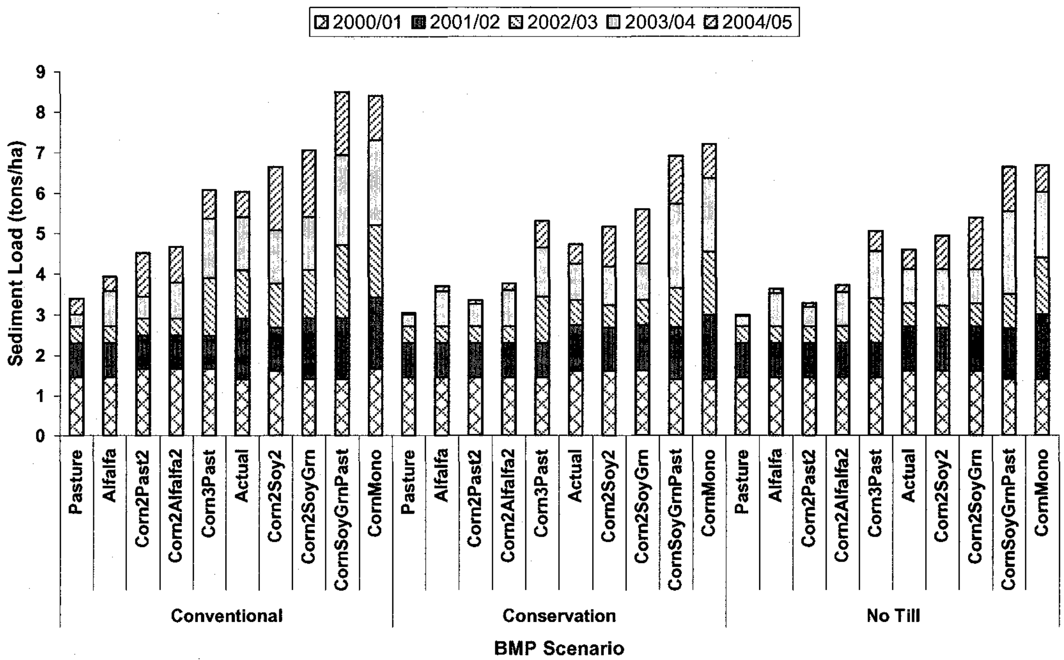
5.3.2. Impact on Sediment

The mean annual sediment load was 0.28 tons ha^{-1} yr^{-1} on site #1 and 1.207 tons ha^{-1} yr^{-1} on site #2. The baseline scenarios on site #1 correspond to an alfalfa-corn rotation while that on site #2 corresponds to a corn-soybean-grain rotation. In addition, the topography and hydrology of the sites have shown much lower sediment loads for site #1 than site #2 as discussed in the previous chapter. The BMP simulations showed marked differences in sediment loads between different crop rotations as well as within a crop rotation for different types of tillage. As seen in Figure 5.3a, rotations involving pasture or alfalfa have total sediment loads from 3.4 to 4.7 tons ha^{-1} while those with soybean, cereals and corn have sediment loads in the range of 6.0 to 8.5 tons ha^{-1} over the five year simulation period. At the same time, a shift from conventional to conservation tillage brings down these losses to the ranges of 3.0 to 3.8 tons ha^{-1} for pasture and alfalfa rotations, and 5.1 to 7.3 tons ha^{-1} for soybean rotations.

