Sustainable management for agriculture, nature and water quality in the Pike river watershed using the SWAT model. Québec – CANADA Project.

Master of Science Thesis
by
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Abstract

Water is indispensable for the life of every living thing; it is needed in a good quality and in a sufficient quantity the reason why the protection of its resources is very important. It is shown that diffuse pollution is often responsible for poor water quality. These problems are characterized by high temporal and spatial variability, understanding and solving them requires dynamic models to point out the important causes of pollution or to predict the effects of pollution reduction's strategies. The development and application of water quality models in watersheds environment all over the world has been increasing, this is something practically helpful for countries development. The ability of a model to simulate the watershed system depends on how well watershed processes are represented inside the model and how well the watershed system is described by model input parameters.

In recent years, cyanobacteria blooms, triggered by an excess of nutrients have caused the degradation of the Missisquoi Bay, in the Lake Champlain (Quebec, Canada). In the Quebec region the water quality deterioration became a major concern for all public sectors involved and encouraged to search for solutions in order to save their environment. The objective was to reduce excess nutrient mainly coming from agriculture fields. A watershed of the main tributary river to this bay, Pike river watershed has been understudy and a watershed, Walbridge's Creek inside the pike river watershed was selected for a better characterization of the area. Two small twin's sub-watersheds were chosen in order to distinguish the area under modelling processes within a SWAT model. The SWAT model is known as a tool that can help to assist to water quality management planning and decision making. This would allow the evaluation of pollution abatement plans for the whole watershed. The two small sub-watersheds "*Intervention*" and "*Temoin*" present different characteristics that are physically independent and that provided wide evaluation of the performance of the SWAT model.

Initially, the capacity of SWAT model to sufficiently predict constituent yields and stream flow for the specific application was evaluated through the hydrological phase where the sensitivity analysis and the model calibration helped to know its predictions limits. The sensitivity analysis was done using the LH-OAT sensitivity analysis method, a combination of One-factor-At-a-Time (OAT) design and Latin Hypercube (LH) method. The LH-OAT method was successful to perform a parameter sensitivity analysis for the Walbridge's watershed to show how parameters affect flow output variable. The sensitivity analysis was used to select important parameters for the calibration. An autocalibration method was used for the optimization of the processes parameters inside the Parasol (Parameter Solution method) method. In all cases the method was found to be efficient according to the set of parameters selected for each run. Less confidence was given to the autocalibration results as the optimized parameters seemed to be only working for single objectives and not for the entire simulation period. As a consequence, the results were not agreeing with the reality and the parameter values were always suspicious. The manual calibration was done for finding better results by working on the parameters adjustment. This was successfully completed.

The ability of the SWAT model was tested and found that modifications were needed for the Walbridge's watershed case through the SWAT source codes. The water in tile drains was too much underestimated. The problem was that the majority of intensively managed agricultural lands in Quebec are subsurface drained and that this subsurface-drainage is the dominant pathway by which water leaves the field. An important presence of tile drains had to be recognized inside the model. After all more emphasis was given to the tile drainage modelling which would make the application of the model more justified if the modifications would guarantee closed water balances and allow the applicability of the model in an integrated modelling environment. The results from modifications done in SWAT were always compared to the first results obtained with SWAT. Unfortunately some approaches were not successfully accomplished because they needed more deep researches for data missing and the research was restricted to that.

Finally, a best concept was chosen and tested. Theoretically the improvements insights provided a better description of the hydrological system, but because of the increased complexity of the model it made the research more difficult to touch every part concerned. As the research is an ongoing project still these results are very useful for a future use and available towards a brighter solution on the Walbridge's watershed and Pike river watershed as a whole.

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Thanks God...

Time comes now to present my thesis work which kept me busy during the last six months. I owe this result to many people whom I'd like to thank now. Special thanks are extended to my mentor Ann van Griensven for giving me this opportunity to do this work and for her support to get results.

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List of abbreviations

BMPs	Agricultural Best Management Practices
CREAMS	Chemical, Runoff and Erosion from Agricultural Management Systems
EPA	United States Environmental Protection Agency
EPIC	Erosion-Productivity Impact Calculator
GLEAMS	Groundwater Loading Effects on Agricultural Management Systems
HRU	Hydrological Response Unit
IRDA	Institut de Recherche et de Développement en Agrœnvironnement
MUSLE	Modified Universal Soil Loss Equation
N	Nitrogen
NO_3	Nitrate
OAT	One-Factor-At-a-Time
OF	Objective Function
P	Phosphorus
PFRA	Prairie Farm Rehabilitation Administration
RMS	Root Mean Square
RWQM	River Water Quality Model
SWAT	Soil and Water Assessment Tool
USEPA	United States Environmental Protection Agency.
WWTP	Waste Water Treatment Plants

Introduction

Picture of the Pike River near Bedford, Québec. (Photo taken by Aubert Michaud)

CHAPTER I: INTRODUCTION

Rivers and other water bodies are a source of livelihood for communities and cities around the world; they are a source of drinking water, water for irrigation, a sink for wastes, recreation among other uses. The fresh surface water in lakes, streams and rivers is a very important part of water which is so significant for terrestrial ecosystems, including humans. We depend on surface and groundwater sources for drinking, generating energy, grow crops, harvest fish, run machinery, carry wastes, to enhance the landscape and for a great deal more. Water is also vital as a habitat for plants and animals (Vale, 2006). Water as a link it acts in connecting many things in a watershed depending on which activities are present. These sometimes opposing uses imply that water resources utilisations have to go hand in hand with management and control of water quality. Analysis of water quality parameters forms a basis for water quality control and serves as a benchmark for restoration of catchments.

River Pike and its catchment is one of the tributaries of Lake Champlain in Missisquoi bay. Its catchment is located in south Quebec in Canada and part of USA with a total catchment area of 630km^2 and total length of 67 km. Known as one of the best water place in north America, its situation is no longer recognized. This region is occupied by 600 000 residents (LCBP, 2002). Each year the watershed was visited by many tourists attracted by its natural and historical place. In 2000, a number of 3.8 billions American dollars was estimated about the tourisms revenue from the watershed (LCBP, 2002). The lake resources are exploited for many purposes. First it serves for potable water supply to 35% of the watershed population and second for the recreational, agricultural and industrial programs in the region. The Lake Champlain has got many benefits which contribute to the economic and social development of the area (Agrosol, 2002). That’s why the presence of its environmental problems requires important measures to be taken in order to preserve its nature.

I.1. Problem definition

I.1.1. River basin management

Economic development is what countries strive to achieve, however this development may harm critical ecosystems with invaluable biodiversity, which in its turn harms the long-term social economic development and environmental security. Water resources pollution is a serious problem all over the world and has been suggested as a leading cause of death and disease worldwide (Pink, 2006). The major causes of pollution for most river basins are the accumulation of nutrients washed off farmlands and industries. Often river basins are shared by different regions or even different countries making pollution control an orders task. This calls for combined approaches to solving pollution problems in catchments. To protect water resources within a watershed context, a mix of point and non-point source discharges, ground and surface water interactions, and water quality/quantity relationships must be considered. The complexity of these issues present considerable challenges to water resource protection programs.

I.1.2. Pike river watershed water quality

In recent years, water quality analysis showed a pollution problem of in the rivers and streams of the Missisquoi bay, especially in the Lake Champlain; cyanobacteria blooms were observed that are triggered by excess phosphorus. The degradation Phosphorus (P) concentration exceeds the target levels by 40% and it was estimated that around 80% of the Phosphorus (P) exports originate from diffuse agricultural sources; the receiving water bodies are badly affected. The major sources of pollution in this catchment are: - Intensification of agriculture due to mechanization and specialization, Excessive use of fertilizers, Livestock wastes, manure storage and disposal and tillage practices. The main river contributing to this bay is the Pike River, as an important tributary of the Missisquoi bay in South Quebec’s territory. The Pike river watershed is characterized by important environmental, biological and cultural functions. In addition, we bear in mind that the river's water quality is the basic aspect connecting land use, nature and drinking water.

Many agro environmental associations concerned by the problem including the Research and Development Institute Agroenvironmental issues (IRDA) started a study on the water quality in the Pike river watershed within its rivers in its different sub-watersheds in the Quebec region. In 2002, the government of the province of Quebec and the state of Vermont agreed on intervening to reduce the influx of phosphorus to the bay as a priority. The major objective was the reduction of the diffused phosphorus and sediments to the rivers (A. Michaud et al.2005). By considering that the determination of the existing situation of agricultural lands, practices used as well as the water quality required to be done in order to ameliorate this by doing different interventions according to the situation.

By using modelling the operation was supposed to improve, resulting in better and more stable water quality; modelling was found to help to define ecological conditions and developing an appropriate program of measures to attain good status. The preservation of the watershed resources water refers to the agricultural field; as the big part of the watershed is agricultural land.

Pike river watershed and cyanobacterial presence

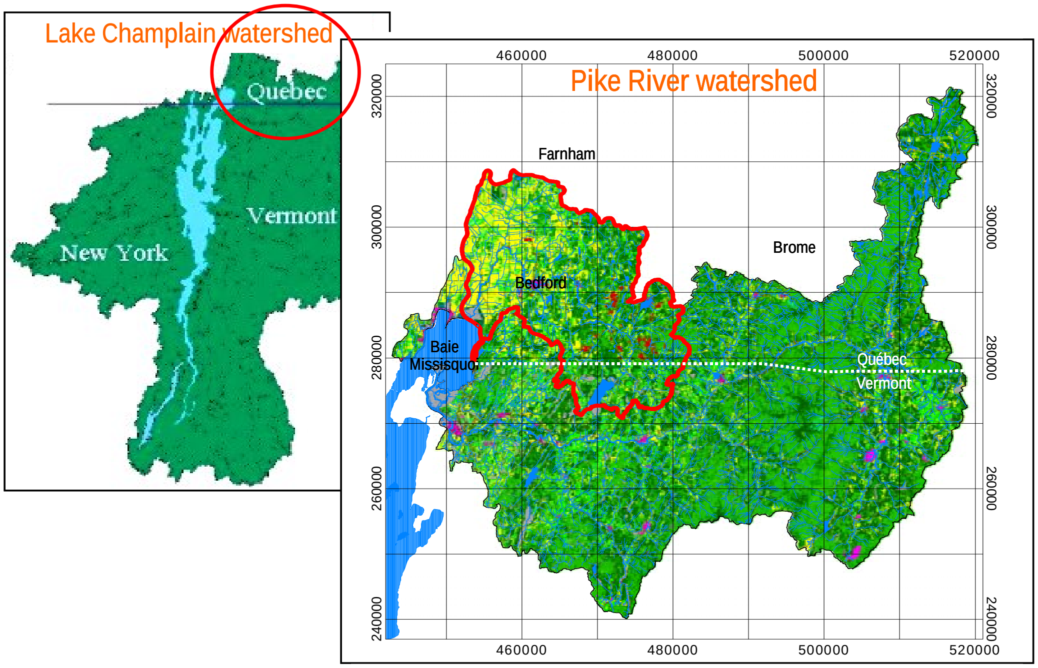


Figure 1: The Lake Champlain and the Pike river watershed.

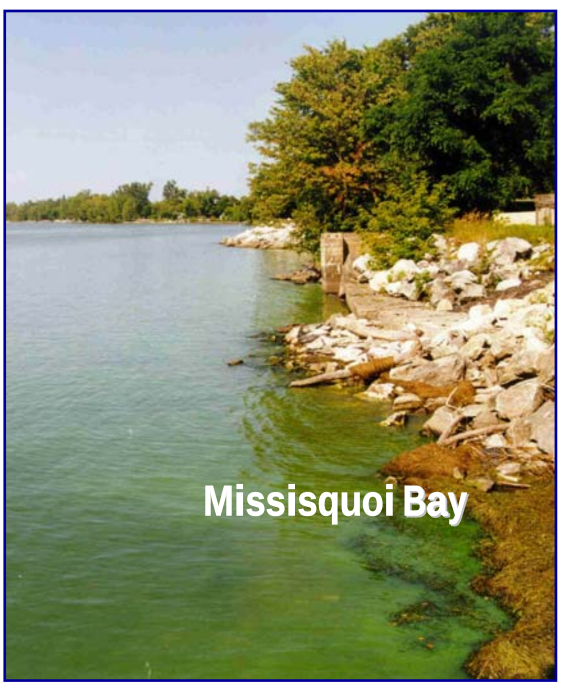


Figure 2: The cyanobacterial presence in Missiquoi Bay.

Many years ago, the water quality deterioration of the Missisquoi bay was shown by the cyanobacteria presence in summer period (figure 2). In 2001 and 2002, some of the bay public's beaches were closed because of that problem which made the place less useful. The health care public services advised to people to avoid any contact with that water (Agrosol, 2002).

I.1.3. Modelling

The water quality monitoring in a watershed needs an understanding of the physical system and its interaction with the environment as a prerequisite for effective planning and management of the area in order to have a sustainable system.

It required to scope or to quantify the problem in order to target and predict. Modelling came with its ability of converting projections concerning some changes into a prediction of watershed conditions and water body response.

I.1.4. Objectives

The main objective of the research is to adapt and calibrate a hydrologic model to the conditions prevailing in the Pike River watershed. The ability of a model to simulate the watershed system depends on how well watershed processes are represented by the model and how well the watershed system is described by model input parameters.

The objectives of this research:

- To calibrate and adapt an hydrological model to the physical conditions of the catchment's area;
- To determine the effects of different model improvements on the water distributions in the hydrological network of the area in focus of meeting the water budget conditions and nutrients dynamics.

I.2. Methodology

The methodology adopted to achieve the stated objectives, applies the Soil and Water Assessment Tool (SWAT) model. SWAT is used to predict the movement of sediments, nutrients, or pesticides within the hydrologic cycle. The test of the simulation is to compare results as simulated by the model with conformance to what is happening in the Watershed. The SWAT2003 model with its in-built sensitivity analysis and auto-calibration tools are tested at a small scale using the Walbridge (7 km²) sub-watersheds, which present contrasting landscape attributes. The idea of choosing two experimental sub-watersheds was based on their results which would be applied to the rest of the Pike river sub-watersheds according to their physical similarities to one of them.

From the hydrological processes, verification in the model codes was done for examination of the numerical technique in the computer code to find out that it truly represents the conceptual model and that there are no inherent numerical problems for obtaining good results. Some modules were added others changed according to the hydrological processes observed in the area. As an open source model, this gave facilities to the research to try to adapt the model to some of the realities in the watershed. The important reality in that watershed is the sub-surface drainage through the tiles which are draining more water from precipitations than on surface.

SWAT model was used for a method of environmental management that may lead to sustainable development in this watershed. Sustainability was defined as maintaining a high quality of the water in the streams and rivers of the watershed area while preserving the nature and landscape. The contribution of two sub-watersheds was to be determined in this research.

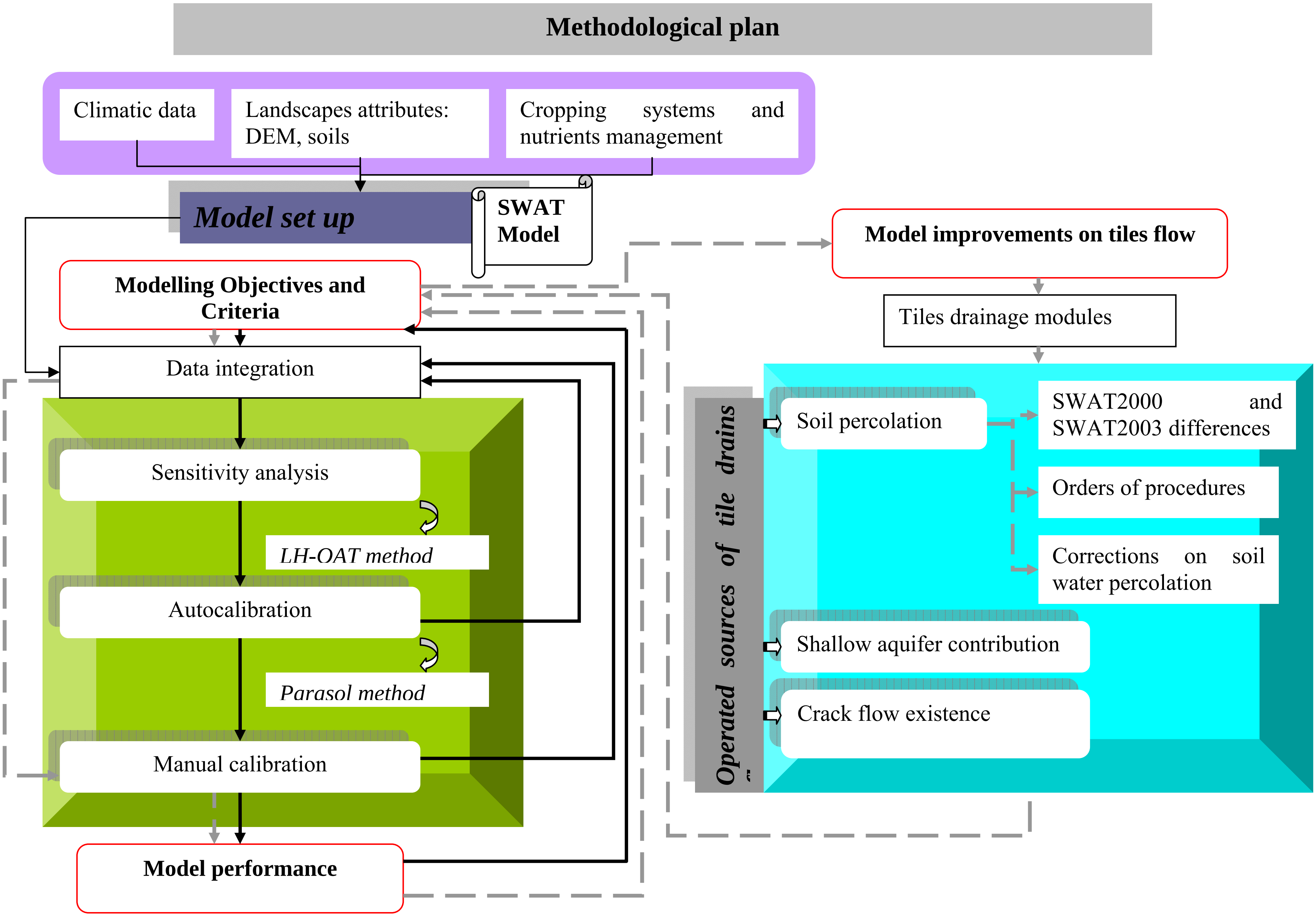
I.3. Tools used

From the problem introduced in Pike river watershed, SWAT model was the only tool used for the necessary modeling tasks. Using *Arcview GIS* interface. This enables it to deal with the landscape attributes: digital elevation map and soils, to distribute cropping systems and nutrients management with required data and to divide the area into sub-watersheds within the area of interest.

I.4. Outline of the thesis

The thesis consists of two main parts: a part reporting the important results obtained in the research, preceded by a part that provides information needed for the understanding of the processes used and the achievement of the results. This includes a literature review on the topics “Modelling environmental processes” *(chapter II)*, “SWAT and processes” (*Chapter III*) which emphasizes on the main physical processes in watershed and river systems.

The first chapter presents the description of the problem. The third chapter explains the SWAT model followed by “The Pike Model application” (*Chapter IV)* which evaluates its application in the Pike River Watershed and Walbridge. The next *Chapter V* describes sensitivity analysis, autocalibration, and manual calibration. The model improvements on Walbridge’s hydrology come in “Tile drainage modelling” (*Chapter VI*). The thesis ends with a chapter for conclusions and recommendations (*Chapter VII*).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Picture of a covered bridge over the Pike River in Pike River, Québec. (Photo taken by Aubert Michaud)

CHAPTER II: MODELLING ENVIRONMENTAL PROCESSES

II.1. Pollution

Water pollution is a serious problem in the global context. It has been suggested that it is the leading worldwide cause of death and disease (Pink, Daniel H. 2006). The pollution occurs that might lead to negative effects on ecosystems, its prevention or reduction of the risk of water pollution wherever possible, is a big issue in these days. The fresh surface water in lakes, streams and rivers is very important part of water which is so significant for many of our terrestrial ecosystems, including humans. The quality of this fresh water is vitally important.

II.1.1. Pollution sources

The main sources of water pollution are from human activities and their by-products which have the potential to pollute water. Large and small industrial enterprises, the water industry, the urban infrastructure, agriculture, horticulture, transport, discharges from abandoned mines, and deliberate or accidental pollution incidents all affect water quality (Vale, 2006). These sources of pollution have each a related characteristic (Carpenter et al., 1998 and Rodhe, W. 1969); the increases in nutrient mainly from agriculture loading may lead to eutrophication, organic wastes such as sewage and farm waste impose high oxygen demands on the receiving water leading to oxygen depletion with potentially severe impacts on the whole eco-system. Industries discharge a variety of pollutants in their wastewater including heavy metals, organic toxins, oils, nutrients, and solids (APIS. 2005). Discharges can also have thermal effects, especially those from power stations, and these too reduce the available oxygen. Silt-bearing runoff from many activities including construction sites, forestry and farms can inhibit the penetration of sunlight through the water column restricting photosynthesis and causing blanketing of the lake or river bed which in turns damages the ecology (Blankenship, R.E., 2002).

Pollutants can also seep down and affect the groundwater deposits; all these pollutants and many other activities may enter surface or groundwater directly, may move slowly within the groundwater to emerge eventually in surface water, may run off the land, or may be deposited from the atmosphere. Water Pollution comprises nonpoint source contamination and pollution arising from often individually point sources. Examples of nonpoint sources (diffuse pollution) are run off from fields or seepage of nutrients from soil into ground water (SEPA, 2005).

II.1.2. Diffuse pollution

Diffuse water pollution can arise from many sources sometimes uniformly dispersed, but often accumulated within a catchment. These are generally dispersed and diverse in nature. Individually these sources may be small, but their collective impact can be damaging. Diffuse pollution can be derived from current and past land use in both agricultural and urban environments. It can also include atmospheric deposition (Vale, J. 2006).

As it is mentioned, diffuse pollution is closely linked to land use; it is mainly related to the way of use and management of land and soil. Diffuse pollution can affect rivers, lakes, coastal waters and ground waters. Ground waters are vulnerable from, and affected by, leaching of pollutants from the land surface and from areas of contaminated land, while surface waters are affected by rainfall that washes over and off the land (run-off). Rivers can also be influenced by the contribution to their flow that comes through springs and seepages from groundwater. Where the groundwater connection with surface waters is high, pollution can pass from one to affect the other. Run-off has increased as agriculture has intensified and particularly where human activities have degraded the natural permeability of the landscape and reduced its capacity to retain water (Vale, J. 2006).

II.1.3. Effects of diffuse pollution

Diffuse pollution can have significant effects on wildlife and our use of water. These effects include:

- nutrient enrichment and eutrophication in rivers and lakes;
- oxygen depletion;
- groundwater and surface water contamination and the subsequent loss, or need for treatment, of drinking water resources;
- microbiological contamination of water supplies;
- Toxicity to plant and animal life, including disturbance in fish life.

II.1.4. Control of diffuse pollution

Unlike point source pollution, the diffuse pollution can not be easily controlled. Nonpoint sources are difficult to regulate and usually vary spatially and temporally (with season, precipitation and other irregular events) (Carpenter et al., 1998). Regulatory approaches have to be more specific and in many cases need to be well connected to the land use planning system.

II.1.5. Diffuse pollution and Agriculture

Agricultural run-off, or the water from the fields that drains into rivers, is a major water pollutant as it contains fertilizers and pesticides. This use of land for agriculture and the practices adopted in cultivation greatly affect the quality of water in streams, rivers and lakes. Intensive cultivation of crops causes chemicals from fertilizers (e.g. nitrate) and pesticides to be transported by run-off. Routine applications of fertilizers and pesticides for agriculture are increasingly being recognized as significant sources of water pollution. The pollutant's content in waterbodies is mainly from run-off from agricultural fields where chemical fertilizers have been used not carefully.

In a published report by a U.K. Environmental Agency (Griffiths, D. 2006), the agricultural diffuse water pollution had been related to arise from:

- Nutrients – Diffuse pollution can be in the form of nutrient leaching to surface and ground waters. Both nitrate and phosphate can enter waters, enriching them and causing changes to the ecology.
- Soil loss to rivers – This can be caused by inappropriate cultivation and poor livestock management or by poorly timed cultivation. Pollution by soil particles when washed into rivers can also affect wildlife in lakes and rivers. Soil particles can have other chemicals adsorbed on them, particularly phosphates and pesticides.
- Pesticides – Diffuse pollution from pesticides can be a problem due to leaching, run-off, or allowing spray to drift over water. Spillage during the mixing up of pesticides can also lead to contamination.

II.2. River water quality

II.2.1. River quality aspects

Rivers and the surrounding land drained by them i.e. catchments are very important wildlife habitats. Water is indispensable for the life of every living thing; it is needed in a good quality and in a sufficient quantity the reason why the protection of its resources is very important. The disturbance of the natural existing waterways which could be from the excessive runoff can increase sedimentation to streams and rivers. Increased sedimentation raises filtering costs for drinking water, increases flood potential by filling up streambeds, and being an obstruction to irrigation systems (BMP Guide, 2002). Fish habitats can be contaminated by improper management activities. For instance, removing shade from streamside areas can increase water temperatures, thus affecting fish and other aquatic life. The entire food in and near streams can be affected and damaged by land management activity; as nutrients and pathogens are one of the cases where situations have been changed by these land management activities.

River water quality is determined by measuring three aspects of river quality: biology, chemistry and physical quality (Bingham, S., 2006). It refers to the assessment of chemical, biological quality and physical properties. In the water chemical quality, nutrients are the most important matter to be taken into consideration because of its bad effect in rivers ecosystem (cause of eutrophication). All these determine the status and the trends in stream and river's water quality in general. There are standards of water quality set for each of these aspects measures.

Biological quality - an indicator of overall 'health' of rivers refers to the number and types of organisms leaving in the waterway.

Chemical quality - an indicator of toxicity pollution in general refers to the chemical attributes of waterway.

Nutrient status - phosphate and nitrate in rivers refers to the chemical parameters; however it is considered apart because of its highest position in causes and effects for a river water quality.

Physical properties – an indicator of the structure of a sampling site refers to the physical attributes of a waterway. The most basic physical attribute of a stream is the path along which it flows.

II.2.2. River water Quality Standards

A variety of standards and targets to help in taking action to protect and improve water quality can be one of the objectives of Environmental Agencies. They are used to calculate the potential impacts of agriculture and industry, for example, to work out the conditions to impose on discharges in order to protect water quality. They also help in checking progression in protecting water quality and in working out where action is needed immediately (Warn, T. 2006). Standards may have a variety of aims. These include the protection of wildlife and nature, the control of risks to the quality of water abstracted for supply to our homes or used to irrigate crops, etc.

II.2.3. Main pollutants

1. **Suspended solids and sediments**

Suspended solids and sediments are regarded as the two leading pollutants of nation's streams and waterbodies (Kalin, L. et al., 2003). Sediment pollution is one of the major causes of surface water impairment. Presence of suspended sediments in rivers and lakes increases turbidity which limits light penetration and thus plant growth for aquatic organisms. Suspended solid and sediment (SSAS) yield has important implications for water quality and water resources. The source of SSAS can be natural such as wind erosion, upland erosion (detachment by rainfall and stream erosion), storm water runoff, and bank erosion, or man-driven such as wastewater discharge, tillage, mining, construction, silvicultural practices, etc. sediments may serve as carriers for pesticides, radioactive materials and nutrients giving rise to water quality issues. Studies have shown that total suspended sediment concentrations are positively related to total phosphorus and nitrate concentrations. Nutrients, while essential for healthy aquatic systems, can have adverse effects at high concentrations by increasing algal and macrophyte production and decreasing dissolved oxygen.

Stream and river's water quality is important not only for protection of aquatic life, but it is frequently used as an indicator of the environmental health of a watershed. Often, Suspended solids and sediments in surface waterbodies are contaminated by chemicals that tend to be attached to fine-grained organic as well as inorganic soil particles. The sources of such contamination can be from existing point or nonpoint sources or from historical spills or discharges. When such contamination exceeds critical levels, they pose ecological and human health risks requiring appropriate remedial actions. Such remedial actions take the form of either isolating the contaminated sediments, reducing their exposure to other parts of the ecosystem, complete removal of the contaminated sediments, or some combinations of the above (Kalin, L. et al., 2003).

Oxidation of organic matter occurs in the water column and in the bottom. The dissolved oxygen (DO; molecular oxygen dissolved in the water) can become reduced in concentration to a point detrimental to aquatic organisms living in the system; the deposition of algal mass and particulate organic matter on bottom sediments and decomposition therein exert sediment oxygen demand (SOD) on the overlying water. Depletion of oxygen by oxidation of particulate organic matter in the water column has undesirable environmental consequences, such as loss of fishery.

The particulate organic matters carried by water settles and within the anaerobic region decompose to yield dissolved CH_4. The methane is later diffused upward to the aerobic zone and gets oxidized generating SOD. Similarly, ammonification of organic N produces ammonium in the anaerobic zone which is later diffused to the aerobic zone where it is nitrified to produce nitrite NO_3^- resulting in SOD.

Changes in Suspended solids and sediments dynamics such as scour and erosion of channel bed and banks, deposition of fine particles, and resuspension of solids in the suspended sediment load of the water column, can have significant effects on the aquatic ecosystem health. Scouring and bank erosion may cause loss habitat used for feeding, reproduction, and cover by fish, algae, birds etc. the consequences of deposition and resuspension are more obscure yet more significant (USEPA, 2002a). High suspended sediment concentrations increase the turbidity in waterbodies that can easily alter the environment for phytoplankton and other aquatic flora from nutrient limited conditions to light limited conditions which can eventually affect dissolved oxygen dynamics (Stanley, 1994). The effects of high turbidity is more severe in the more tranquil waters of lakes, reservoirs and estuaries than streams and rivers due to accumulation of suspended solids in the water column from multiple sources (USEPA, 2002a).

2. Nutrients

Eutrophication

Eutrophication can be defined as enrichment of waters by inorganic plant nutrients, particularly nitrogen and phosphorous (Lenntech Eutrophication sources, 2006). Most frequently it is used to refer to nuisance growth of algae or other aquatic plants associated with nutrient enrichment. This phenomenon can be caused by various sources, both artificial and natural. Eutrophication has relevant effects on water bodies: the main are algal blooming, excessive aquatic macrophyte growth and oxygen depletion (Fischer, P et al. 1990).

Different solutions for the problem of eutrophication are being analysed or are already applied like the nutrient's limitation in water bodies while all nutrients reaching the surface water (principally N and P) is mostly taken originating from agricultural land (fertilizers, animal wastes).

Sources

Eutrophication by the definition given previously, is considered as enrichment of waters by inorganic plant nutrients, particularly nitrogen and phosphorous. This phenomenon can be either artificial (or *cultural*: human–caused, accelerated eutrophication is called "cultural eutrophication") or natural, depending natural causes. Sources of artificial pollution are either urban or rural; rural sources include agriculture, forest management, and rural dwellings.

Agriculture is a major contributor to nitrate pollution of freshwater; up of half of the nitrogen applied to crops is lost to groundwater. The loss of nitrate from agricultural land is largely caused by erosion. The other main source of agricultural eutrophication is livestock farming. Forest management may have local effects on nutrient loading of rivers. In some countries forests are regularly fertilized, and this may result in local eutrophication (Lenntech Eutrophication sources, 2006).

Eutrophication and fertilizers

The main problem – causing nutrients in fertilizers are nitrogen and phosphorus; high input of nutrients stimulates the growth of algae in receiving water bodies (lakes, rivers, coastal areas). This may result in a change in the composition of the algal population and in population explosion of certain nuisance causing species, referred to as "blooms". Basically, the fertilizers make a water body more productive, as they stimulate algal primary productivity (Lubberding et al., 2006).

However, from a multiple use perspective, such stimulation has undesirable consequences:

- Penetration of light into the water is diminished. Diminished light penetration decreases the productivity of plants living in the deeper waters (and hence their production of oxygen).
- The water becomes depleted in oxygen. When the abundant algae die and decompose, oxygen is consumed by those decomposers. Oxygen in the water is also lowered by the lack of primary production during the night and in the darkened, deeper waters.
- Lowered oxygen results in the death of fish that need high levels of dissolved oxygen ("DO"). The biological community of the water body changes leading to dominating organisms that can tolerate low DO.
- Further, some of the algal species that "bloom" produce toxics that render the water non-potable.

Nitrogen

Nitrates as in fertilizers containing NO3- are highly water soluble, and so move readily with surface runoff into rivers or with water percolating through the soil profile into the groundwater below. Only about 18% of nitrogen that is applied to fields as fertilizers leaves the fields in the form of produce (Lubberding et al., 2006). This means that the remaining 82% is left behind as residue or in soils, where it either accumulates, erodes with soil (often to surface waters), leaches to groundwater, or volatilises into the atmosphere (and can act as greenhouse gasses).

Phosphorus

Phosphates are also applied abundantly in fertilizer, and contaminate water. Unlike nitrate, however, phosphate is not water soluble, so moves only with soil movement, as it adheres to soil particles. A large portion of this P accumulation is in agricultural soils, as might be expected. A major problem associated with this increased P content of soils is that any factors that increase soil erosion will also increase runoff of P with soil to streams and rivers.

II.2.4. Main effects

1. **Ecology**

Algal and cyanobacterial blooms

Cultural eutrophication causes excessive algal bloom in water bodies, with consequent algal overload (Fischer, P. et al. 1990). Under certain conditions of darkness and warm temperatures these blooms may die, decompose and produce offensive sewage-like odour. If the receiving water is used as a raw water supply for some public or private agency, algae may be difficult to remove and hence add certain objectionable tastes to the delivered water. Algae also have the tendency to absorb and concentrate mineral nutrients in their cells. When they die, at the end of the growing season, they settle to the stream or lake bottom, from which they release these mineral and organic nutrients at the beginning of the next growing season.

In lakes, eutrophication is shown by the development of blue-green algal (Cyanobacteria) blooms. They can be generated by human activity: for example, sediment runoff from construction sites may greatly diminish water clarity and therefore decrease the amount of light available for phytoplankton (Fischer, P. et al. 1990). Cyanobacteria are able to maintain themselves near the surface of the water by means of special gas-filled vacuoles that give the plants slight positive buoyancy. Once cyanobacteria or more generally algal blooms reach high concentrations, problems can occur: they have a negative impact on water quality, creating taste and odorous problems and interfering with certain water treatment processes. When certain bacteria populations reach very high proportions, they can also produce toxins that can render water unsafe for consumption.

Excessive aquatic macrophyte growth

Increased nutrient levels can stimulate other forms of primary production, in addition to algae and cyanobacteria. The littoral zones of many nutrient-enriched water bodies are often chocked with excessive growths of aquatic macrophytes, which can influence recreational and industrial activity and alter the structure of the food web (Fischer, P. et al. 1990). Excessive growth of phytoplankton and macroscopic plants in the water create aesthetic problem and reduce the value of the body water as a recreational resource. From a purely aesthetic point of view, crystal clear water characteristic is most attractive for swimming and boating. High phytoplankton concentrations cause the water to appear turbid and aesthetically unappealing. Macroscopic plants can completely cover the entire surface of eutrophic waters making the water almost totally unfit for swimming and boating.

Deepwater oxygen depletion

Oxygen is required for all life forms on this planet, with the exception of some bacteria. For this reason oxygen depletion is considered to be a serious waterbodies management problem often associate with eutrophication: this causes an increased organic matter production, so more material is sedimenting down into the profundal waters, consuming oxygen (Fischer, P. et al. 1990). Since it is impossible for some organisms to function efficiently unless the oxygen concentration in the water is near saturation, such organisms are often absent from eutrophic environments. This problem can prevent fish or other biota from inhabiting deepwater regions of contaminated waters.

2. Human

The effects of eutrophication are not only devastating to ecology but also to humans being. Eutrophicated water is unsuitable for drinking, recreation, agriculture, and industry. More seriously, contaminated water destroys aquatic life and reduces its reproductive ability. Eventually, it is a hazard to human health. Nobody can escape the effects of polluted water.

Drinking water treatment

Water requires special treatment for eliminating the algal cells when it is to be used for potable water production. We depend on surface and groundwater sources for our drinking water. Many areas of surface and groundwater water are now contaminated with heavy metals, persistent organic pollutants, and nutrients that have an adverse affect on health (Bartram et al., 1999). Water-borne diseases and water-caused health problems are mostly due to inadequate and incompetent management of water resources.

Sometimes the water gets polluted at source due to various reasons and mainly due to inflow of sewage into the source. A large number of chemicals that either exist naturally in the land or are added, due to human activities are dissolved in the water, thereby contaminating it leading to various diseases. Some are the following:

Pesticides

The organophosphates and the carbonates present in pesticides affect and damage the nervous system and can cause cancer (Bartram et al., 1999).

Nitrates

In addition, much of the concern about fertilizers and water quality relates to nitrates, which can cause health problems in human's body. When ingested, nitrates are converted into nitrite in the intestine, which then combines with haemoglobin to form methemoglobin. Methemoglobin has reduced oxygen carrying capacity, and is particularly problematic in children, who are most readily affected by this "nitrite poising." (Lubberding et al., 2006). Drinking water that gets contaminated with nitrates can prove fatal especially it is linked to some digestive tract cancers.

Salts

It makes the fresh water unusable for drinking and irrigation purposes. Exposure to salt water can cause diarrhea, skin irritation, respiratory problems, and other diseases, depending on the pollutant that is in the water body. Causes most damage to human health.

Recreational, shipping

As the algal blooms occur only in the top layer (epilimnion) of a lake, thereby rendering the water unattractive for recreation i.e. it diminishes the aesthetic quality of lakes and rivers (Lubberding et al., 2006). Macroscopic plants can completely cover the entire surface of eutrophic lakes making the water almost totally unfit for swimming and boating.

II.2.5. Solutions

Some of the possible solutions for eutrophication reduction or prevention are:

1. Reducing diffuse pollution from agriculture

The sources of water pollution in rivers or streams could be from the known point sources like dumped wastes (from industries, etc) or from nonpoint sources (diffuse sources) which are taken as the most important problem to be fixed for the reason that they are difficult to control. On the other hand, the point sources could be easily controlled, reduced or treated before their discharges in waterways.

One of the significant benefits of attaining a sustainable agricultural system would be a reduction in diffuse water pollution (Griffiths, D. 2006). From many activities done in a watershed, the agriculture is generally considered to have the greatest potential to increase the nonpoint source pollution by erosion (runoff) to the waterbodies, and subsequently to degrade water quality. This potential impact is dependent on slope, soil types, area affected, and intensity of these activities on the region (BMP Guide, 2002).

A reduction in diffuse pollution can only be achieved by appropriate land management techniques (Jackie, Vale. 2006). Farmers themselves can make the greatest improvements by adopting good land management practices. Good soil cultivation is central to many of these practices on farms to help convert to better systems. The pollution is the most difficult source of nutrients to manage. The literature suggests, though, that when these sources are controlled, eutrophication decreases.

Nutrients load source reduction

Excessive nutrient enrichment is the root cause of eutrophication, which as many negative repercussions on aquatic systems (P, Fischer et al. 1990). Although waterbodies naturally receive nutrient input from their catchments and the atmosphere, as already discussed many human activities have accelerated and are accelerating the eutrophication problem through, for example, sewage inflows, runoff from agricultural fields and industrial effluents. Some of the symptoms include excessive growths of algae (included cyanobacteria) and aquatic macrophytes.

The eutrophication problem can be solved by reducing the external load of nutrients or directly manipulating the water body ecosystem (P, Fischer et al. 1990). Nitrogen and phosphorus are the most likely of the macronutrients to be limiting photosynthesis and thus organic biomass. However, the prevention of excessive input of these nutrients is hardly achievable since most of it is from diffuse sources. This reduction in nutrients load could be related to reducing diffuse pollution from agriculture by applying appropriate land management.

There is no single solution to tackling the diffused pollution. The most effective approach is the application of Agricultural Best Management Practises (SEPA, 2005).

2. Remedial measures

Reaeration

The reaeration is one of the measures which could be applied in the case when the river is highly polluted by nitrates and phosphates (Twiki, 2006). When the high nutrient concentrations stimulate blooms of algae (e.g. phytoplankton) i.e. eutrophication, due to respiration of the algae in the dark, oxygen shortages can exist. To compensate for this effect and to ensure aerobic conditions for the river at any time, in-stream aeration can be applied. The reaeration could be a natural reaeration where cascades, dams and weirs etc. could help, or an artificial reaeration accomplished by mechanical aerators or underwater air diffusers.

Shading

Shading as a measure to improve river water quality is based on the fact that planting trees and bushes along the river lowers the water temperature of the stream and diminishes the amount of radiation which makes algae grow slower or not at all (Twiki. 2006). Water shaded by trees and shrubs is cooler than unshaded water and can therefore hold a higher concentration of dissolved oxygen. This aspect can be especially important in streams suffering from high organic pollution loads since higher dissolved oxygen concentrations increase a stream's capacity to assimilate organic wastes from sewers, treatment plants or diffuse sources. Furthermore, lower temperatures decrease the rates of bacterial breakdown of organic matter, reducing thus dissolved oxygen consumption. From an ecological point, water temperature is one of the parameters that determine the growth and development rates of most aquatic organisms.

II.3. Agriculture best management practices – BMP's for water quality

II.3.1. The big picture

Sustainable agriculture requires that soil, water and air quality to be maintained (Hilliard, C. et al., 2003). Water is continually cycling. The water that we use has been used before. Producers and consumers, rural and urban people and the public and private sectors, are all responsible for using water wisely and ensuring that the resource is maintained for others. BMPs are one way for the agricultural sector to help preserve water quality. Some farm practices have the potential to cause environmental harm, which may affect rural and urban areas alike. Many of the potential negative impacts of farming can be greatly reduced by use of Agricultural Best Management Practices (BMPs).

In some cases, adopting BMPs is simply a matter of common sense and carries little or no extra cost, such as proper disposal of hazardous materials. In other instances, significant costs may be incurred. For example, planting of buffers to protect water quality may be costly (Hilliard, C. et al., 2003). BMPs are primary directed to control erosion; it is known erosion can lead to sedimentation, which is the entry of soil into waterways. BMPs are proven methods to lessen the potential damage from land-disturbing activities (BMP Guide, 2002).

Pollution prevention here means source reduction; preventing or reducing pollutants where it originates, at the source. It includes practices that conserve natural resources by reducing or eliminating pollutants through increased efficiency in the use of land, water and other raw materials encountered in the environment (Hilliard, C. et al., 2003). These pollution-prevention farming methods are known as Agriculture Best Management Practices (BMPs).

II.3.2. Controlling erosion and runoff

By C. Hilliard and S. Reedyk, in a PFRA's publication presented on Agricultural Best Management Practices (Hilliard, C. et al. 2000. Agricultural Best Management Practices) it is mentioned, controlling erosion and runoff is an important best management strategy. Erosion degrades the soil resource and can affect nutrient and pesticide application rates, and transport through the soil profile and in direct runoff. Practices such as strip-cropping, shelterbelts and use of cover crops prevent erosion and reduce the movement of nutrients and pesticides from agricultural land. Residue management through conservation tillage and continuous cropping is also effective at controlling erosion. A balance between erosion control and protection of water quality may have to be established to maximize conservation.

Also, grassed waterways act as buffers to trap sediment and nutrients moving into the waterway from surrounding agricultural lands. The vegetation also stabilizes the banks and shores from the erosive action of the waterway itself. Grassed waterways act as buffers to trap sediment and nutrients. Farm practices that prevent erosion will help to protect surface water quality.

Sustaining agricultural production for high commodity yields and quality has been a major goal of the agricultural community. One component of agricultural sustainability has been proven to be the control of erosion and sediment transport on agricultural fields (BMP Guide, 2002).

II.3.3. General types of BMP's

By definition a "best management practice" is a practical, affordable approach to conserving a farm's soil and water resources without sacrificing productivity (OMAFRA Staff, 2001).

Some of the adopted "best management practices" for controlling or preventing nonpoint source of pollution from croplands are:

- Conservation Tillage;

- Pest Management;
- Crop Nutrient Management;
- Conservation Buffers.