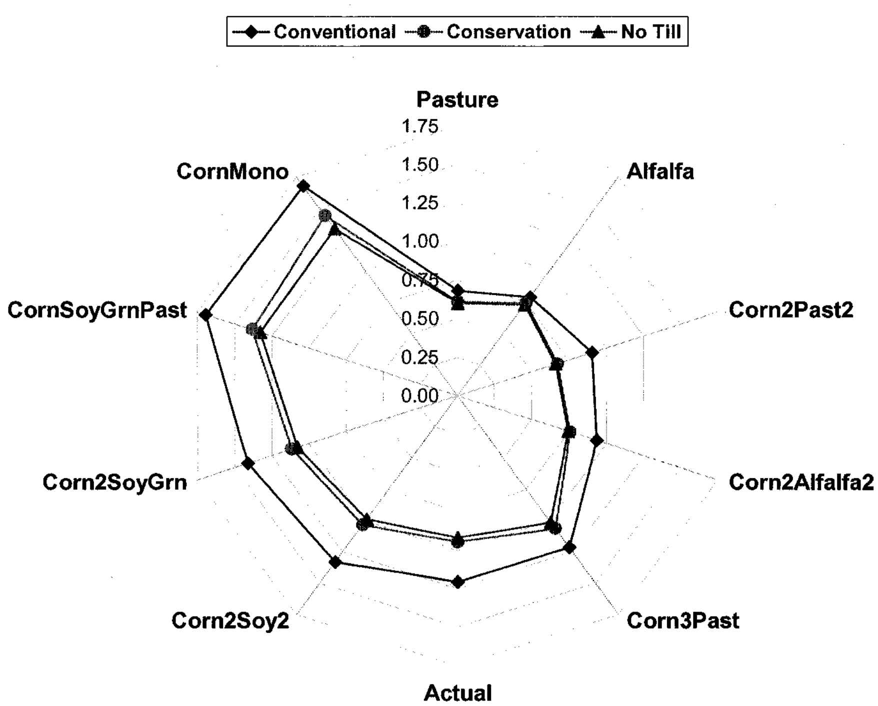
Figure 5.3b illustrates the impact of opting for conservation tillage or no till practices over conventional tillage. The distance between the outer polygon (conventional tillage) and the two inner polygons (conservation, no till) is around 0.25 tons ha^{-1} yr^{-1}, and this difference is specially exaggerated for soybean, which was more susceptible to erosion losses. Continuous pasture has lowest erosion potential, with average annual losses being only 0.6 tons ha^{-1} yr^{-1} when conservation tillage is practiced. In contrast, corn monoculture and the corn-soybean-grain-pasture rotation had the highest erosion losses of 1.7 tons ha^{-1} yr^{-1} with conventional tillage, and this reduced to 1.33 tons ha^{-1} yr^{-1} if no till was used instead. Losses can be reduced to up to 50% if corn is replaced with pasture. Even if the existing rotation scenario were continued, SWAT predicts that a shift from conventional to conservation tillage will reduce sediment losses by around 25%.

Figure 5.3: Comparison of sediment loads under different BMP scenarios (shown for site #2)