Conservation Tillage - leaving crop residue (plant materials from past harvests) on the soil surface reduces runoff and soil erosion, conserves soil moisture, helps keep nutrients and pesticides on the field, and improves soil, water, and air quality;

Pest Management - varied methods for keeping insects, weeds, disease, and other pests below economically harmful levels while protecting soil, water, and air quality;

Crop Nutrient Management - Nutrient management is the practice of applying fertilizers and manures only in the amounts that can be taken up by a crop. Applications in excess of these needs have the potential to enter surface and ground waters.

Fully managing and accounting for all nutrient inputs helps ensure nutrients are available to meet crop needs while reducing nutrient movements off fields. It also helps prevent excessive buildup in soils and helps protect air quality;

Reducing inputs is an important element of pollution prevention. The less a potentially harmful substance is used in agriculture, the less likely it is to affect other parts of the environment. This applies most directly to fertilizers, manures and pesticides.

Conservation Buffers - from simple grassed waterways to riparian areas, buffers provide an additional barrier of protection by capturing potential pollutants that might otherwise move into surface waters.

In general, conservation buffers are small areas or strips of land in permanent vegetation, designed to intercept pollutants and manage other environmental concerns. Buffers include: riparian buffers, filter strips, grassed waterways, shelterbelts, windbreaks, living snow fences, contour grass strips, cross-wind trap strips, shallow water areas for wildlife, field borders, alley cropping, herbaceous wind barriers, and vegetative barriers (NRCS, 2006). Strategically placed buffer strips in the agricultural landscape can effectively reduce the movement of sediment, nutrients, and pesticides within farm fields and from farm fields. When coupled with appropriate upland treatments, including crop residue management, nutrient management, integrated pest management, winter cover crops, and similar management practices and technologies, buffer strips should allow farmers to achieve a measure of economic and environmental sustainability in their operations (NRCS, 2006). Buffer strips can also enhance wildlife habitat and protect biodiversity.

Benefits of Buffers

Conservation buffers slow water runoff, trap sediment, and enhance infiltration within the buffer. Buffers also trap fertilizers, pesticides, pathogens, and heavy metals, and they help trap snow and cut down on blowing soil in areas with strong winds. In addition, they protect livestock and wildlife from harsh weather and buildings from wind damage. If properly installed and maintained (NRCS, 2006), it is recognized that they have the capacity to:

- Remove up to 50 percent or more of nutrients and pesticides;

- Remove up to 60 percent or more of certain pathogens;
- Remove up to 75 percent or more of sediment.

Conservation buffers reduce noise and odour. They are a source of food, nesting cover, and shelter for many wildlife species. Buffers also provide connecting corridors that enable wildlife to move safely from one habitat area to another. Conservation buffers help stabilize a stream and reduce its water temperature. Buffers also offer a setback distance for agricultural chemical use from water sources. If used as part of a comprehensive conservation system, buffers will make good use of areas that often should not be cropped.

Riparian Vegetation

Stream or river banks are riparian areas, and the plants that grow there are called riparian vegetation (King county, 1999). Riparian vegetation is extremely important because of the many functions it serves like:

- Bank stabilization and water quality protection,
- Fish habitat, Wildlife habitat,
- Food chain support,
- Thermal cover,
- Flood control.

The roots of riparian trees and shrubs help hold stream banks in place, preventing erosion. Riparian vegetation also traps sediment and pollutants, helping keep the water clean.

Benefits of Riparian Vegetation

Riparian vegetation is essential for maintaining high water quality in streams, rivers, lakes, and along shorelines. Then, riparian vegetation could be relatively protected from agricultural best management practices. Studies show greater numbers of fish and more species live in areas with good riparian vegetation (NSW, 2001).

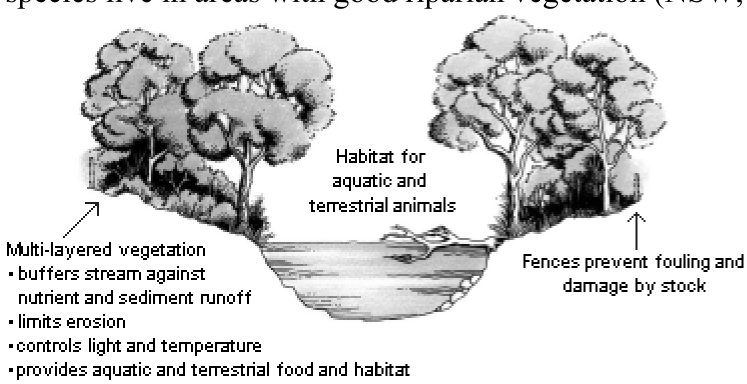


Figure 3: Healthy riparian vegetation has many benefits for fish. Illustration by Carolyn Brooks. Adapted from Riparian Land Management Technical Guidelines Vol1 Land and Water Resources

II.3.4. Limitations of BMP'S

Management practices are a powerful tool for protecting water. However, they cannot be expected to solve all water quality problems (Hilliard, C. et al., 2003). Many of the factors which reduce water quality on the Prairies are naturally occurring. Water treatment is necessary to satisfy the water quality requirements of many specific uses. BMPs are the first step in the treatment process.

II.4. Watershed system

II.4.1. Watershed definition

One definition says a watershed is "a geographical area determined by the watershed limits of the system of waters, including both surface and underground waters, flowing into a common terminus" (Price, R. K. et al., 2004). Recognized that a watershed is the area of land where all of the water that is under it or drains off it goes into the same place (USEPA, 2006). John Wesley Powell, scientist geographer, put it best when he said that a watershed is:
"that area of land, a bounded hydrologic system, within which all living things are inextricably linked by their common water course and where, as humans settled, simple logic demanded that they become part of a community." Watersheds come in all shapes and sizes. They cross county, state, and national boundaries. No matter where you are, you're in a watershed!

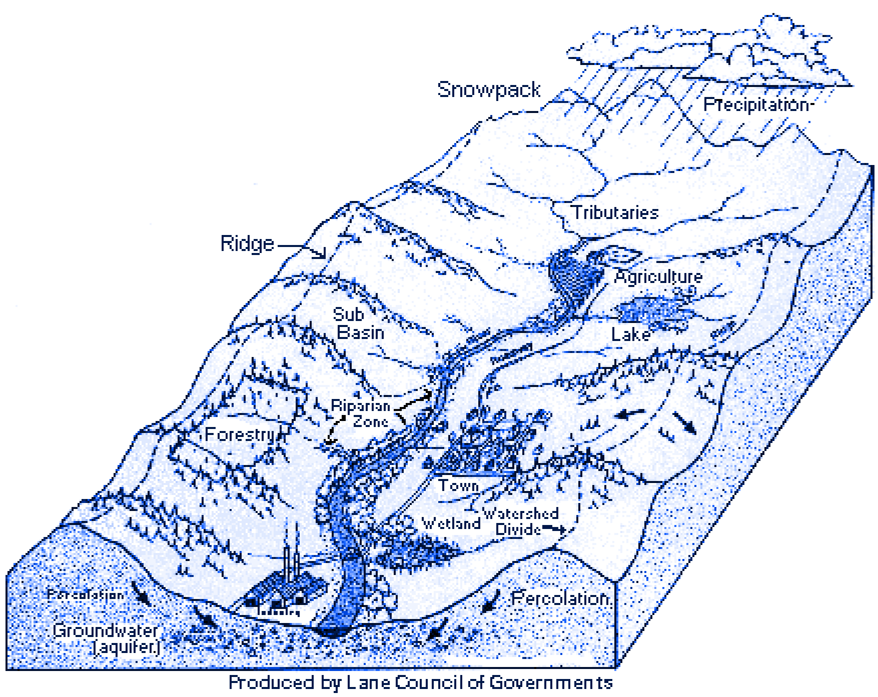


Figure 4: Figure from U.S Environmental Protection Agency – WATERSHEDS reports.

II.4.2. Watershed features

Everything that is done in a watershed affects the watershed's system. The water quality problems in watersheds were traced to the obvious causes of pollution; point source pollution and nonpoint-source pollution – diffuse pollution. However, water quality problems from nonpoint-source pollution are more difficult to isolate and control as explained earlier; these sources are often hard to identify and difficult to measure (UC ANR, 2006). It results from a wide variety of activities over a wide area.

The watershed is considered as a complex web of natural resources - soil, water, air, plants and animals. Yet, everyday activities can impact these resources, ultimately impacting our well-being and economic livelihood (UC ANR, 2006). To deal with water quality problems in a watershed the need of understanding the watershed system i.e. the main features of a watershed is always a basic requirement; every watershed has many features that make it unique and special. The important features of a watershed are:

Size - One important feature is the size of the watershed. Very large watersheds include many smaller river basins or watersheds. These smaller watersheds can be subdivided into even smaller areas. It is easier to study and analyze the water quality in these different river basins (watersheds); by considering the contribution of each to the water quality through the entire area as well as to observe improvements too.

Boundary - Another important feature is the geographic boundary of the watershed. The boundary is formed by a ridge or high area from which water drains either toward or away from a watershed.

Terrain - The topography (terrain) is another important feature. How flat or steep the land is, impacts how fast water drains; the faster the drainage, the more potential for flooding and increased soil erosion.

Soil type - Soil type is also important. For example, some type of soils allows the ground to soak up water faster. This reduces surface runoff, but can affect ground water, on the other hand, others are tighter and do not allow as much water infiltration. This can lead to more runoff and soil erosion.

Other features - Whether a watershed drains into a stream a river etc, the area nearest the water greatly affects water quality. The filter/buffer strips, wildlife habitat, wetlands and riparian areas are other important aspects of a watershed.
Both filter/buffer strips and wetlands utilize nutrients and tie up sediment to help improve water quality. Wetlands also act as natural sponges to absorb peak flows of water and reduce flooding. Many fish and wildlife species rely on wetlands for rearing their young, and for food and shelter (UC ANR, 2006). To fully understand a watershed, it also requires considering how it is used. The land uses, natural resources uses etc in addition contribute to the main characteristics of a watershed which make it distinctive from others.

Land uses and trends - All activities within the watershed have an impact on its natural resources. Cities, homes, roads and factories modify the watershed and affect its natural resources. Farming (pesticide, fertilizer's use), recreation, mining, construction and forestry can also significantly affect a watershed. These activities could lead to significant changes in land use which can affect water quality.

Natural resource uses - Water can be used by municipalities and local industries. Farms also rely on water for irrigation and livestock. Many people enjoy water for recreational uses like fishing, swimming and boating. So the water quality and quantity are important to the watershed's stakeholders. Air quality, wildlife, soil quality and the other natural resources can also be important aspects of watershed management (UC ANR, 2006).

II.4.3. Better Environmental Results

In one of the EPA report about the management of watersheds, it is mentioned that since watersheds are defined by natural hydrology, they represent the most logical basis for managing water resources. The resource becomes the focal point, and managers are able to gain a more complete understanding of overall conditions in an area and the stressors which affect those conditions. It says again, traditionally, water quality improvements have focused on specific sources of pollution, from point sources such as sewage discharges, or from diffuse points.

Watershed management can offer a stronger foundation for uncovering the many stressors that affect a watershed. The result is improved management to determine what actions are needed to protect or restore the resource because managing water resource programs on a watershed basis makes good sense environmentally, financially, and socially (EPA, 1996).

Watershed Management

Additionally to watershed management information (USEPA, 2002), the Definition of Watershed Management is given as an iterative process of integrated decision-making regarding uses and modifications of lands and waters within a watershed. This process provides a chance for stakeholders to balance diverse goals and uses for environmental resources, and to consider how their cumulative actions may affect long-term sustainability of these resources.

Human modifications of lands and waters directly alter delivery of water, sediments, and nutrients, and thus fundamentally alter aquatic systems. People have varying goals and values relative to uses of local land and water resources. Watershed management provides a framework for integrated decision-making, where we strive to: (1) assess the nature and status of the watershed ecosystem; (2) define short-term and long-term goals for the system; (3) determine objectives and actions needed to achieve selected goals; (4) assess both benefits and costs of each action; (5) implement desired actions; (6) evaluate the effects actions and progress toward goals; and (7) re-evaluate goals and objectives as part of an iterative process.

As a form of ecosystem management, watershed management encompasses the entire watershed system, from uplands and headwaters, to floodplain wetlands and river channels. It focuses on the processing of energy and materials (water, sediments, nutrients, and toxics) downslope through this system. Of principle concern is management of the basin's water budget, which is the routing of precipitation through the pathways of evaporation, infiltration, and overland flow. This routing of groundwater and overland flow defines the delivery patterns to particular streams, lakes, and wetlands; and largely shapes the nature of these aquatic systems.

Watershed management requires use of the social, ecological, and economic sciences (USEPA, 2002). Common goals for land and water resources must be developed among people of diverse social backgrounds and values. An understanding of the structure and function (historical and current) of the watershed system is required, so that the ecological effects of various alternative actions can be considered. The decision process also must weigh the economic benefits and costs of alternative actions, and blend current market dynamics with considerations of long-term sustainability of the ecosystem.

II.4.4. Watershed modelling

To support watershed studies, Modelling is one among many assessment tools used in watershed planning and management. As in general, models are representations of systems or processes (Butcher, J. et al., 2002); there are two points to remember when discussing models:

- Models are a type of tool, and are used in combination with many other assessment techniques.
- Models are a reflection of our understanding of watershed systems. As with any tool, the answers they give are dependent on how we apply them.

Application of computer programs that describe the water flow, the transport of substances in the water and the reactions between substances interactions between substances, microbiology and macro-biology in a watershed (Postma et al., 2006) are commonly used in the world of today, for the aim of:

- Obtaining insight in cause i.e. the effect relationships in the water system;
- Being able to assess likely answers on ‘what-if’ questions;
- Having a computerized representation of the water body, guided by measured and predicted external forcing and delivering the likely state of water quality and ecology all over the area, also at locations that were not monitored.

Modelling is needed to scope or to quantify a problem and the use of a model helps to convert projections concerning some changes into a prediction of watershed conditions and water body response. Indeed, it is not possible to monitor the future, so modeling is the default choice (Butcher, J. et al., 2002). For example the land use or land cover for agriculture fields could be used for giving predictions by trying many simulations.

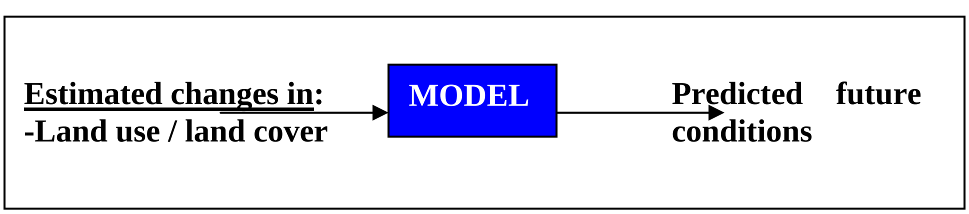


Figure 5: Prediction system described by modelling.

1. Mathematical models

Models are extensively used by water resources planners, water quality managers, engineers and scientists to evaluate the effectiveness of various control strategies in water systems. Mathematical models are representations of systems; they use a series of mathematical equations. The number, form, and interconnections of these equations in a model can range from very simple to highly sophisticated (Butcher, J. et al., 2002).

Mathematical models can help us understand the important processes and interactions that affect the water quality of water bodies in a particular watershed. Further, they can be used in making decisions regarding pollution control strategies by evaluating their effectiveness on water quality improvement and performing cost-benefit analysis (Kalin, L. et al., 2003).

The success in utilization of models in diverse field has resulted in wide acceptance of models as an objective evaluation tool and as a result they are often given higher credibility than what they actually deserve (Kalin, L. et al., 2003). Models are only approximate representations of the complex natural processes and due to time and budget constraints involve many assumptions made by the model creator who develops the relationships and define the processes, and the model programmer who carries the model into computer platforms. Moreover, modelers usually simplify processes that are seemingly not as important as other processes. Yet this simplification might not be valid for other applications due to uniqueness of the problem. Modelling also involves a profusion of uncertainty; intended for the model to accurately represent the physical, chemical and biological processes implying that modelling cannot be deemed as representing the absolute truth. Therefore, care must be taken when interpreting the results obtained through models. This clearly calls for the need for implementing risk management approaches using Best Management Practices (BMP), since model limitations, lack of perfect knowledge of physicochemical and biological processes, and inherent uncertainties preclude accurate (Kalin, L. et al., 2003).

2. Water flow through catchments

Note that the models can examine not only the flow of water but also the flow of any substance being carried (or transported) by the water (Price, R.K. et al., 2004). Movement of material through catchments is dependent on rates and pathways of water flow. In channels, the hydrodynamics of advection – dispersion and material transport support most simulation modelling. The hydrodynamics in open channels can be presented in one, two or three dimensions. All kind of ways of water in a watershed are described in models like obstacles which could modify the movement of water within the watershed area. For example when sediment's suspension, nutrient removal happen while water slow down or chemicals adsorbed to the soil particles etc.

3. Water quality modelling

When a water quality issue is first identified, the level of understanding of the severity and sources of the problem is often limited. Modeling here is frequently used to help build understanding of a water quality problem (Butcher, J. et al., 2002). It is used to predict how conditions are expected to change over time; it is also helpful for extrapolating from current conditions to potential future conditions.

4. Water quality processes

It involves the prediction of water pollution using mathematical simulation techniques i.e. use of mathematical language to describe the behavior of the water system. A typical water quality model consists of a collection of formulations representing physical mechanisms that determine fate and transport of pollutants in a water body; these are called processes. Most of them provide a system for documentation of mathematical descriptions of ecological processes. Models are available for individual components of the hydrological system such as surface runoff; addressing hydrologic transport.

The use of appropriate mathematical models can help to describe or predict ecological processes and response to natural driving variables (Water Framework Directive, 2002). Here, models can guide management and policies and help in the design of monitoring programs and interpretation of the results such programs generate. With these hydrological and ecological processes inside the models, they can:

- Help understand complex processes operating within the catchment;
- Fill gaps in monitoring data;
- Identify sources of pollution;
- Predict system response to change; and
- Evaluate management alternatives.

Water quality is modeled by one or more of the following formulations (wikipedia):

- Advective Transport formulation;
- Dispersive Transport formulation;
- Surface Heat Budget formulation;
- Dissolved Oxygen Saturation formulation;
- Reaeration formulation;
- Carbonaceous Deoxygenation formulation;
- Nitrogenous Biochemical Oxygen Demand formulation;
- Sediment oxygen demand formulation (SOD);
- Photosynthesis and Respiration formulation;
- pH and Alkalinity formulation;
- Nutrients formulation (fertilizers);
- Algae formulation;
- Zooplankton formulation;
- Coliform bacteria formulation (e.g. "Escherichia coli").

II.4.5. Application of Agriculture BMP's in watershed modelling

By using modelling for watershed management, some models are adapted to include agricultural Best Management BMPs and tested for the predictions. These agricultural BMPs are implemented in models in order to meet the desirable environmental quality criteria of a certain area. Most of them are selected according to the environment problems, their sources, causes and effects in order to direct them in the right direction of preventing or reducing the defined risk.

Agriculture Best Management Practices have been implemented in models and some studies had been done in order to evaluate their effectiveness in managing some stressors on waterbodies changes for instance suspended solids and sediments (USEPA, 2002b). According to that, BMPs had been found to reduce pollutant concentrations and loads in runoff by infiltration into the soil, physical infiltration by grass or other vegetation, adsoption on to the soil and plants, bacterial decomposition, plant uptake, and sediment deposition (Komor, 1999). Varieties of BMPs are available to trap sediments and control nutrients at the watershed scale varying from structural such as wet and dry ponds, vegetative filter strips, riparian buffers, conservation tillage, and improved fertilizer and animal-waste management.

II.4.6. Watershed models classification as water quality modelling an objective

As described in watershed management section, the watershed modelling encompasses the entire watershed system, from uplands and headwaters, to floodplain wetlands and river channels. It focuses on the processing of energy and materials (water, sediments, nutrients, and toxics) down slope through this system. This implies to watershed modelling to present like two important sections in water quality modelling for obtaining the whole representation of the ecosystem acting like a network.

1. **Loading models**

Models in this group simulate field or watershed scale hydrologic processes and determine the generation and transportation of Suspended solid and sediment, and nutrients from source in the upper lands to the receiving water.

2. **Receiving water models**

Again based on the functionality, receiving water models can be divided into two subclasses: **hydrodynamic** and **water quality models**.

Hydrodynamic models solve for the hydraulics of water quality models including transport, deposition, circulation and the stratification processes.

Water quality / Ecological models describe the main modelled processes of nutrient cycling, oxygen dynamics and primary production, as well as external forcing required for the ecological model (hydrodynamics, suspended sediments and river loads).

The ecological model instrument has two main tasks:

1. It calculates the transport of model substances (state variables) in the water column as a function of advective and dispersive transport (provided by hydrodynamic model.

2. It calculates the water quality and ecological processes affecting the concentrations of the state variables. These processes are defined as ‘reactions’ that causes one or more state variables of the model to appear, to disappear or to change into another state.

Transport of substances

In addition to transport, concentrations of substances are determined by various physical, chemical and biological reactions, which are referred to as ‘water quality and ecological processes’.

Water quality and ecological processes

A number of water quality and ecological processes are included; as stated these are physical, biological and/or chemical reactions that cause one or more state variables of the model to appear, to disappear or to change into another state variable. For the eutrophication problem, the processes are related to algae growth and mortality, mineralization of organic matter, nutrient uptake and release, and oxygen production and consumption.

II.5. Model choice

Models in each group can be stand alone or they may be coupled with other models. Often hydrodynamic and pollutant models are integrated under the same modeling system. This is called direct or internal linkage. If not under the same system, the output of the hydrodynamic model such as water velocity, temperature, salinity, etc., may be fed externally into the pollutant model as input, called indirect or external linkage. So, there exist available and potential model linkages between loading, hydrodynamic and water quality models for obtaining the whole watershed functionality success. To simulate more BMPs is recommended along with development of more linkages between loadings and hydrodynamic as well as water quality models.

SWAT model incorporated with all this features, is easily linked with other water simulators tools. It can be used for the evaluation of the mentioned tasks; from the hydrology to water quality analysis and the BMP’s applications and assessment in a watershed. This ability made it a promising management tool for the environmental managers taking charge of the watershed development and improvement.

CHAPTER III: SWAT AND PROCESSES

III.1. SWAT – Soil and Water Assessment Tool

III.1.1. Introduction

SWAT is a conceptual, continuous time model and is more suitable for large river basins. The SWAT model emerged from the models SWRBB, CREAMS, GLEAMS, EPIC and ROTO. It operates on daily time step. The watershed is divided into sub-watersheds and each sub-watershed is further partitioned into Hydrologic Response Units (HRU) having uniform topographic, soil and land use properties. Input information for each sub-watershed is grouped or organised into the following categories: weather or climate; unique areas, soil, and management within the sub-watershed (hydrologic response units or HRUs); ponds/reservoirs; groundwater; and the main channel, or reach, draining the sub-watershed. In SWAT water balance is the driving force behind everything that happens in the watershed. Simulated hydrologic processes are surface runoff with SCS curve number or Green-Ampt infiltration, lateral subsurface flow, ground water flow, evapotranspiration, snowmelt, transmission losses from streams and water storage and losses from ponds flow is routed through the channel using a variable storage coefficient method. Sediment yield is computed from MUSLE for each sub-basin. The transport of sediment in the channel is controlled by the simultaneous operation of two processes, deposition and degradation. Deposition in the channel is based on sediment particle fall velocity calculated with Stoke's Law. Streams power is used to predict degradation in the routing reaches. An *ArcView* interface is available which enables extraction of input parameters easily, and visualization of results (Kalin, L. et al., 2003).

As mentioned before, conceptually, the semi-distributed deterministic model is build from a number of previously-developed agro-environmental modeling tools, namely: SWRRB model (Simulator for Water Resources in Rural Basins) (Williams et al., 1985; Arnold et al., 1990). Also, Specific models that contributed significantly to the development of SWAT were CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), GLEAMS (Groundwater Loading Effects on Agricultural Management Systems) (Leonard et al., 1987), and EPIC (Erosion–Productivity Impact Calculator) (Williams et al., 1984). (SWAT2000manual)

III.1.2. Loading Models in SWAT

Loading models in SWAT are based on EPIC (Erosion-Productivity Impact Calculator) and GLEAMS (Ground Loading Effects of Agricultural Management systems) (SWAT2000manual).

EPIC was developed to assess the effect of soil erosion on soil productivity. EPIC is a continuous simulation model that can be used to determine the effect of management strategies on agricultural production and soil and water resources. The drainage area considered by EPIC is generally a field-sized area up to 100 ha (weather, soils, and management systems are assumed to be homogeneous). The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, plant growth, soil temperature, tillage, economics, and plant environment control.

GLEAMS is a continuous simulation, field scale model, which was developed as an extension of the chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) model. GLEAMS assumes that a field has homogeneous land use, soils, and precipitation. It consists of major components: hydrology, erosion/sediment yield, pesticide transport, and nutrients. GLEAMS was developed to evaluate the impact of management practices on potential pesticide and nutrient leaching within, through, and below the root zone. It also estimates surface runoff and sediment losses from the field.
GLEAMS was not developed as an absolute predictor of pollutant loading. It is a tool for comparative analysis of complex pesticide chemistry, soil properties, and climate. GLEAMS can provide estimates of the impact management systems, such as planting dates, cropping systems, irrigation scheduling, and tillage operations, have on the potential for chemical movement. Application rates, methods, and timing can be altered to account for these systems and to reduce the possibility of root zone leaching. The model also accounts for varying soils and weather in determining leaching potential. GLEAMS can also be useful in simulations for pesticide screening of soil/management. The model tracks movement of pesticides with percolated water, runoff, and sediment. Upward movement of pesticides and plant uptake are simulated with evaporation and transpiration. Degradation into metabolites is also simulated for compounds that have potentially toxic products. Flow is determined by SCS curve number method. Erosion in overland flow areas is estimated using modified USLE. Erosion in chemicals and deposition in temporary impoundments such as tile outlet terraces are used to determine sediment yield at the edge of the field.

III.1.3. Receiving Water Models in SWAT

SWAT incorporates to the river and stream water quality model QUAL2E.

QUAL2E is applicable to well mixed dendritic streams. It is basically one-dimensional and operates as a steady state model. It can simulate up to 15 water constituents including dissolved oxygen, biochemical oxygen demand, temperature, algae, organic nitrogen, ammonia, nitrite, nitrate, organic phosphorus, and dissolved phosphorus. Advection, dispersion, dilution, constituent reactions and interactions, and sources and sinks are all considered within the model. Analyzing the impact of waste loads on the stream quality, effects of diurnal variations in meteorological data on water quality (mainly dissolved oxygen and temperature) and diurnal oxygen variations due to algal growth are some potential areas of use of QUAL2E.

In spite of its one-dimensional, steady state flow component, QUAL2E is a widely used water quality model for streams and rivers (Kalin, L. et al., 2003). Although it is not suited for sediment transport, it simulates for particulate organic matter; therefore, can be linked to watershed loading models to evaluate the impact of BMPs on transport and fate of nutrients in surface waterbodies. This model is integrated into the SWAT system where it is coupled with a watershed model which provides flow data to QUAL2E.

III.2. SWAT Processes

III.2.1. SWAT a physically based model

As SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. To satisfy this objective, the model is physically based. Rather incorporating regression equations to describe the relationship between input and output variables, SWAT requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modeled by SWAT using this input data (SWAT User Manual 2003).

Physically based distributed model, SWAT can in principle be applied to almost any kind of hydrological problem. Its hydrological system is based on our understanding of the physics of the hydrological processes which control catchment's response and use physically based equations to describe these processes.

III.2.2. SWAT main hydrological physical processes

This part is mostly focusing to the main hydrological processes considered in the Walbridge's modelling case.

SWAT hydrological system

In general, when the input information for each sub-watershed is grouped into categories, the hydrologic response units (HRU) comes with the specifications of each lumped land areas within the sub-watershed with unique land cover, soil, and management combinations. The water balance is the driving force behind everything that happens in the watershed. To accurately predict the movement of sediments, nutrients or pesticides the hydrologic cycle as simulated by the model must conform to what is happening in the watershed.

Well known, Simulation of a watershed hydrology can be separated into two major divisions.The first division is the land phase of the hydrological cycle which controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each subwatershed. The second division is the water or routing phase of the hydrologic cycle which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet.

Land phase of the hydrologic cycle

The hydrologic cycle as simulated by SWAT is based on the water balance equation (SWAT2005 Theoretical Documentation):

$$SW_t = SW_o + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \qquad \textit{Equ. (1)}$$

Where: SW_t is the final soil water content (mmH_2O), SW_o is the initial soil water content on day i (mmH_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mmH_2O), Q_{surf} is the amount of surface runoff on day i (mmH_2O), and Q_{gw} is the amount of return flow on day i (mmH_2O).

The subdivision of the watershed enables the model to reflect differences in evapotranspiration for various crops and soils. Runoff is predicted separately for each HRU and routed to obtain the total runoff for the watershed. This increases accuracy and gives a much better physical description of the water balance. Different inputs are required in this phase of hydrologic cycle. Regarding the Walbridge case, most essential were the following:

1. ***Climate:***

It provides the moisture and energy inputs that control the water balance. The climatic variables required by SWAT consist of daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity (inputs are from observed data or generated during the simulation.).
This includes the weather generator, precipitations, temperatures data inputs which participate in generating outputs given by the equations relations.

Snow

SWAT classifies precipitation as rain or freezing rain/snow using the average daily temperature.

Snow Melt

Snow melt is controlled by the air and snow pack temperature, the melting rate, and the areal coverage of snow. If snow is present, it is melted on days when the maximum temperature exceeds $0^{o}C$. Melted snow is treated the same as rainfall for estimating runoff and percolation.

Elevation Bands

The model allows the watershed to be split into a maximum of ten elevation bands. Snow cover and snow melt are simulated separately for each elevation band. By dividing the watershed into elevation bands, the model is able to assess the differences in snow cover and snow melt caused by orographic variation in precipitation and temperature.

Soil Temperature

Soil temperature impacts water movement and the decay rate of residue in the soil. Daily average soil temperature is calculated at the soil surface and the center of each soil layer. The temperature of the soil surface is a function of snow cover, plant cover and residue cover, the bare soil surface temperature, and the previous day's soil surface temperature. The temperature of a soil layer is a function of the surface temperature, mean annual air temperature and the depth in the soil at which variation in temperature due to changes in climatic conditions no longer occurs. This depth, referred to as the damping depth, is dependent upon the bulk density and the soil water content (SWAT2003 Theoretical Documentation).

2. ***Hydrology:***

As precipitation descends, it may be intercepted and held in the vegetation canopy or fall to the soil surface. Water on the soil surface will infiltrate into the soil profile or flow overland as runoff. Runoff moves relatively quickly towards a stream channel and contributes to short-term stream response. Infiltrated water may be held in the soil and later evapotranspired or it may slowly make its way to the surface-water system via underground paths. The potential pathways of water movement simulated by SWAT in the HRU are illustrated in the following figure:

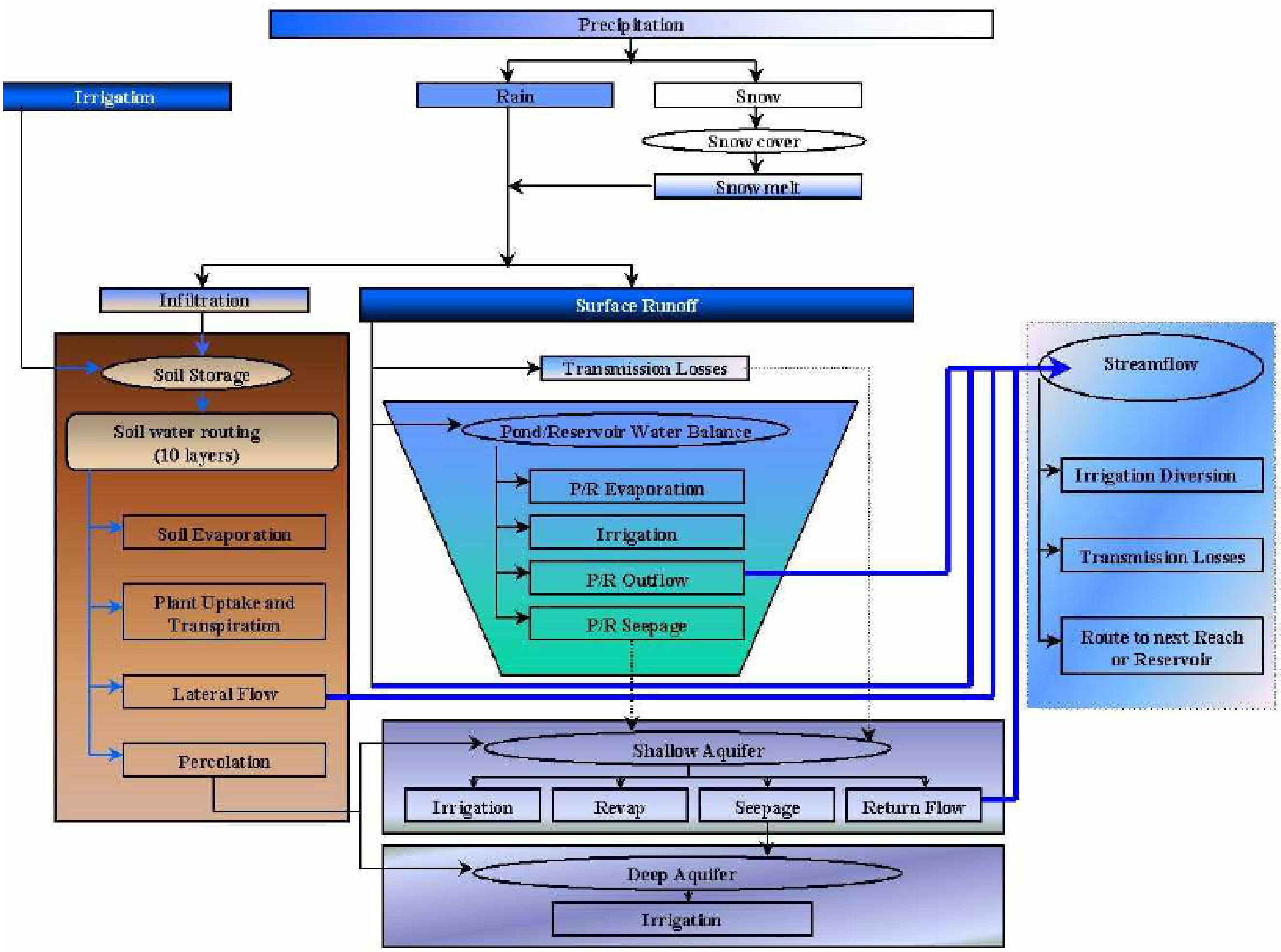


Figure 6: Schematic of pathways available for water movement in SWAT.

Canopy Storage

Canopy storage is the water intercepted by vegetative surfaces (the canopy) where it is held and made available for evaporation. When using the curve number method to compute surface runoff, canopy storage is taken into account in the surface runoff calculations. Normally, SWAT allows to input the maximum amount of water that can be stored in the canopy at the maximum leaf area index for the land cover. This value and the leaf area index are used by the model to compute the maximum storage at any time in the growth cycle of the land cover/crop. When evaporation is computed, water is first removed from canopy storage.

Infiltration

Infiltration refers to the entry of water into a soil profile from the soil surface. As infiltration continues, the soil becomes increasingly wet, causing the rate of infiltration to decrease with time until it reaches a steady value. The initial rate of infiltration depends on the moisture content of the soil prior to the introduction of water at the soil surface. The final rate of infiltration is equivalent to the saturated hydraulic conductivity of the soil. Because the curve number method used to calculate surface runoff operates on a daily time-step, it is unable to directly model infiltration. The amount of water entering the soil profile is calculated as the difference between the amount of rainfall and the amount surface runoff.

Redistribution

Redistribution refers to the continued movement of water through a soil profile after input of water (via precipitation or irrigation) has ceased at the soil surface. Redistribution is caused by differences in water content in the profile. Once the water content throughout the entire profile is uniform, redistribution component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Downward flow, or percolation, occurs when the field capacity of a soil layer is exceeded and the layer below is not saturated. The flow rate is governed by the saturated conductivity of the soil layer. Redistribution is affected by soil temperature. If the temperature in a particular layer is $0^{o}C$ or below no redistribution is allowed from that layer (SWAT2003 Theoretical Documentation).

Different water distribution ways considered in SWAT model:

It refers to the continued movement of water through a soil profile after input of water (via precipitation or irrigation). This depends on water content throughout the entire profile.

Evapotranspiration- It includes evaporation from rivers and lakes, bare soil, and vegetative surfaces; evaporation from within the leaves of plants (transpiration); and sublimation from ice and snow surfaces. The model computes evaporation from soils and plants separately as described by Ritchie (1972).

Potential soil water evaporation is estimated as a function of potential evapotranspiration and leaf area index (area of plant leaves relative to the area of the HRU). Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant transpiration is simulated as a linear function of potential evapotranspiration and leaf area index. The model offers three options for estimating potential evapotranspiration: Hargreaves (Hargreaves et al., 1985) is the one which was used in this study.

Surface runoff- Surface runoff, or overland flow, is flow that occurs along a sloping surface. Using daily or sub daily rainfall amounts, SWAT simulates surface runoff volumes and peak runoff rates for each HRU.

Surface Runoff Volume is computed using a modification of the SCS curve number method (USDA Soil Conservation Service, 1972). In the curve number method, the curve number varies non-linearly with the moisture content of soil. The curve number drops as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation. Water that does not infiltrate becomes surface runoff. SWAT includes a provision for estimating runoff from frozen soils but still allows significant infiltration when the frozen soils are dry.

Runoff volume:

SCS Curve number procedure

The SCS runoff equation is an empirical model involving rainfall-runoff relationships from a small rural watersheds accross the U.S. The model was developed to provide a consistent basis for estimating the amounts of runoff under varying land use and soil types (Rallison and Miller).

The SCS curve number equation is (SCS, 1972):

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{R_{day} - I_a + S} \qquad \textit{Equ. (2)}$$

Where Q_{surf} is the accumulated runoff or rainfall excess (mmH_2O), R_{day} is the rainfall depth for the day (mmH_2O), I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mmH_2O), and S is the retention parameter (mmH_2O). The retention parameter varies spatially due to changes in soils, land use, management and slope and temporally due to changes in soil water content.

SCS Curve number

The SCS curve number is a function of the soil's permeability, land use and antecedent soil water conditions.

Tributary channels- it specifies the main channel and tributary channels.

Groundwater

Ground water is water in the saturated zone of earth materials under pressure greater than atmospheric, i.e. positive pressure. Water enters ground water storage primarily by infiltration / percolation, although recharge by seepage from surface water bodies may occur. Water leaves groundwater storage primarily by discharge into rivers or lakes, but it is also possible for water to move upward from the water table into the capillary fringe.

Shallow aquifer

Recharge

Water that moves past the lowest depth of the soil profile by percolation or bypass flow enters and flows through the vadose zone before becoming shallow aquifer recharge. The lag between the time that water exits the soil profile and enters the shallow aquifer will depend on the depth to the water table and the hydraulic properties of the geologic formations in the vadose and groundwater zones.

Groundwater / Base flow / Return flow

Return flow, or base flow, is the volume of streamflow originating from groundwater. SWAT partitions groundwater into two aquifer systems: a shallow, unconfined aquifer which contributes return flow to streams within the watershed and a deep, confined aquifer which contributes return flow to streams outside the watershed (Arnold et al., 1993). Water percolating past the bottom of the root zone is partitioned into two fractions – each fraction becomes recharge for one of the aquifers. In addition to return flow, water stored in the shallow aquifer may replenish moisture in the soil profile in very dry conditions or be directly removed by plant. Water in the shallow or deep aquifer may be removed by pumping.

The shallow aquifer contributes base flow to the main channel or tributary within the watershed. Base flow is allowed to enter the tributary only if the amount of water stored in the shallow aquifer exceeds a threshold value specified.

Revap

Water may move from the shallow aquifer into the overlying unsaturated zone. In periods when the material overlying the aquifer is dry, water in the capillary fringe that separates the saturated and unsaturated zones will evaporate and diffuse upward. As water is removed from the capillary fringe by evaporation, it is replaced by the water from the underlying aquifer. Water may also be removed from the aquifer by deep-rooted plants which are able to uptake water directly from the aquifer.

Percolation to Deep Aquifer

A fraction of the total daily recharge can be routed to the deep aquifer. Percolation to the deep aquifer is allowed to occur only if the amount of water stored in the shallow aquifer exceeds a threshold value specified.

3. *soils:*

Soil Water

Water that enters the soil may move along one of several different pathways. The water may be removed from the soil by plant uptake or evaporation. It can percolate past the bottom of the soil profile and ultimately become aquifer recharge. A final option is that water may move laterally in the profile and contribute to stream flow. Of these different pathways, plant uptake of water removes the majority of water that enters the soil profile.

Soil structure

Percolation

Percolation is calculated for each soil layer in the profile. Water is allowed to percolate if the water content exceeds the field capacity water content for that layer. When the soil layer is frozen, no water flow out of the layer is calculated. The volume of water available for percolation in the soil layer is calculated:

$$SW_{ly,excess} = SW_{ly} - FC_{ly} \quad \text{If } SW_{ly} > FC_{ly} \qquad \textit{Eq. (3)}$$

$$SW_{ly,excess} = 0 \quad \text{If } SW_{ly} \le FC_{ly} \qquad \textit{Eq. (4)}$$

Where $SW_{ly,excess}$ is the drainable volume of water in the soil layer on a given day (mmH_2O), SW_{ly} is the water content of the soil layer on a given day (mmH_2O) and FC_{ly} is the water content of the soil layer at field capacity (mmH_2O).
The amount of water that moves from one layer to the underlying layer is calculated using storage routing methodology i.e. an equation used to calculate the amount of water that percolates to the next layer.

Lateral flow

Lateral subsurface flow- is stream flow contribution which originates below the surface but above the zone where rocks are saturated with water. Lateral subsurface flow in the soil profile (0-2m) is calculated simultaneously with redistribution (*refer to hydrology section).* A kinematic storage model is used to predict lateral flow in each soil layer. The model accounts for variation in conductivity, slope and soil water content.

Lateral flow will be significant in areas with soils having high hydraulic conductivities in surface layers and an impermeable or semi permeable layer at a shallow depth. A soil layer is considered to be saturated whenever the water content of the layer exceeds the layer's field capacity water content. The drainable volume of water stored in the saturated layer is calculated in the same way like in percolation *Eq. (3)* or *Eq. (4).*

4. ***Land cover/plant growth:***

SWAT utilizes a single plant growth model to simulate all types of land covers. The model is able to differentiate between annual and perennial plants. Annual plants grow from the planting date to the harvest date or until the accumulated heat units equal the potential heat units for the plant. The plant growth model is used to assess removal of water and nutrients from the root zone, transpiration, and biomass/yield production.

Potential Growth

The potential increase in plant biomass on a given day is defined as the increase in biomass under ideal growing conditions. The potential increase in biomass for a day is a function of intercepted energy and the plant's efficiency in converting energy to biomass. Energy interception is estimated as a function of solar radiation and the plant's leaf area index.

Potential and actual transpiration

Nutrient uptake

Plant use of nitrogen and phosphorus are estimated with a supply and demand approach where the daily plant nitrogen and phosphorus demands are calculated as the difference between the actual concentration of the element in the plant and the optimal concentration. The optimal concentration of the elements varies with growth stage as described by Jones (1983).

Growth Constraints

Potential plant growth and yield are usually not achieved due to constraints imposed by the environment. The model estimates stresses caused by water, nutrients and temperature.

5. ***Erosion:***

Erosion and sediment yield are estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). While the USLE uses rainfall as an indicator of erosive energy, MUSLE uses the amount of runoff to simulate erosion and sediment yield. The hydrology model supplies estimates of runoff volume and peak runoff rate which, with the watershed area, are used to calculate the runoff erosive energy variable.

6. ***Nutrients:***

SWAT tracks the movement and transformation of several forms of nitrogen and phosphorus in the watershed. In the soil, transformations of nitrogen or phosphorus are governed by their cycle.
Nutrients may be introduced to the main channel and transported downstream through surface runoff and lateral subsurface flow.

Nitrogen:

Plant use of nitrogen is estimated using the supply and demand approach described in the plant growth. In addition the plant use, nitrate and organic N may be removed from the soil via mass flow of water. Amounts of NO_3-N contained in runoff, lateral flow and percolation are estimated as products of the volume of water and the average concentration of nitrate in the layer. Organic N transport with sediment is calculated with a loading function developed by McElroy et al.(1976) and modified by Williams and Hann(1978) for application to individual runoff events. The loading function estimates the daily organic N runoff loss based on the concentration of organic N in the top soil layer, the sediment yield, and the enrichment ratio. The enrichment ratio is the concentration of organic N in the sediment divided by that in the soil.

Phosphorus:

Plant use of phosphorus is estimated using the supply and demand approach described in plant growth. In addition to plant use, soluble phosphorus and organic P may be removed from the soil via mass flow of water (P is not a mobile nutrient; it has to be in solution). Sediment transport of P as described in organic N transport.

7. ***Pesticides:***

SWAT simulates pesticide movement into the stream network via surface runoff (in solution and attached to sediment transported by the runoff), and into the soil profile and aquifer by percolation (in solution).

8. ***Management:***

SWAT allows defining management practices taking place in every HRU. The beginning and the ending of the growing season may be defined; specify timing and amounts of fertilizer, pesticide as well as timing of tillage operations. At the end of the growing season, the biomass may be removed from the HRU as yield or placed on the surface as residue.

Rotations

Rotation is defined as the growing of different crops in succession in one field, usually in a regular sequence. A rotation in SWAT refers to a change in management practices from one year to the next.

III.2.3. SWAT management practices application

Quantifying the impact of land management and land use on water supply and quantity is a primary focus of environmental modelling. SWAT allows very detailed management information to be incorporated into a simulation.

In general, management operations that control the plant growth cycle, the timing of fertilizer and pesticide and the removal of plant biomass are basic management practices used in SWAT.

Planting / Beginning of Growing Season

The plant operation initiates plant growth. This operation can be used to designate the time of planting for agricultural crops or the initiation of plant growth in the spring for a land cover that requires several years to reach maturity (forests, orchards, etc).

The plant operation will be performed by SWAT only when no land cover is growing in an HRU. Before planting a new land cover, the previous land cover must be removed with a kill operation or a harvest and kill operation. Information required in the plant operation includes the timing of the operation (month and day). There is an option of varying the curve number in the HRU throughout the year. New curve number values may be entered in a plant operation, tillage operation and harvest and kill operation. The curve number entered for these operations are for moisture condition II. SWAT adjusts the entered value daily to reflect change in water content. For simulations where a certain amount of crop yield and biomass is required, the user can force the model to meet this amount by setting a harvest index target and a biomass target. These targets are effective only if a harvest and kill operation is used to harvest the crop.

Harvest Operation

The harvest operation will remove plant biomass without killing the plant. This operation is most commonly used to cut hay or grass. The only information required by the harvest operation is the date. However, a harvest index override and harvest efficiency can be set.

Grazing operation

The grazing operation simulates plant biomass removal and manure deposition over a specified period of time. This operation is used to simulate pasture or range grazed by animals.

Harvest & Kill Operation

The harvest and kill operation stops plant growth in the HRU. The fraction of biomass specified in the land cover's harvest index (in the plant growth database) is removed from the HRU as yield. The remaining fraction of plant biomass is converted to residue on the soil surface. The only information required by the harvest and kill operation is the timing of the operation (month and day or fraction of plant potential heat units).

Kill /End of Growing Season

The kill operation stops plant growth in the HRU. All plant biomass is converted to residue. The information required is the timing of the operation (month and day or fraction of plant potential heat units).

Tillage

The tillage operation redistributes residue, nutrients, pesticides and bacteria in the profile. Information required in the tillage operation includes the timing of the operation (month and day), and the type of tillage operation. There is an option of varying the curve number in the HRU throughout the year. New curve number values may be entered in a plant operation, tillage operation and harvest and kill operation. The curve number entered for these operations are for moisture condition II. SWAT adjusts the entered value daily to reflect change in water content.

Fertilizer application

The fertilizer operation applies fertilizer or manure to the soil. Information required in the fertilizer operation includes the timing of the operation (month and day or fraction of plant potential heat units), the type of fertilizer / manure application.

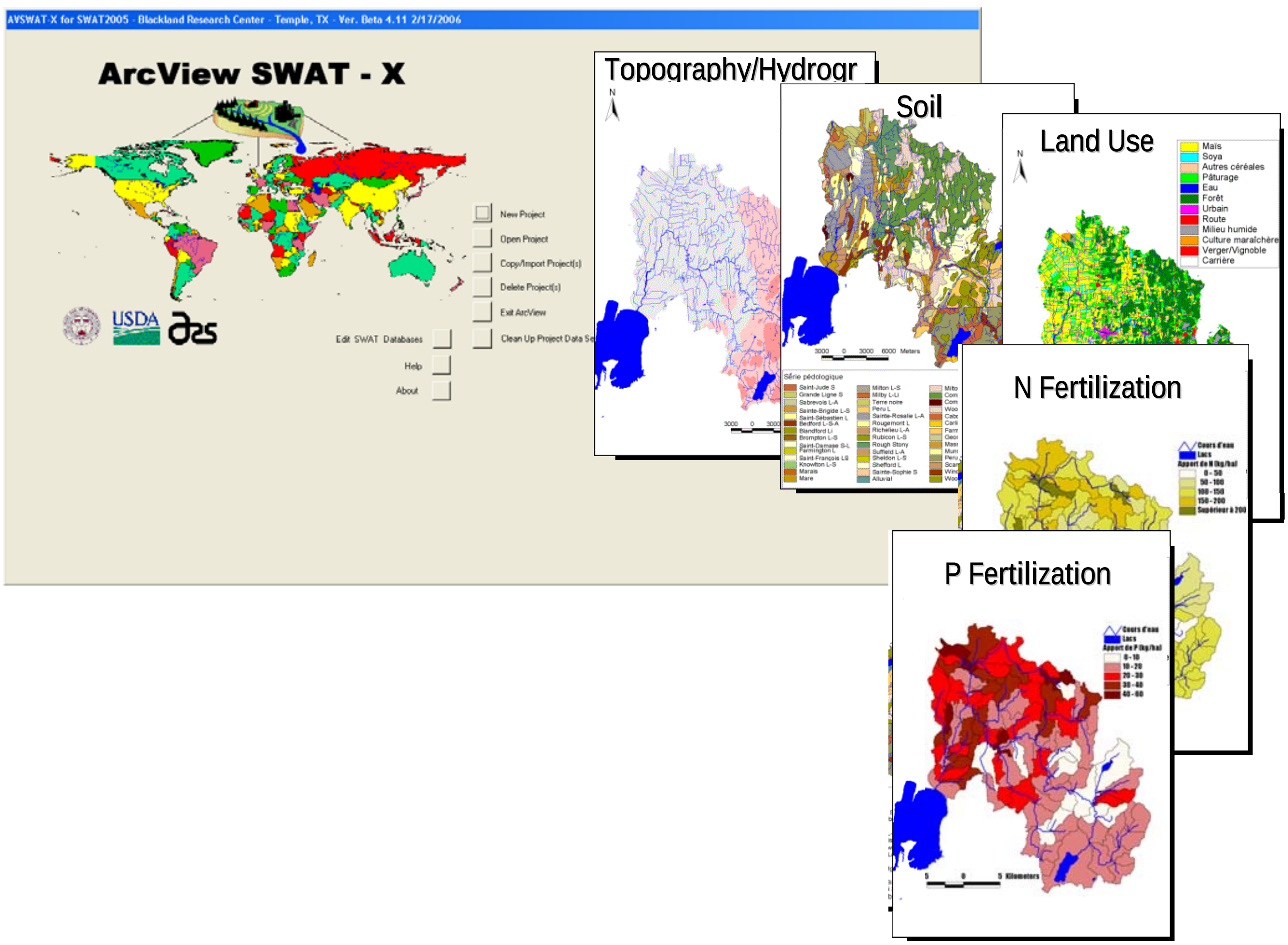
Tile drainage

To simulate tile drainage in an HRU, a depth from the soil surface to the drains must be specified, the amount of time required draining the soil to field capacity, and the amount of lag between the time water enters the tile till it exits the tile and enters the main channel. Tile drainage occurs when the soil water content exceeds field capacity. In the soil layer where the tile drains are installed, the amount of water entering the drain on a given day is calculated:

$$tile_{wtr} = (SW_{ly} - FC_{ly}) \cdot \left(1 - \exp\left[\frac{-24}{t_{drain}}\right]\right) \qquad \text{If } SW_{ly} > FC_{ly} \qquad \textit{Eq. (5)}$$

Where $tile_{wtr}$ is the amount of water removed from the layer on a given day by tile drainage (mm H_2O), SW_{ly} is the water content of the layer on a given day (mm H_2O), and t_{drain} is the time required to drain the soil to field capacity (hrs).

Pike River Watershed



Picture of the SWAT-2003 ArcView Interface with SWAT data required on the Pike river watershed.

CHAPTER IV: THE PIKE MODEL APPLICATION

IV.1. Description of the Pike Watershed

IV.1. 1. Problem description

Reducing agricultural non-point source water-borne particulate and dissolved phosphorus (P) reaching the trans-border Lake Champlain in the province of Quebec, Canada, and states of New York and Vermont in the United States, has been cited as a critical priority by the multi-stakeholder Management Conference on Lake Champlain (Vermont, New York and Quebec, 1993). A severe impairment of water quality by cyanobacterial blooms in the lake's northerly-situated Missisquoi bay, led to the governments of Quebec and Vermont reaching a specific agreement on phosphorus loads in the bay (Quebec Government and Vermont Government, 2002). Phosphorus loads entering the bay were apportioned 60% to Vermont and 40% to Quebec. Given that 80% of the non-point P load has been linked to agricultural sources (Hegman *et al*., 1999), management plans have focused on agricultural best management practices (BMPs) of soil and water resources. Vermont and Quebec have cooperatively monitored P concentrations in the bay and its two largest tributary watersheds (Missisquoi and Pike Rivers). Annual mean total-P concentrations in the bay have consistently exceeded Vermont and Quebec's water quality criterion of 25 µg P L^{-1}, neither rising nor declining significantly between 1990 and 2000. Phosphorus loads contributed to the bay through its two largest tributary watersheds have consistently exceeded the management targets derived from watershed load allocations (Medalie and Smeltzer, 2004).

A research program was initiated in 1997 within the Pike River basin, an important tributary watershed situated within Canada, seeking to describe non-point source P transfer to aquatic ecosystems. some of the research fields were: testing of effects and interactions of benchmark soils properties, manure inputs and crop cover on P loads and speciation (Michaud and Laverdière, 2004), monitoring of P losses in surface runoff and subsurface drainage waters (Enright and Madramootoo, 2004), characterization of spatio-temporal variability in P fluxes across the watershed (Michaud *et al*., 2004a; 2005), and assessment of management effects on water quality through a paired-basin design (Michaud *et al*., 2004a), and indexation of P mobility (Deslandes *et al*., 2004). Having extensively characterized the Pike River watershed, the modelling was the best way of answering questions on the potential efficacy of BMPs in reducing P loads.

Given its well documented ability to support long-term simulations of the effects of different land use management scenarios on water transfers and transport of sediments and associated nutrients over large, heterogeneous watersheds, the SWAT model (Soil and Water Assessment Tool; Arnold *et al*., 1998) was chosen to devise cropping systems and land development scenarios that could meet target P-loads set by the Quebec-Vermont agreement. The well known SWAT has been widely used to predict non-point source sediment, nutrient and pesticide loads in various researches in North America and Europe (Santhi *et al*., 2001; Neitsch *et al*., 2002b; Arnold *et al*., 2005; Van Griensven *et al*., 2005). In order to extrapolate potential effects of alterations in management practices, a hydrologic model must be calibrated and validated.

IV.1. 2. Pike River Watershed

The Pike River has been identified as one of the main contributors of P to Missisquoi bay (Hegman *et al*., 1999). Its drainage basin covers 630 km^2, of which 99 km^2 (15.7%) are located in Vermont. The watershed presents clear spatial gradients in land-use and geophysical attributes. Spanning the Appalachian piedmont the watershed's upstream region (390 km^2) is dominated by sandy and shaly loams, dominantly humic gleysols and podzols. Elevations range from 50 to 710 m above mean sea level (AMSL), with a 5° mean slopes. Given the types of soils and the land's rugged features, this region is ill-suited for intensive agriculture. Overall, only 35% of the region's area is devoted to agriculture, 22% to perennial forage crops and 13% to annual crops, reflecting the predominance of dairy and swine production (Deslandes, J. et al., 2006).

Stretching from the town of Bedford to the river's mouth, the watershed's downstream region (240 km^2) draws upon the plains of the St. Lawrence lowlands and Appalachians. Clays of marine and lacustrine origin (gleysolic) occupy the low-lying areas, whereas calcareous and shaly tills (brunisolic and podzolic) occupy the higher elevations and rolling hills. Elevation ranges from 20 to 130 m AMSL, with flatter slopes [0.6° (1%) on average]. Three quarters of the downstream region is cultivated, and of cultivated lands roughly 20, 30 and 50% respectively, are devoted to hay crops, perennial forages, and field crops [corn — *Zea mays* L. and soybean — *Glycine max* (L.) Merr.]. Animal production follows the same pattern as in the upstream region of the watershed, albeit more intensively. The downstream region contains the industrial and population (approx. 9000) centres of the region.

IV.1. 3. Walbridge sub-watersheds

Within the larger Pike River watershed two smaller (<8 km^2) experimental sub-watersheds, "*Intervention*" and "*Temoin*" located inside the agricultural (>60% by area) watershed of the Walbridge Creek, were monitored for suspended solids and P loads in addition to stream flow. Most of the farmers are exploiting the watershed's lands since long time.

Walbridge catchment's area

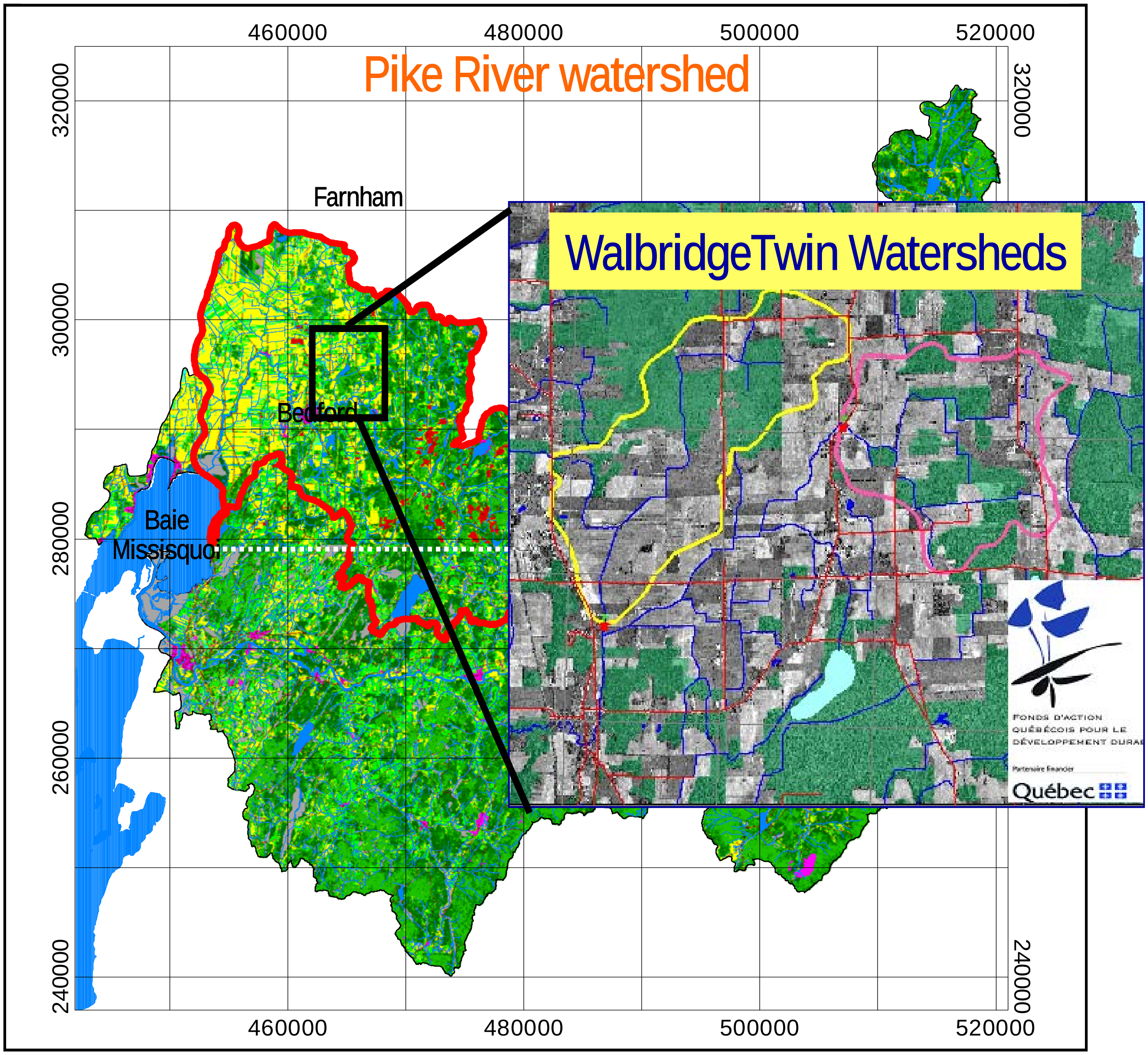


Figure 7: The Walbridge's Twin watersheds, "Intervention" *and* "Temoin".

Originally, given their contrasting geomorphologies and hydrological responses, the Walbridge experimental watersheds (Michaud et al., 2004a) served as the basis for discriminatingly assigning values to SWAT calibration parameters related to exported P and sediment loads, for the upstream *vs*. downstream portions of the Pike River watershed, all measurements were collected for flow, sediments and nutrients yield. The modelling of the two experimental Walbridge's twins sub-watershed's was a target, based on that the expected results on the Walbridge experimental sub-watersheds, parameter values would be applied to the rest of the Pike river sub-watersheds. Therefore, the future results at the Pike Watershed scale would enable a better targeting and implementation of appropriate pollution reduction strategies.
Between 2000 and 2003, the first data were collected some 166 water samples were drawn at the outlet of each of the Walbridge experimental watersheds. One station located at the outlet of a watershed characterized by rolling upland landscapes typical of the Appalachian piedmont (6.3 km^2), "*Intervention*" sub-watershed; while the other located at the outlet of "*Temoin*" sub-watershed which is characterized by flatter lands typical of the St. Lawrence lowlands (7.9 km^2). The performance of the watershed was considered to be represented by the two sub-watersheds selected for modelling processes; '*Intervention*' and '*Temoin*'. Additionally, Walbridge watershed models were built from the data taken on the overall Pike river watershed.

"Intervention" sub-watershed

The 'intervention' sub-watershed is a small, hilly basin situated upstream of the pike river watershed. The average elevation measures 88.33mm with the highest top reaching 102.5 mm and the watershed outlet lying between 70 and 74.16 mm. The 'intervention' sub-watershed drains an area of about 6.3 km^2; the main crops grown are corn and oats. Geographic information system (GIS) analysis of land use land cover data for the sub-watershed indicated distributions percent of ha area is 41.39 % corn and 13.91 % of oats with seventeen percent (17%) of pasture. The predominant soil type is "*complexe Mislsi*" (17% of the area).

At an elevation of 102 mm, geographically it's a high elevated sub-watershed and management plans have focused on agricultural best management practices (BMPs) of soil and water resources in one part of the sub-watershed. Having extensively characterized the Pike River watershed, answering questions pertaining to the potential efficacy of BMPs in reducing P loads would be referred to this sub-watershed.

"Temoin" sub-watershed

The 'Temoin' sub-watershed is also a small, low lands watershed situated near the "*Intervention*" sub-watershed draining an area of 7.9 km^2. The highest top reaches 93.05 mm with the average elevation measure of 74.16 mm and the watershed outlet lying between 60 and 65 mm. Geographic information system (GIS) analysis of land use land cover data for the sub-watershed indicated distributions percent of ha area is 30% inhabited with main crops grown 34% occupied by corn, 30% of forests and 27% of the watershed consists of pasture. The predominant soil type is Milton with 30% of the area.

The catchment is characterized by high surface runoff value which results from its specific geological structure. On '*Temoin*' sub-watershed, there is no agricultural best management practices applied except the subsurface water drainage with tile drains. The '*Temoin*' presents a low elevated area which could explain a presence of a ground water near the surface where high runoff values could be experienced than in '*Intervention*' sub-watershed (high elevated area), shown by the following figure.

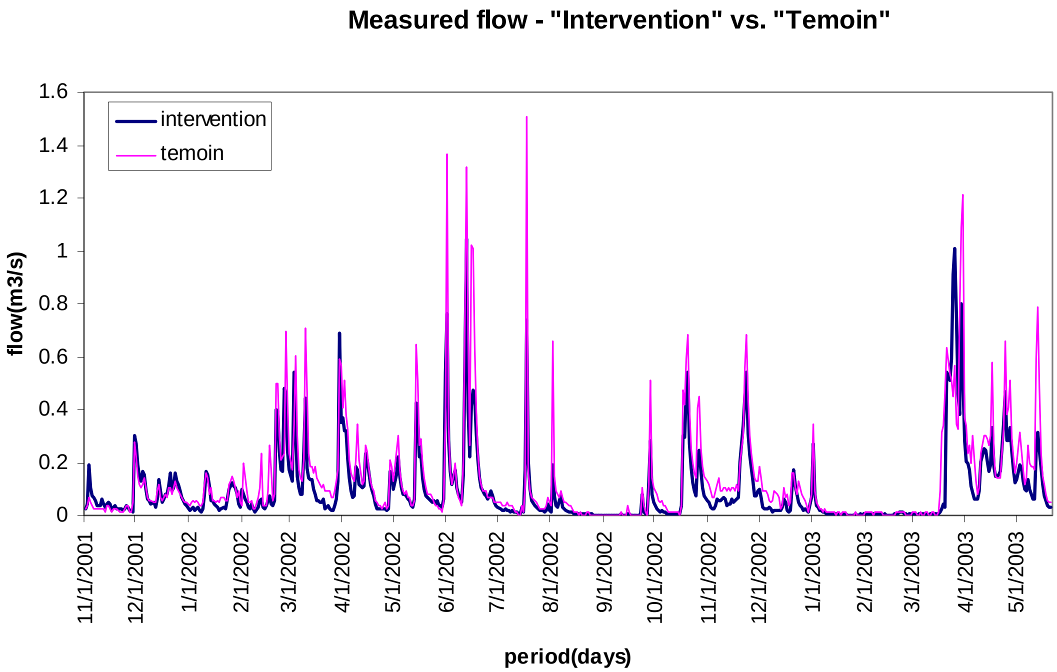


Figure 8: "Temoin" and "Intervention" physical differences, runoff values (measured data).

According to the flow measurements taken the high peaks were observed in the "Temoin". Another difference shown by the two graphs is their graphs recessions which refer to their response to ground water recharge in some periods of the year.

IV. 2. SWAT Model implementation

The implementation of the SWAT modelling project, covered the study period of 2000 to 2005. For the land phase of the hydrological cycle, SWAT subroutines allowed the daily simulation of the soil's evolving nutrient content, plant growth and nutrient uptake, as well as water, sediment and nutrient exports from the field to the hydrological network. Simulations were undertaken at the level of the individual hydrologic response unit (HRU), each sub unit representing a unique combination of physical properties, land use, and localization within each one of the two sub-watersheds of the Walbridge's watershed.

IV.2.1. SWAT Model input

Climatic Data

Daily precipitation and temperature data for the 1997-2003 study period were drawn from the Philipsburg (45°02'N and 73° 05'W, elev. 53.30 m), Farnham (45°18'N and 72° 54'W, elev. 68.00 m) and Sutton (45°09'N and 72° 38'W, elev. 243.80 m) weather stations, located around the periphery of the Pike river watershed (MDDEPQ, 2003). Solar radiation, wind speed and relative humidity were drawn from SWAT's weather generator database for the nearby Plattsburgh weather station (44°42'N and 73°30'W; Arnold and Fohrer, 2005). Thirty-year (1971-2000) annual mean precipitations at the Farnham, Philipsburg et Sutton stations were 1156 mm, 1095 mm and 1272 mm, respectively, highlighting the orographic gradient existing across the watershed (30-210 m). Annual mean temperature and snowfall ranged from 5.8° and 390 mm in Sutton, near the higher elevations of the basin's headwaters, to 6.8° and 247 mm in Phillipsburg on the shores of Missisquoi Bay.

Crop growth modelling was adjusted on the basis of a corn heat unit (CHU) range of 2500 to 2900, typical of the region (Bootsma *et al*., 1999). Crop growth parameters were adjusted in successive iterations in order to generate biomass and yields as generally observed in the region (Deslandes, J. et al., 2006).

Landscape Attributes

The task of delimiting the watershed and its sub-watersheds initially involved an integrated analysis of hydrographical, topographical, hydrological and land use data from the Quebec and Vermont portions of the Pike River watershed (Deslandes, J. et al., 2006). A digital elevation model (DEM), developed from a multi-source 30 m pixel-scale database (Deslandes *et al*. 2004) showed an accuracy of roughly 1.3 m in elevation, as estimated by comparison to a high resolution elevation map developed for the Walbridge reference sub-watershed (Duguet et *al*., 2002). A Landsat 7 ETM+ image (5 July 1999) served in land use mapping (Cattaï, 2004), while soil-type mapping drew from a number of sources (Talbot, 1943; Cann *et al*., 1946; USDA-NCRS, 1999). Soil physical and chemical properties, including particle size analysis, saturated hydraulic conductivity, bulk density and percent organic matter were drawn from Quebec (Tabi *et al*., 1990) and American (USDA-NCRS, 1999) databases. Soil particle size analyses and organic matter content served to determine available soil water (USDA-NCRS, 2005), while soil erodibility factors were drawn from Bernard (1996) or estimated from the Wischmeier (1971) nomograph. The exact extent of subsurface drainage in the basin was unknown, therefore, for modelling purposes the area under annual field crops was taken as being drained. The resulting field-scale drained area of 60% was comparable to those inventoried on experimental sub-watersheds within the study region (Michaud et al., 2004a, b). Based on standard drainage design encountered in Quebec (Beaulieu, 2001) and for modelling purposes, mean drain depth was set at 0.9 m, time to reach field capacity at 48 hr, and time for water to reach a stream at 24 hr (Deslandes, J. et al., 2006).

Cropping Systems and Nutrient Management

The spatial distribution of crops, derived from the classification of a 1999 satellite image (Cattaï, 2004) was maintained throughout the modelling process. Sowing, tillage, and fertilizer application dates were adjusted annually according to the type of crop, probable field-scale management schedule, and 2000-2003 precipitation patterns.

IV.2.2. Hydrological SWAT Model creation

Walbridge SWAT Model description

The SWAT2003 model was used in this application, previously the model were developed in SWAT2000 before being transferred in its improved version of SWAT2003. The simulator i.e. the used AVSWAT extendable version of the model is integrated in a GIS by an Arc-View pre-processor (Di Luzio et al., 2002) which uses gridded DEM data, polygon/grid coverages of some basic inputs to the model; soils and land use. The '*Intervention*' and '*Temoin*' sub-watershed's hydrological models, intentionally created for multivariable's purpose gave simulations to variables flow, sediments, and phosphorus according to the present situation in the watershed's area. Well known, the hydrological model representing the flows is the governor of other variables processes in a watershed. In fact, the routing phase of the hydrological cycle, exports of water, sediments and nutrients, cumulated at the sub-watershed scale, are drawn upon by subroutines to simulate the processes of erosion, deposition, resuspension, biodegradation and transformation within the hydrographical network.

Initially, the development of a reliable hydrological model must determine at the same time approaches of what are most hydrological sensitive parameters concerning hydrological system of the area, sediments transportation and nutrients supply towards streams and rivers in order to calibrate and validate the model.

GIS processing

A set of GIS input files (basic) needed for the SWAT model were inserted; including the coverages of digital elevation model (DEM), land cover, soil layers and point coverage of weather stations. The determination of the threshold area which defines the minimum drainage area was set to 300 ha. This threshold was required for the formation of the origin of streams; it determined the detail of the streams network, the size as well as the number of sub-watersheds created. Within SWAT, the catchment was partitioned into a number of sub-watersheds based on this threshold specification. The

SWAT Arcview Interface (Di Luzio et al., 2002) delineated the watershed into sub-watersheds; five sub-watersheds were obtained. After that, sub-watersheds were divided into hydrologic response units (HRUs) according to the specified land use and soil percentage. The percentages were all set to zero and this allowed each surface of the watershed to be represented without neglecting any surface area with its specific properties. 199 HRUs were obtained,these are lumped land areas consisting of unique combinations of land cover, soil and management (Neitsch et al., 2002a). The sub-watersheds outlets were added and the selection of the main outlet was selected at the end of the virtual stream network draining the Walbridge watershed.

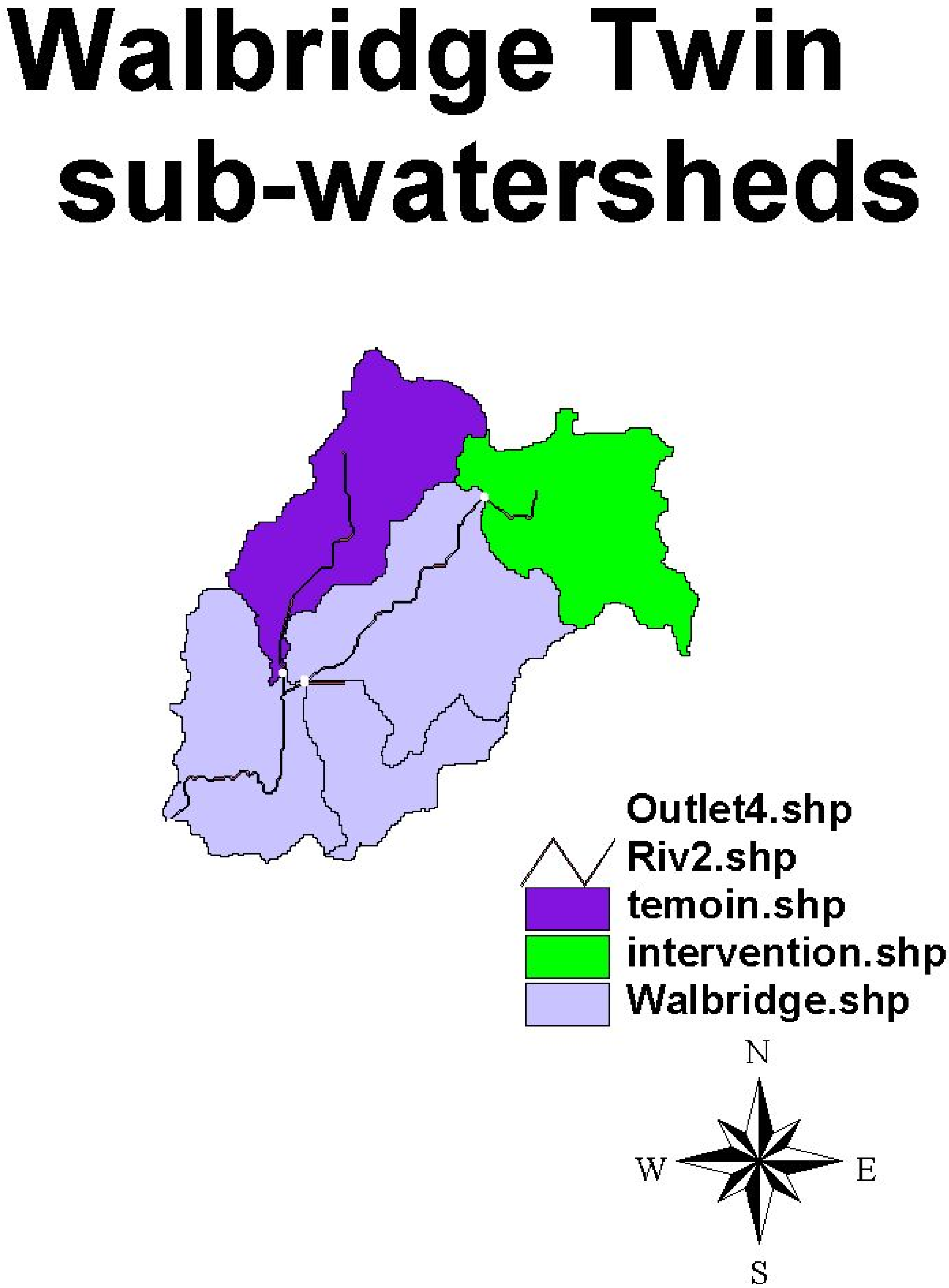
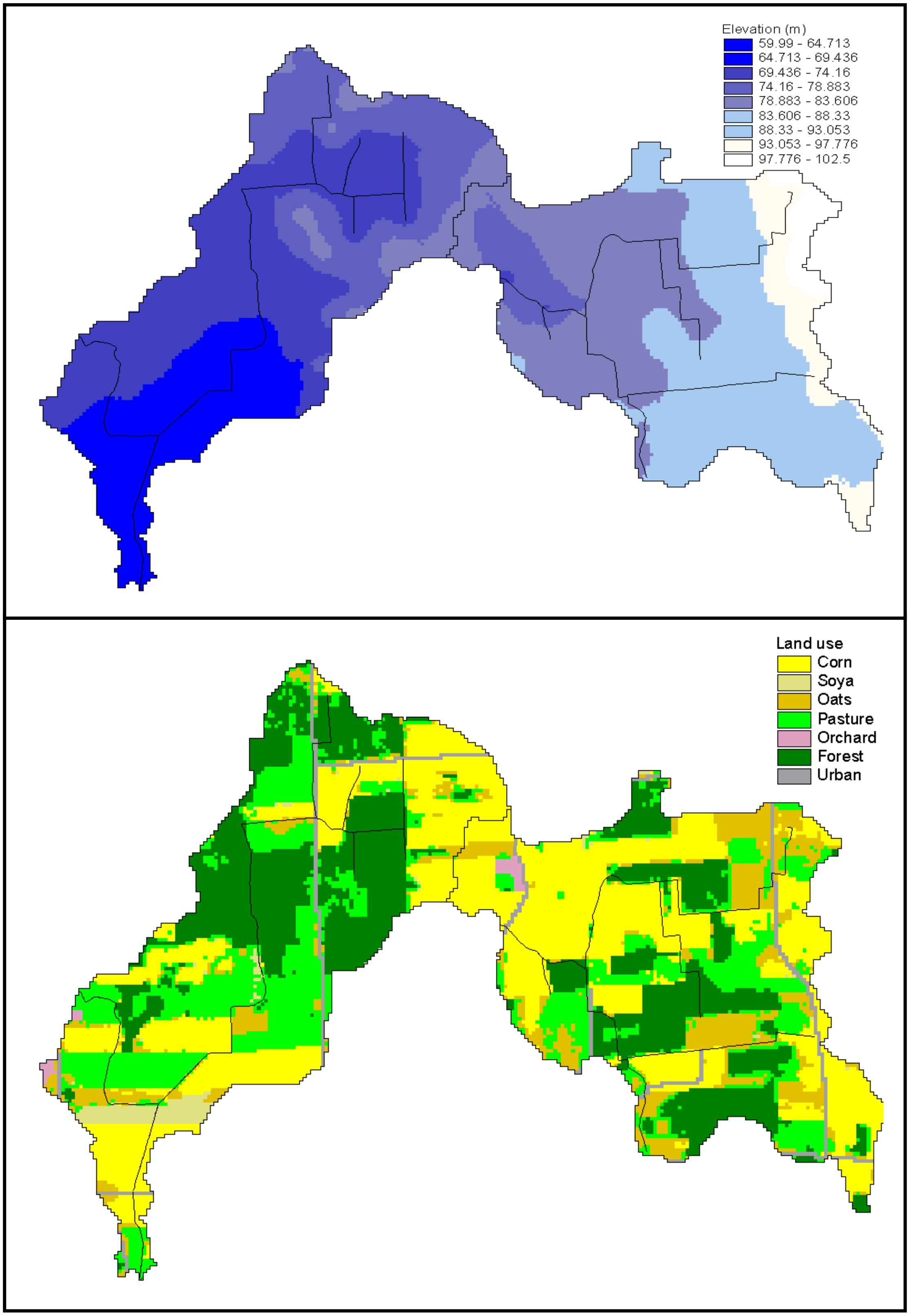


Figure 9: Walbridge's sub-watershed built in SWAT2003.



Figures 10: Elevations and Landuse maps provided by SWAT for the two sub-watersheds, “Intervention” *and* “Temoin”.

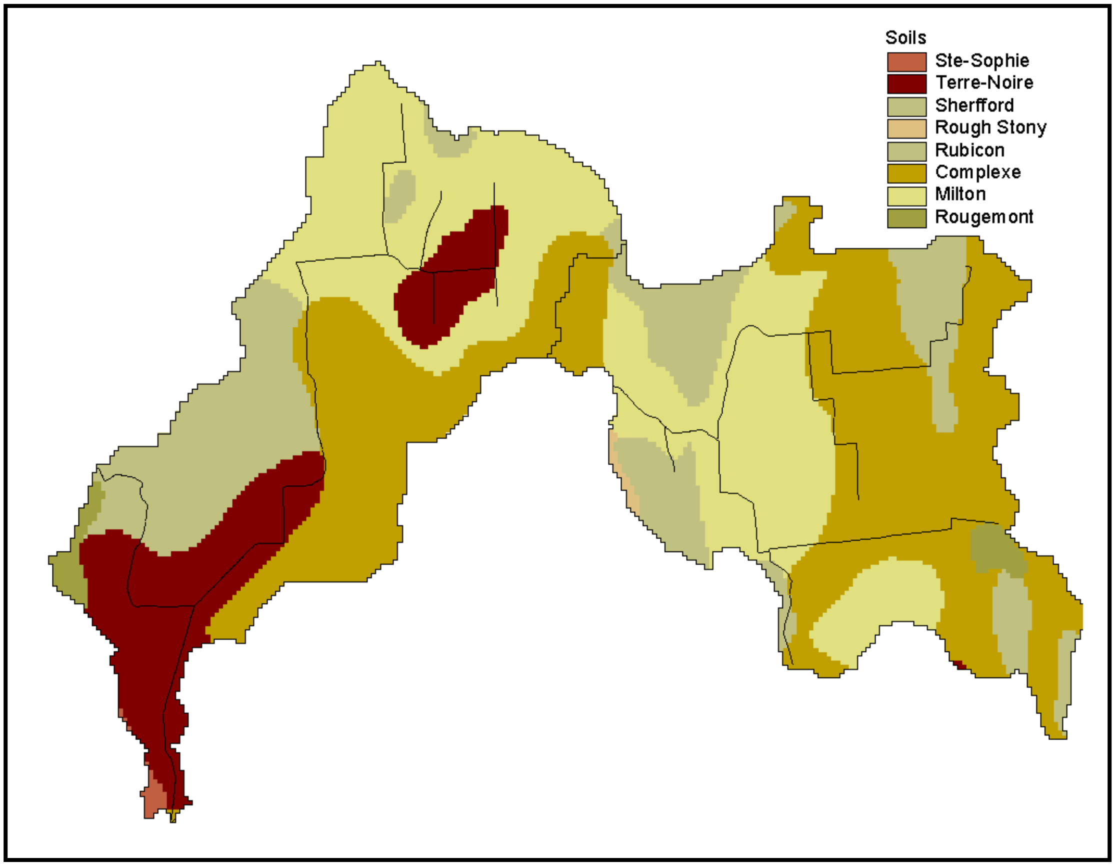


*Figure 11: Soils map provided by SWAT, "*Intervention*" and "*Temoin*" sub-watersheds.*

The partition of the watershed into a number of sub-watersheds was particularly beneficial because in simulations when different areas of the watershed are dominated by land uses or soils dissimilar enough in properties to impact hydrology. By partitioning the watershed into five sub-watersheds, it gave the ability to reference different areas of the watershed to one another spatially.

Management files data

These data were maintained as prepared previously for SWAT2000 model (Deslandes, J., 2006). The ability of SWAT to define specific agriculture practices i.e. tillage operations, fertilizers types, fertilizers spreading, and etc. added to SWAT utility in representing the particular Walbridge's watershed. These non-point components were integrated into the model based on best available information. Agricultural operations were simulated in SWAT at HRU level i.e. within the sub-watersheds to represent pasture management conditions each distinctive in its combination of soil properties, topography, fertilizer inputs in the region under study. According to the period of simulation, the management's files containing all information concerning crops manure operations and crop rotations in the Walbridge's sub-watershed were adjusted annually according to the type of crop, probable field-scale management schedule, and 2000-2005 precipitation patterns. Once well prepared they were used as management's input files for the new SWAT2003 model. Annual agricultures operations rates were obtained from records in the Canadian government farm registration forms.

Climatic data

For the Walbridge sub-watersheds, weather data from station Farnham (45°18'N and 72° 54'W, elev. 68.00 m) were incorporated to provide the most representative precipitation and temperature data available. Other meteological data required by SWAT (solar radiation, wind speed, and relative humidity) were estimated using the SWAT weather generator.

All parameters from SWAT2000 model calibrated and validated were used for this application. The simulation time was from year 2000 to year 2005. The year 2000 and some months of 2001(January to October) allowed the model to stabilize and obtain values that became initials for the period of interest. Therefore, from beginning November 2001, the model was considered to represent conditions in the watershed. Specific datasets were identified to perform calibration and validation of the SWAT model. The model's calibration and validation were based on flow data from two hydrometric stations located at the outlet of the two experimental watersheds. The calibration part data was from November 2003 to May 2003 and from October 2004 to the end of the year 2005 was for validation, the data between those periods were not available.

For the water quality side, a focus would be given to spatial gradients in landscape attributes, soil P and N stocks, agricultural inputs and cropping systems and how they relate to model sensitivity in its predictions of runoff depth, sediment loads P and N fluxes. The water quality data were measures obtained by samples taken in different periods of the year and treated for giving the concentrations of different variables i.e. sediments, P and N (Deslandes, J. et al., 2006).

Simulation of the hydrological model in SWAT2000 and SWAT2003

The limitations of data availability were taken into account in order to be aware of the limitations of all forms of the modelling process in SWAT selected as a model that meet the precise needs of the project. As described before, the model was originally built in SWAT2000. The Simulation of the hydrology of the two sub-watersheds in Swat2000 was done by using manual calibration with one approach of calibrating the parameters influencing the main hydrological processes representing the surface and subsurface flow.

Based on this information, a calibration had been performed for a limited number of influential parameters. The calibration performance was then evaluated by performance criteria of correlation coefficient, the Nash-Sutcliffe (N-S) coefficient of efficiency (Nash and Sutcliffe, 1970) and the coefficient of deviation i.e. the percentage in differences of volumes (between simulated and measured flow volumes). The correlation obtained was of 0.8 with a Nash-Sutcliffe (N-S) coefficient of 0.6 for the two different Walbridge's twin models.

Figure 12(a)

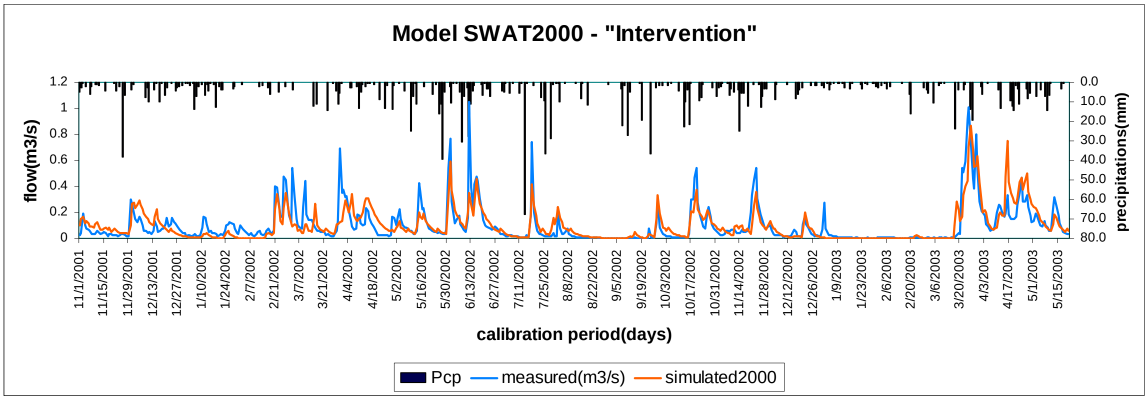
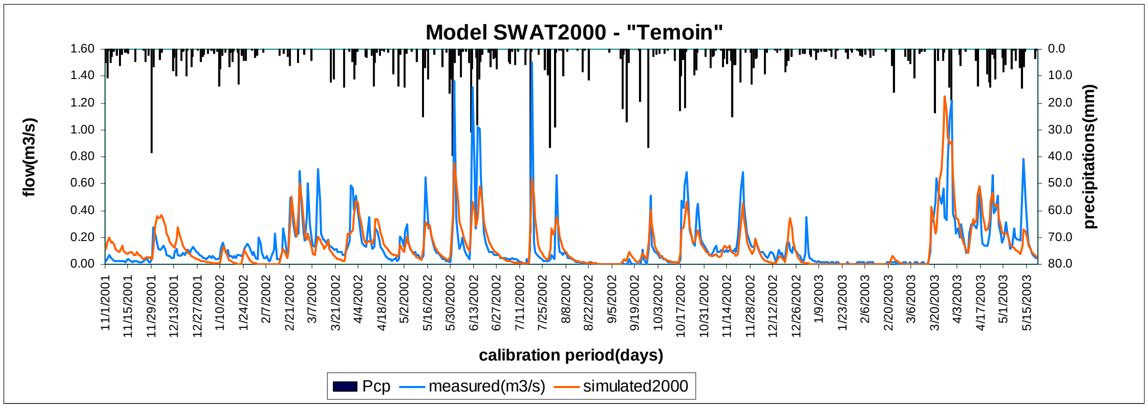


Figure 12(b)



Figures 12: Models calibrated and validated in SWAT2000 for sub-watersheds, "Intervention" *and* "Temoin".