(a) Simulated sediment loads showing annual contributions



(b) Mean annual sediment load

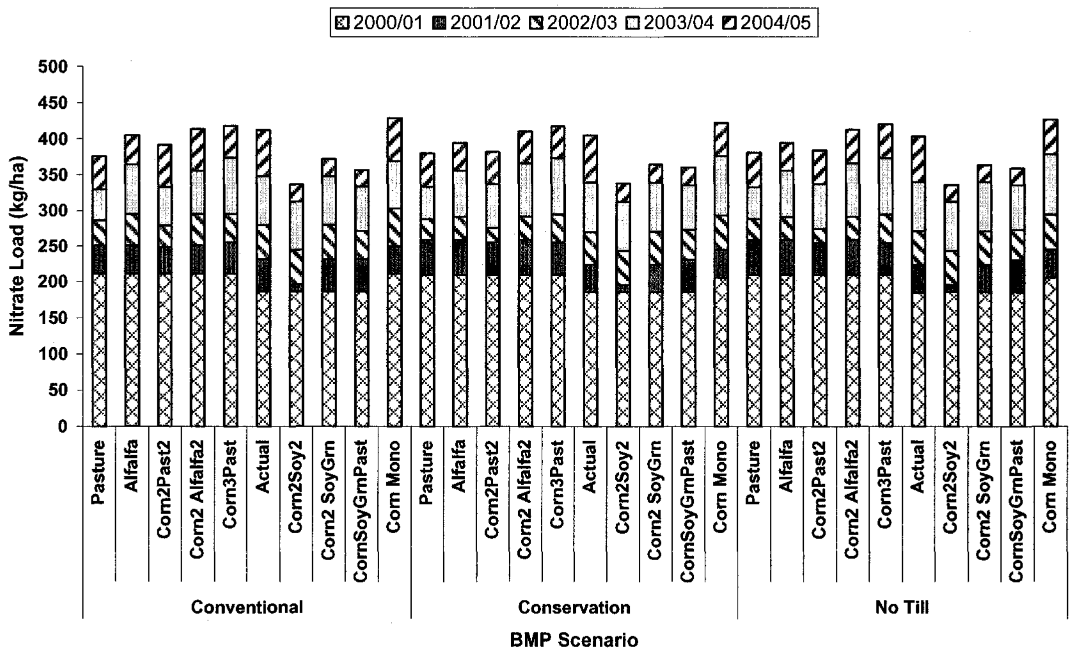


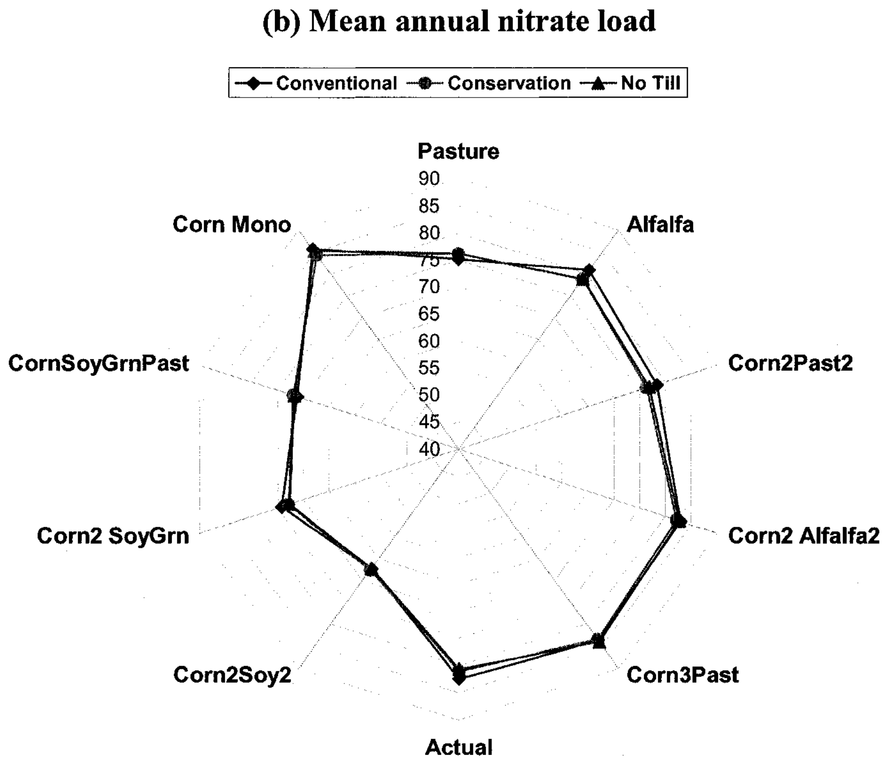
5.3.3. Impact on Nitrate Loads

The results for nitrate loads present a contrast to the general trend of reduced losses with conservation tillage. No significant difference was obtained between the three types of tillage practices simulated as shown in Figure 5.4. However, the results show an interesting trend with the BMP scenarios involving soybeans. The *corn2soy2* rotation had the lowest nitrate loads of 67 kg ha^{-1} yr^{-1} among all scenarios and was 22% lower than the baseline value of 82 kg ha^{-1} yr^{-1}. The main reason for this is that the use of nitrogen fertilizers is minimal when soybean is cultivated. Thus, on fields where nitrate loads are very high, this rotation serves well to control losses. Past studies have shown differences in nutrient loads with tillage due to the differences in the degree of soil mixing, since this determines the extent of soil-nutrient interaction. However, SWAT simulations did not demonstrate any such difference with changing tillage practices. A better way of limiting nitrate losses would be by varying the timing and extent of fertilization.