While transferring the model in SWAT2003 version, the two models showed a big difference. Justified by the results of correlation and N.S coefficients; 0.3 and -1.3 in SWAT2003, the following figures are showing how results were for each individual sub-watershed:

Figure 13(a)

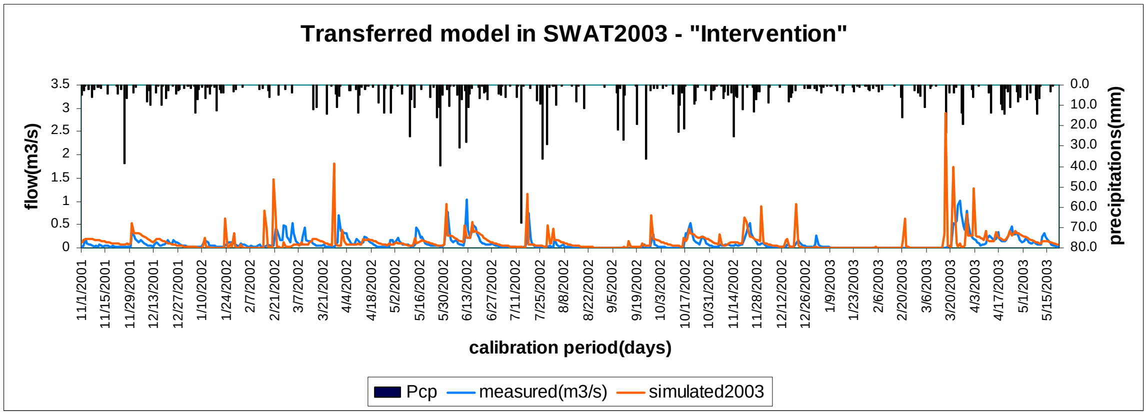
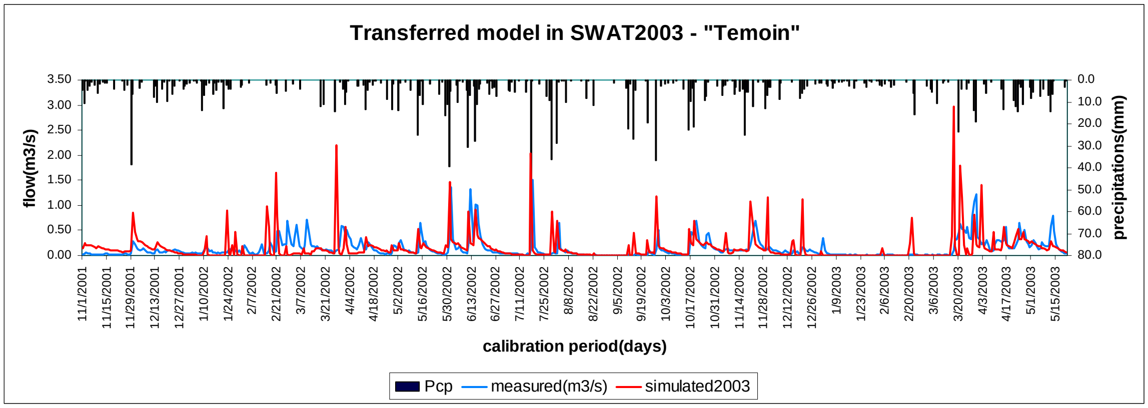


Figure 13(b)



*Figures 13: Transferred models in SWAT2003 for the sub-watersheds, “*Intervention*” and “*Temoin*”.*

For both sub-watersheds, the surface flow was overestimated i.e. the daily surface flows values became very high with very high peak runoff. A new calibration was needed for the adjustments of hydrological parameters in SWAT2003. The sensitivity analysis of parameters needed to be done correctly and at the same time to know exactly which parameters required a readjustment in SWAT2003.

Sensitivity Analysis and Calibration

Picture of the Pike River near Bedford, Québec. Photo taken by Jean-Daniel Sylvain in April 2007

CHAPTER V: SENSITIVITY ANALYSIS AND CALIBRATION IN SWAT2003

To sufficiently predict, the hydrological system was evaluated through sensitivity analysis and calibration, the main physical processes gave corresponding parameters to be considered.

Referring to one of the objectives of the research saying that the model would be used to extrapolate potential effects of alterations in management practices, the hydrologic model had to be calibrated taking into account the main physical realities. The calibration was started by the sensitivity analysis taken as giving information to identify parameters that were important for the reproduction of the system response. Some of the parameters identified were subsequently fixed or removed, which reduced the dimensionality of the calibration problem. The calibration was divided in two parts; the autocalibration option integrated in SWAT2003 and the manual calibration.

The main objectives considered in the sensitivity analysis and calibration part were:

1. To conduct sensitivity analysis for influential parameters for the Walbridge's hydrology system;
2. To perform calibration of the hydrological models at the two different sites.

The sensitivity analysis, autocalibration and manual calibration were conducted based on different periods of the hydrological year. Winter and spring, summer and autumn analysis were done separately in order to approximate values of parameters by avoiding influence of other period's parameters between them. However the manual calibration was mainly performed on the completed period of simulation.

For each analysis done, the following sequence of activities was followed:

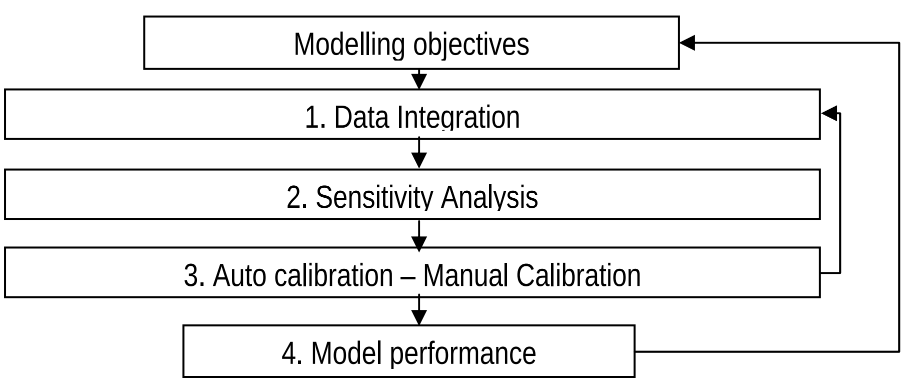


Figure 14: Methodological plan in sensitivity analysis and calibration on "Intervention" *and* "Temoin".

V.1. Sensitivity Analysis

Sensitivity is measured as the response of an output variable to a change in an input parameter, with the greater the change in output response correspond to a greater sensitivity (Van Griensven, 2006). Sensitivity analysis evaluated how different parameters influenced the predicted outputs. It supported the calibration process which means the parameters identified in sensitivity analysis were used to calibrate a model. The sensitivity analysis incorporated in SWAT2003 is called LH-OAT sensitivity analysis.

V.1.1. The LH-OAT sensitivity analysis

In this study we utilized the LH-OAT sensitivity analysis built-in SWAT2005. The LH-OAT method combines the One-factor-At-Time (OAT) design and Latin Hypercube (LH) sampling by taking the Latin Hypercube samples as initial points for an OAT design (Van Griensven and Meixnnr, 2006).

Latin Hypercube sampling (McKay, 1988) is a sophisticated way to perform random sampling such as Monte-Carlo sampling, resulting in a robust analysis requiring not too many runs (Satelli et al., 2000). It subdivided the distribution of each parameter into *m* ranges, each with a probability of occurrence equal to 1/*m*. Random values of the parameters were generated, such that each range was sampled only once. For each of the *m* random combinations of the parameters an OAT loop was performed.

In the OAT design (Morris, 1991), only one input parameter is modified between two successive runs of the model. Therefore, the change in model output (e.g. SSE of the surface runoff) can then be unambiguously attributed to such a parameter modification by means of an elementary partial effect $S_{i,j}$ defined by Eq. (6).

$$Si,j = \left[\frac{SSE(\phi_1,...,\phi_i*(1+f),...,\phi_p) - SSE(\phi_1,...,\phi_i,...,\phi_p)}{f} \right] \qquad \textit{Eq. (6)}$$

Where $S_{i,j}$ is a partial effect for parameter Φ_i around LH point j, f is the fraction by which the parameter Φ_i is changed (a predefined constant) and SSE is the sum of squared errors. In *Eq.* (6), the parameter is randomly increased or decreased with the fraction *f*. Considering *p* parameters, one loop involves performing *p+1* model runs to obtain one partial effect for each parameter. As the influence of a parameter may depend on the values chosen for the remaining parameters, the experiment is repeated for all the *m* LH samples. The final effect will then be calculated as the average of a set of the *m* partial effects.

As a result, the LH-OAT sensitivity analysis method is a robust and efficient method: for m intervals in the LH method, a total of *m**(*p*+1) runs is required. The LH-OAT provides ranking of parameter sensitivity based on the final effects. Using the LH and One-factor-At-a-Time techniques in unison means that the sensitivity of model output to a given parameter is assessed across a number of different values for other parameters in the model, thus incorporating a limited amount of parameter interaction (Srinivasan et al., 2006).

- **Hydrological Parameter sensitivity**

As mentioned, the sensitivity analysis was conducted to determine the influence a set of parameters have on predicting total flow. Sensitivity was approximated using LH and One-factor-At-a-Time techniques. In the output file "*Sensresult.out*", a list of parameter's ranks was provided.

The sensitivity analysis was performed for 33 hydrological parameters that may have a potential to influence daily flows. The ranges of variation of these parameters were based on a listing provided in the SWAT manual (Neitsch et al., 2002a) and were sampled by considering a uniform distribution. The distributed parameters were modified by replacement, by addition of an absolute change or by a multiplication of a relative change (a certain percentage), whereby they were restricted to their physical range. The analysis was carried out using daily simulations for hydrology for the period between the 2000 and 2005. Different sensitivity analyses were done; sensitivity analysis over the whole simulation period and sensitivity analysis over winter, spring, summer and autumn. The year 2002 was chosen for the sensitivity analysis through separated periods, it was considered as the most stable year along the whole simulation period.

Table 1: Used parameters for the sensitivity analysis on "Intervention" *and* "Temoin" *sub-watersheds.*

Parameters	Min	Max	Definition
Alpha_Bf	0	1	Base flow alpha factor(days)
Alpha_Bnk	0	1	alpha factor for bank storage recession curve(days)
BLAI	-50	50	Leaf area index for crop*
canmx	0.001	10	maximum canopy storage(mm H2O)
CH_K2	0	150	Effective hydraulic conductivity in main channel alluvium (mm/h)
ch_n	-20	20	Manning coefficient for channel
Cn2	-35	35	SCS runoff curve number for moisture condition II*
DDRAIN	-10	50	depth to the sub-surface drain (mm)
Epco	0.01	1	plant evaporation compensation factor
Esco	0	1	plant evaporation compensation factor*
EVRCH	0	1	Reach evaporation adjustment factor.
FILTERW	-50	50	filter strip width for bacteria transport (m)
GDRAIN	-50	900	drain tile lag time(hrs)
Gw_Delay	0	50	Groundwater delay (days)
Gw_Revap	0.02	0.2	Groundwater "revap" coefficient
Gwqmn	0	5000	Threshold depth of water in th shallow aquifer required for return flow to occur (mm)
Lat_ttime	0.01	20	lateral flow travel time (days)
ov_n	-50	50	Manning's "n" value for overland flow
Rchrg_Dp	0	1	Goundwater recharge to deep aquifer
REVAPMN	0	500	Threshold depth of water in tha shallow aquifer required for "revap" to occur (mm)
Sftmp	-1.5	1	Snowfall temperature (deg C)
shallst	0.5	6000	depth of water in shallow aquifer (mm H2O)
SLSOIL	0	0.6	slope length for lateral subsurface flow (m)
Smfmn	1	7	Minimum melt rate for snow during year (Dec. 21) where deg C refers to the air temperature (mm/deg C/day)
Smfmx	1	7	Maximum melt rate for snow during year (June 21) where deg C refers to the air temperature (mm/deg C/day)
Smtmp	-2	3	Snow melt base temperature(deg C)
SNO50COV	0.01	0.94	Fraction of SNOCOVMX that corresponds to 50% snow cover
SNOCOVMX	0	50	Minimum snow water content that corresponds to 100% snow cover (mm H2O)
sol_alb	-50	50	bulk density of the soil (Mg/m**3)
sol_awc	-50	50	available water capacity of soil layer (mm H20/mm soil)
sol_bd	-50	50	albedo when soil is moist
sol_k	-50	50	saturated hydraulic conductivity of soil (mm/hr)
sol_z	-50	50	depth to bottom of soil layer (mm)
Sol_zmx	0.001	3500	maximum rooting depth (mm)
Surlag	0	10	Surface runoff lag time.(days)
TDRAIN	-50	0	time to drain soil to field capacity (hrs)
Timp	0.01	1	Snow pack temperature lag factor

*Relative percent change

italised and bolded parameters used in calibration part

V.1.2. Parameters selection

The approach of evaluating how changes in model parameters affected the model output variable gave information to be used in identifying parameters that were not important for the reproduction of the system response. Most of these parameters were parameters obtained by measures taken on the field; they were fixed values taken approximately close to the reality. Soil properties such as field capacity(FC) or wilting point (WP) and other soils physics properties were derived from a few point of samples analyzed at the laboratory (most likely by making the additional assumption that the value for the dominant soil type in the catchment is the correct one). These soil properties were directly equivalent to lumped conceptual parameters which were effective values since they are estimated from the integrated response of the watershed without taking into consideration the unique combination of soil types present but with respect to their hydrological behavior.

In the sensitivity analysis parameter's set, the parameter's related to the subsurface drainage especially the tile drains were added in the sensitivity analysis. Considered as fixed values also, this was done to see if the parameters could show such important sensitivity which could be taken as having an impact on the hydrological response in the watershed. The parameters added for that reason were the time to drain soil to field capacity "*TDrain*" and the lag time for the tile drain *"GDrain"*, together with the ground water parameter, the initial depth of water in shallow aquifer "*Shallest*".

V.1.3. Sensitivity analysis over the whole period of simulation

Previously mentioned, the sensitivity analysis was first done over the whole period of simulation. Results obtained showed that there could be an influence of parameters between themselves. This was directly verified and was proved by results obtained by sensitivities runs over separated data set by considering different periods of the year, their results were different. The following figure the parameters rank order given in sensitivity results files. The ranks were given to parameters according to main processes considered in the area. This is obviously determined by measured data prepared in observations files specified to the analysis during its run. The measured data were data taken during the simulation period for sites, *"Intervention"* and *"Temoin"* sub-watersheds.

The following figure shows the parameter's rank order given by the first sensitivity analysis:

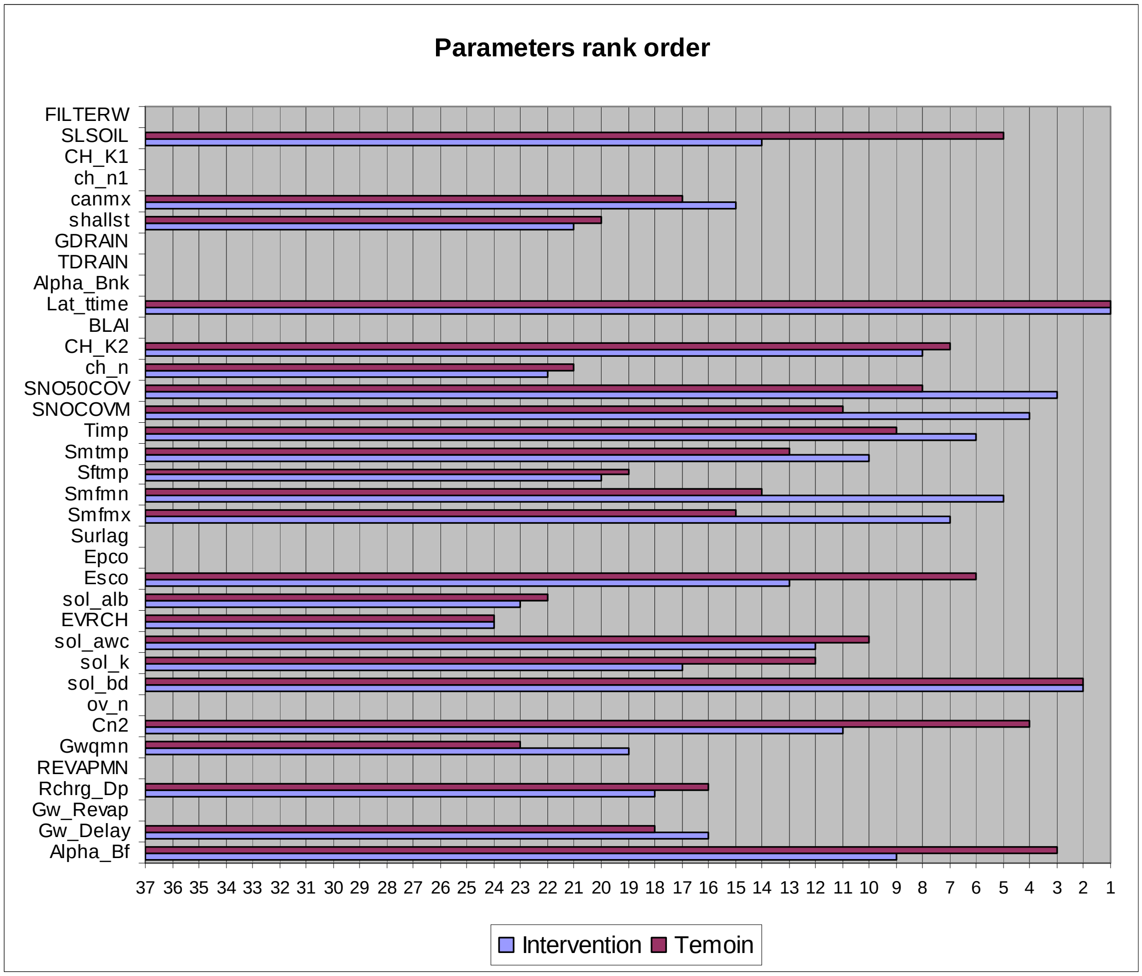


Figure 15: Summarizes the sensitivity ranking for the performance for flow over the whole period of simulation on "Intervention" *and* "Temoin".

- **Discussion**

In both cases, the soils physics properties like the sol moisture content (*sol_bd*), the soil hydraulic conductivity (*sol_k*) and the soil bulk density (*sol_awc*) were among the most sensitive parameters followed by the curve number (*CN2*) and the ground water parameters such as the base flow factor (*Alpha_Bf*) and the slope length for lateral subsurface flow (*slsoil*) The importance of the ground water parameters were not surprising, due to the fact that drainage through the subsurface area is high and had its origin in the presence of tiles drainage, given information in management's files.

The first analysis over the whole period helped for the primary reduction of parameters; like soil physics parameters already fixed values proved from tests done in laboratory.

The tiles drain parameters did not show any sensitivity but the initial depth of water in shallow aquifer is showed somehow to be sensitive. This could be related to its participation to the base flow or tile flows, its value could be determining the quantity of water in those areas, which could have a significant effect on their values. This could be detailed later in *chapter VI*.

V.1.4. Sensitivity analysis over yearly hydrological periods

The sensitivity analysis was carried on particular periods of the hydrological year. Because of significance duration of the hydrological periods in the region, separated sensitivity analysis tests were found necessary in order to check how sensible parameters are related to the periods where they seem to be very important. This was done not only to give more precise on their sensibility but also to avoid other period's parameters influences.

1. Sensitivity analysis over winter and spring period

Winter period was taken from November 2001 to February 2002 while spring was from March to April 2002. The parameters selected were similar as the processes in winter and spring were supposed to be approximately the same, the spring is mainly characterized by the snow melting period but for the two periods the same parameters are still important. These parameters were mainly focusing on snowfall and snow melting physical processes.

Figure 16(a)

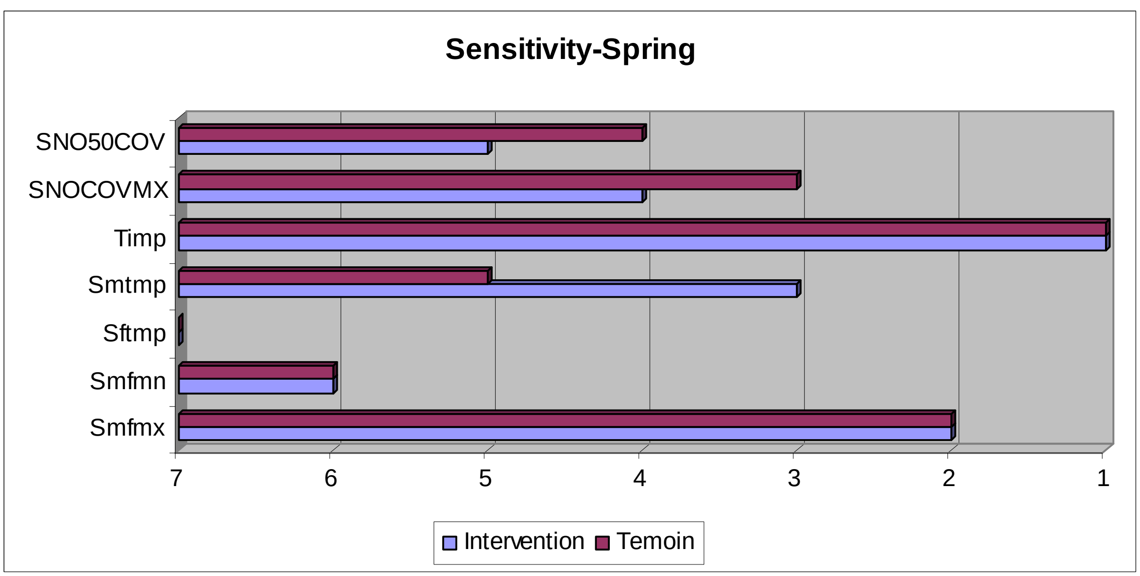
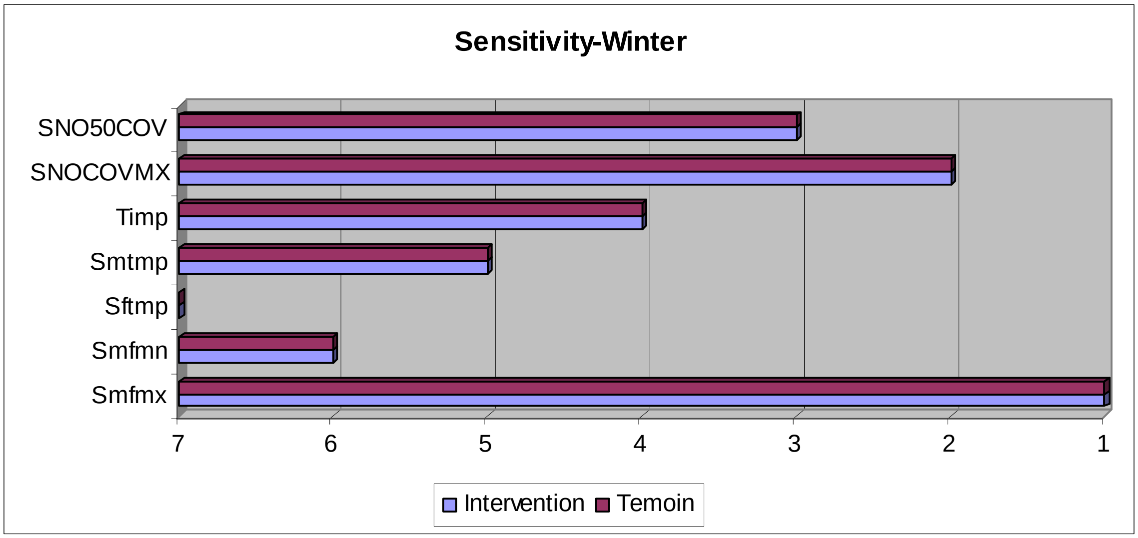


Figure 16(b)



Figures 16: Parameters rank on spring and winter periods on "Intervention" *and* "Temoin".

- **Discussion**

When we focused on the winter period (November-February) and the spring periods (March-April), the same parameters appeared to be important. In both periods, winter and spring, the maximum melt rate (*Smfmx*), the minimum snow water content that corresponds to 100% snow cover (*SNOCOVMX*) and the fraction of (*SNOCOVMX*) that corresponds to 50% snow cover (*SNO50C0V*) showed their high sensitivity except the snow pack temperature (*timp*) which was the most sensitive in spring, this could be linked to the reality as the temperature of the snow pack could be affected as the snow starts melting during that period of spring.

All parameters were chosen for the calibration process, they seemed to be depending; the values of one parameters were very sensitive to others parameters values. So to change them could be done together rather than changing only one parameter.

1. Sensitivity analysis over summer and autumn period

Periods from May 2002 to October 2002 were selected to check the sensitivity of parameters considered to have a big impact on summer and autumn events. Following is the parameters rank order obtained by the sensitivity test; this was run on measured data taken during that period.

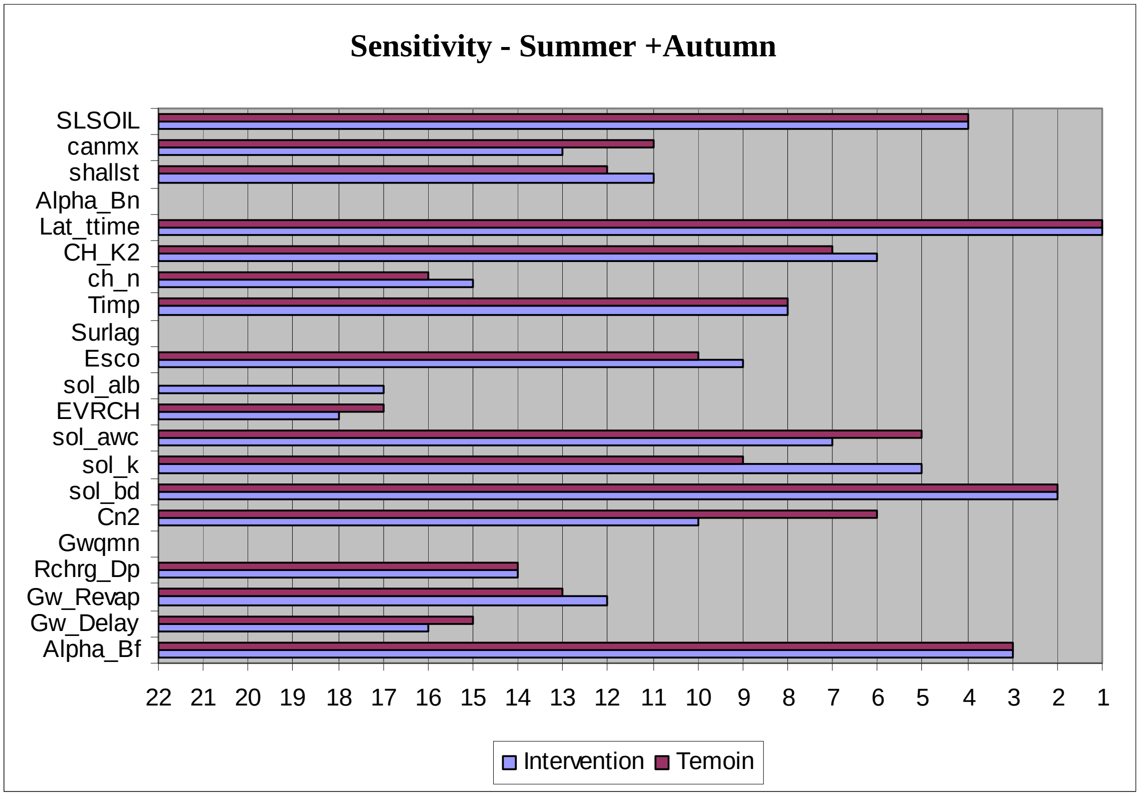


Figure 17: Parameters rank on summer and autumn periods on "Intervention" *and* "Temoin".

- **Discussion**

Dominant parameters were the curve number (*CN2*), the base flow factor (*Alfa_Bf*), the recharge to deep aquifer (*rchrg_dp*) and the initial depth of water in the shallow aquifer (*shallest)*.The sensitivity of the soil properties parameters is consistence with results determined in previous sensitivities tests (*Figure 15 - sensitivity analysis over the whole period of simulation*), as they were fixed measures their sensitivity was taken as a good result but they had to be removed and not used in calibration. The lateral flow time travel time was initially set to zero (default value set by SWAT), that's why it showed a big sensitivity. It was fixed later as mentioned in the SWAT Theoretical Documentation, version2003 (section2 chapter3, page 162), its values when tile drains are present, it could be obtained by using this equation:

$$TT_{lag} = \frac{tile_{lag}}{24} \qquad \textit{Eq. (7)}$$

Where TT_{lag} the lateral flow travel is time (days) and $tile_{lag}$ is the drain tile lag time (hrs).

By means of the LH-OAT sensitivity analysis, the dominant parameters were determined and a reduction of the number of model parameters was performed. Subsequently, the selected parameters were expected to be adjusted in calibration.

Conclusion

- **Winter period (November – February)**

SWAT classifies precipitation as rain or freezing rain/snow using the average daily temperature and the snow melt controlled by the air and snow pack temperature, the melting rate, and the areal coverage of snow; if snow is present, it is melted on days when the maximum temperature exceeds 0^{o}C. Melted snow is treated the same as rainfall for estimating runoff and percolation (SWAT2003 Theoretical Documentation). This justified the sensibility of the winter parameter at the beginning of the calibration period November-February 2001 temperatures records are above 0^{o}C (following *Figures 18*), same for the precipitations in that period we had some rains. The sensitivity analysis run on the whole period and the separated period of winter did not show same rank order for the taken winter parameters. According to SWAT input output relations, the results were right. At that time some temperature records are above zero, which could have a great impact on other parameters while run on the whole period of simulation. SWAT uses other parameters like for the infiltrations rate at that period where the temperature records were above O^{0}C, and all processes of rainfall runoff conversation are used on that particular time. Parameters sensibility was based not only on which are processes taking place but also on the observations data.

Figure 18(a)

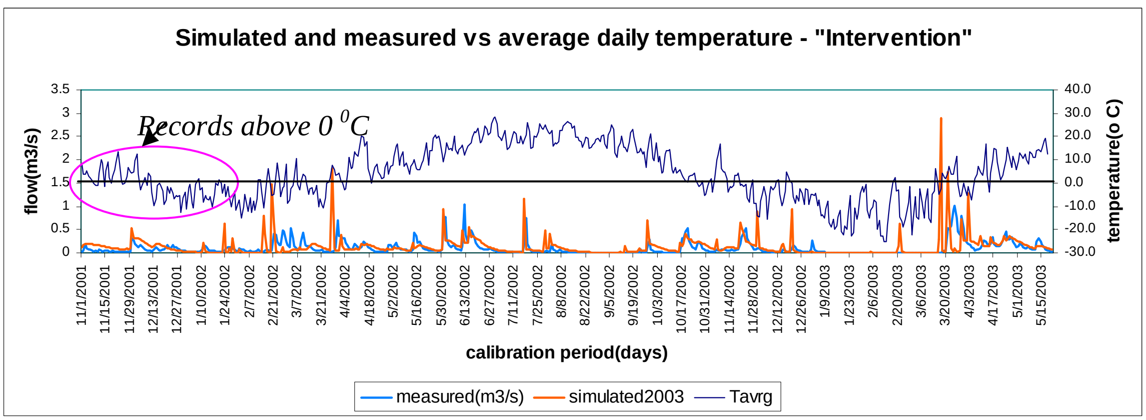
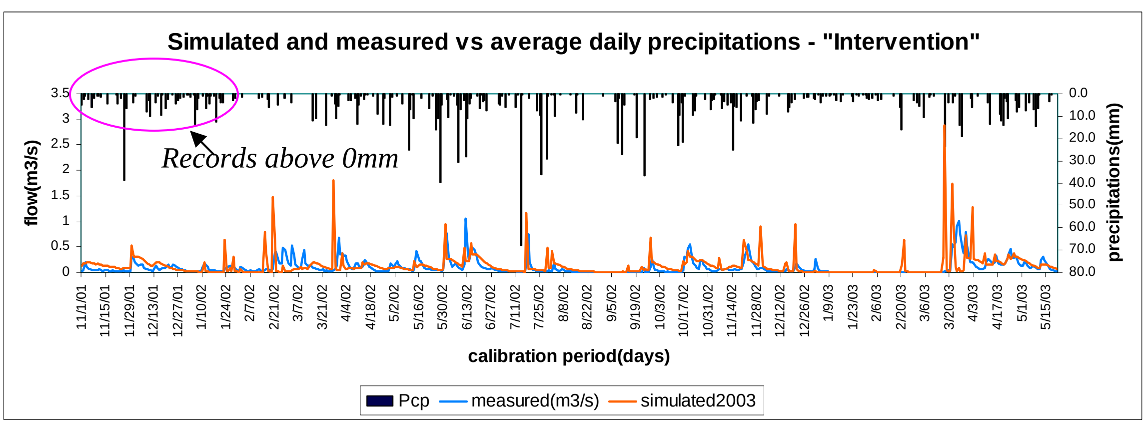


Figure 18(b)



Figures 18: Temperature and precipitations records during winter and spring periods, "Intervention".

Land use input sensitivity

The two sub-watersheds were physically different and it was needed to run each individual sensitivity test for avoiding the parameters influence or land uses input data influences, this was considered on sensitivity analysis tests run on separated periods of the hydrological year. This was done not only because of that difference but also the way they are placed physically it showed their output are very independent (Figure 7).

V.2. Calibration

The model calibration procedure was done by using the two methods; autocalibration incorporated in SWAT2003 and manual calibration. Both methods were supported by the sensitivity analysis information.

Normally, the calibration parameter's set contain parameters that are typically refer to a collection of aggregated processes. Therefore they often do not have a direct physical interpretation and can not be measured in the field. Instead they can be estimated using a calibration procedure whereby the model parameters are adjusted until system and model output shows an acceptable level of agreement. This agreement is typically measured using an objective function (OF) (Neitsch, S.L., 2002). Thus, an iterative search is required to identify the optimum parameter values; this can be done by using an automatic search algorithm, a manual procedure, or a combination of both approaches. Manual calibration is time-consuming and difficult to achieve in the presence of parameter dependence. Automatic calibration algorithms have the potential to reduce this problem (Neitsch, S.L., 2002). Parameters used in calibration are italized and bolded in *Table 1*. Their ranges were based on other sensitivity analysis published results or defaults set by SWAT.

Table 2: Calibrated parameters for winter and spring periods

Parameters	unit	Definition	scale (file)	Imet	Low bound	Upper bound
Smfmx	mm/deg C/day	Maximum melt rate for snow	BSN	1	1	7
Smfmn	mm/deg C/day	Minimum melt rate for snow	BSN	1	1	7
Sftmp	deg C	Snowfall temperature	BSN	1	-1.5	1
Smtmp	deg C	Snow melt base temperature	BSN	1	-2	3
Timp	none	Snow pack temperature lag factor	BSN	1	0.01	1
SNOCOVMX	mm H2O	Minimum snow water content that corresponds to 100% snow cover.	BSN	1	0	50
SNO50COV	none	Fraction of SNOCOVMX that corresponds to 50% snow cover.	BSN	1	0.01	0.94

Table 3: Calibrated parameters for summer and autumn periods

Parameters	unit	Definition	scale (file)	Imet	Low bound	Upper bound
Alpha_Bf	days	alpha factor for groundwater recession curve	HRU(gw)	1	0	1
Gw_Delay	units-days	groundwater delay	HRU(gw)	1	0	50
Rchrg_Dp	none	recharge to deep aquifer	HRU(gw)	1	0	1
shallst	mm H2O	depth of water in shallow aquifer	HRU(gw)	1	0.5	6000
Gwqmn	mm H2O	threshold depth of water in shallow aquifer	HRU(gw)	1	0	5000
Esco	none	soil evaporation compensation factor	HRU or BSN	1	0	1
Lat_ttime	days	lateral flow travel time	HRU	1	0.01	20
Surlag	days	Surface runoff lag time	BSN	1	0	10
Alpha_Bnk	days	alpha factor for bank storage recession curve	RTE and BSN	1	0	1
Gw_Revap	none	revap coeff	HRU(gw)	1	0.02	0.2
CH_K2	mm/hr	effective hydraulic conductivity of main channel	RTE and BSN	1	0	150

The Imet number 1 and 3 refer whether the parameter's change is done by addition of an absolute change (1) or by a multiplication of a relative change (3).

V.2.1. Autocalibration

A complex hydrologic model is generally characterized by a multitude of parameters. Due to spatial variability, measurements errors or incompleteness in description of both the elements and the processes present in the system, etc., the values of many of these parameters will not be exactly known. Therefore, to achieve a good fit between simulated and measured data, models need to be conditioned to match the reality by optimizing their internal parameters.

The automatic calibration incorporated function in SWAT2003 uses The Parasol (Parameter Solutions method) method. The method has got algorithms that optimize an objective function by systematically searching the parameter space according to a fixed set of rules (A. van Griensven et al., 2006). Observations data taken from the Walbridge's stations were evaluated inside the automatic optimization in SWAT.

1. **Parasol (Parameter Solutions method)**

It is an optimization method which uses the "Shuffled complex evolution algorithm". It is a global search algorithm for the minimization of a single function for up to 16 parameters (Duan et al., 1992). It combines the direct search method of the simplex procedure with the concept of a controlled random search of Nelder and Mead (1965), a systematic evolution of points in the direction of global improvement, competitive evolution (Holland, 1995) and the concept of complex shuffling.

2. **Objective function**

One of the objective functions used aimed at matching the simulated series to the measured time series and is called "Sum of the squared of the residuals (SSQ)". It is similar to then Mean Square Error (MSE).

$$SSQ = \sum_{i=1,n} \left[X_{i,measured} - X_{i,simulated} \right]^2 \qquad \textit{Eq. (8)}$$

With *n* number of pairs of measured $X_{measured}$ and simulated $X_{simulated}$ variables.

Parameter change

Parameters given to the automatic option were changed over the entire sub-watersheds; area of interest given by the observations file created for the autocalibration. They were modified by replacement, by addition of an absolute change or by multiplication of a relative change, imet number (*Table 2 and 3*). The relative change means that the parameters are changed by a certain percentage. The parasol output results were predicted values for surface runoff together with the best parameters changes suggested by the method. The best parameters obtained were corresponding to the predicted flows.

3. Results

The autocalibration was run on different periods of the hydrological year as it was done in the sensitivity analysis, using the most sensitive parameters observed by sensitivity tests. Different runs were done by trying to use different parameters set and see which set could give best results. The following figures are showing results obtained by runs obtained using best parameters set provided by the autocalibration techniques.

Auto calibration – winter

Figure 19(a)

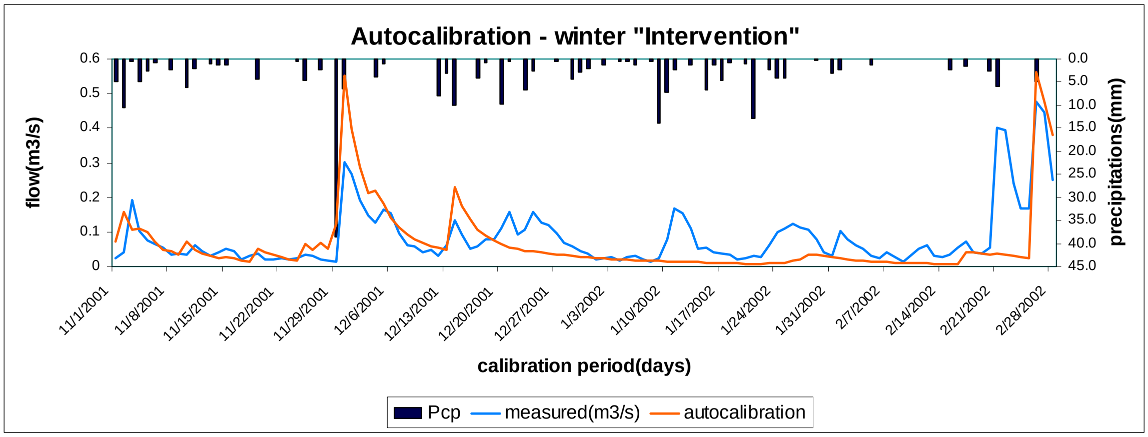
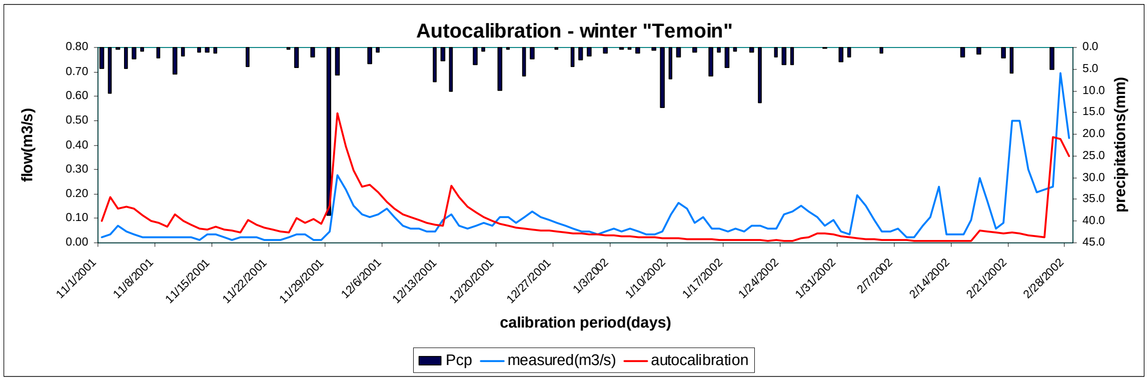


Figure 19(b)



Figures 19: Autocalibration results on winter period, "Intervention" *and* "Temoin".

The results with a best parameter set in winter period completed showed it did not arrive to simulate well the period of January to February 2002, it was predicting low flows during that period and this resulted in an underestimation of flows during winter period for the two sub-watersheds.

Auto calibration – spring ***Figure 20(a)***

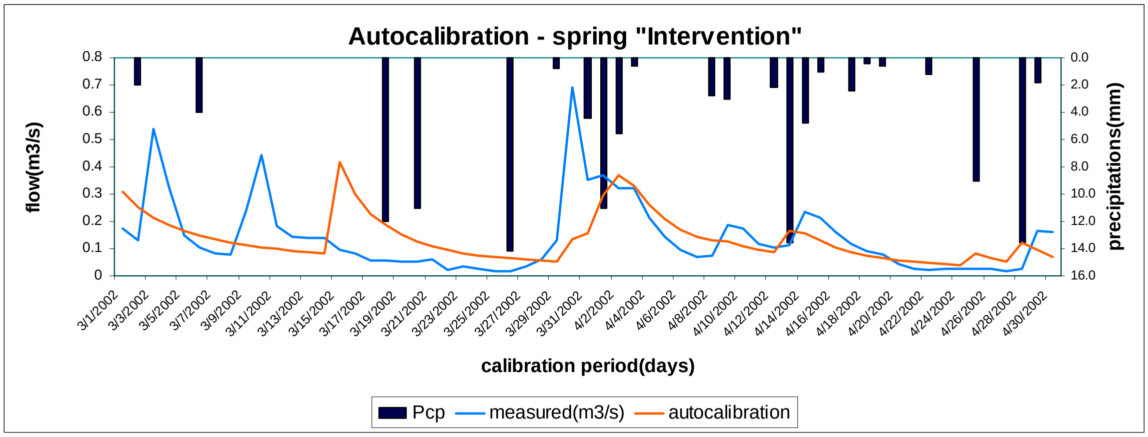
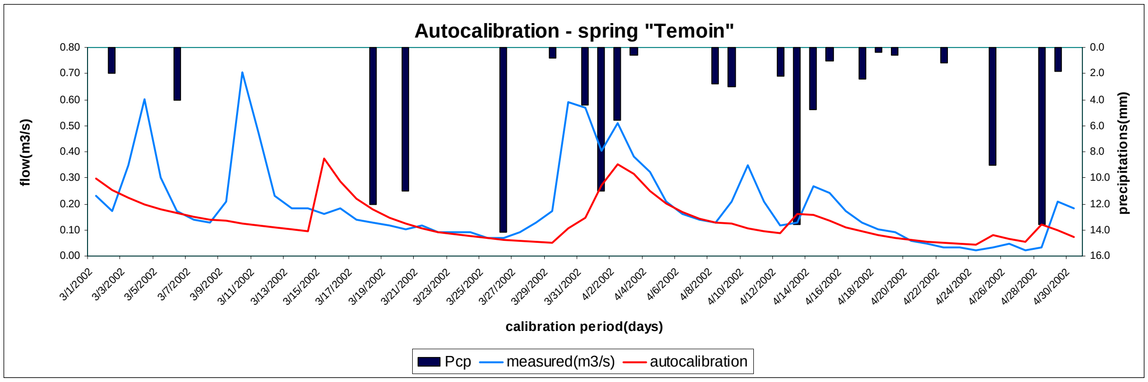


Figure 20(b)



Figures 20: Autocalibration results on spring period, "Intervention" *and* "Temoin".

The best parameter set obtained by autocalibration run on spring was presenting well the surface runoff but it resulted in a shift of the simulated (autocalibration) hydrograph for both sub-watersheds.

Auto calibration – summer and autumn ***Figure 21(a)***

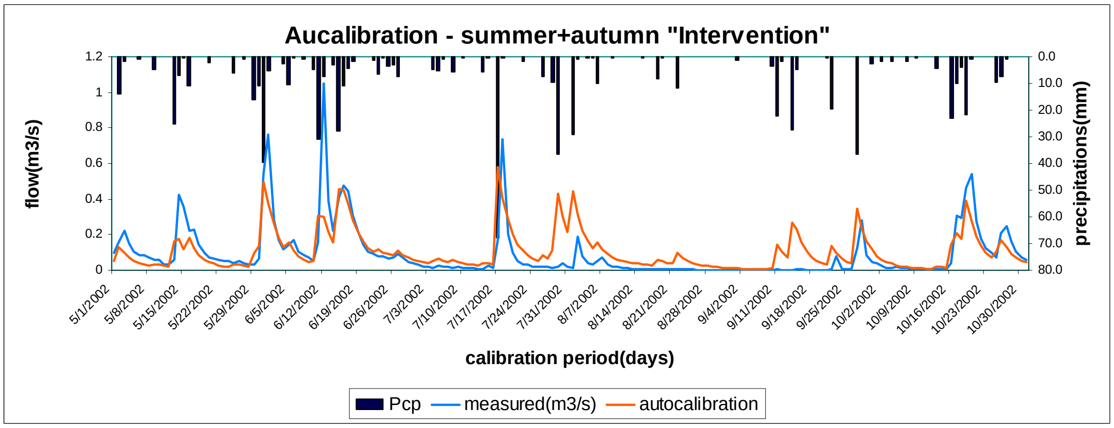
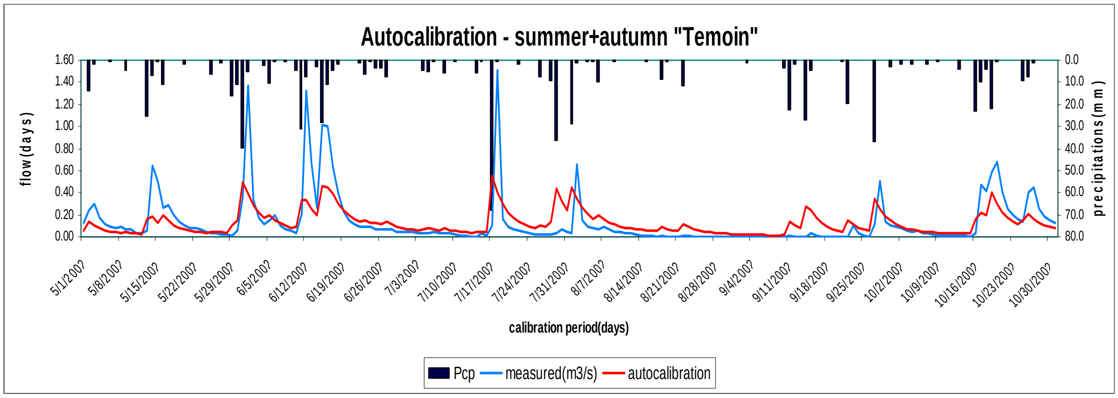


Figure 21(b)



Figures 21: Autocalibration results on summer and autumn periods, "Intervention" *and* "Temoin".

For the autocalibration run on summer and autumn periods, the error between the measured and the simulated results were reduced and the presentation of peak flows was poor, which resulted to an underestimation of the runoff strongly considerable for the sub-watershed *"Temoin"*.

4. Conclusion

All runs done by using autocalibration seem to have a similarity on their results; it was observed on all cases an underestimation of surface flows and doubtful results for the suggested parameters values changes. Mainly, the values of parameters removed and used as fixed were taken as to be one of reasons to obtain such results. Among those parameters the mostly considered to affect were the soils characteristics parameters and curve numbers. These fixed parameters forced the model to search appropriate value for other parameters used in autocalibration, thus resulted in some exaggerated values.

Curve number updates with time

SWAT automatically updated the curve number daily based on changes in soil moisture. The initial values were based on given values in SWAT2000, which were already reduced up to 20% in '*Intervention*' and by 10% in '*Temoin*' sub-watersheds (Deslandes, J., et al., 2006) from the suggested values in SWAT. During autocalibration, the curves number updates lead to a smaller value of them, resulting in underestimation of surface runoff prediction (*Figures 20 and 21*). This was considered as one factor to influence water missing on the surface.

Other parameters changes

The parameters values suggested by the autocalibration results did not satisfy. Some were with high values number and others were too much minimized. In addition, the parameters values given by the auto calibration were depending on which parameters supplied to the auto calibration and which period data were matching with their corresponding physical process. These were observed by running many tests with different parameters.

Suggested parameters values by autocalibration

The autocalibration provided the predicted flow results together with suggested changes on the parameters set; this gave the presented results in figures 19, 20 and 21. The corresponding outputs were often not matching with the reality. The objective function by searching minimizing the error is not limited to the values extends and sometimes obtained values were exaggerated for some parameters. In addition the parameters values obtained by the autocalibration failed to be applied on the whole period of simulation, it seems those values were limited to periods they belongs and when run in other periods they are no longer working well because of many processes involved now and other parameters influence on them.

However it helped much in understanding how parameters were changed according to their dependences between them. This gave enough information for carrying out the manual calibration which needed enough knowledge of the conception of things inside the model.

V.2.2. Manual calibration

Supported by techniques of sensitivity analysis too, same parameter’s set from the autocalibration were optimized during the manual calibration.
The parameters were adjusted based on values close to the previously calibrated values in SWAT2000 in order to be close to the reality. The measured values were compared with predicted ones at every change of a certain parameter. This took time but it was the best way for observing the parameters change and their impact on different periods of simulation. The manual calibration was done over the whole period of simulation in order to avoid dependence of parameters on a particular period of time.

Aim

The aim was to bring the optimized values to better estimates that allow the model to represent the physical conditions of the area.
That was controlled by a certain group of criteria which were checked at each simulation and this was done in order to improve the model performance.

Model performance

1. Statistical performance

The parameter sensitivity analysis provided insights on which parameters contribute most to the output variance due to input variability. The model's accuracy with respect to measured data was evaluated according to three statistical indices: (i) the Pearson correlation coefficient (*r*), (ii) the Nash Sutcliffe coefficient (N-S), an indicator of goodness of fit recommended by the American Society of Civil Engineers for use in hydrological studies (ASCE, 1993) — a value of 1.0 (one) indicates a perfect fit between observed and predicted data, while a negative value indicates that the model predicted worse than using the mean of the observed data, and (iii) percent deviation of predicted water from measured data. During calibration, differences between observed and predicted fluxes were minimized by adjusting the selected model parameters. This was analyzed through the comparison of the computed values of these statistical indexes considered as goodness-of-fit indexes. Shown by daily hydrographs produced with the measured and the simulated series, the three statistical indices were observed at each change of parameters.

Pearson Correlation: This is a linear correlation between the measured and simulated values.

$$r = \frac{\frac{1}{n}\sum_{i=1}^{n}(Q_i - \mu_{Q_i}) - (Q'_i - \mu_{\bar{Q}_i})}{\sigma_x * \sigma_y} \qquad \textit{Eq. (9)}$$

value, Q'_i is the simulated value by SWAT, μ_{Q_i} $\mu_{\bar{Q}_i}$ are the mean values for measured or simulated values, σ_x, σ_y are the standard deviations for measured or simulated values and n indicates the number of daily observations.

Nash-Sutcliffe: This shows a good adjustment of peaks between measured and simulated series.

$$N.S = 1 - \frac{\sum_{i=1}^{n}(Q_i - Q'_i)^2}{\sum_{i=1}^{n}(Q_i - \mu)^2} \qquad \textit{Eq. (10)}$$

Where Q_i is the daily measured value, Q'_i corresponds to the simulated value by SWAT, μ represents the measured mean value for the simulation period and n is the observations number for compared values.

Deviation: this shows the model capacity to reproduce the flow volumes observed for hydrological system of the area during the period of interest.

$$D_v(\%) = \frac{V * - V}{V} * 100 \qquad \textit{Eq. (11)}$$

Where $V*$ is the simulated flow volume while V is the measured one for the hydrological system of the area.
The calibration was done using the above three indexes, the objective was to minimize the errors between measured and simulated values, this was accomplished by adjustment of the concerned model parameters.

- **Results**

By changing parameters one by one and check what could be the effect of that parameter according to the output changes, the manual calibration carried obtained following parameters values for the whole period of simulation. The difference with the auto-calibration, the manual calibration was done over the whole period of simulation; no particular period was done separately.

Parameters values

Table 4: Winter period obtained values for the watershed

Winter period parameters - values for the watershed

Parameters	unit	Definition	scale (file)	Initial values	Obtained values
Smfmx	mm/deg C/day	Maximum melt rate for snow	BSN	4.5	6.5
Smfmn	mm/deg C/day	Minimum melt rate for snow	BSN	4.5	6.5
Sftmp	deg C	Snowfall temperature	BSN	0	0.6
Smtmp	deg C	Snow melt base temperature	BSN	-1	-2
Timp	none	Snow pack temperature lag factor	BSN	0.45	0.46
SNOCOVMX	mm H2O	Minimum snow water content that corresponds to 100% snow cover.	BSN	280	310
SNO50COV	none	Fraction of SNOCOVMX that corresponds to 50% snow cover.	BSN	0.2	0.3

Table 5: New parameters values obtained by manual calibration for other parameters

				"Intervention"		"Temoin"	
Parameters	**unit**	**Definition**	**scale (file)**	**Initial value**	**Obtained value**	**Initial value**	**Obtained value**
Alpha_Bf	days	alpha factor for groundwater recession curve	HRU(gw)	0.6	0.9	0.9	0.95
Gw_Delay	units-days	groundwater delay	HRU(gw)	7	5	7	5
Rchrg_Dp	none	recharge to deep aquifer	HRU(gw)	0.15	0.3	0.15	0.15
shallst	mm H2O	depth of water in shallow aquifer	HRU(gw)	500	5000	500	5000
Gwqmn	mm H2O	threshold depth of water in shallow aquifer	HRU(gw)	395	1000	200	1000
Esco	none	soil evaporation compensation factor	HRU or BSN	0.85	1	1	1
Lat_ttime	days	lateral flow travel time	HRU	0	1	0	1

Manual calibration hydrographs

Figure 22(a)

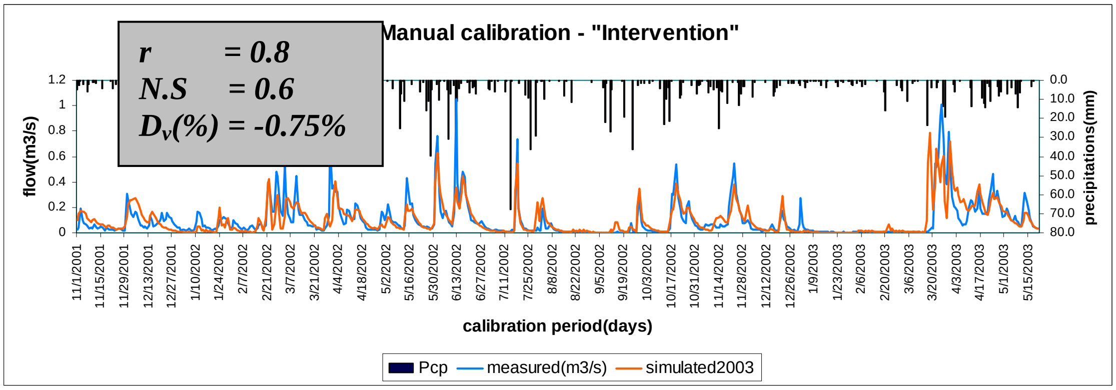
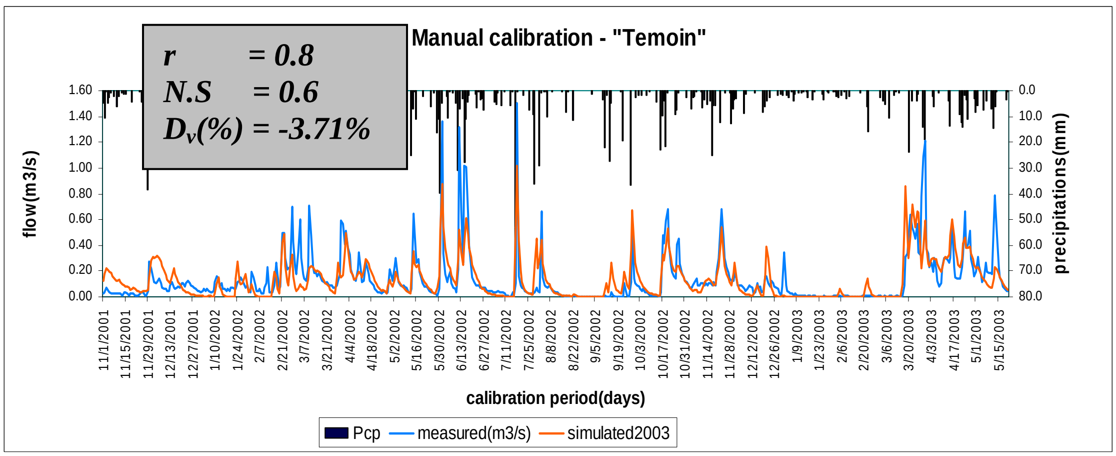


Figure 22(b)



Figures 22: Manual calibration results along the whole period of simulation, "Intervention" *and* "Temoin".

The manual calibration resulted in a good fit between measured and simulated series; the obtained results were not too much changed compared to initial values used from SWAT2000.

- **Conclusion**

Not all of the parameters identified by sensitivity analysis were modified during calibration. Based on that, a calibration was performed for a limited number of influential parameters; the calibrated model's accuracy was evaluated based on its performance in this phase of calibration. Parameters other than those identified during sensitivity analysis were used in calibration primarily due to the goal of matching the model as closely as possible to processes naturally occurring in the watershed. Therefore sometimes it was necessary to change parameters other than those identified through sensitivity analysis because of the type of the error observed in predicted variables. Parameters chosen except those identified during sensitivity analysis were not randomly selected, but rather based on calibration parameters identified in the SWAT2000 calibration published results (Michaud, A. et al., 2006)

Peak flow simulation

Simulation of extreme flow events is also important in runoff predictions. The model predictions could not simulate well the observed peak flows as they were mostly generated by the peak rainfalls events considered as with a high return period i.e. occurrence of those events was considered as negligible, mainly considerable in summer periods. Both '*Intervention*' and '*Temoin*' sub-watersheds surface runoff were underestimated, shown by the manual calibration results where the volume deviations were negative values (*Figures 22*).

2. Physical performance

The hydrological performance was given by two parts, its statistical and physical performances. This last one is the most problematic part of the model to arrive at a good representation of some realities in the watershed area.

- **The water distribution**

The model's water distribution is divided in two parts: the surface flow and the subsurface flow. The surface flow as observed (given by recent data observed on field collected values – year2005), it showed one third of the water coming from precipitations was given as surface flow and two third were going trough percolation in the sub subsurface areas. The subsurface water is water distributed to laterals, tile drains and shallow aquifer.

Figure 23(a)

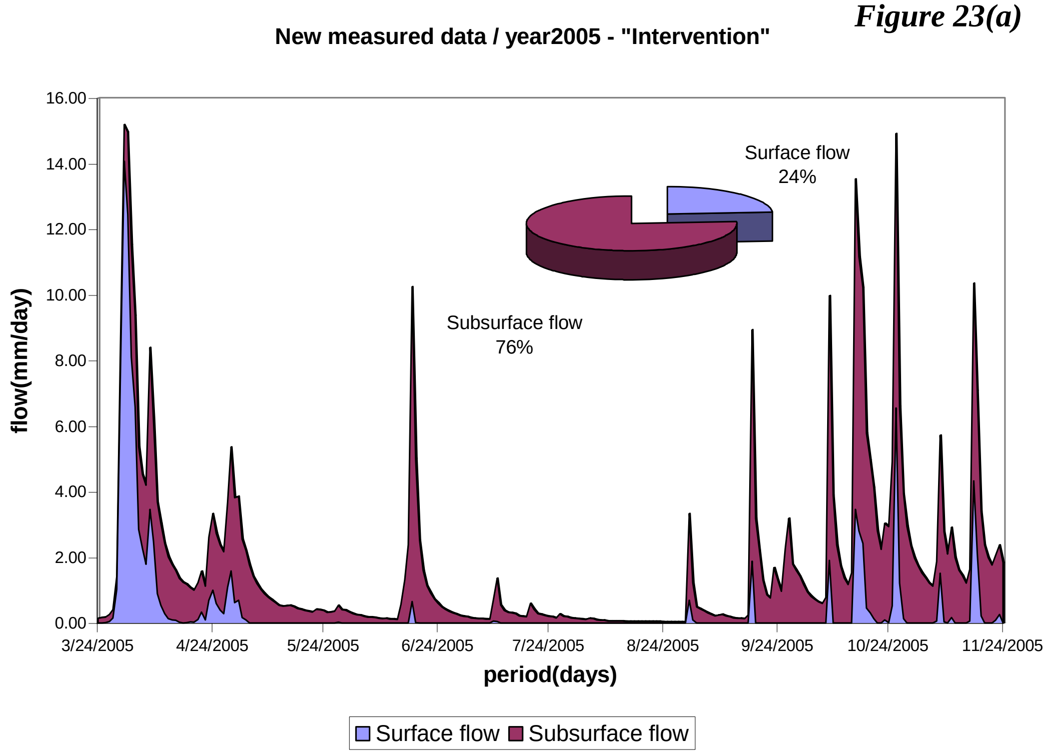
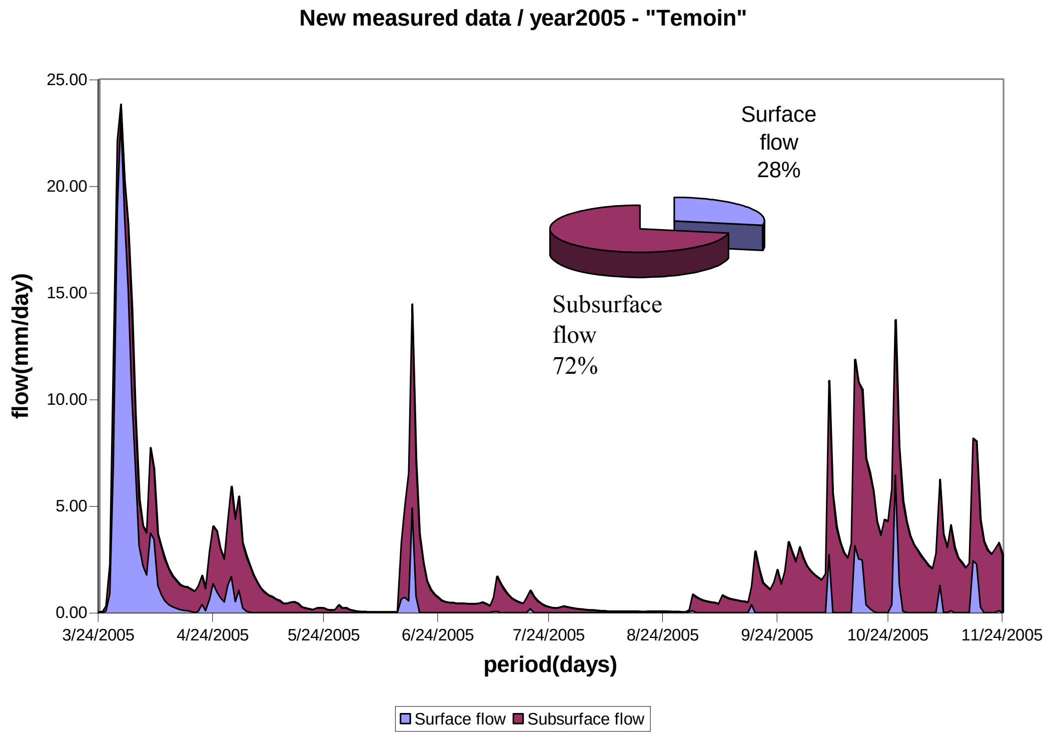


Figure 23(b)



Figures 23 : Actual situation of surface flows and subsurface flows, Year 2005, “Intervention*” and* “Temoin*”.*

- **Failure of the model**

The model was supposed to perform well all these realities and if not it had to be adapted in conditions where it could give the expected results. With the results obtained with manual calibration approximately 43% of generated water from rains was on the surface and the other 57% was going to subsurface area on “*Temoin*” while on “*Intervention*” more water was going into the subsurface areas, around 67% and 33% on surface (following *Figures 24*). These were obtained by yearly simulation on a crop/rougemont HRU for year 2002.

Figure 24(a)

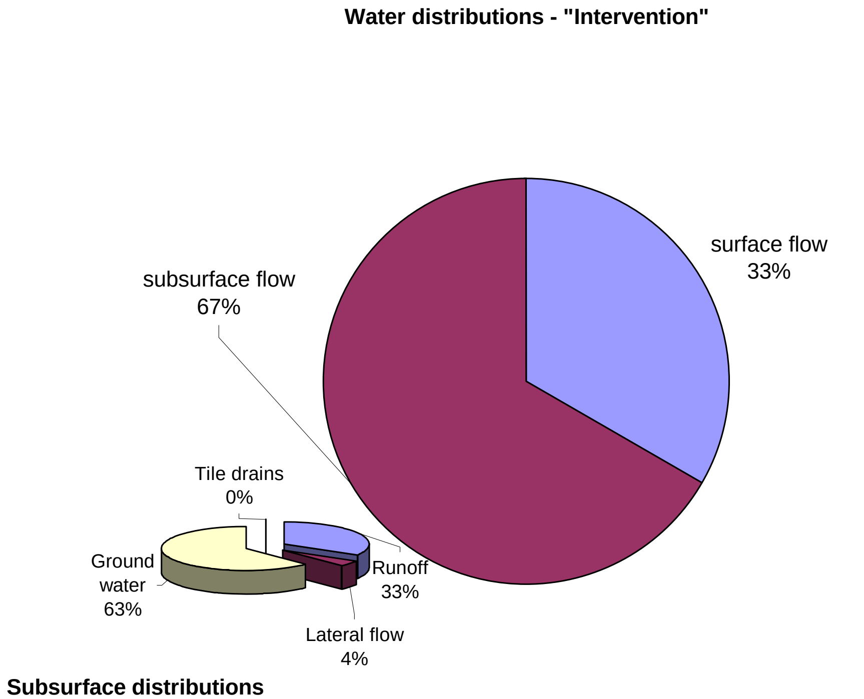
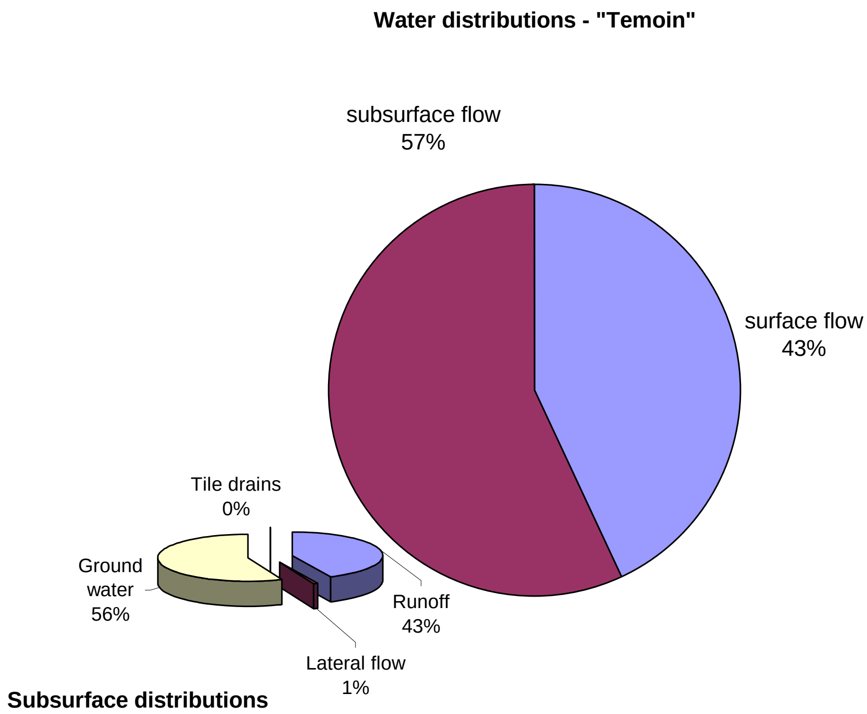


Figure 24(b)



Figures 24: Water distributions obtained with the model calibrated, "Intervention" *and* "Temoin"*.*

That was the first reality to be faced, another one a very important issue were about the quantity of water passing through the tile drains; its quantity were too small approximately no water was coming through the tile drains to the rivers (0%). This quantity could match a certain percentage according to results obtained in studies done in the same area, about the environmental benefits of tile drainage (Fraser, H. et al., 2001), the phosphorus losses in surface runoff and subsurface drainage waters on two agricultural fields in Quebec (Enright, P. et al., 2003). All these publications discussed on a similar issue about a great quantity of water drained through the tile drains. This quantity is higher than 50% of water coming from precipitations drained to the rivers of the area.

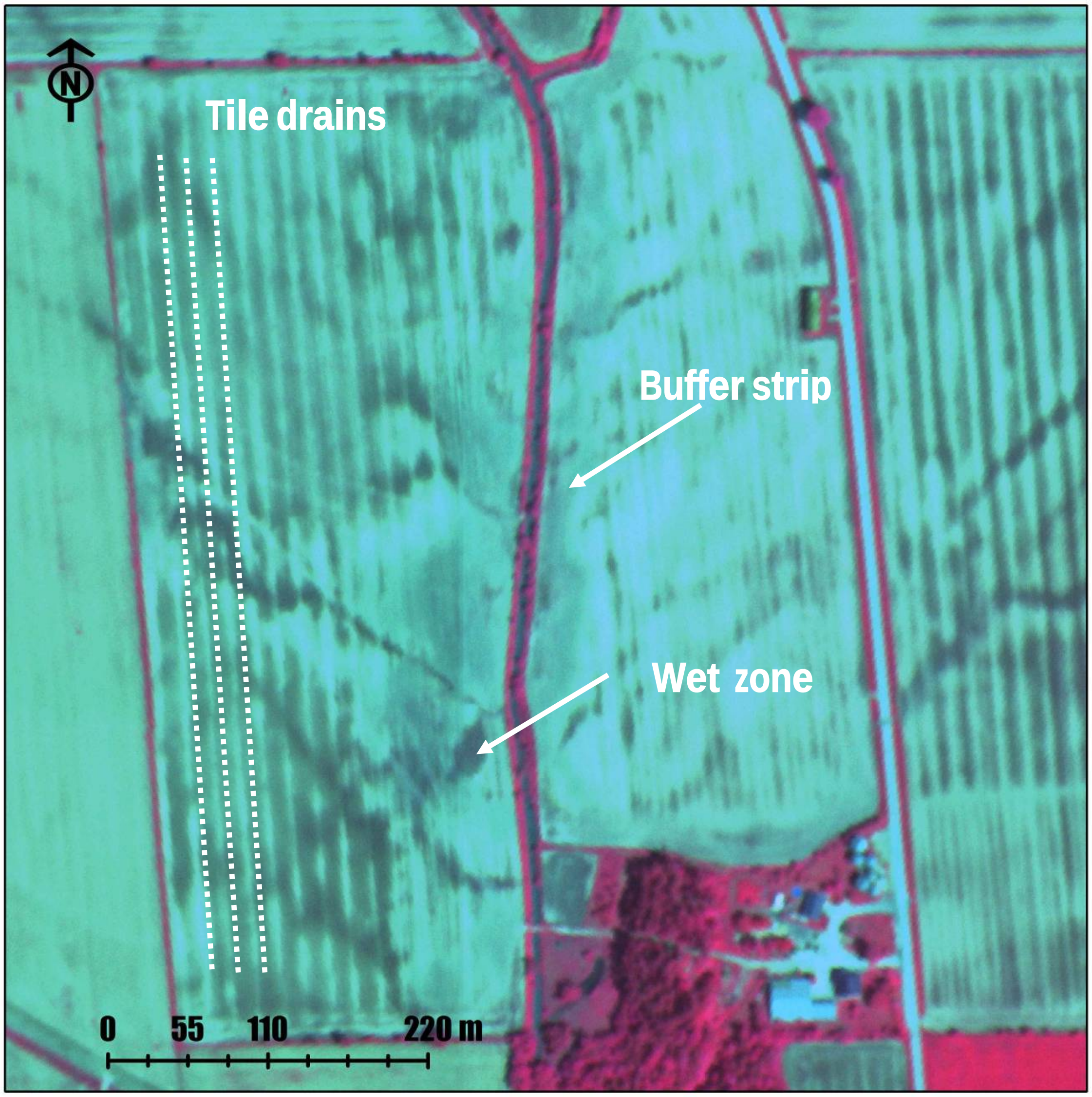
According to results of the model, the big part of subsurface water going to rivers and streams of the area was coming from the ground water "*the base flow*" and water through tiles to the hydrological network was completely insignificant, 0%.
So the next step was to adapt the model through the SWAT source codes which needed modifications for this case. Tiles have to contribute the most compared to other subsurface area, laterals and ground water. This is going to be discussed in details in the next chapter.

V.3. Conclusion

The methodology used to achieve information about sensitive parameters and model inputs for hydrology in SWAT, was achieved. An LH-OAT sensitivity analysis for hydrology allowed for the screening of the large set of input parameters and the focus on sensitive parameters lead to a better understanding of the system. A selected subset of parameters was used for the model calibration. The results of auto calibration brought the parameters to a good adjustment and helped the manual calibration process to a better estimation of the parameter values and it resulted in good fits to the observed flows.

The model improvements on tile drains water quantity calculation became an objective of the following work in the next chapter.

Tile Drainage Modelling



Picture of an aerial image taken with a Duncan 3100 camera in May 2001

CHAPTER VI: TILE DRAINAGE MODELLING

The objective is to improve tile drainage modelling in SWAT in order to predict the path of water and nutrients towards the river in a correct way. This was done by identifying equations related to tile processes. SWAT incorporated the ability of tile drainage but the model was found unsuccessful to give a required water distribution budget on the Walbridge's sub-watershed. The inability of the model to effectively address the importance of flow passing through the tile drains was thus recognized. This was a serious problem as tiles drainage has been proved to be the dominant pathway for N and significant pathway for P in addition much nitrogen transport in the river basin appeared to originate from tile drains.

VI.1. Tile drainage

The term tile drainage refers to those subsurface conduits for removing excess water from the soil. In many areas, runoff water from farm fields, collected in streams through tile drains or small ditches, contains significantly high concentrations of sediment and agricultural chemicals that pollute receiving water bodies during early stages of planting (late spring or early summer). Agricultural chemicals include chemicals applied through fertilizer, herbicides, and pesticides, and chemicals produced naturally most importantly through atmospheric deposition, fixation, and mineralization. Understanding and dealing with these complex hydrologic, soil, and sediment transport processes have been quite a challenge for modellers, without a correct representation of these processes mathematical models used are becoming invaluable tools to analyze these complex processes and to evaluate land use and best management practices (BMPs) in reducing the damaging effects of soil erosion, sedimentation, and contamination on drinking water supplies and other valuable water resources.

VI. 2. Tile drainage in Quebec area

Due to the wetness of the Quebec region, the predominant practice for promoting drainage of water from agricultural fields in the Pike river basin is through the use of artificial subsurface drainage tubes, also known as tile drainage systems. The region is typical of many other regions of the Quebec where entire watersheds are almost exclusively drained by tile drainage systems. The area is having too much water because of a strong winter which consequently gives a lot of water during snow melting period (early spring March-April). In pike river basin, there are about 60% fields drained and while looking at the Walbridge's twin sub-watersheds scale roughly around 50% of fields are tile drained. Unfortunately, this information was not available at field or HRU scale. So it was supposed that all row crops (corn, oats and soy) were tile drained.

Since the majority of intensively managed agricultural lands in Quebec are subsurface drained, this represented an important presence of tile drains. The majority of

Quebec rivers are receiving water from surface runoff and water from subsurface drainage. The subsurface-drainage is the dominant pathway by which water leaves the field. On average, tile drainage accounted for 79% of the total annual drainage (Enright, P., et al., 2003). Subsurface drainage was considered as one of the practices for preventing the nutrients losses from agricultural lands towards the Quebec rivers. This was confirmed by the results obtained (Enright, P., et al., 2003); the subsurface drainage was taken as an important pathway for P- phosphorus losses from agricultural fields.

Table 6: Measured annual drainage depths, a table from studies done on two agricultural fields in Quebec, results from Enright, P. and Madramootoo, C., 2003.

	2000/2001		2001/2002		2002/2003	
	site#1 (mm/ha)	site#2 (mm/ha)	site#1 (mm/ha)	site#2 (mm/ha)	site#1 (mm/ha)	site#2 (mm/ha)
subsurface drainage	––	96(52%)*	371(93%)	338(89%)	273(81%)	239(82%)
surface runoff	––	88(48%)	27(7%)	42(11%)	64(19%)	53(18%)
total drainage	––	184	398	381	337	293

–– indicates missing data
* values in brackets indicate the percentage of the annual total.

However, the tile drainage could enhance transport of soluble agricultural chemicals from fields to surface waters (Zucker and Brown, 1998). Much of the nutrients transport in the stream's water appeared to originate from watersheds where tile drainage is common (Goolsby et al., 1999). In order to simulate variation in water quality in this case, the hydrological model must account for the influence of tile drainage pathways.

Because of the underestimation of tile drain water in relation to the water budget of the area, the hydrological model had to be adapted to the real situation. This was done in order to obtain a reliable hydrological model which was intended to simulate properly the dynamic behaviors of the water and its constituents' movements. So a major modeling effort was needed to develop and implement the varying physical tile processes in the watershed. This was to adapt the existing model to the actual situation of the area by means of corresponding governing equations.

VI.2. Expectations on Walbridge's case

Hydrological simulation

This particular model had to meet certain criteria in order improve to the model and validate its capacity to simulate tiles drainage flow on the two experimental sites. It has to take into account the quantity of water passing through tile drainage which must result in a higher fraction than other sources of water contributing to the Quebec rivers flow (*Table 6*). To provide the information about the location and characteristics of existing tile drainage systems, the drainage information were required in prepared and used in management files in SWAT.

As an open source code, the SWAT model allows to cooperate when it requires modifications for adapting the model to a situation. Model operational for agricultural best management practices was the reason of touching the source codes. The presence of tiles was the major concern to the model improvements. By accurately reproducing the water and nutrient balance and this reality, it is important that the model is able to represent the different pathways for the water since this affects the simulation of the management practices of the area.

The model has three major components: hydrology, soil erosion and sediment transport, and nutrient and pesticide transport. These model components might be based on approximate analytical solutions of the physically based governing equations, and preserving the dynamic behaviors of the water, sediment, and accompanying chemical movements. These and other model improvements on Walbridge watershed were done in order to successfully simulate the water movement which carry nutrients and sediments, and all agricultural chemicals commonly used in agricultural fields according to where it passes. In that way the transport of sediments, phosphorus and nitrates by the surface runoff waters and tile drainage waters exiting the agricultural fields would be well simulated. Thus the impact of nutrients loads passing there would be determined.

The NO3-N nitrogen was among the most problematic source of pollution. Known highly soluble in water; amount of NO_3-N contained in runoff, lateral flow and percolation are estimated as products of the volume of water and in this case it shows the importance of obtaining right results within the hydrological system.

VI.3. Modification of SWAT modules

VI.3.1. Tiles flow – SWAT2003

Actually, the generated flow distributions with SWAT simulation are summarized per each HRU according to land use and soils properties. The mainly focused output was the water yield (WYLD), this was the total amount of water leaving the HRU and entering main channel. It was estimated to be equal to:

$$WYLD = SURQ\_CNT + LATQ + GWQ - TLOSS - \text{pond abstractions} \qquad \textit{Eq. (12)}$$

Where $WYLD$ is the water yield (mm H_2O), $SURQ\_CNT$ is the surface runoff contribution to stream flow in the main channel (mm H_2O), $LATQ$ is the lateral flow contribution to stream flow (mm H_2O), GWQ is the groundwater contribution to stream flow (mm H_2O), $TLOSS$ is the transmission losses (mm H_2O) i.e. water lost from tributary channels via transmission through the bed. The pond abstractions were not considered as it could be optional according to the situation.

In case for tile drainage presence, in the water yield, tile flow was added and *Eq(12)* became:

$$WYLD = SURQ\_CNT + LATQ + GWQ + Tileflow - TLOSS \qquad \textit{Eq. (13)}$$

Eq (13) is the equation used and it was giving the estimated tiles flow on each HRU at each simulation.

The capacity of soils to drain water was the number one to be focused on. The reason was that depending on their characteristics these determine the amount of water to be drained and reaching the tile drains. The percolation through soil layers, the types of soil and their characteristics were taken into consideration because of the importance to the model to simulate properly the movement of water through the soil profile. This was the most interesting part of processes present in SWAT, how they were represented and the order of procedures which could affect the water distributions from surface to the subsurface areas. This was done and its impacts were checked on hydrology of the area and nitrogen quantity from the tiles and laterals pathway.

First of all, on earlier version of SWAT2003, SWAT2000 simulated high quantity of water through the tiles compared to SWAT2003 even if its quantity was still underestimated but it gave something. By taking this into consideration, it was found that there were important differences in subsurface water distribution on computation systems between the two models, SWAT2000 and SWAT2003.

The water that enters the soil may move along one of several different pathways. The water may be removed from the soil by plant uptake or evaporation. It can percolate past the bottom of the soil profile and ultimately become aquifer recharge. A final option is that water may move laterally in the profile and contribute to stream flow (SWAT2003 Theoretical Documentation).

All these distributions were described by algorithms located in SWAT source codes located in the files, *percmicro.f* and *percmain.f (appendices 2 and 3)*. The subroutines *percmicro (ly1)* computes percolation and lateral subsurface flow from a soil layer when the field capacity is exceeded while the *percmain* is the master soil percolation component where the update for the soil profile water is done after its distribution to the different places i.e. where it can be hold through the soil profile. The *percmicro* is called by *percmain* for giving results of obtained values of these components lateral, tiles and seepages from soil profile (*Appendix 10: SWAT2003 Flow Chart).*

VI.3.2. Tiles flow – First changes

1. SWAT2000 and SWAT 2003 subroutines differences

The subsurface water areas of distribution considered were the lateral flow, the tiles flow and the ground water: percolation to the shallow aquifer and the deep aquifer. Concerning the SWAT2000 and SWAT2003 differences on tiles flow calculations, SWAT2000 was allowing water to go in tiles from the soil profile level, there was a quantity of water calculated at each layer profile, exceeding from the field capacity, called soil water excess (gravity drained water) (*sw_excess)* (mm H_2O) (*appendix 1*). This water was distributed either to tiles if they are located in that layer and if not to the laterals. The choice was first given to the tiles when water was exceeding in a layer where tile drains are present.

In SWAT2003, the subroutine lines for soil water exceeding the field capacity which could contribute to tiles flow were deactivated in *percmicro* subroutine and the only water coming to the tiles was water from the shallow aquifer (*appendix 2*). This was set as when the shallow aquifer level exceeds the drain level that is when tiles flow could be obtained. The contribution of the shallow aquifer had to be positively satisfied while the water level in shallow aquifer (*wt_shall*) could exceed the tile drain's level.

In SWAT the shallow aquifer is separated by the deep aquifer by a layer called "*deep impervious*". To know the shallow aquifer water level, the depth at which the deep impervious is located must be determined (*dep_imp*) in the source code, taken as the impervious layer location from the ground level. Together with the subsurface drain (*ddrain*) depth at which tiles tubes are layed from the ground level, they could determine the location of the tiles from impervious layer level (*appendix 2*). The drains in Quebec are set to 900mm below the ground and the *"dep_imp"* is defined in SWAT to be located at 6000mm below the ground level source code (*Appendix 4: readhru* and *readbsn*). This showed a big gap between drains level and the impervious layer level to be filled before the water in the shallow aquifer could reach the tiles level for allowing water to flow in tiles, the difference was approximately equal to 5000mm depth of water to be filled.
This gave a trial with the parameters responsible of determining water level in the shallow aquifer. The initial water depth in the shallow aquifer, (*shallst*) parameter was increased by expecting to increase the water table in order to reach tile drains level. As a result, the ground water table continued to increase without success of obtaining its contribution to the tiles. The conclusion was that in SWAT2003, the ground water contributions to streams were calculated apart and apparently there was no relation of water entering through the shallow aquifer from the recharges with the tiles drainage. New modules with two methods, each with a different way of obtaining water in tiles were inserted and compared to SWAT2003 option.

2. SWAT 2003 soil water percolation – order of procedures

The *percmain* as the master of the soil percolation component performs this by using the values from other subroutines. The calls command located in *percmain* are coming one after the other that means their sequence in processes depending on which values are needed. All processes in *percmain* are the processes related to water entering soil layers. As described by the SWAT flow chart: appendix 10, the main called subroutines by *percmain* are:

...... call *percmain*
- call *percmacro*
- call *percmicro*
- call *sat excess*

This is the order how they are successively called by the *percmain*. The *percmacro* is called for the calculated water through cracks, for this if they exist, their option is activated and they are calculated from overland flow. The *percmicro* gives the calculated tile flow, lateral flow and percolated water through layers. The *sat_excess* does the redistribution of soil water if it is still above field capacity.

In SWAT2003, the tile flow computation was located in *percmain* related to the shallow aquifer contribution. Its computation was coming after the call *percmicro* command. This means the water was distributed first in *percmicro* for the lateral and seepages calculations also done and tiles were waiting and computed after in *percmain*.

Its calculation was done from what was remaining from laterals (*Appendix 3:* SWAT 2003 *percmain,* before changes).

The new improved way of computation and distribution was to let water distribution for tiles, laterals and seepages calculations being done in *percmicro* and being called all distributions completed (*Appendix 5:* SWAT2003 *percmicro,* First changes). So the computation of tile flow in *percmain* was shifted to the *percmicro* where it replaced the deactivated method of tile flow. Together with the laterals their values were computed in *percmicro* and were given to the *percmain* when *percmicro* called.