Figure 5.4: Comparison of nitrate loads under different BMP scenarios (shown for site #2)

(a) Simulated nitrate loads showing annual contributions





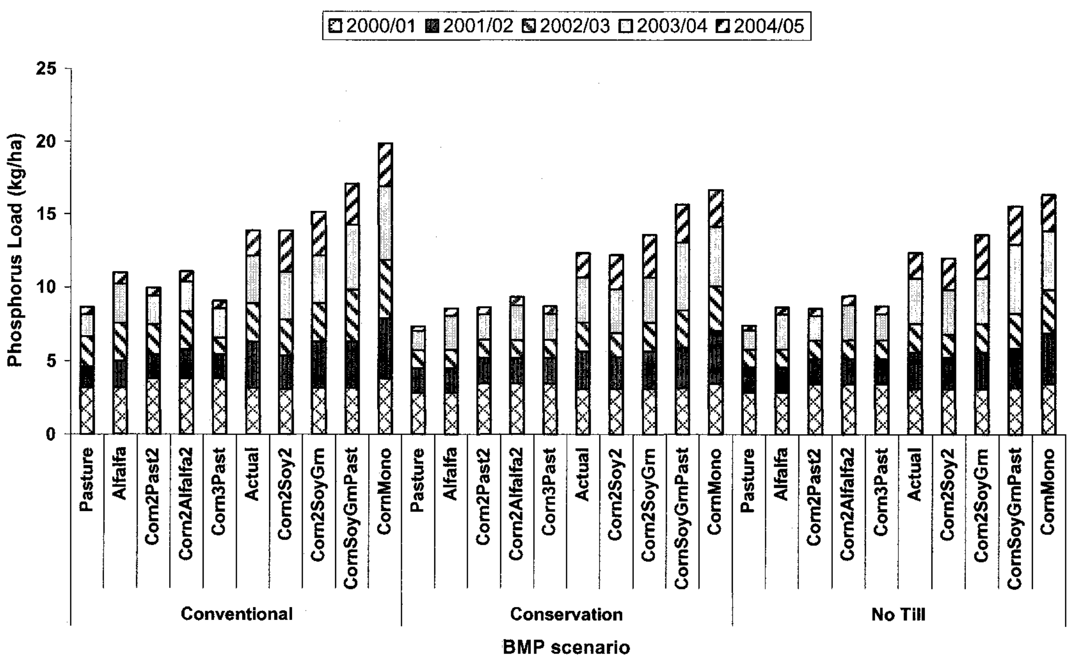
5.3.4. Impact on Phosphorus Loads

The baseline scenario *(actual)* has a mean annual phosphorus load of 1.0 kg ha^{-1} yr^{-1} for site #1 and 2.8 kg ha^{-1} yr^{-1} for site #2. When conservation tillage practices were employed retaining the same crop rotation sequence, total phosphorus loads decreased to 0.95 kg ha^{-1} yr^{-1} and 2.5 kg ha^{-1} yr^{-1} on sites #1 and #2 respectively. This decrease is marginal to employ conservation tillage as a BMP to limit phosphorus losses. When conventional tillage is retained but other crop rotation scenarios are simulated, SWAT results showed that corn monoculture can increase phosphorus losses to up to 4.0 kg ha^{-1} yr^{-1} on site #2 and 1.7 kg ha^{-1} yr^{-1} on site #1. In comparison, soybean and cereal rotations can limit these losses to the range of 1.0 - 1.4 kg ha^{-1} yr^{-1} on site #1 and 2.75 – 3.5 kg ha^{-1} yr^{-1} on site #2. Two years of soybean with two years of corn gave lower losses compared to rotations with cereals and soybean. The percentage difference between continuous corn and the *corn2soy2* rotation was 31%.

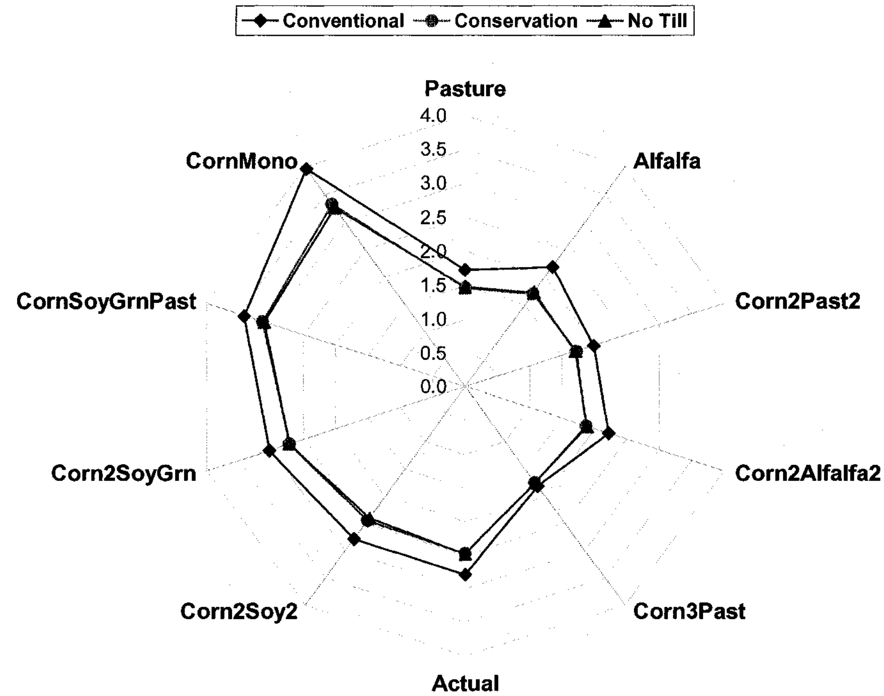
Alternatively, pasture and alfalfa provide the best option on fields with excessive phosphorus. Converting a corn field to continuous pasture for a five year duration can drastically reduce phosphorus losses by more than 50% per annum. On site #1, the mean annual phosphorus transport decreased from 1.7 kg ha^{-1} yr^{-1} to 0.8 kg ha^{-1} yr^{-1} when continuous pasture was employed on a field that was earlier practicing corn monoculture. This decrease is accentuated for site #2 – from 4.0 kg ha^{-1} yr^{-1} to 1.5 kg ha^{-1} yr^{-1}. Even if corn was cultivated with two years of pasture or alfalfa in a four or five year rotation sequence, significant reductions in P losses were obtained, especially if the corn was tilled under conservation or no till practices. On site #1, these two year rotations resulted in average annual P loads in the range of 0.9-1.0 kg ha^{-1} yr^{-1} and on site #2 the corresponding range was 1.7-2.2 kg ha^{-1} yr^{-1}. Between alfalfa and pasture, the latter provided marginally better results. This may be due to the fact that the initial bed preparation for alfalfa involves a series of field operations in the first year, which would have increased the total phosphorus loads associated with sediment (Figure 5.5).

Figure 5.5: Comparison of phosphorus loads under different BMP scenarios (shown for site #2)

(a) Simulated phosphorus loads showing annual contributions



(b) Mean annual phosphorus load



5.4. CONCLUSIONS

As hypothesized, the trends obtained for both the fields from the BMP scenarios were comparable for nitrogen, phosphorus and sediment transport. On either site, it was found that tillage practices alone were not a sufficient BMP for limiting phosphorus losses. At the same time, conservation tillage gave consistently lower loads for sediments and phosphorus when compared to conventional tillage. Although the differences in mean annual loads between conventional and conservation tillage were marginal within continuous corn, the adoption of soybean for two years in a four or five year rotation with corn reduced losses by up to 25% for sediments, 22% for nitrates and 31% for phosphorus. The adoption of continuous pasture as BMP has the potential to further reduce these losses to about 50% in the case of sediments and phosphorus. However, similar reductions were not possible for nitrate loads when pasture was grown instead of corn. In this case the reductions were only 9%. Thus, the best management practice for an agricultural field would be dependent on the extent of severity of nutrient pollution. In general, soybean rotations are recommended for fields with high nitrate leaching potential and pasture is preferred on fields with high phosphorus leaching risk.

Of the two fields on which this thesis is based, site #1 has total nitrate loads in the range of 150-200 kg ha^{-1} yr^{-1} and phosphorus loads from 0.85-1.35 kg $ha^{-1}yr^{-1}$. Hence, recommended BMP for this site is a five year rotation with two years of soybean and three years of corn with conservation tillage, which is expected to reduce nitrate loads to around 140-160 kg ha^{-1}. Phosphorus loads after BMP implementation are expected to range 0.75-0.95 kg $ha^{-1}yr^{-1}$ on site #1. For site #2, annual nitrate loads range 65-70 kg $ha^{-1}yr^{-1}$ and total phosphorus loads range 2.4-4.0 kg $ha^{-1}yr^{-1}$. Since phosphorus pollution is of critical concern here, it is recommended to keep the field under continuous pasture or alfalfa for three to five years, before returning to a corn-soybean rotation if necessary. This is expected to keep phosphorus loads between 1.5-1.8 kg $ha^{-1}yr^{-1}$ in the years under pasture, and around 1.9-2.5 kg $ha^{-1}yr^{-1}$ under corn. Current nitrate loads on this site are within acceptable limits, and this BMP should maintain annual nitrate loads within the same range.