3. Three cases tested

The modifications started with the modules for tile flow computation in the *percmicro* subroutine. As discussed above in this subroutine water is now distributed to tiles and laterals. These variables values are used in *percmain* subroutine after the *percmicro* call command for the final updating of the seepages through the soil profile. When tile drains are located in a particular layer, tiles drain come to the first place in calculations which means the water exceeding is first given to tile drains otherwise it is distributed to the lateral.

Primarily, the deactivated part in SWAT2003 was tested but did not improve the distributions. Another way of calculations used was based on the SWAT2003 theory of water percolation through the soil profile described in its theory (SWAT2003 Theoretical Documentation, page 150). The modules added and tested were from the SWAT2000 option modified, SWAT-M this is a modified and tested version of SWAT (Du, B. et al., 2005) and SWAT2003, they are all described in *Appendix 5*.

Case (1) SWAT2000 routine modified

This is the soil water percolation method elaborated for giving water to tile drains as described in the theory of SWAT, water percolates through the soil and if the amount of water in a soil layer exceeds field capacity (gravity drained water) called *" sw_excess"*, the tile flow *(lyrtile)* is calculated, this condition is always verified when the second layer temperature is above zero i.e. when frozen no water is supposed to flow between layers (*Appendix 5*). At this time SWAT2000 soil water percolation (option modified based on theory) was giving more chances to tiles to retain water from the soil in layer where they were located.

Case (2) based on the works of Du et al. (2005)

This was a result of a research done with SWAT model by simulating tile flow and pothole landscapes that are common in much of the Corn Belt and Great Lakes states (USA). In this study SWAT was modified to simulate water table dynamics and linked with a simple tile flow equation. The SWAT-Modified (Du, B. et al., 2005) were including new algorithms added to SWAT for simulation of potholes (closed depressions), surface tile inlets, and aeration stress on plants. In the Walbridge's case potholes were not considered what disqualified this case.

Case (3)

This is the usual SWAT2003 subroutine of computing tile flow from shallow water table depth. As earlier explained, there was still a problem of the *dep_imp* set at a higher level, 6000mm which could not be filled easily by the model.

4. Case selection

The three cases were tested on: how they were predicting the amount of water through the tiles and its quantity flowing to the rivers from the two sites. The following table shows by each case the predicted tiles flow with the corresponding water yield during the year 2002. The year 2002 was selected for the observations of the changes done; hydrologically it was known to be a stabilized year. A corn cropped field on rougemont type of soil, known well drained, was used to check what could be the predictions for tiles flow.

Table 7: Comparison of obtained results with the three tested cases on yearly tiles flow predictions

Cases	case1		case2		case3	
Sites	"Intervention"	"Temoin"	"Intervention"	"Temoin"	"Intervention"	"Temoin"
Water yield (mm/year)	429	525	1222	1343	381	480
Tiles flow prediction (mm/year)	215	288	824	859	0	0
%	50%	55%	67%	64%	0%	0%

The case (2) was not relevant to the Walbridge's case as its method were linked to potholes simulation; the Walbridge's case was not presenting those characteristics. The only reason to use it was to see how much it could predict on the tiles flow. Case (1) and case (3) compared on yearly simulations, case (1) was predicting more than 50% of water flowing to rivers coming from the tiles (*Table 7*). On both sites it gave enough water through the tiles while case (3) results showed like no water was passing through the tiles. Hence, case (1) was found to be the most applicable and it was chosen for further improvements on tiles flow simulation inside the SWAT source code.

5. Results of First changes

Using case (1), this resulted with an increased tile flow quantity contributing to the rivers. The ground water – base flow to the channel decreased for both the two sub-watersheds. The laterals did not change too much, only the tiled drains fields presented some decrease in water quantity through laterals (*Figures 26*). The first changes done affected only the soy, corn and oats fields mentioned as tile drains fields (shown on the following figures 25, 26, 27).

Figure 25(a)

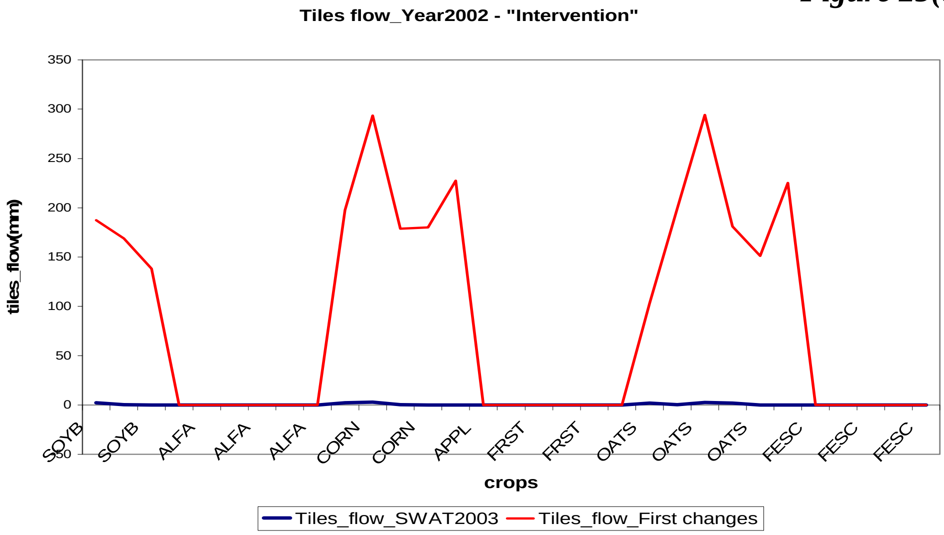
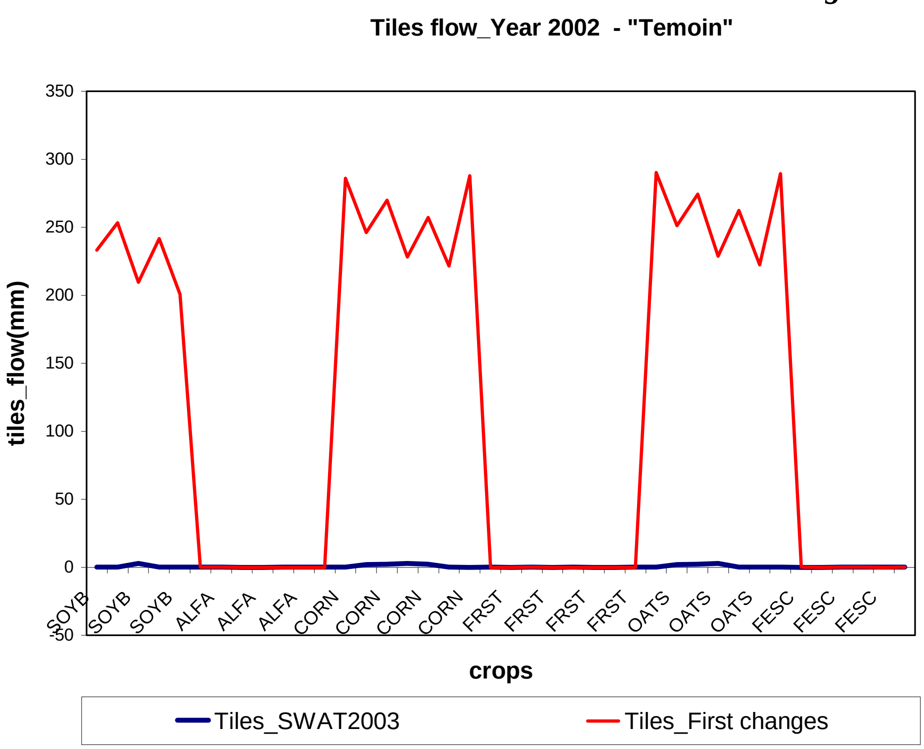


Figure 25(b)



Figures 25: Yearly simulation results, tiles flow increase after first changes, “Intervention” *and* “Temoin”.

Tiles flow increased considerably, for yearly simulation the water increased from 0mm to approximately 300 mm in HRUs cropped drained. This made a significant change mainly because of sequence of procedures modified in SWAT processes.

Figure 26(a)

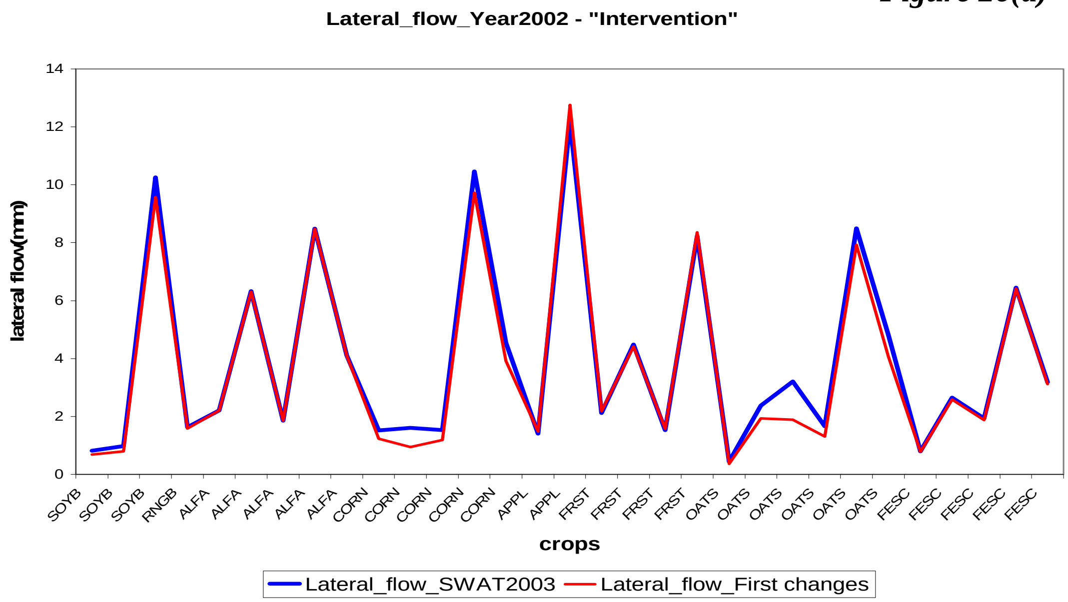
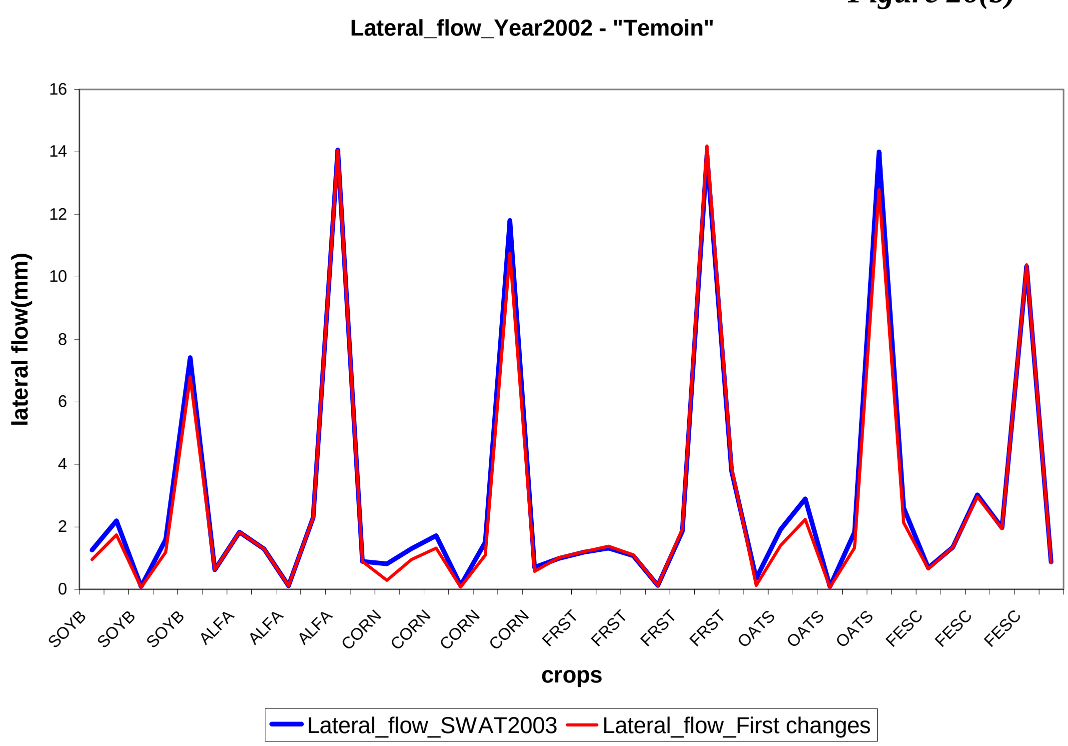


Figure 26(b)



Figures 26: Yearly simulation results, laterals flow increase after first changes, “Intervention” *and* “Temoin”.

The lateral flow did not change apparently too much, but they decreased in those HRUs cropped tile drained and its quantity for year 2002 varied between 0mm and 14mm for both sub-watersheds which was really a small amount of water per year.

Figure 27(a)

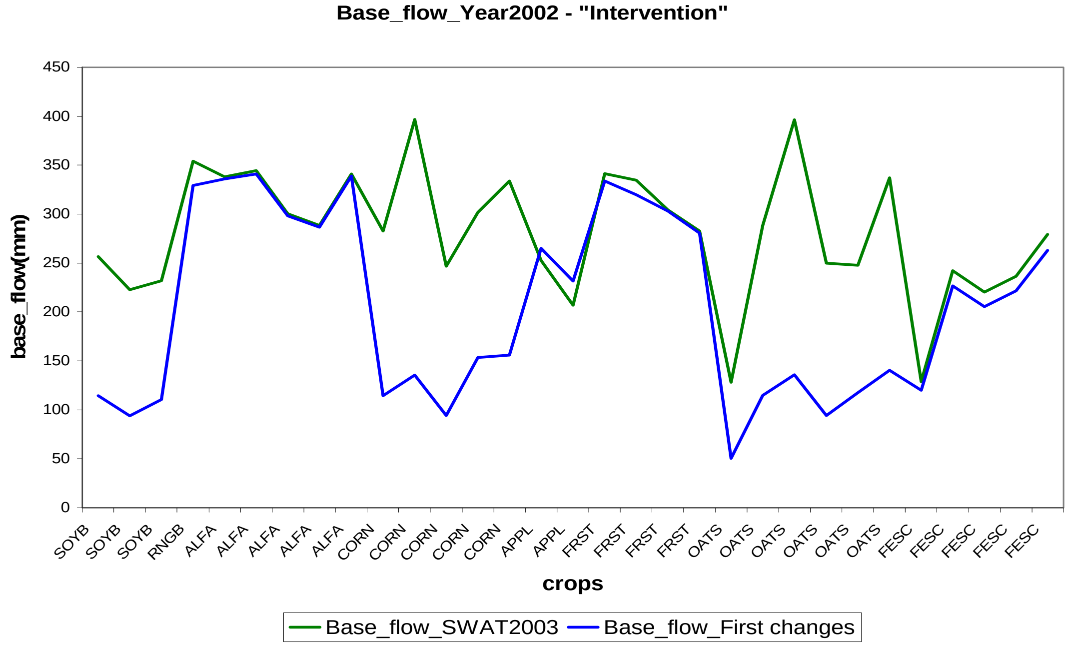
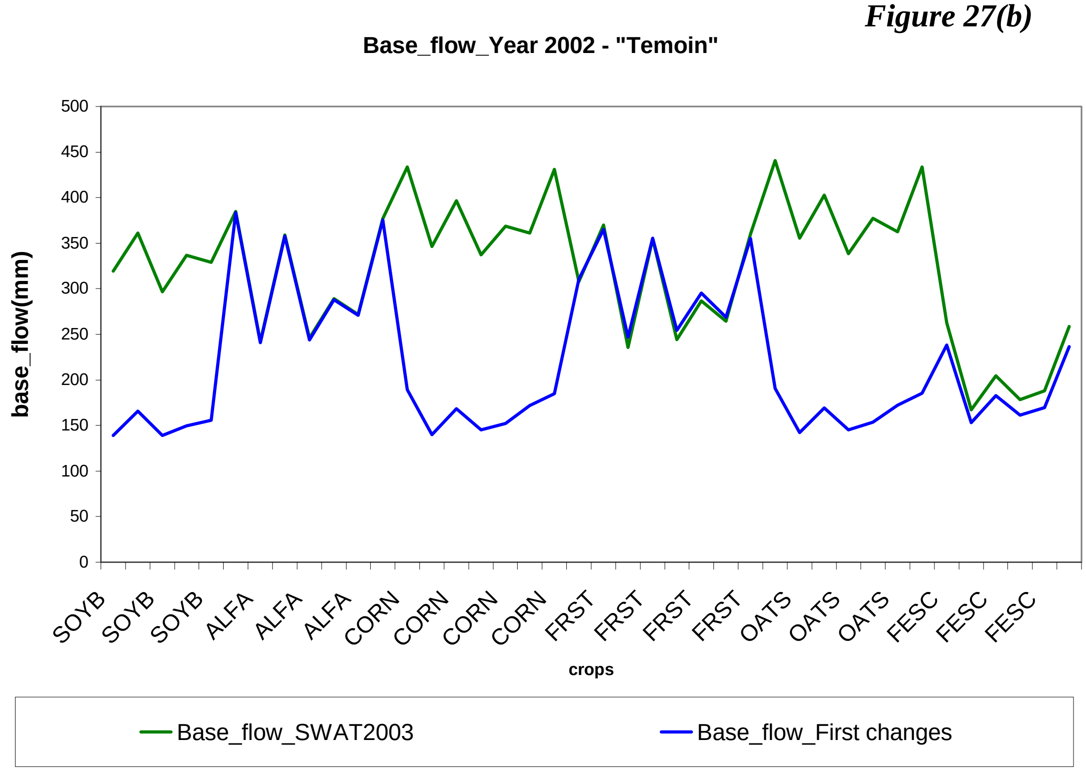


Figure 27(b)



Figures 27: Yearly simulation results, base flow reduction after first changes, “Intervention*” and* “Temoin”.

The base flow decreased too much in the tiles drained HRUs, the figures (27) are showing it decreased around 150mm from their values before changes. This proved a significant change caused by the modules and processes order which affected the base flow contributions to rivers.

The high amount of water going to tiles was linked to the way water was defined by modules for its seepage; SWAT estimates each day a certain amount to percolate through the soil profile (*Appendix 6*). It was observed that the way water was percolating was not clearly defined; it was not taking into consideration the soils properties. More precise and limits to water seeping into the soil were inserted. This was answered by another change to be done in *percmain* about the water percolation through different soil layer by taking into account the soil properties of each layer.

VI.3.3. Tiles flow – Second changes

1. Improved water percolation through soil layers

The existing method for soil water percolation was calculated through the whole soil profile; this was giving a summary of water supposed to percolate through the whole soil profile. It was observed that water was not controlled according to soils properties for each layer. As well known the soils physics properties differ from soil's type. Since in the case (1) modified SWAT2000 soil water percolation was considering the percolation through each layer of the soil profile. This was found right to the seepage to work the same by taking into account the soil properties for each layer. Here the focus was on the soil conductivity properties which could limit amount of water passing through each layer and that was very important and matching with the reality as amount of water to percolate is given by the soils properties and the amount of water available. A new option of modules were inserted in the source codes and two cases were to be chosen; the first one was the original case in SWAT2003 and the second the new added one (*Appendix 6*). The original method computed the percolation from soil layer (*sepday*) by using the amount of water in soil that exceeds field capacity, *"sw_excess "*. This was done for each layer of the soil profile and it has to stop when it reaches the last layer where it verifies if there was water exceeding and give it to the aquifer.

The advantages of case (2), was to verify an important condition before allowing water to seep through the soil profile, calculated for each layer. The soil conductivity (*solcon)* of a soil was limiting the soil conductivity; in this case it has to be equal to the saturated hydraulic conductivity of the soil layer (*sol_k)*. In addition that was not the only condition to let water passing, it has to verify the saturated hydraulic conductivity (*sol_k)* between the successive layers and decide to take the minimum between those two values *(Appendix 6*). Because the quantity which has to pass must be equal to the capacity of the next soil layer to let it pass and it depends too to the quantity which has been accepted to pass by the previous soil layer. This condition did not exist in the original seepage computation routine. It was an advantage for limiting the water seeping through the soil and in case water is too much in a certain layer it had to go to the tiles first if they are in that layer and if not to go to the laterals.

2. Results of Second change

This made a significant change in water distributions, mainly for base flow and tile flow. In addition, the water seeping was supposed to decrease as water was restricted to pass easily through the soil profile; the conditions were not allowing too much water to reach the tiles and these also kept too much water on the surface to flow to rivers and streams what was not arranging the problem. The soils conductivity of soils in "*Intervention*" and "*Temoin*" were varying between 14.6 and 275 mm/hr. the dominant soil on the "*Intervention*" was the "*complexe Mislsl*" (47%) which has a soil conductivity of 68.5 mm/hr, this is not a very high soil conductivity value which could influence water to seep in a big amount through the soil. The HRUs with this type of soil were observed to present high surface runoff and low tiles flow. on the "*Temoin*", the dominant soil was the milton (30%) with a high conductivity of 275mm/hr followed by the *"complexe Mislsl"* (25%) with another type in a significant portion of 24%, called *"terrenoire"* with a low hydraulic conductivity of 68.5mm/hr. Theses hydraulic conductivities were measurements tested and obtained from fields already under drained conditions, so they were fixed values to be used without changing them in order to increase the tiles flow. These soils properties were one of the factors influencing the reduction of water through the tiles and as they were fixed results were taken as obtained.

Another factor to influence this could be the soils layers depositions and their different characteristics on the two sites as well. Even if a soil layer could have a high conductivity its capacity to drain water is depending by the previous layer which affect the next layer, so the different combination of soils could affect the drainage of water through the soil profile. This was taken into consideration by the new option case (2) seepage method.

One more factor to influence again was the type of crops, the dominant crop was corn. This crop does not hold or consume a high amount of water. All these enumerated factors were considered to influence the water reduction through laterals and tiles shown on following figures.

Figure 28(a)

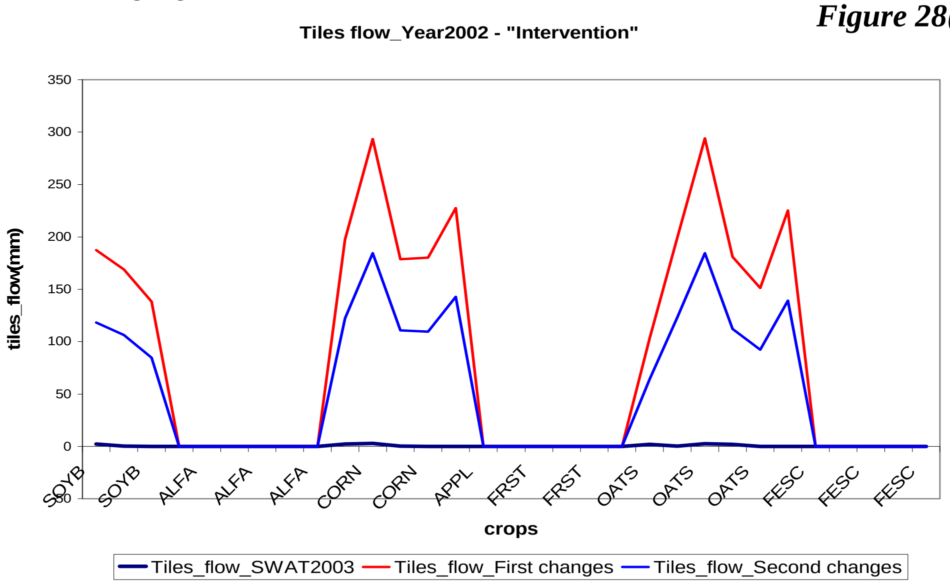
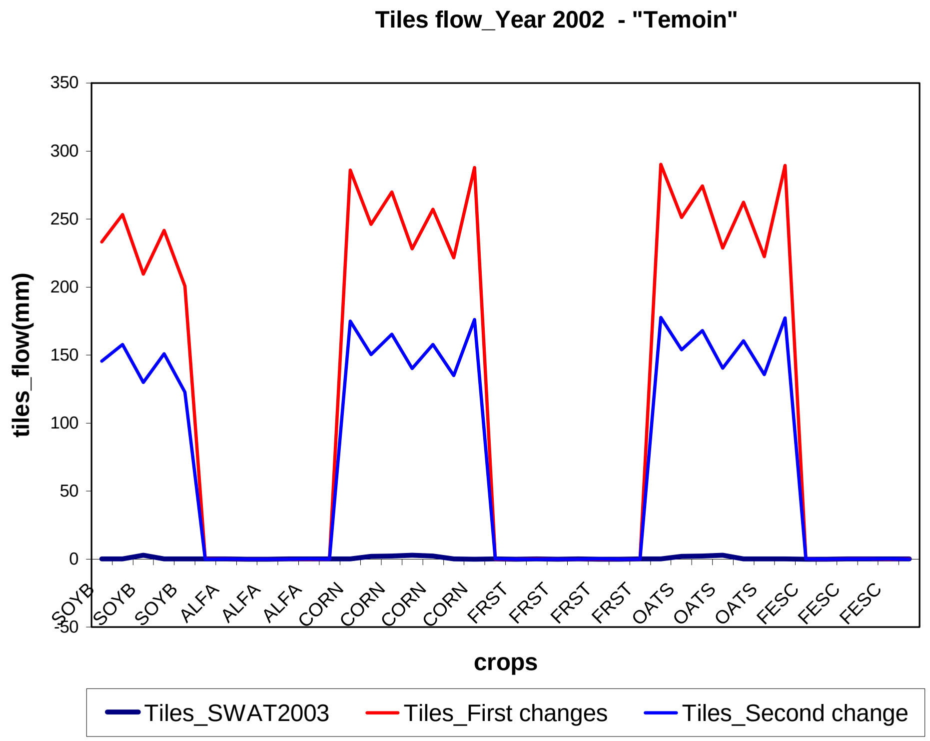


Figure 28(b)



Figures 28: Yearly simulation results, tiles flow decrease after second change, "Intervention*" and* "Temoin*".*

The tiles flow decreased of about 100mm which is a big problem for our objective of raising this quantity. But what was important was to have well described and trustfully physical processes inside the model.

Figure 29(a)

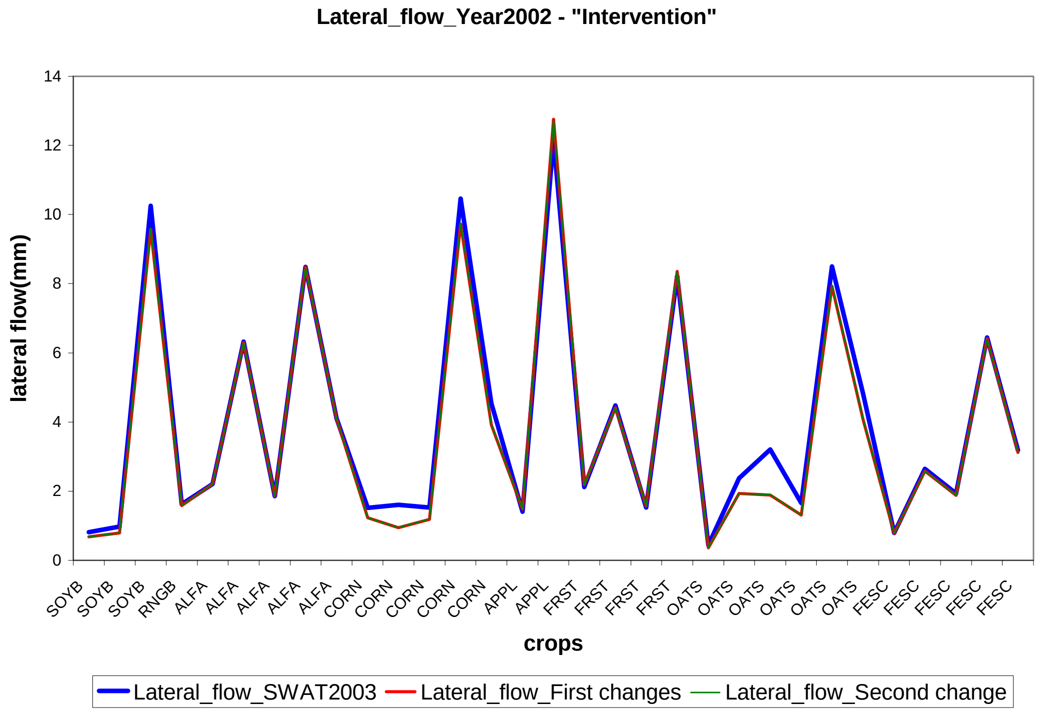
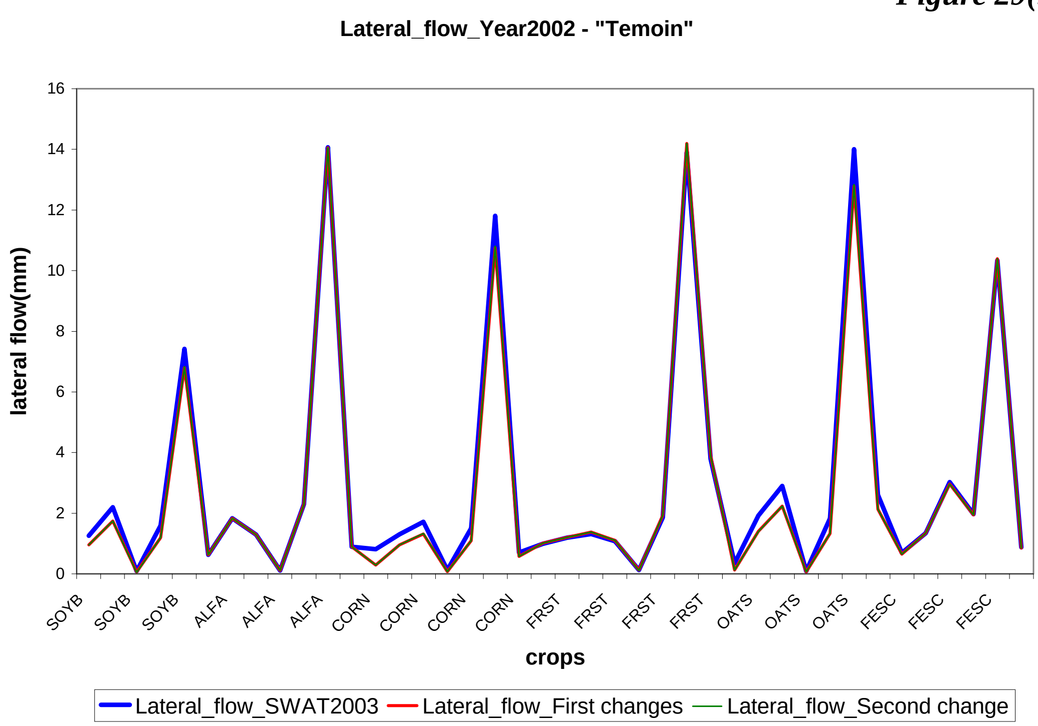


Figure 29(b)



Figures 29: Yearly simulation results, Laterals flow after second change, “Intervention” *and* “Temoin”.

The laterals continued to be not very sensible; their values compared to previous changes were approximately same.

Figure 30(a)

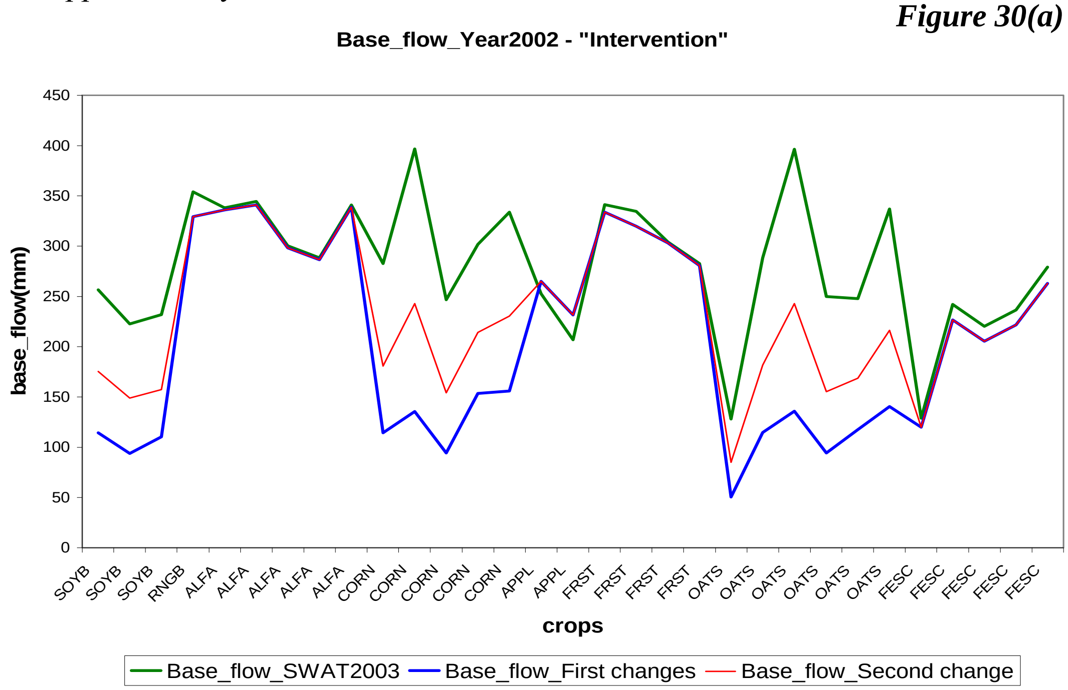
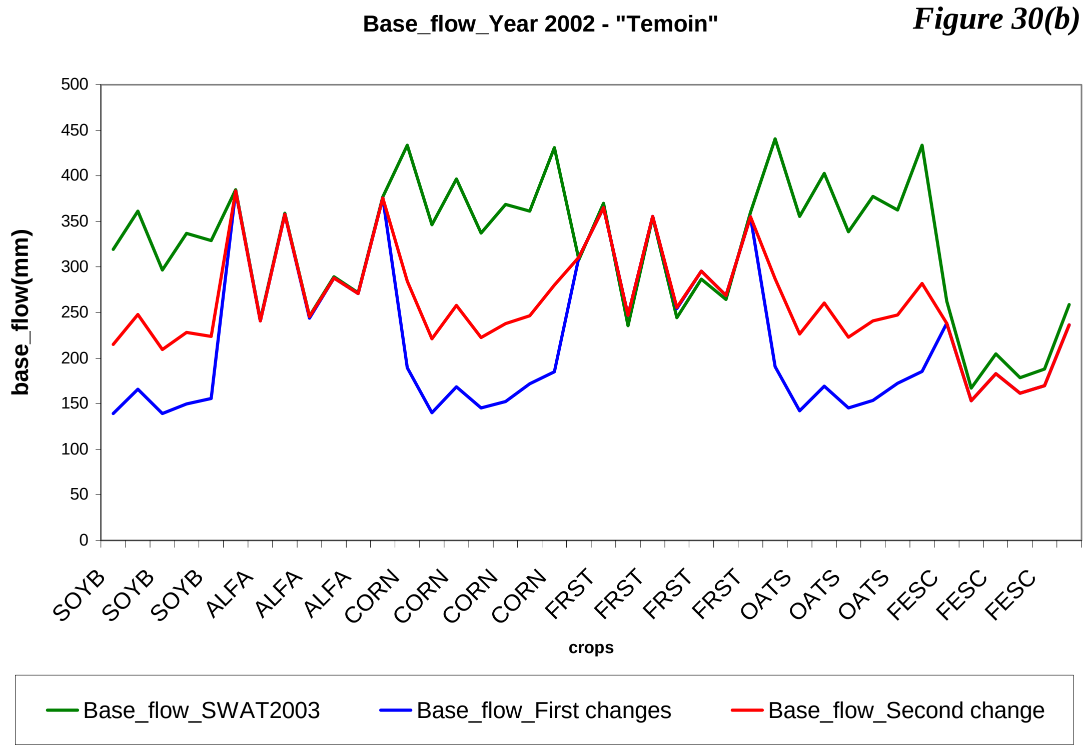


Figure 30(b)



Figures 30: Yearly simulation results, Base flow increase after second change, “Intervention” *and* “Temoin”.

The base flow is increased and it seems that the decrease in tiles flow and laterals gave chance to ground water table to flow in a big quantity through the rivers. The recharge of the shallow aquifer was not depending to the water soil's percolation which did not affect it at all. There is another factor which is governing the water recharge to the shallow aquifer. The next change is more detailed on ground water recharges and its contributions to rivers.

VI.3.4. Tiles flow – Third changes

The other way of improving the water quantity in tiles was to think which could be other possible origins of water passing through tiles. The possibilities which were remaining after soil water percolation, was the contributions of cracks from the surface and the contribution of ground water from shallow aquifer storage.

1. Crack flow

Previously mentioned, the tile drainage is one of the management practices for better improved lands in agricultural production system. Consequently, tile drainage can affect the physical properties of the soil. The removal of excess water results in creating additional storage volume within the soil profile. Thus, the soil type plays a major role in tile drainage volume and rate. During dry periods, because of the presence of tiles underground, route ways could be established that are cracks. These cracks would support a rapidly drainage response during wet periods.

Agriculture practices such as tile drainage can alter effective soil properties (i.e. infiltration rates, hydraulic conductivity) and even topography. The soils could shrink when dried and swell when moistened. When the soil is dry, large cracks form at the soil surface. This behavior is a result of the type of soil material present and the climate. Some types of soils in Quebec could be classified like that mostly caused by the climate where a strong winter period is well known.

In SWAT model, one criteria used to classify a soil like that is the formation of shrinkage cracks in the dry season that penetrate to a depth of more than 50cm and are at least 1 cm wide at 50 cm depth (SWAT2005 Theoretical Documentation). The cracks can be considerably wider at the surface. To accurately predict surface runoff and infiltration in areas dominated by soils that present such properties, the temporal change in soil volume must be quantified. SWAT calculates the crack volume of the soil matrix for each day of simulation by layer. On days in which precipitation events occur, infiltration and surface runoff is first calculated for the soils using the curve number or Green & Ampt method. If any surface runoff is generated, it is allowed to enter the cracks. A volume of water equivalent to the total crack volume for the soil profile may enter the profile. Surface runoff in excess of the crack volume remains overland flow (SWAT2003 Theoretical Documentation).

Water that enters the cracks fills the soil layers beginning with the lowest layer of crack development. After cracks in one layer are filled, the cracks in the overlaying layer are allowed to fill.
The crack volume initially estimated for a layer is calculatetd:

$$crk_{ly,i} = crk_{\max,ly} \cdot \frac{coef_{crk} \cdot FC_{ly} - SW_{ly}}{coef_{crk} \cdot FC_{ly}} \qquad \textit{Eq. (14)}$$

Where $crk_{ly,i}$ is the initial crack volume calculated for the soil layer on a given day expressed as a depth (mm), $crk_{\max,ly}$ is the maximum crack volume possible for the soil layer (mm), $coef_{crk}$ is an adjustment coefficient for crack flow, FC_{ly} is the water content of the soil layer on a given day (mmH_2O). The adjustment coefficient for crack flow $coef_{crk}$ is set to 0.10.

- **Crack flow calculations – source codes**

This option of cracks in SWAT was activated and did not change too much the water balances within the different paths of water, especially tiles volumes. The reason was that in SWAT source code there were no relation between the water flowing in tiles and water entering in soil through cracks. All water through cracks was supposed to go to the seepage bottom, which gave contribution to the shallow aquifer volumes. A new variable was declared *tile_crack*, for retaining water through cracks and allow it to flow in tiles. It was supposed that along its way through the soil profile water passes first to tiles before reaching the ground water table in case tiles are present in that part. In addition, among these cracks which could be present on the surface area, most of them are supposed to be located where the tile drains are laid and logically water passes through would first go to the tiles.

The modules were located in the *percmacro* subroutine of the SWAT source codes; this *percmicro* is also called by the *permain* for final update for soil profile water (*Appendix 3)*. The modules were again modified and tried with the variable *(tilecrack*) representing the water supposed to go to tiles (*Appendix 7*). The variable (*tilecrack)* was taking water from crack to the drains if water reaches in the layer where tiles are located else the water was going to be taken as a part of water percolating from bottom of soil profile and recharging the shallow aquifer.

- **Problems**

The water in cracks had to be limited by a volume given by cracks maximum which could be determined in SWAT database. Its value differs from soil to soil and it is something to be determined from tests to be done on field. Hence, a set of soils which could shrink must be known as well as their potential volumes of cracks they could present. The approximated values for these data were not really known. During this research, some values of crack volumes were tried but they showed incredible results; the cracks were draining more water than what the precipitations could give. The conclusion was that their values must be determined and could be available by doing on field tests first then the idea of activating cracks in the SWAT model was not advanced anymore.

2. Ground water contribution to the tiles

The recharge of the shallow aquifer from percolation of water from bottom of soil profile increases the shallow aquifer water level i.e. the water table level. The water table could arise and reach the tiles level in that way this could contribute to the tiles flow volumes. From this option, the research tried to provide a relation between the tiles level and shallow aquifer level and when conditions are fulfilled water from shallow aquifer could contribute to the tile drains.

- **Ground water systems in SWAT**

The shallow aquifer, whose upper boundary is the water table, is recharged via percolation to the water table from a significant portion of the land surface. The shallow aquifer is identified to contribute to flow in the rivers of the sub-watershed. This is the base flow. Water that enters the deep aquifer is assumed to contribute to stream flow somewhere outside of the watershed (Arnold et al., 1993).

Normally, water enters groundwater storage primary by infiltration and a recharge by seepage from surface water. Water leaves groundwater storage by discharge into rivers or lakes, water could also move upward from the water table into the capillary fringe, a zone above the groundwater table that is saturated.

Shallow aquifer

The water balance for the shallow aquifer (SWAT Theoretical Documentation, Version 2003) is:

$$aq_{sh,i} = aq_{sh,i-1} + w_{rchrg,sh} - Q_{gw} - w_{revap} - w_{pump,sh}$$

This a daily simulation where $aq_{sh,i}$ is the amount of water stored in the shallow aquifer on a particular day (mm H_2O), $aq_{sh,i-1}$ is the amount of water stored in the shallow aquifer on the previous day (mm H_2O), $w_{rchrg,sh}$ is the amount of recharge entering the shallow aquifer on that day (mm H_2O), Q_{gw} is the groundwater flow, or base flow, into the main channel on that day (mm H_2O), w_{revap} is the amount of water moving into the soil zone in response to water deficiencies on that day (mm H_2O), and $w_{pump,sh}$ is the amount of water removed from the shallow aquifer by pumping on that day too (mm H_2O).

Recharge

Water that moves past the lowest depth of the soil profile by percolation enters and flows through the vadose zone before becoming shallow and/or deep aquifer recharge. The lag between the time that water exits the soil profile and enters the shallow aquifer will depend on the depth to the water table and the hydraulic properties of the geologic formations in the vadose and groundwater zones.

Groundwater/base flow

The shallow aquifer contributes base flow to the rivers and streams within the watershed. Base flow is allowed to enter the river only if the amount of water stored in the shallow aquifer exceeds a threshold value specified inside SWAT inputs parameters. The change in water table height is changing within the time and mainly determined by the amount of recharge entering the shallow aquifer, the ground water flow into the main channel.

A direct index of ground water flow response to changes in recharge (Smeda ad Rycrofft, 1983), called the base flow recession constant, α_{gw} is used for the determination of the water quantity reserved to flow to rivers. Its values vary from 0.1-0.3 for land with slow response to recharge to 0.9-1.0 for land with a rapid response.

The base flow recession constant for the two sub-watersheds were obtained by analyzing the measured stream flow during periods of no recharge in the area (for good observations in summer and autumn). This is another way of the base flow recession calculations. α_{gw} values 0.6 and 0.9 for the "Intervention" and "Temoin" sub-watersheds were obtained according to measured data; the "Temoin' was recognized to have a direct response to the changes in recharge because of its high value of α_{gw}. The shallow aquifer is recharged regularly and this could have a big impact on how much water for ground water recharge is removed every time step in SWAT simulations.

Revap

For the water which may move from the shallow aquifer into the overlying unsaturated zone. In periods when the material overlying the aquifer is dry, water in the capillary fringe that separates the saturated and unsaturated zones will evaporate and diffuse upward. As water is removed from the capillary fringe by evaporation, it is replaced by water from the underlying aquifer. Water may be also being removed from the aquifer by deep-rooted plants which are able to uptake water directly from the aquifer. SWAT models the movement of water into overlying unsaturated layers as a function of water demand for evapotranspiration. This process is significant in watersheds where the saturated zone is not very far below the surface or where deep rooted plants are growing. Because the type of plant cover will affect the importance of revap in the water balance, the parameters governing revap are usually varied by land use. Revap is allowed to occur only if the amount of water stored in the shallow aquifer exceeds a threshold value specified by a corresponding parameter value.

Deep aquifer

The water balance for a deep aquifer is given by the amount of water stored in the deep aquifer on a particular day, the amount of water stored in the deep aquifer on the previous day, the amount of water percolating from the shallow aquifer into the deep aquifer on that particular day, and the amount of water removed from the deep aquifer for other activities on that day. Water entering the deep aquifer is not considered in future water budget calculations and can be considered to be lost from the system.

- **Ground water - source codes**

Ground water estimates for its contributions to the stream flow are calculated and updated in the *gwmod* subroutine. All the above mentioned proceedings are described and computed in that subroutine (*Appendix 8*): first it starts by the computation of the aquifers, shallow aquifer and deep aquifer levels for current day, second computation for the water required in the root zone based on the threshold of water in the shallow aquifer required to allow revaporation from this to occur and at the last comes the computation of the ground water flow (base flow) from shallow aquifer storage.

The most interesting part was the last *(to remove ground water flow from shallow aquifer storage*) where each time a certain quantity reserved for base flow when the depth of water in the shallow aquifer (*shallst)* level exceeds a threshold depth of water in shallow aquifer required before ground water flow will occur (*gwqmn)*; this water was flowing to rivers, determined by a variable (*gw_q)* in the codes *(Appendix 8*). However no water from water table was allowed to flow to tiles. From that it showed how ground water continues to be calculated apart. To obtain its contribution to tiles could meet the same condition of filling the water table and when water exceeds and reach the tiles drain level, water could flow to them.

The modified ground water flow from shallow aquifer is adding more modules allowing water to flow in tiles when conditions arise to them (*Appendix 9*). These modules give possibilities to tiles to retain water from the ground when the depth of water in the shallow aquifer (*shallst*) reaches the tiles level. Then a certain amount for tiles (*gw_tile*) would be subtracted from the ground water flow reserved for the base flow to streams (*gw_q*). And after this, if the depth of water in the shallow aquifer is higher than the threshold of water specified for the base flow to occur, the base flow could be calculated.

While testing with the added modules, the water in shallow aquifer was not enough to compensate the big gap between the deep impervious *"dep_imp*" and the drains level "*ddrain* ". The first idea to fill this gap was to change the parameters supposed to play a major role here. Inside the model, by changing parameters values of initial water level in the shallow aquifer (*shallest*) together with the threshold of groundwater specified for the occurrence of the base flow to start flowing, *(gwqmn)* the water was expected to reach the tiles. These two parameters values needed adjustments for their values in order to have reasonable results of the water budgets on the two different sites. Initially they were very small values, the "shallest "was set to 500mm for both sites and the *(gwqmn)* was one at 395mm for the "*Intervention*" and 200mm for the "*Temoin*". The two sub-watersheds were reacting differently depending to physical conditions compatibilities and in reality these initial values are not well known.
This involved those parameters to be changed and set to new values and that was done in the part of a new calibration of the model. *"Shallst "*, initial water level in the shallow aquifer and " *gwqmn* ", the threshold of water set for allowing water to flow to the rivers were considered as the most important to determine which amount could flow to rivers, base flow and which amount could go to tiles.

3. Results of Third change

Results with the initial parameters values obtained are presented in following figures where results were approximately same like what was obtained after the second change. No water could flow from shallow aquifer to the tiles because of lower values of "*Shallst"* and "*gwqmn* ".

Figure 31(a)

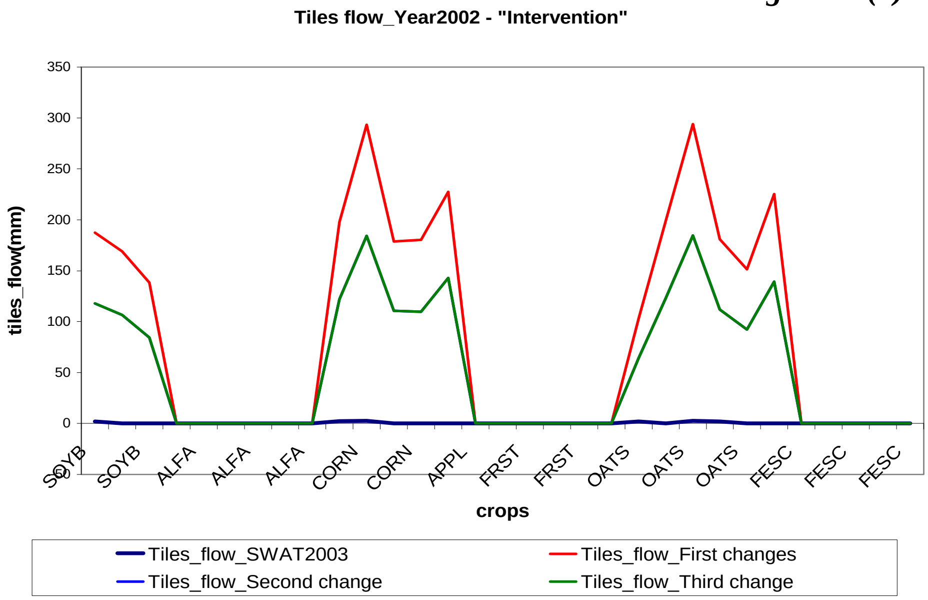
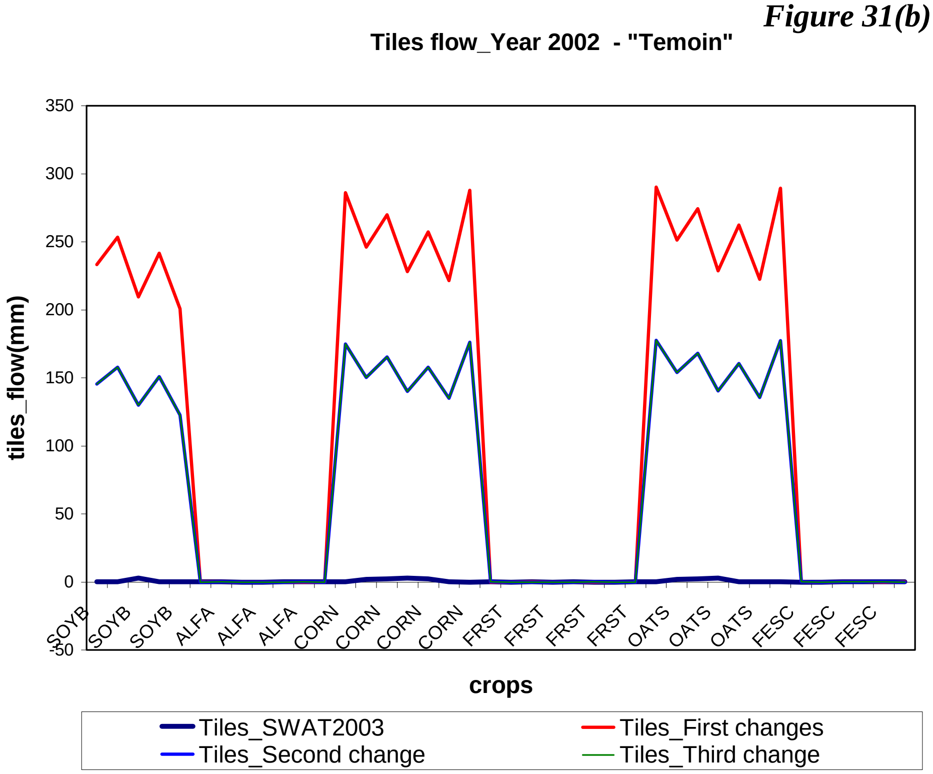


Figure 31(b)



Figures 31: Yearly simulation results, tiles flow after third change, “Intervention*” and* “Temoin*”.*

Tiles flow graphs for the second change and the third change obtained same values, they were following one graph. This was explained by the water level not enough in the shallow aquifer to supply tiles.

Figure 32(a)

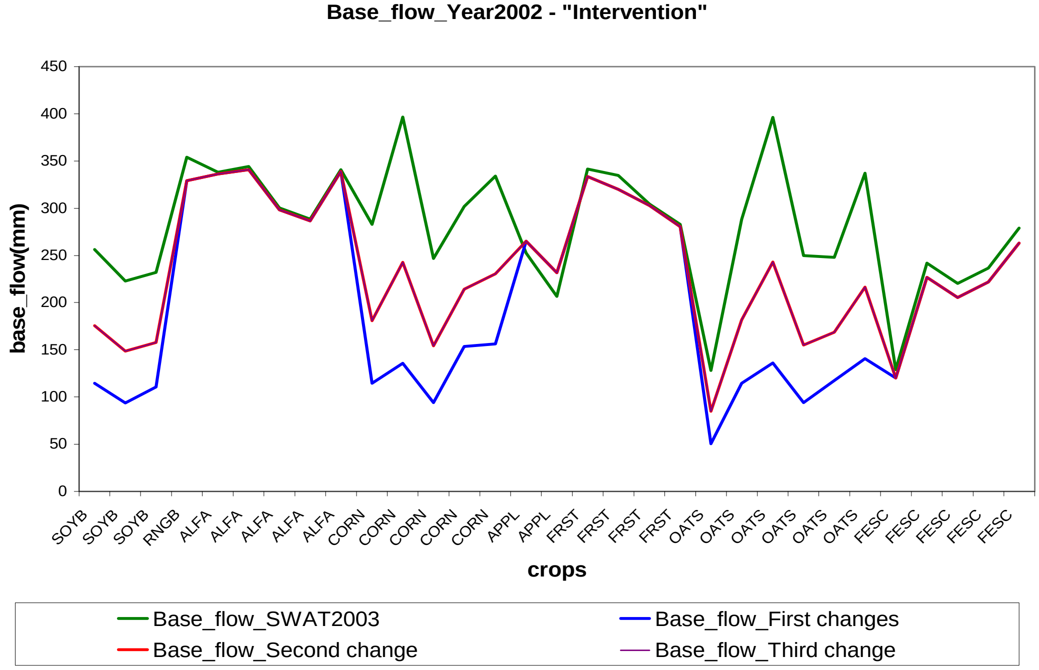


Figure 32(b)

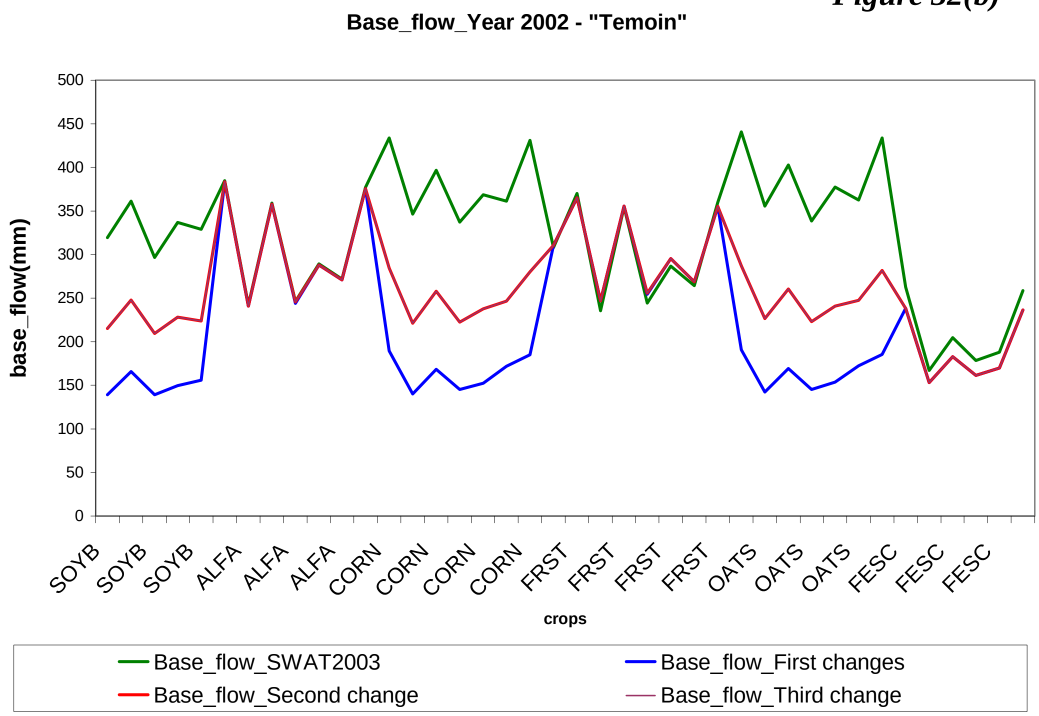


Figure 32: Yearly simulation results, Base flow after third, “Intervention” *and* “Temoin”.

The same for the base flow, second change and third change are same, which shows the ground water table did not arise in order to reach the tiles. This needed a new calibration of parameters supposed to reduce base flows and increase tiles flows.

VI.4. New calibration

The model needed readjustments to fit the data. The manual calibration was done and winter parameters were the mostly changed together with the ground water initial levels. Following are results obtained from the tried calibration and new parameters values were obtained in the next tables (8) and (9).

1. Parameters values

Table 8: Winter period obtained values for the watershed

Winter period parameters - values for the watershed

Parameters	unit	Definition	scale (file)	Initial values	Obtained values
Smfmx	mm/deg C/day	Maximum melt rate for snow	BSN	4.5	6.5
Smfmn	mm/deg C/day	Minimum melt rate for snow	BSN	4.5	6.5
Sftmp	deg C	Snowfall temperature	BSN	0	0.6
Smtmp	deg C	Snow melt base temperature	BSN	-1	-1
Timp	none	Snow pack temperature lag factor	BSN	0.45	0.46
SNOCOVMX	mm H2O	Minimum snow water content that corresponds to 100% snow cover.	BSN	280	310
SNO50COV	none	Fraction of SNOCOVMX that corresponds to 50% snow cover.	BSN	0.2	0.3

Table 9: New parameters values obtained by manual calibration

Parameters	unit	Definition	scale (file)	"Intervention" Obtained value	"Temoin" Obtained value
Alpha_Bf	days	alpha factor for groundwater recession curve	HRU(gw)	0.7	0.9
Gw_Delay	units-days	groundwater delay	HRU(gw)	7	7
Rchrg_Dp	none	recharge to deep aquifer	HRU(gw)	0.15	0.15
shallst	mm H2O	depth of water in shallow aquifer	HRU(gw)	3000	5000
Gwqmn	mm H2O	threshold depth of water in shallow aquifer	HRU(gw)	2000	5000
Esco	none	soil evaporation compensation factor	HRU or BSN	1	1
Lat_ttime	days	lateral flow travel time	HRU	1	1

2. Manual calibration results:

Figure 33(a)

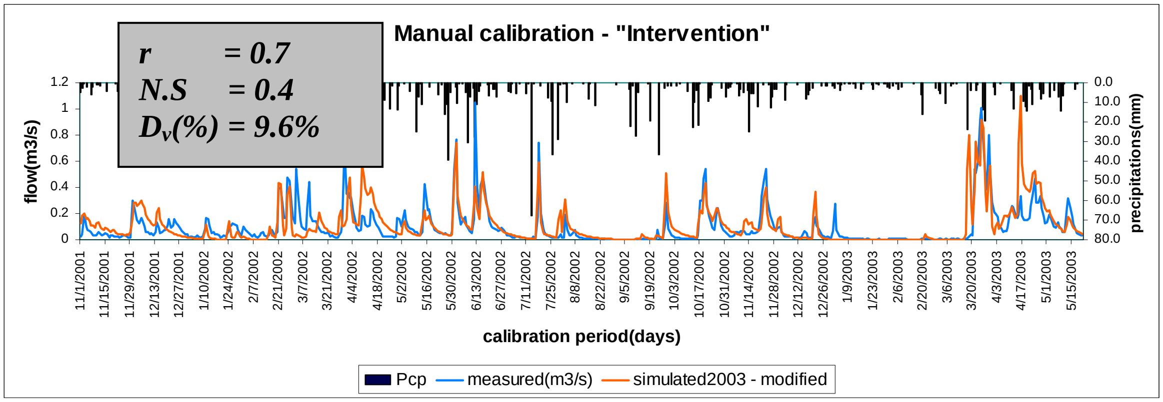


Figure 33(b)

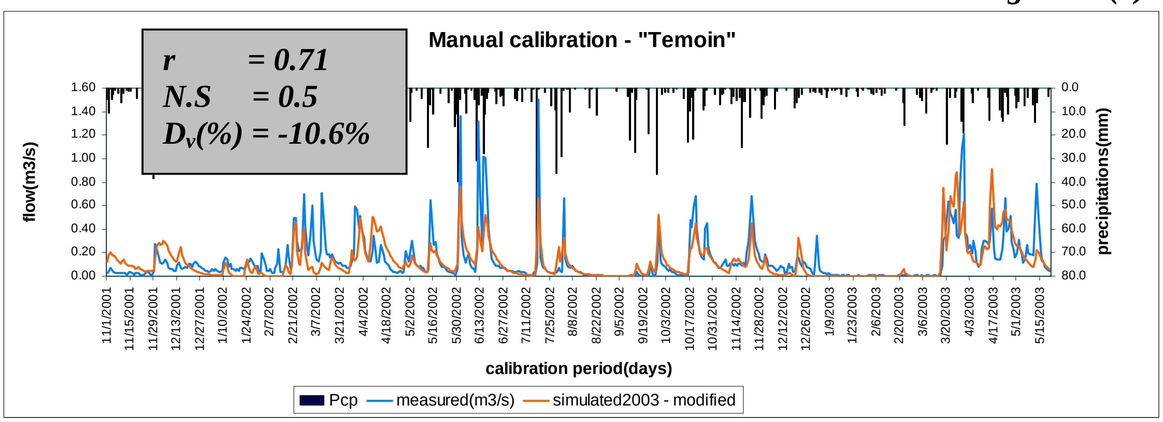


Figure 33: Manual calibration results with the SWAT2003-modified, "Intervention" *and* "Temoin"*.*

The "*Intervention*" sub-watershed simulation gave an overestimation of surface runoff values. In contrast, these values were underestimated in the "*Temoin*" sub watershed. This was linked to their physical characteristics differences where more management practices were applied on "*Intervention*" while "*Temoin*" is assumed to do not present any other management practices except the tile drains.

Another explanation to this, was found by changing the values of α_{gw} by which the ground water recharge is higher in "*Temoin*" than in "*Intervention*". So this was taken as the main reason of the underestimation of the surface runoff in "*Temoin*", more water was going to recharge the shallow aquifer. One more reason for that was the CN values used for the "*Temoin*" decreased for 10% from the suggested SWAT values; reducing hereby the surface runoff for this site.

In brief, the model was not fully calibrated because it was still under uncertainty conditions. It was very difficult to obtain good statistical results, the water distributions was not yet well simulated as the problem of water in tiles was not yet accomplished.

VI.5. Results

1. Hydrological impact - HRU guidance

The model improvements done were considered having a big impact on the hydrological system of the area. These were mainly proved by the soils and different land uses which in fact reacted differently according to the homogeneous parts organized by SWAT in the sub-watersheds: the HRUs. The participation of each HRUs daily, monthly or yearly simulation could be giving their contribution to the stream flows. Before for the changes (*First changes, Second change and Third change*) it was interesting to observe how different tiles drained HRUs according to which type soil and land use were increasing or decreasing their values related to which changes applied. Now, one HRU known to be well drained was chosen to show how its contribution was affected by theses different changes done on tiles flow. The corn crop is taken as the dominant crop in the watershed and its fields are almost drained the only difference to drain water through these corn cropped fields was the soils type. The soil type "rougemont" was considered to be well drained, having high soil conductivity, this was assumed to have an impact on the amount of water that reaches the drains. Most of the time found in two layers on both sites, a homogeneous area (HRU) given by corn and rougemont was chosen to show well how could be the representation of tiles flow. This was given by yearly simulations. The results of initial simulations (*Figures 34 (a) and 34 (c)*) were compared to results obtained from the three changes done *(Figures 34 (b) and 34(d)).*

Figure 34(a)

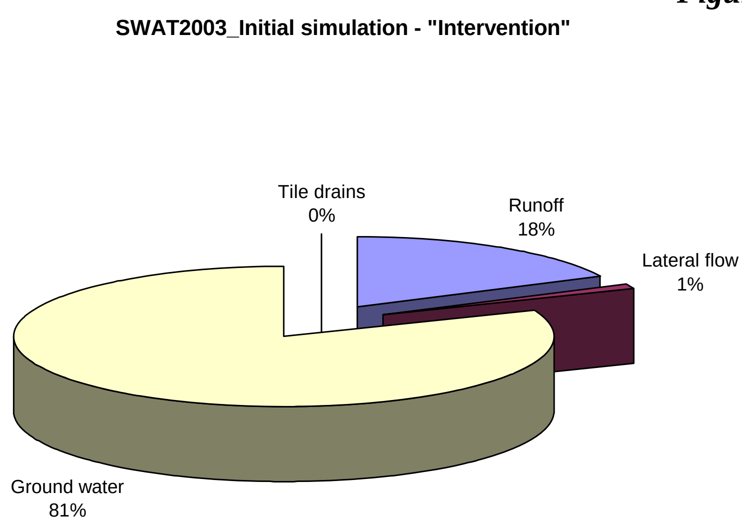


Figure 34(b)

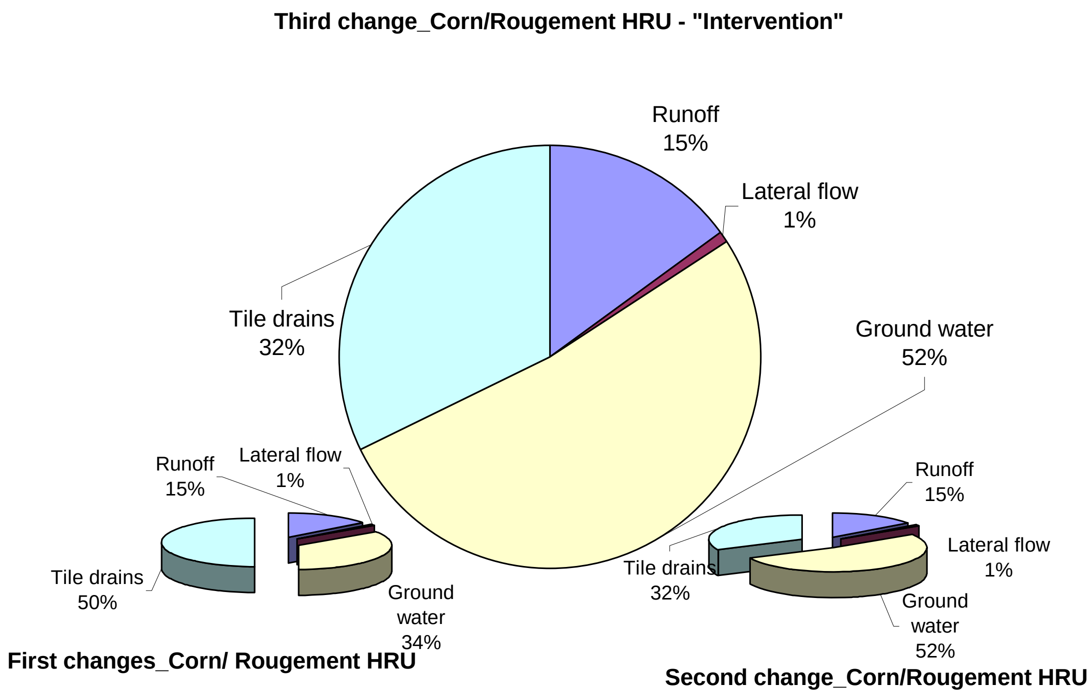


Figure 34(c)

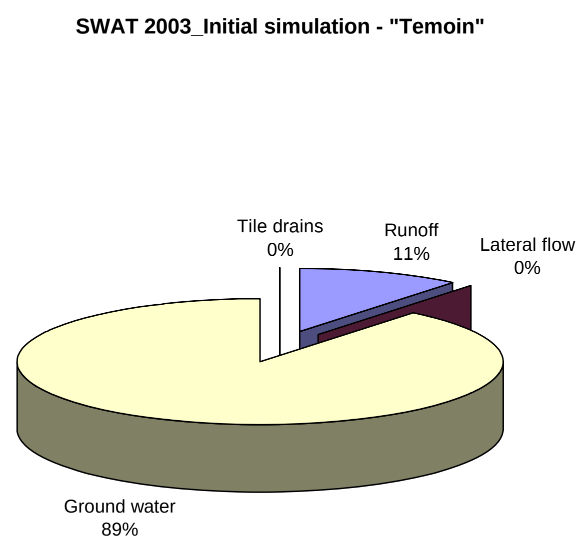
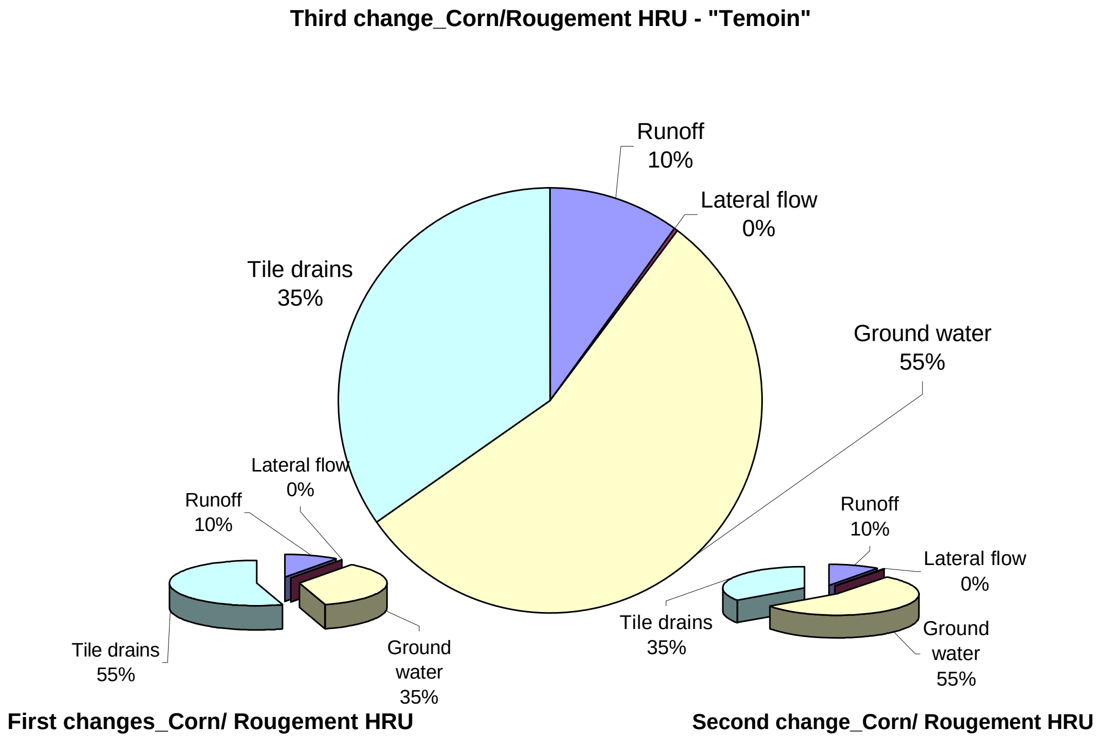


Figure 34(d)



Figures 34: Comparison between the three changes done on tiles computation; water distributions on surface and subsurface area, Year2002, "Intervention" *and* "Temoin".

In general, the three changes done increased the tiles flow compared to the initial simulation (*Figures 34 (a) and(c))*. The initial tiles flow simulated were very small (0 %). Which compared to modifications simulations a considerable change showed an increase of 50% in the first change while with the second and the third changes it increased up to 30%. By comparing the changes results between them, the first change increased the tiles flow while second and third changes reduced it. In "*Intervention*", tiles flow fractions from the total water flowing to rivers were 50% from the first changes, 32% for both second and third changes by using same parameters. In "*Temoin*" it was 55% for first changes and 35% for the second and the third changes. The first changes let a high amount of water reaching the drains. This was reduced when came the soil conductivity check of soils layers. This condition was right as the water in lateral and tiles was wrongly obtained. The dominance of the type soil "*complexe Mislsl*" with its low soil conductivity in the two sub-watersheds influenced the amount of water to seep. Also another factor to influence this reduction of tiles flow was the sequences of layers in the soil profile. By considering sands and clays percentages in soils layers, it can work positively when the first layer is sand but in the other way when it is overlaid by the clay the drainage could be taken as poor. The water was restricted to pass easily and it was remaining two choices for that, to go to ground water or to flow on surface. So water was distributed according to parameters obtained values.

The ground water recharges from percolation through soil layer from the surface is governed by base flow recession constant, α_{gw}. As earlier explained the two sub-watersheds presented different values of that parameter "*Intervention*" with 0.7 (*Table 6,* *New calibration*)not a very high value and "*Temoin*" 0.9 which is assumed to have a rapid response to the recharge to ground waters what is based on the observations done on measured data and hydrographs recessions in selected periods (*Figure 8*). For the "*Temoin*" water was recharging the shallow aquifer with a higher response and as continually recharged enough base flow was available for the stream flows while the surface runoff did not obtain enough water.

The third change gave approximately same results as the second one. Supposed to allow the shallow aquifer to contribute to the tiles, the water was still not enough to reach the drains level. Initially the "*shallst*" water was set to 500mm so with only the recharges and others small events extracting water from the shallow this could not be compared to the deep impervious (*dep_imp)* set to 6000mm in SWAT. The reason of changing the initial conditions of the shallow aquifer and start with enough water in this shallow given by the *"shallst"* parameter together with other parameters values allowed to have a certain quantity of water in tiles from the ground water table but not very significant (*Figures 34*).

- **Results – manual calibration**

Figure 35(a)

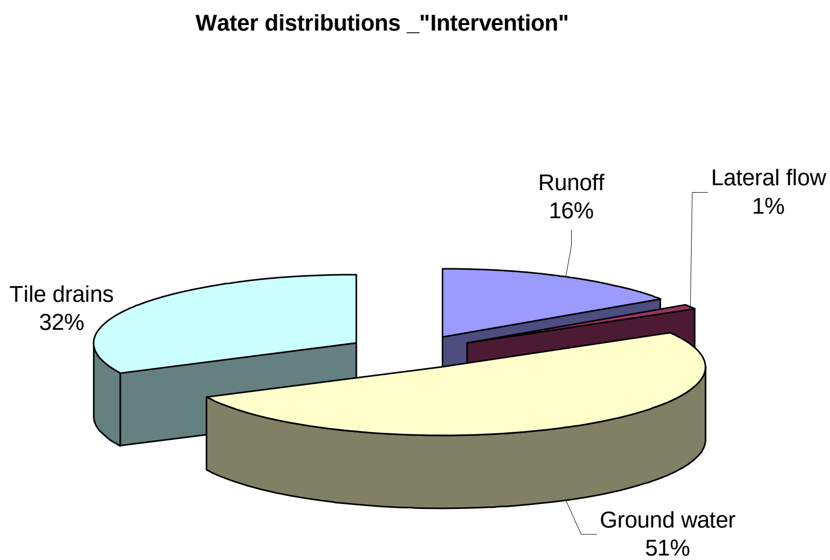
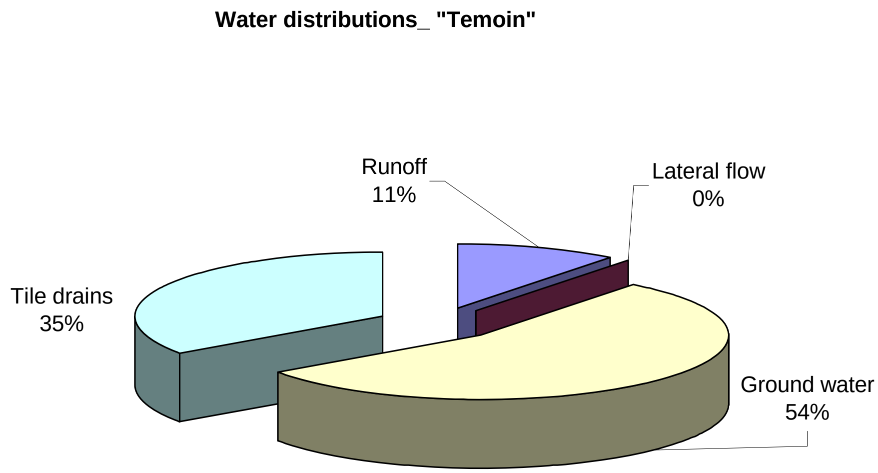


Figure 35(b)



Figures 35: Results of calibration, water distributions on a corn cropped/rougemont HRU, Year2002, "Intervention*" and* "Temoin*".*

The base flow contributions reduced about 1% and the tiles values remains unchanged with 32% in "*Intervention*" and 35% in "*Temoin*". The runoffs presented an increase of 1%, the calibration reduced the quantity of water seeping to the shallow aquifer and water was flowing to rivers.

In brief the third change arranged the reduction of ground water, base flow which was dominating other areas in the subsurface contributing to rivers of the area. It is still high but that option was shown able to reduce the ground water which is still a problem.

Within the modifications, the total amount of water "*water yield*", leaving the HRU and entering main channel during the time step, showed changes within the tile drained fields. The following figures (*36*) illustrate the contribution of each HRU to the main channel.

Figure 36(a)

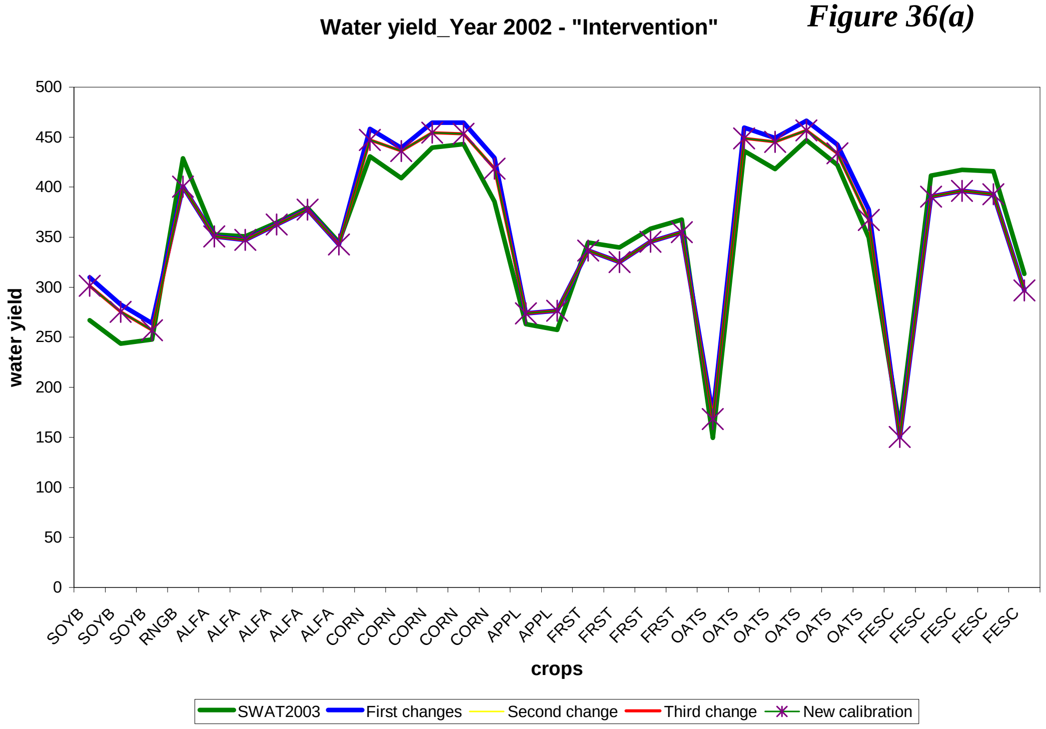
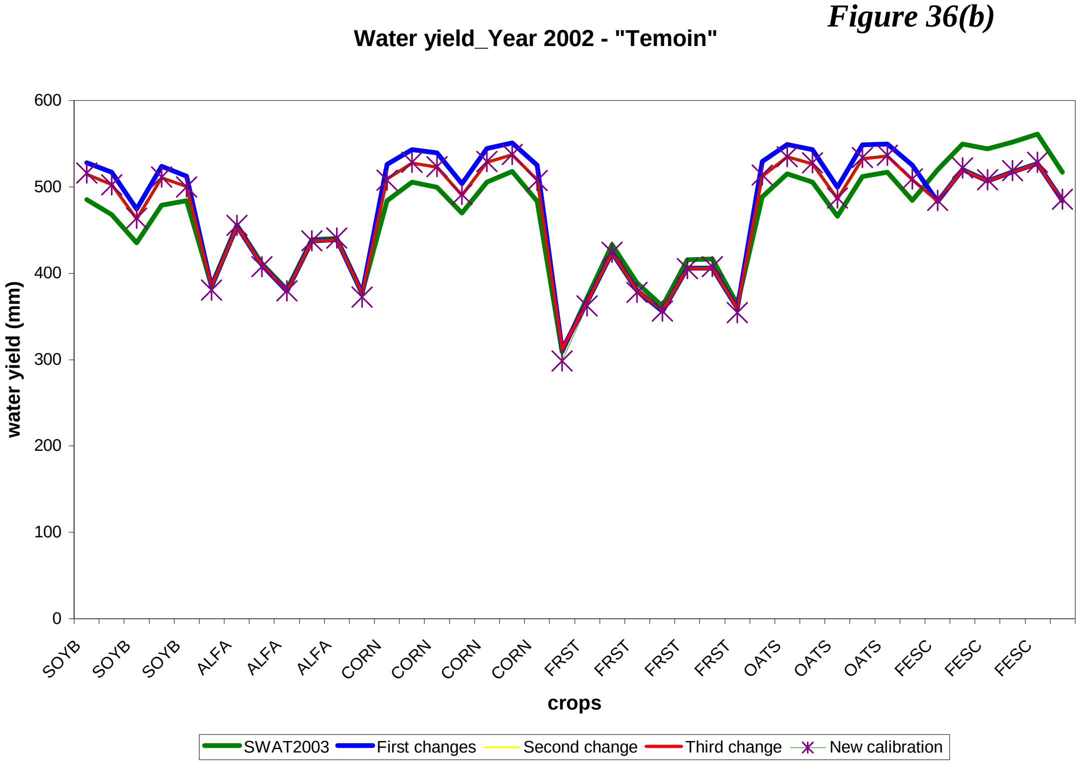


Figure 36(b)



Figures 36: Initial simulation and changes water yield's results, "Intervention" *and* "Temoin"*.*

All changes and the new calibration done increased the water yield from all tile drained fields; the soy, corn and oats HRUs.

Monthly simulation were also done in order to show when the water yield increased all over the year 2002, the main increase of water yield are in *April*, *may*, *June* (*spring period*), and it increases again in *October* and *November* (*autumn period*). This increase of water yields were justified by the increase of tiles flow which also presented their highest value in spring and autumn.

Figure 37(a)

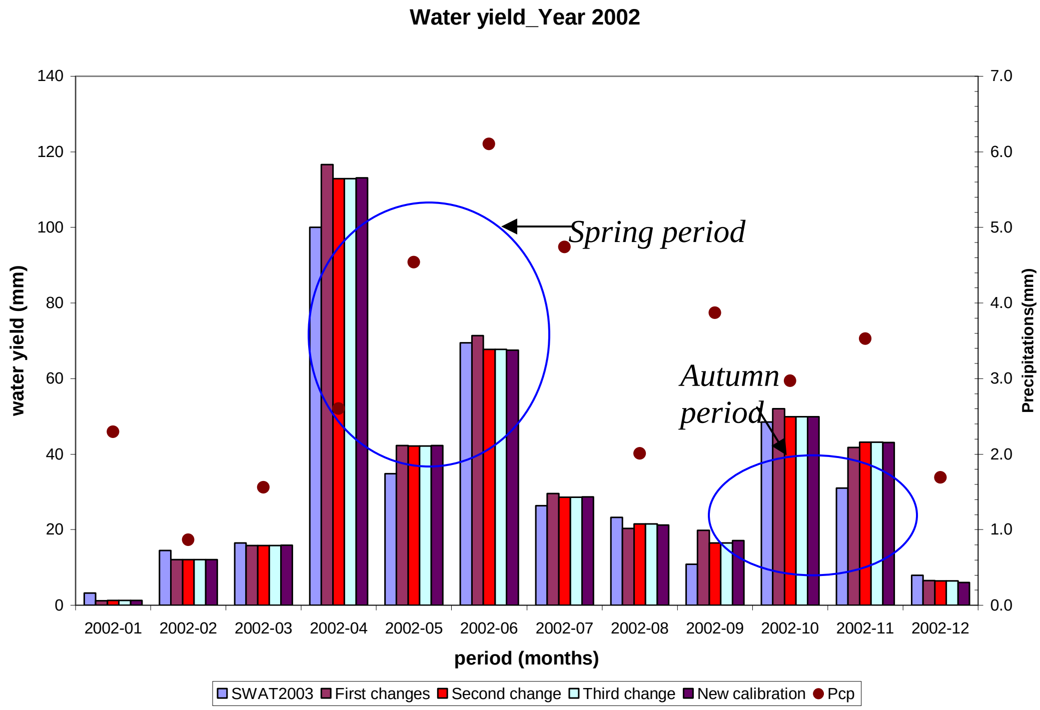
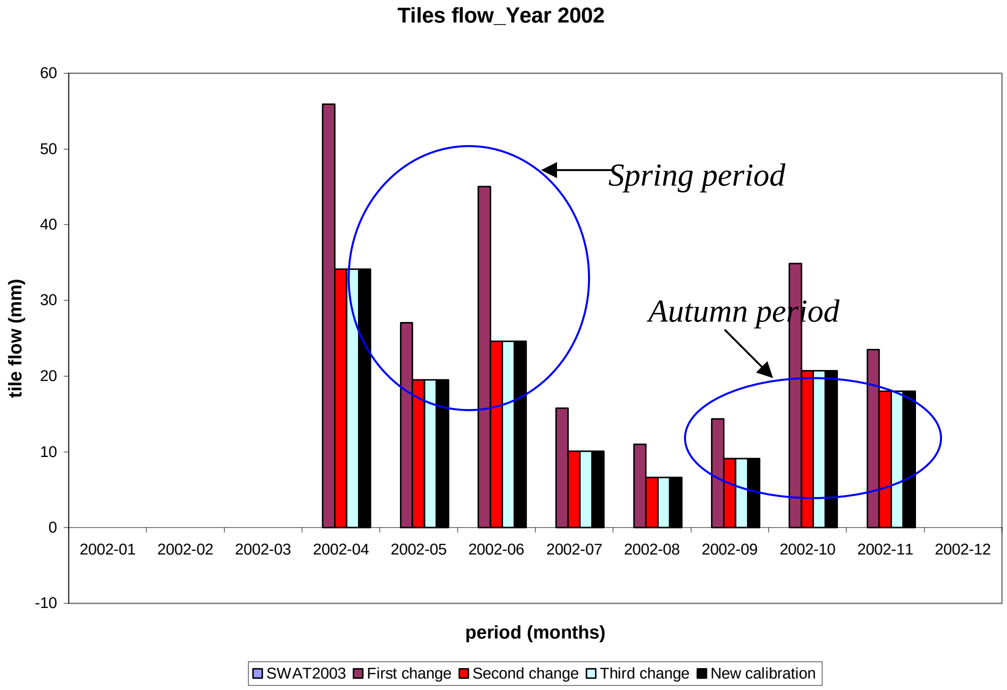


Figure 37(b)



Figures 37: Water yield and tile flow, monthly simulation, "Intervention".

These high values in spring are related to the reality when starts the snow melting period, together with some high rains *(Figure 37(a))* in those periods water level increases. Compared to other periods of the year, this distinguished these periods from others on tiles flow with high depth.

2. Nitrogen

The high presence of nitrogen in rivers and streams of the area is originally linked to the applications of fertilizer's types, agricultural land use i.e. type of crops and soils capacities to fix nitrogen. This varies time to time with climatic conditions. Not all of the nitrogen fertilizer applied to agricultural fields stays to nourish crops. Some is washed off of agricultural fields by rain or irrigation water, where it leaches into surface or ground water and can accumulate.