CHAPTER 6: Summary and Conclusions

6.1. Summary

This study was conducted on two tile-drained agricultural fields in Southern Quebec. Climatic data collected between October 2000 and September 2005 were used as inputs to the SWAT model. Field hydrology (surface runoff; tile drainage) and water quality (TSS, NO_3-N, and P) data over two years were used in model calibration and validation. The model was calibrated for hydrologic and nutrient transport processes and its performance was evaluated at a daily, monthly and seasonal scale. The applicability of SWAT to Southern Quebec's climatic and hydrologic conditions was also assessed. Lastly, BMP scenarios for crop rotation and tillage practices were created and tested using SWAT. Crop rotations varied from continuous corn to continuous pasture/alfalfa. Soybean and cereals were also used in rotation with corn.

6.2. Conclusions

In general, it was found that the SWAT model was capable of simulating hydrological and water quality process at the field-scale. The model was also able to simulate snowfall and snowmelt satisfactorily, demonstrating its potential to be adapted to Quebec's climatic conditions. Sensitivity analysis showed CN and soil moisture content as the main factors influencing runoff while timing and depth of tillage and fertilization were important in nutrient load estimation. Monthly or seasonal load predictions were more reliable compared to daily values. SWAT, however could not adequately address issues related to tile drainage simulations and the movement of the different forms of phosphorus down the soil profile. Total water yields and nutrient loads were estimated well but the partitioning of surface runoff and subsurface drainage could be improved through changes to the tile drainage component of SWAT. The specific conclusions drawn from the study have been listed below:

i. The selected curve numbers were modified based on empirical equations using the antecedent precipitation index. These curve numbers were lower than AMC-based values and helped reduce excessive runoff volume estimates.

ii. The coefficients of performance for water yield, surface runoff and subsurface flow for the calibration year 2002-03 were 0.21, 4.49 and 0.35 for site #1; 0.45, 1.35 and 0.76 for site #2. Surface runoff events were few and did not permit accurate calibration compared to subsurface flow. A longer calibration period including more surface runoff events should improve runoff predictions and the partitioning of drainage and surface runoff components of streamflow.

iii. For the validation year 2003-04, the coefficients of performance for sites #1, and #2 were 0.32, 0.64 for total water yield; 0.67, 0.62 for surface runoff; and 2.21, 2.28 for subsurface flow respectively. The poor subsurface flow prediction was mainly due to inaccurate partitioning of the 2003 snowmelt runoff. However, total snowmelt runoff nearly matched observed amounts for all four site-years, with the average error in streamflow between the months of February and April being only - 3.7 %.

iv. It was hypothesized that preferential flow conditions enhanced sediment and phosphorus movement down the soil profile. Sediment losses occurred mostly through surface transport on site #1 (82%) but were equally distributed between surface runoff (53%) and subsurface drainage (47%) on site #2. Since SWAT does not address this phenomenon adequately, comparisons were limited to loads in total streamflow only.

v. Total simulated sediment yields were 0.60 tons ha^{-1} and 1.77 tons ha^{-1} on sites #1 and #2 respectively, corresponding to errors of 87.8% and 1.2%. In contrast, in the validation year sites #1 and #2 had -2.0% and -46.6% errors. This opposite response was brought about by the markedly different hydrologic characteristics of the sites and the dominant flow events in each year (summer storms in 2002 and spring snowmelt in 2003).

vi. SWAT underestimated nitrate loads in surface runoff and subsurface drainage consistently. Total nitrate loads were below observed values by 36.1% and 38.3% during calibration and by 10.6% and 11.9% during validation, on sites #1 and #2 respectively.

vii. Surface runoff accounted only for 2.3% and 13.3% of total nitrate load during the study period. In comparison, SWAT simulated 0.5% and 4.0% of total nitrate load in surface runoff on sites #1 and #2 respectively.

viii. Total phosphorus load was highly overestimated in 2002 although total water yields were almost equal. The reason for this is that SWAT routed most of the snowmelt through surface runoff whereas a majority of snowmelt exited through tile drainage that year. In contrast, most of the total P was transported through surface runoff during the 2003 snowmelt and in this instance SWAT performed well and P loads were more accurate.

ix. 61.2% (site #1) and 87.7% (site #2) of total phosphorus exiting the fields was as particulates sorbed to sediments. Using SWAT returned corresponding percentages of 55.1% and 76.3%. Thus the different forms of phosphorus in streamflow were partitioned well but there is a need to mathematically model its movement through subsurface flow and incorporate into SWAT.

x. The coefficients of performance and regression coefficients for both sites gave similar results for model efficiency, and demonstrated that SWAT results were reliable at a monthly time-scale for total sediments and particulate phosphorus. For nitrates, only seasonal or annual totals gave a fair estimate.

xi. The BMP simulations demonstrated the utility of SWAT in predicting load reductions under varying scenarios. The recommended BMP for site #1 is a five year rotation with two years of soybean and three years of corn with conservation tillage. This is expected to reduce nitrate loads to around 140-160 kg ha^{-1}. Phosphorus loads between 0.75-0.95 kg $ha^{-1}yr^{-1}$ are expected after BMP implementation.

xii. For site #2, phosphorus pollution is the major concern, and the best scenario would be to keep the field under continuous pasture or alfalfa for three to five years. After BMP implementation, phosphorus loads can reduce by up to 2.0 kg $ha^{-1}yr^{-1}$ when under pasture to 1.5-1.8 kg $ha^{-1}yr^{-1}$. In the years under corn, total P loads between 1.9-2.5 kg $ha^{-1}yr^{-1}$ are anticipated. Current nitrate loads on this site are within acceptable limits, and this BMP will keep annual nitrate loads within the same range (65-70 kg $ha^{-1}yr^{-1}$).

CHAPTER 7: Directions for Further Research

This thesis work, while validating SWAT for the field-scale, has identified several areas in which further investigation and research is required. The recommendations made in this chapter are divided into two sections: the first section deals with the field monitoring component and suggests the incorporation of additional field studies to measure parameters that were earlier estimated from literature; the second section is oriented towards enhancing SWAT performance through program modifications, based on the knowledge gained through this study. The implementation of these steps could make SWAT a robust model for field-scale simulations and in developing agro-environmental indicators for phosphorus.

7.1. Field Monitoring

i. Continued monitoring of the sites will provide an expanded dataset which could be used to increase calibration and validation periods. It is expected that a wider range of data will effectively improve the calibration procedure.
ii. The availability of solar radiation, wind speed and relative humidity measurements from new site installations and nearby meteorological stations provide scope to verify and improve evapotranspiration estimates, which are a major component of the overall water balance.
iii. During the study period, downstream pressure transducers were installed to monitor backwater effects (occasionally encountered during snowmelt). This additional parameter is expected to improve field measurements of snowmelt runoff and improve calibration data quality.
iv. Field tests should be performed to quantify sensitive parameters more accurately, such as soil chemical concentrations, soil moisture and snow water equivalence.
v. Accurate information of management practices (e.g. tillage depth, fertilization dates and amounts, harvest dates, etc.), especially during the calibration period can significantly improve water quality predictions.
vi. The hypothesis of preferential flow could be tested through lab or field studies.

7.2. Modeling

i. SWAT simulations lacked most in their ability to partition streamflow between surface runoff and subsurface drainage efficiently. This aspect merits an in-depth study, especially for regions where tile drainage is a dominant practice.

ii. Field results have shown that P losses through subsurface flow were significant. Thus, there is a need to develop a phosphorus partitioning model to calculate the ratios of the different forms of P in surface runoff and subsurface drainage using existing inputs and incorporate into SWAT.

iii. Sediment loads in subsurface flow were significant on one of the two sites and showed a high correlation with particulate P loads. An appropriate sediment transport model that accounts for subsurface sediment movement needs to be developed and tested with SWAT.

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