Plant use of nitrogen is estimated using the supply and demand approach described in the plant growth. In addition the plant use, nitrate and organic N may be removed from the soil via mass flow of water. Highly soluble in water, amounts of NO_3-N contained in runoff, lateral flow and percolation are estimated as products of the volume of water and the average concentration of nitrate in the layer. The different processes modelled by SWAT in the HRUs and the various pools of nitrogen in the soil are described. The simulation could show by comparison, nitrate loads in streams and rivers from different paths according to where water passes.

The model intentionally modified for a better representation of the Walbridge's watershed's situation. An evaluation of the effects of the changes to the codes on the water path was done in order to understand the transports of nutrients in different ways of water. What was very interesting was the significance of nitrate loads transported through

tiles and laterals. This would help to develop and improve best management practices for reduction of nutrients export together with sediments from agricultural fields to rivers and lakes in Quebec.
The research showed how important are the modifications done inside the model on nitrogen. The modified version results were compared to the original version SWAT2003 results (following figures 36) on the two different sites. These results were obtained by running the model with default values; no calibration was done on nitrate.

Figure 38(a)

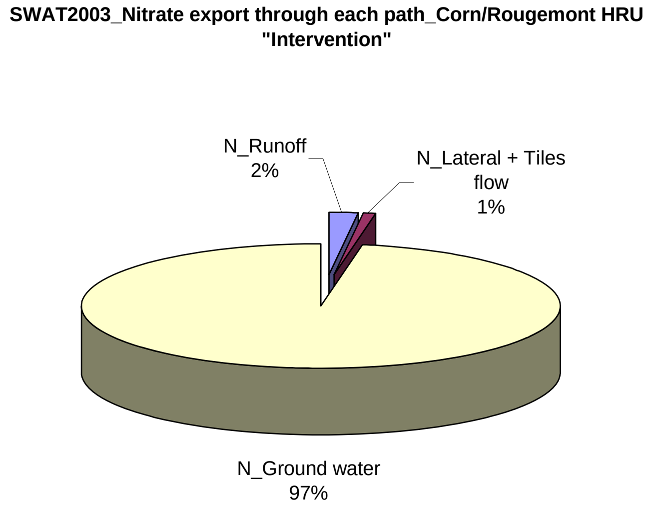
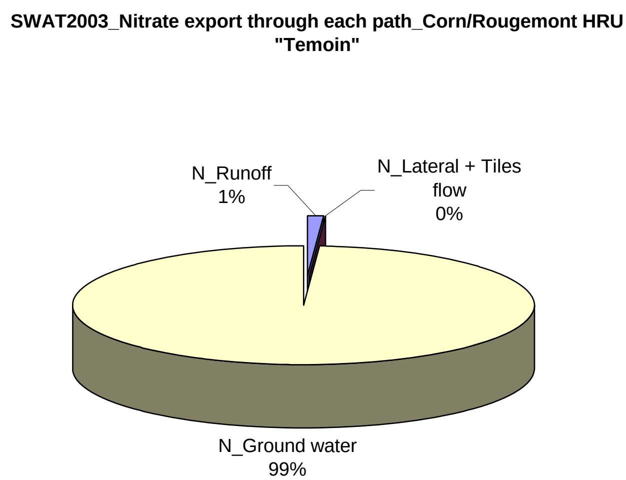


Figure 38(b)



Figures 38: Yearly simulation - Nitrate export, results obtained from the SWAT2003 first simulation before doing any modification, “Intervention” *and* “Temoin”.

From the previous figures (38), it is well shown how the nitrate exported to the hydrological network, the ground water – base flow was the major source of the nitrate presence in the rivers and streams of the area. This is related to the obtained high fraction of water exiting from the shallow aquifer (*Figures 34 (a) and (c)*) and this was expected to change after modifications on the tile drains system.

Studies have shown that nitrate nitrogen (NO_3-N) is one of the main pollutants produced primarily from the tile drainage (Du, A., et al., 2006). The evaluation of impact of the tiles on nitrate showed after changes more reasonable results. Following figures are the results obtained by comparisons between the quantity of water contributing to rivers from the laterals, tile drains, ground water and surface runoff and the nitrate concentrations exported through each to rivers. In SWAT model, water in tiles and laterals are summed up and nitrates concentrations is calculated and obtained as one concentration coming from lateral and tiles flow. As in our case, lateral flows were very low, it was assumed tiles flow were dominating in that way much nitrate loads were related to tiles.

Figure 39(a)

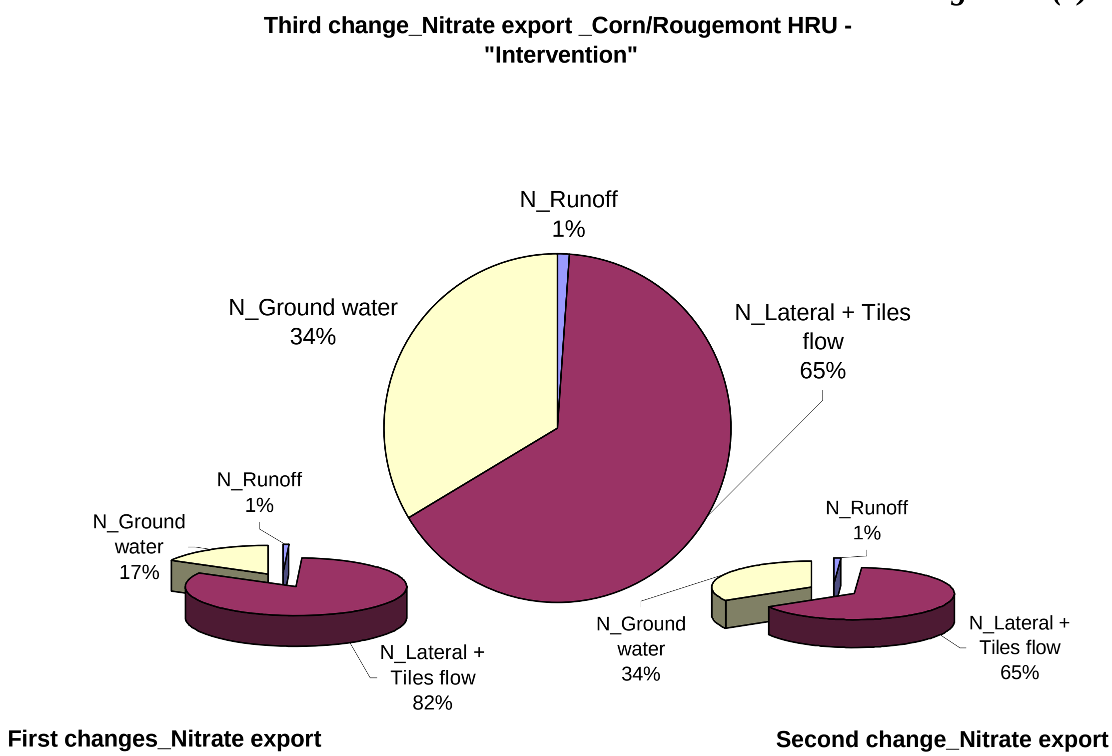
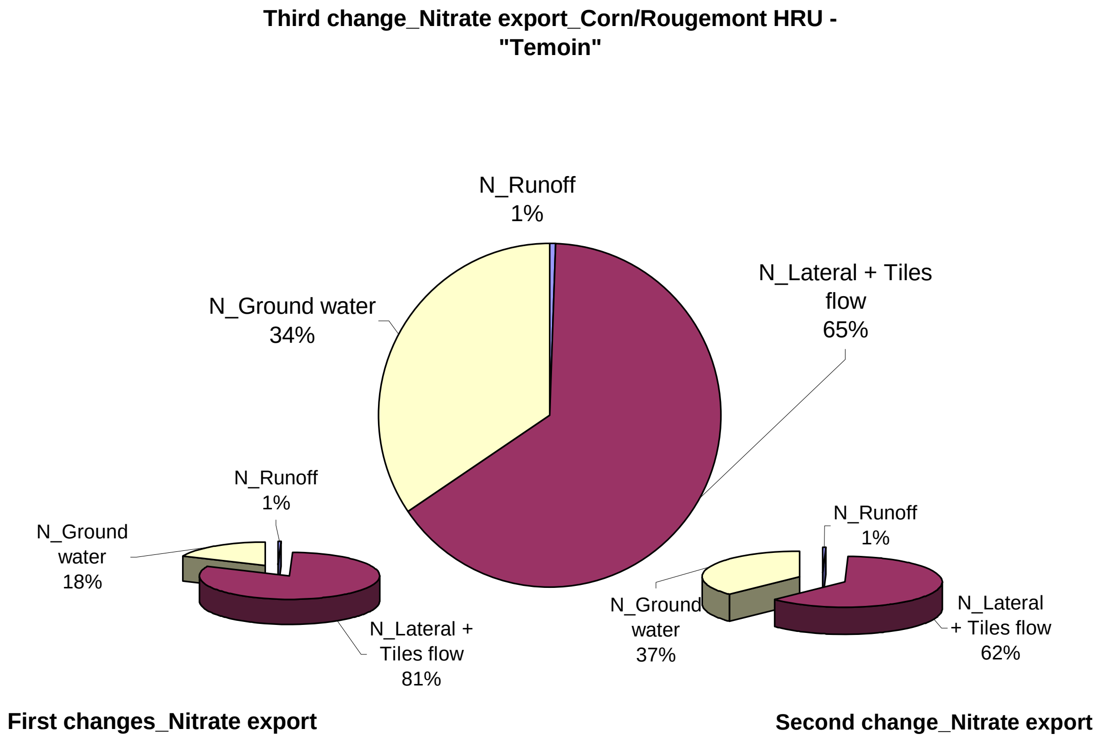


Figure 39(b)



Figures 39: Yearly simulation - Nitrate export, year 2002. Results of all the three changes done, “Intervention*” and* “Temoin”.

The nitrate was found to be high in laterals and tiles even if water is decreasing (*Figures 35-new calibration*). This showed how important is the tiles flow on nitrate export and why this needs more improvements for a better simulation of the Walbridge's hydrological system.

- **Results from calibrated modified model**

Figure 40(a)

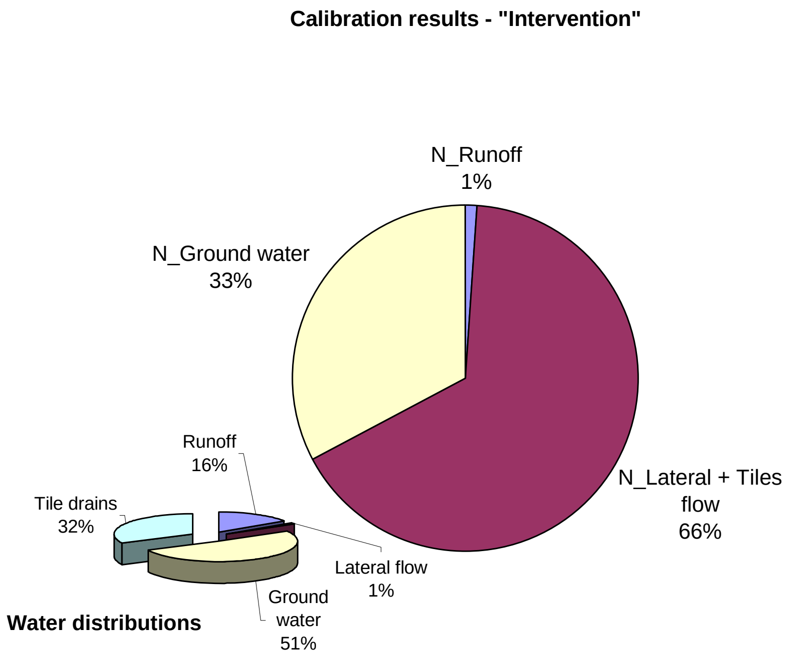


Figure 40(b)

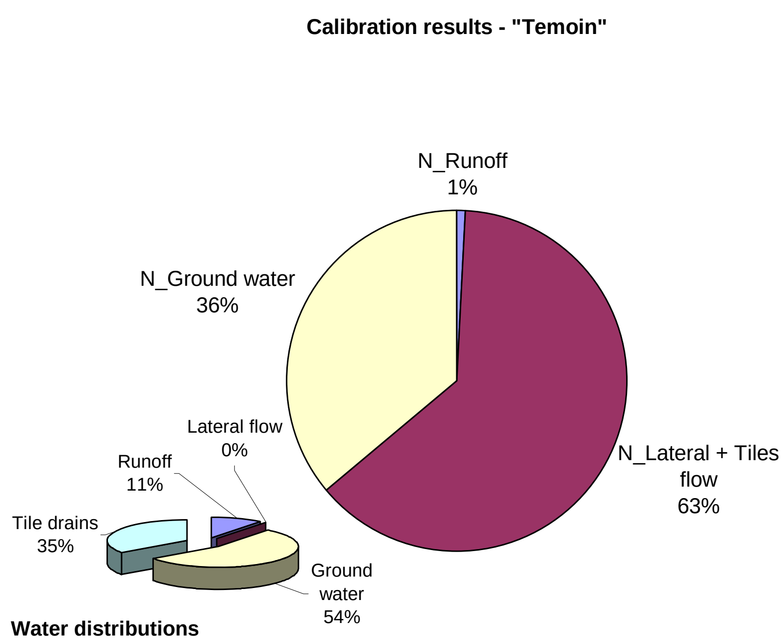


Figure 40: Yearly simulation - Nitrate export, Year 2002. Results of calibration on a corn/rougemont HRU, "Intervention" *and* "Temoin".

The results from the calibration continued to show a high nitrate load in laterals and tile drains. Even if the quantity of water in tiles and laterals were underestimated, the nitrate loads coming from them to the rivers. For instance on the "*Temoin*", calibration results gave 63% of nitrate in 35% of water coming from tiles to the rivers. The ground water contribution to rivers was 54% of the water flowing to rivers with 36% of nitrate load.

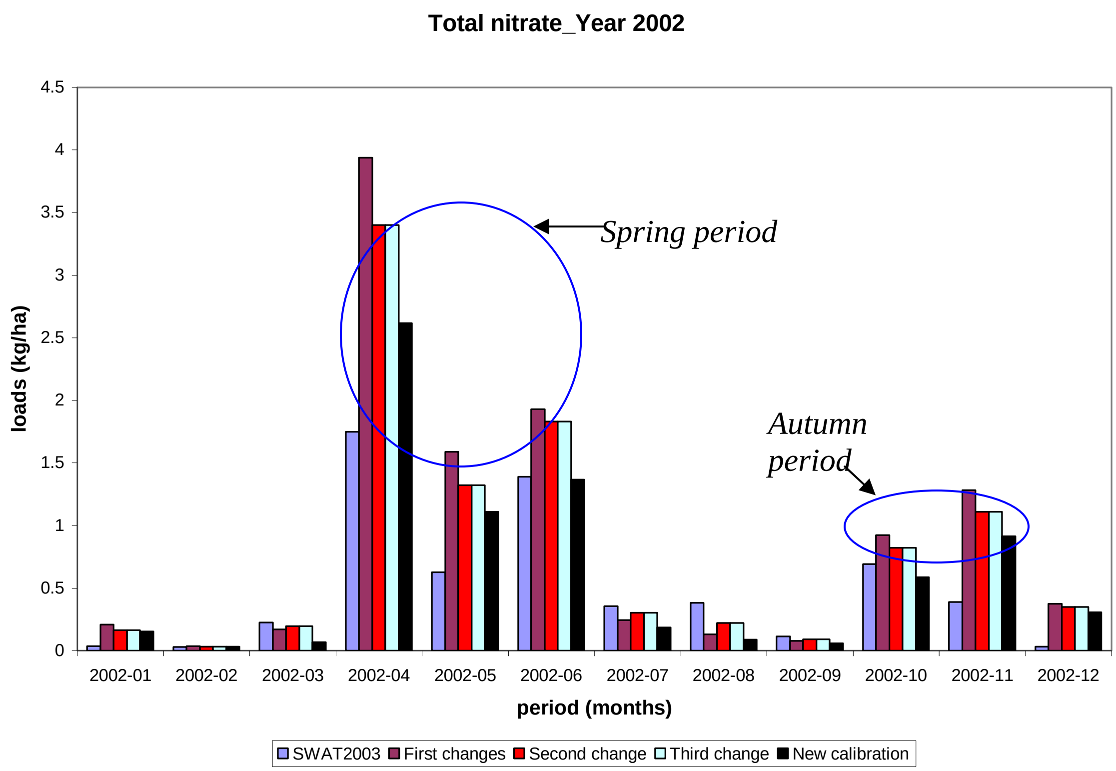


*Figure 41: Nitrate export, monthly simulation, "*Intervention*".*

The total load of nitrate exported to main channel from surface, laterals, tiles and base flow was also increased or decreased throughout the year. While the water yield and tiles flow to increase in spring period and late autumn (*Figures 37*), the nitrate loads exported to the rivers did the same. Its increase is basically justified by the increase of the tiles flow to the rivers. However the new calibration showed the decrease of nitrate (*on this previous figure 41*). This is related to the base flow which was decreased in the third change whereby the surface runoff was increased. As well known nitrate is not easily transported in surface runoff (also shown by *figure 40*).

3. Discussion on results

We did not cover the full investigations of soils and infiltration governing equations but we provided in this research a view of how the SWAT had been adapted to tiles flow option, approached in different ways. There were many issues surrounding the deviation of the governing equations as presented in the new calibration, the tiles modelling required hydraulic parameters that were representative of the Walbridge's situation to be readjusted. Improving efficiency and reliability in water distribution the hydrological model modified through the SWAT source codes were tested on the two Walbridge's watershed.

To run the model, a number of parameters were needed. Many of the parameters: soil physics parameters and tile drainage parameters were taken from experiments, which made the calibration very difficult because they were fixed values from already done on-field measurements. The calibration was not fully completed; more parameters are needed related to some processes found not well studied. Parameters values were not too much changed except those used in the third changes about the ground water contributions. Others were kept in a reasonable range according to the SWAT2000 calibration results.

Modifications to the source codes were incorporated in SWAT2003 whereby some modules were modified, some corrected and new modules were added. The soil percolation system provided a more realistic simulation of tile flow with increasing tile depth. The modifications changed the flow paths of the water in the drained areas. On its turn, this had a significant impact on the calculated nitrate export in the model. Although the SWAT model has been greatly enhanced and the tile drain modelling need further improvement in order to obtain a higher accuracy in predicting flow of watersheds with tile drains.

Conclusions and Recommendations

Picture of buffer strip along a tributary channel in the Walbridge watershed, Québec (Photo taken by Jacques Desjardins)

CHAPTER VII: CONCLUSIONS AND RECOMMENDATIONS

VII.1. CONCLUSIONS

According to the hydrological processes observed in the Pike river watershed, the model was adapted to represent the path of water and its constituent's movements towards the river in an improved way.

Conclusion1

Sensitivity, Autocalibration and manual calibration

The sensitivity analysis was very useful in determination of hydrological sensitive parameters. An LH-OAT sensitivity analysis for hydrology allowed for the screening of the large set of input parameters. The selected subset of parameters was then used for model calibration. In general, the sensitivity analysis showed that the parameters sensitivity has a high positive correlation with the inputs data. The most sensitive parameters were ground water parameters and curve number values (CN2).

An autocalibration in different periods of the year was not successfully established for the whole period of simulations. There were limitations created while separating data which resulted in dependences of parameters on periods. The application of these parameters values on the whole period of simulation was not acceptable. So a manual calibration was done in order to get parameters values which could work for all periods. The manual calibration resulted in good fits to the observed flows. In brief, the sensitivity analysis, autocalibration and manual calibration helped a lot for the parameters estimation. Information provided in previous publications regarding calibration in SWAT2000 was very useful both for the sensitivity analysis and calibration.

Conclusion 2

Tile flow simulation improvements

In this study the modifications, corrections and then implementation of new modules from processes related to tiles flow modelling in SWAT improved the model's ability to predict tiles, laterals and base flow in Walbridge's twin watershed. The procedures obtained during this study could be very useful for the next improvements on the effectiveness of tiles flow simulations.

Tiles drainage modules
Water distribution through soil profile

First of all it was pointed out that the existing concepts did not fulfill to the essential requirements: to close the water balance and to be applicable for agricultural management practices; areas with tile drainage. The inclusion of the first applications was successful to bring the tiles drainage up to 35% of the water yield, previously its value was much underestimated, around 0 % of the water yield. Therefore, some important adaptations were performed to enable tile drainage modelling on the Walbridge watershed. It was difficult to identify each and every processes influence on tiles flows.

Conclusion3

Nutrient management planning

With tile drainage reducing runoff volumes, it was observed that less of the nutrients are transported to surface waters. It was expected to have elevated losses of nitrogen from tiles as nitrates NO3-N, highly mobile in the soil is easily dissolved in water and the model showed the same. SWAT model has been greatly enhanced from its previous version (SWAT2003), but its tile drainage module still needs further improvement to obtain higher accuracy in predicting NO3-N in stream discharge of sub-watersheds from tile drains.

VII. 2. RECOMMENDATIONS

Future directions

Sensitivity analysis and autocalibration tools

More emphasis should be set in determining more parameters appropriate to different periods of hydrological year that enables a clear analysis of the relationships between parameters and periods. This would reduce errors which are still unknown to the users and at the same time improve the model accuracy when fitting output to measured values. For instance the soils parameters are not really remaining the same in winter as in summer or spring. It means more researches could be done on this matter.

In addition, more objective functions are needed in autocalibration for allowing the tool to be more trustfully on its output values, the method should be rendered effective and be efficient as possible.

Environmental benefits of tile drainage modelling

Better performance might be expected if SWAT is extended to directly handle the physical processes that govern the movement of water to sub-surface drains. This would work especially for sediments and phosphorus loads discharged in streams as the tile drainage was proven to be an effective method of reducing non-point source pollution in areas where sediments and phosphorus are the major concerns (Loudon et al., 1986). Also, given the importance of preferential transfer of P to tile drainage waters reported in Quebec, the improvements of SWAT capacity to accurately predict tile drain flow remains a priority for allowing its utilization for decision support under the specific conditions of the region.

Model code management

Like SWAT model allows site-specific modifications; the special attention should be paid to the structure of the codes and increase a better understanding of the model output relations. This would give a more understandable network inside the model and help users to build more reliable systems depending on their cases.

Pike river watershed management

As the work done expected to improve a tool that would be useful for supporting the decision makers on the water quality management in the Pike river watershed, the model needs further improvements for a better simulation of the hydrological system network. So, it was found that a better understanding is needed on some options involved in tiles modelling, for instance more tests are needed on the Walbridge's sites:

- To know deeply the soils mechanics of the regions especially for cracks and their possibility to change the hydrological system of the area.
- To know precisely what could be the sources of water in tiles and approximately what could be their different contributions in that area;

This could be applied in a standardized manner, where the types of problems encountered in the Walbridge's watershed modelling would be guiding the all procedures using the model.

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APPENDICES - SWAT source codes (*fortran90*)
Modules changes

Part I

SWAT2000 and SWAT2003 before changes

Appendix 1

File	Code
SWAT2000 subroutine for tile drains and lateral flow computation	
percmicro.f	

```
!! if temperature of layer is 0 degrees C or below
   !! there is no water flow
   if (sol_tmp(ly1,j) <= 0.) then
     sep = 0.
     return
   end if
   if (ldrain(j) == ly1) then
     !! Compute lateral flow with tile drains
     lyrtile = 0.
     lyrtile = sw_excess * (1. - Exp(-24. / tdrain(j)))
   else
     !! COMPUTE LATERAL FLOW USING HILLSLOPE STORAGE METHOD
     if (ly1 == 1) then
       yy = 0.
     else
       yy = 0.
       yy = sol_z(ly1-1,j)
     end if
     dg = 0.
     ho = 0.
     latlyr = 0.
     dg = sol_z(ly1,j) - yy
     ho = 2. * sw_excess / ((sol_ul(ly1,j) - sol_fc(ly1,j)) /  dg)
     latlyr = adjf * ho * sol_k(ly1,j) * slope(j) / slsoil(j) * .024
   end if
   if (latlyr < 0.) latlyr = 0.
   if (latlyr > sw_excess) latlyr = sw_excess
```

Appendix 2

File	Code
SWAT2003	**subroutine tile drains, lateral and seepage computation**
percmicro.f	

```
!! if temperature of layer is 0 degrees C or below
   !! there is no water flow
   if (sol_tmp(ly1,j) <= 0.) then
     sepday = 0.
     return
   end if
!! The deasactivated lines
!     ldrain(j) = 0
!     if (ldrain(j) == ly1) then
!       !! COMPUTE LATERAL FLOW WITH TILE DRAINS
!       lyrtile = 0.
!       lyrtile = sw_excess * (1. - Exp(-24. / tdrain(j)))
!     else
!! Compute lateral flow using hillslope storage method
     if (ly1 == 1) then
       yy = 0.
     else
       yy = 0.
       yy = sol_z(ly1-1,j)
     end if
     dg = 0.
     ho = 0.
     latlyr = 0.
     dg = sol_z(ly1,j) - yy
     if (sol_ul(ly1,j) - sol_fc(ly1,j)==0.) then
       ho=0.
     else
       ho = 2. * sw_excess / ((sol_ul(ly1,j) - sol_fc(ly1,j)) /  dg)
     end if
     latlyr = adjf * ho * sol_k(ly1,j) * hru_slp(j) / slsoil(j)       &
  &                                                * .024
   if (latlyr < 0.) latlyr = 0.
   if (latlyr > sw_excess) latlyr = sw_excess
   !! compute seepage to the next layer
   sepday = 0.
   sepday = sw_excess * (1. - Exp(-24. / sol_hk(ly1,j)))
   !! restrict seepage if next layer is saturated
   if (ly1 == sol_nly(j)) then
     xx = (dep_imp(j) - sol_z(ly1,j)) / 1000.
     if (xx < 1.e-4) then
       sepday = 0.
     else
       sepday = sepday * xx / (xx + Exp(8.833 - 2.598 * xx))
     end if
   end if
```

```
!! check mass balance
if (sepday + latlyr > sw_excess) then
  ratio = 0.
  ratio = sepday / (latlyr + sepday)
  sepday = 0.
  latlyr = 0.
  sepday = sw_excess * ratio
  latlyr = sw_excess * (1. - ratio)
endif
if (sepday + lyrtile > sw_excess) then
  sepday = 0.
  sepday = sw_excess - lyrtile
endif
return
end
```

Appendix 3

File	Code
SWAT2003	**soil percolation**
percmain.f	

```
!! initialize water entering first soil layer
      if (icrk == 1) then
        sepday = Max(0., inflpcp - voltot)
      else
        sepday = inflpcp
      end if
      !! calculate crack flow
      if (icrk == 1) call percmacro
      do j1 = 1, sol_nly(j)
        !! add water moving into soil layer from overlying layer
        sol_st(j1,j) = sol_st(j1,j) + sepday
        !! determine gravity drained water in layer
        sw_excess = 0.
        sw_excess = sol_st(j1,j) - sol_fc(j1,j)
        !! initialize variables for current layer
        sepday = 0.
        latlyr = 0.
        lyrtile = 0.
        lyrtilex = 0.
        if (sw_excess > 1.e-5) then
          !! calculate tile flow (lyrtile), lateral flow (latlyr) and
          !! percolation (sepday)
          call percmicro(j1)
          sol_st(j1,j) = sol_st(j1,j) - sepday - latlyr - lyrtile
          sol_st(j1,j) = Max(1.e-6,sol_st(j1,j))
!! redistribute soil water if above field capacity (high water table)
          call sat_excess(j1)
!         sol_st(j1,j) = sol_st(j1,j) - lyrtilex
!         sol_st(j1,j) = Max(1.e-6,sol_st(j1,j))
        end if
        !! summary calculations
        if (j1 == sol_nly(j)) then
          sepbtm(j) = sepbtm(j) + sepday
        endif
        latq(j) = latq(j) + latlyr
        qtile = qtile + lyrtile
        flat(j1,j) = latlyr + lyrtile
        sol_prk(j1,j) = sol_prk(j1,j) + sepday
      end do
```

!! compute shallow water table depth and tile flow

```
qtile = 0.
if (sol_tmp(2,j) > 0.) then
  por_air = 0.5
  d = dep_imp(j) - ddrain(j)
  if (sol_sw(j) > sol_sumfc(j)) then
    yy = sol_sumul(j) * por_air
    if (yy < 1.1 * sol_sumfc(j)) then
      yy = 1.1 * sol_sumfc(j)
    end if
    xx = (sol_sw(j) - sol_sumfc(j)) / (yy - sol_sumfc(j))
    if (xx > 1.) xx = 1.
    wt_shall = xx * dep_imp(j)
  if (ddrain(j) > 0.) then
      if (wt_shall < d) then
        qtile = 0.
      else
        dmod_m = wt_shall - d
        sw_excess = (dmod_m / wt_shall) * (sol_sw(j) -
&                                      sol_sumfc(j))
        qtile = sw_excess * (1. - Exp(-24. / tdrain(j)))
      end if
    end if
```

Appendix 4

File	Code
SWAT2003	**soubroutine reading files**
read.hru	
	!! set default values if (dep_imp(ihru) <=0.) dep_imp(ihru) = depimp_bsn
read.bsn	
	set default values for undefined parameters if (depimp_bsn <= 1.e-6) depimp_bsn = 6000.

Part II

SWAT2003 - First changes

Appendix 5

File	Code
SWAT2003	**the three tested cases**
percmicro.f	

```
! NEW COMPUTE - TILE FLOW WITH 3 METHODS

  !! compute shallow water table depth and tile flow
      if (ldrain(j) == ly1) then
      qtile = 0.
        if (sol_tmp(2,j) > 0.) then

              select case (tileDrainOPT)
```

case (1) !! SWAT2000 routine modified

```
      sw_excess = 0.
              if (sol_st(ly1,j) > sol_fc(ly1,j)) then
                          sw_excess = sol_st(ly1,j) - sol_fc(ly1,j)
               if (ddrain(j) > 0.) then
          lyrtile = sw_excess * (1. - Exp(-24. / tdrain(j)))
                lyrtile =  min(sw_excess, lyrtile)
                         sw_excess = sw_excess-lyrtile
               end if
              end if
```

case (2) !! based on the works of Du et al. (2005)

```
               if (sol_sw(j) > sol_sumfc(j)) then
                     sw_excess= sol_sw(j)-sol_sumfc(j)
                if (ddrain(j) > 0.) then          !no. 3
                      wt_shall= 0
                      d= sol_z(sol_nly(j), j)- ddrain(j)
                            lyTile= sc
                 do while ( (sw_excess > solSatDrain(lyTile, j)) .and.!
!                 (lyTile > 0) )
                       if (lyTile == 1) then
                        lySol= sol_z(lyTile, j)
                             else
                        lySol= (sol_z(lyTile, j)-sol_z(lyTile-1, j))
                             end if
                                   wt_shall= wt_shall + lySol
                       sw_excess= sw_excess-solSatDrain(lyTile, j)
                       lyTile= lyTile-1
                 end do
                      if ((sw_excess > 0) .and.       !
!                 (wt_shall==sol_z(sol_nly(j), j))) then
                  wt_shall=wt_shall+sw_excess
                            else if (((sw_excess > 0) .and.                        !
!                 (wt_shall < sol_z(sol_nly(j), j))) ) then
                       if (lyTile == 1) then
                        lySol= sol_z(lyTile, j)
                       else
                        lySol= sol_z(lyTile, j)-sol_z(lyTile-1, j)
                       end if
                                   wt_ly= (sw_excess/solSatDrain(lyTile, j))*lySol
                  wt_shall=wt_shall+wt_ly
                                   if  (wt_shall > d) then
                        qtile = (wt_shall-d) * (1. - Exp(-24. / tdrain(j)))
                       end if
                      end if  !ferme. 4
                     end if   !ferme no. 3
                    end if
```

case (3) SWAT2003

!! compute shallow water table depth and tile flow

```
          por_air = 0.5
          d = dep_imp(j) - ddrain(j)
          if (sol_sw(j) > sol_sumfc(j)) then
            yy = sol_sumul(j) * por_air
            if (yy < 1.1 * sol_sumfc(j)) then
              yy = 1.1 * sol_sumfc(j)
            end if
            xx = (sol_sw(j) - sol_sumfc(j)) / (yy - sol_sumfc(j))
            if (xx > 1.) xx = 1.
            wt_shall = xx * dep_imp(j)
          if (ddrain(j) > 0.) then
              if (wt_shall < d) then
                qtile = 0.
              else
                dmod_m = wt_shall - d
                sw_excess = (dmod_m / wt_shall) * (sol_sw(j) -
     &                                         sol_sumfc(j))
                qtile = sw_excess * (1. - Exp(-24. / tdrain(j)))
              end if
C                  write(*,*) 'Possibilities for tile flow', qtile, xx, wt_shall,!
C     !                 d, sol_sw(j), sol_sumfc(j), yy
          end if
          end if
                    end select
```

SWAT2003 - Second change

Appendix 6

File	Code
SWAT 2003	**seepage computation**
percmicro.f	

```
!! compute seepage to the next layer
        select case (sepopt)
case(1)      !! original
   sepday = 0.
   sepday = sw_excess * (1. - Exp(-24. / sol_hk(ly1,j)))
   !! restrict seepage if next layer is saturated
   if (ly1 == sol_nly(j)) then
     xx = (dep_imp(j) - sol_z(ly1,j)) / 1000.
     if (xx < 1.e-4) then
       sepday = 0.
     else
       sepday = sepday * xx / (xx + Exp(8.833 - 2.598 * xx))
     end if
   end if
   !! check mass balance
   if (sepday + latlyr > sw_excess) then
     ratio = 0.
     ratio = sepday / (latlyr + sepday)
     sepday = 0.
     latlyr = 0.
     sepday = sw_excess * ratio
     latlyr = sw_excess * (1. - ratio)
   endif
   if (sepday + lyrtile > sw_excess) then
     sepday = 0.
     sepday = sw_excess - lyrtile
   endif
```

```
        case(2) !! new option
                sepday=0.
                if (ly1 == sol_nly(j)) then
                solcon=     sol_k(ly1,j)
                else
                solcon=min(sol_k(ly1,j),sol_k(ly1+1,j))
                end if
                sepday=min(solcon*24,sw_excess)
          sumday = sepday+latlyr
c               in case dra
                if (sumday > sw_excess) then
                sepday = sepday*sw_excess/sumday
                latlyr = latlyr*sw_excess/sumday
                end if
c       in case of oversaturation, excess will move with lateral flow
                toomuch=sw_excess-sumday-sol_ul(ly1,j)
                if (toomuch > 0.) then
                  if (ldrain(j) == ly1) then
                        lyrtile=lyrtile + toomuch
                  else
                        latlyr = latlyr + toomuch
                        end if
                end if
                end select
```

SWAT2003 – Third changes

Appendix 7

File	Code
SWAT2003	**crack flow computation with tile drains**
percmacro.f	

	! new added for transferring water through tiles
	if (ldrain(j) == ly) then
	tilecrack = tilecrack + crk
	else
	sepbtm(j) = sepbtm(j) + crk
	end if

Appendix 8

File	Code
SWAT 2003	**ground water contribution to stream flow**
gwmod.f	

!! compute shallow aquifer level for current day

```
      rchrg(j) = 0.
      rchrg(j) = (1.-gw_delaye(j)) * sepbtm(j) + gw_delaye(j) * rchrg1
      if (rchrg(j) < 1.e-6) rchrg(j) = 0.
```

!! compute deep aquifer level for day

```
      gwseep = rchrg(j) * rchrg_dp(j)
      deepst(j) = deepst(j) + gwseep
      shallst(j) = shallst(j) + (rchrg(j) - gwseep)
      gwht(j) = gwht(j) * alpha_bfe(j) + rchrg(j) * (1. - alpha_bfe(j)) &
     &    / (800. * gw_spyld(j) + 1.e-6 * alpha_bf(j) + 1.e-6)
      gwht(j) = Max(1.e-6, gwht(j))
```

!! compute groundwater contribution to streamflow for day

```
      if (shallst(j) > gwqmn(j)) then
        gw_q(j) = gw_q(j) * alpha_bfe(j) + (rchrg(j) - gwseep ) *       &
     &                                     (1. - alpha_bfe(j))
      else
        gw_q(j) = 0.
      end if
```

!! compute revap to soil profile/plant roots

```
      revapday = gw_revap(j) * pet_day
      if (shallst(j) < revapmn(j)) then
        revapday = 0.
      else
        shallst(j) = shallst(j) - revapday
        if (shallst(j) < revapmn(j)) then
          revapday = shallst(j) + revapday - revapmn(j)
          shallst(j) = revapmn(j)
        end if
      end if
```

!! remove ground water flow from shallow aquifer storage

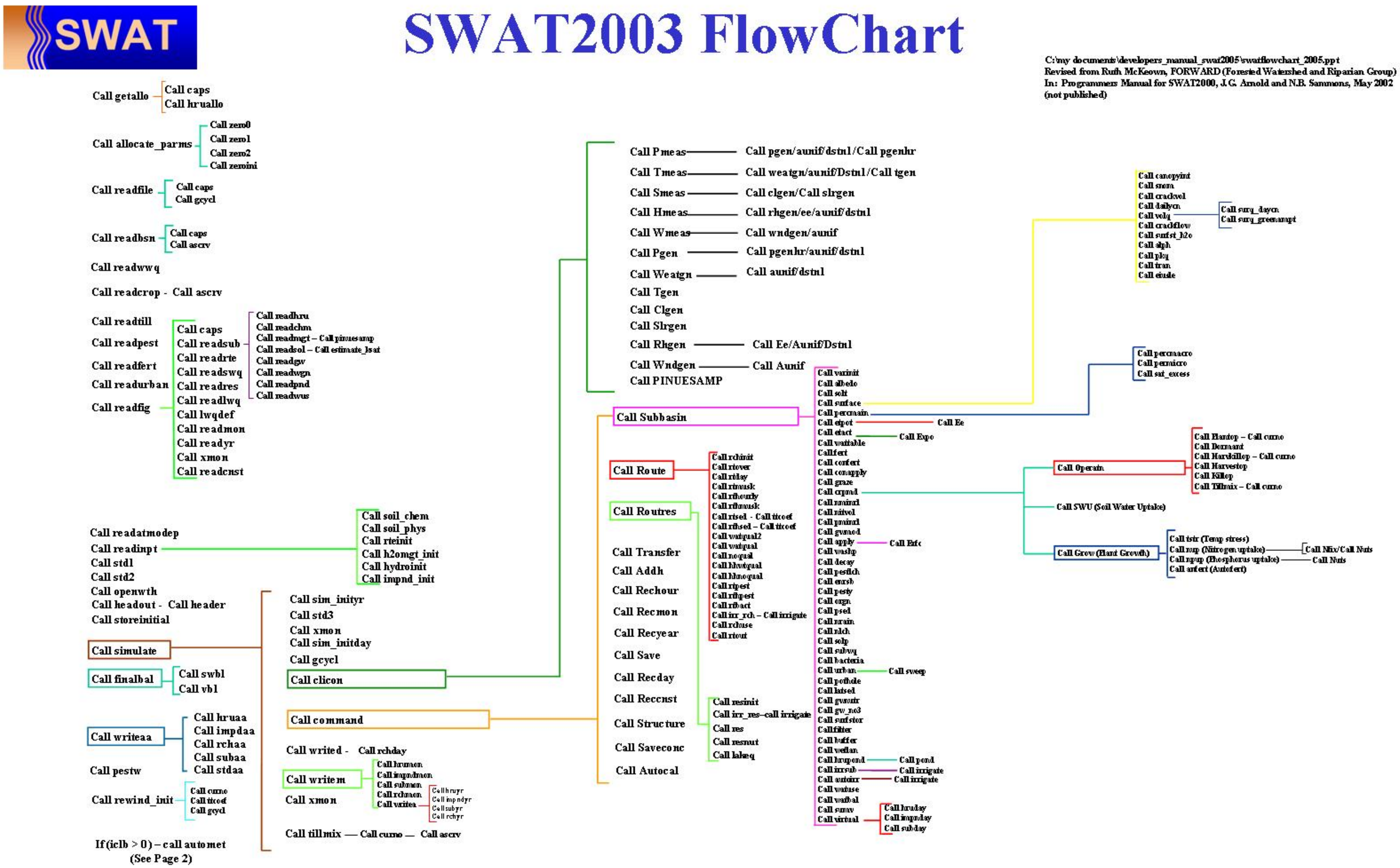
```
      if (shallst(j) >= gwqmn(j)) then
        shallst(j) = shallst(j) - gw_q(j)
        if (shallst(j) < gwqmn(j)) then
          gw_q(j) = shallst(j) + gw_q(j) - gwqmn(j)
          shallst(j) = gwqmn(j)
        end if
      end if
      return
      end
```

Appendix 9

File	Code
SWAT2003	**ground water contribution to stream flow with tile drains**
gwmod.f	

```
!! New added
!! remove tile water flow from shallow aquifer storage
            if (shallst(j) > dep_imp(j) - ddrain(j) ) then
   gw_flow=gw_q(j)
    gw_tile_vol = (shallst(j) - (dep_imp(j) - ddrain(j)))
    gw_tile = gw_tile_vol * (1. - Exp(-24. / tdrain(j)))
   gw_q(j) = gw_flow - gw_tile
    shallst(j) = shallst(j)-gw_tile
            qtile=qtile + gw_tile
            end if
!! remove ground water flow from shallow aquifer storage
    if (shallst(j) >= gwqmn(j)) then
      shallst(j) = shallst(j) - gw_q(j)
      if (shallst(j) < gwqmn(j)) then
        gw_q(j) = shallst(j) + gw_q(j) - gwqmn(j)
        shallst(j) = gwqmn(j)
      end if
    end if
    return
```

Appendix 10



SWAT
SWAT2003 FlowChart
C:\my documents\developers_manual_swat2005\swatflowchart_2005.ppt
Revised from Ruth McKeown, FORWARD (Forested Watershed and Riparian Group)
In: Programmers Manual for SWAT2000, J.G. Arnold and N.B. Sammons, May 2002
(not published)
Call getallo
Call caps
Call hruallo
Call allocate_parms
Call zero0
Call zero1
Call zero2
Call zeroini
Call readfile
Call caps
Call gcycl
Call readbsn
Call caps
Call ascrv
Call readwwq
Call readcrop - Call ascrv
Call readtill
Call readpest
Call readfert
Call readurban
Call readfig
Call caps
Call readsub
Call readrte
Call readswq
Call readres
Call readlwq
Call lwqdef
Call readmon
Call readyr
Call xmon
Call readcnst
Call readhru
Call readchm
Call readmgt – Call pinuesamp
Call readsol – Call estimate_ksat
Call readgw
Call readwgn
Call readpnd
Call readwus
Call readatmodep
Call readinpt
Call std1
Call std2
Call openwth
Call headout - Call header
Call storeinitial
Call soil_chem
Call soil_phys
Call rteinit
Call h2omgt_init
Call hydroinit
Call impnd_init
Call simulate
Call finalbal
Call swbl
Call vbl
Call writeaa
Call hruaa
Call impdaa
Call rchaa
Call subaa
Call stdaa
Call pestw
Call rewind_init
Call curno
Call ttcoef
Call gcycl
If (iclb > 0) – call automet
(See Page 2)
Call sim_inityr
Call std3
Call xmon
Call sim_initday
Call gcycl
Call clicon
Call command
Call writed - Call rchday
Call writem
Call hrumon
Call impndmon
Call submon
Call rchmon
Call writea
Call hruyr
Call impndyr
Call subyr
Call rchyr
Call xmon
Call tillmix — Call curno — Call ascrv
Call Pmeas
Call pgen/aunif/dstn1/Call pgenhr
Call Tmeas
Call weatgn/aunif/Dstn1/Call tgen
Call Smeas
Call clgen/Call slrgen
Call Hmeas
Call rhgen/ee/aunif/dstn1
Call Wmeas
Call wndgen/aunif
Call Pgen
Call pgenhr/aunif/dstn1
Call Weatgn
Call aunif/dstn1
Call Tgen
Call Clgen
Call Slrgen
Call Rhgen
Call Ee/Aunif/Dstn1
Call Wndgen
Call Aunif
Call PINUESAMP
Call Subbasin
Call Route
Call rchinit
Call rtover
Call rtday
Call rtmusk
Call rthourly
Call rthmusk
Call rtsed - Call ttcoef
Call rthsed – Call ttcoef
Call watqual2
Call watqual
Call noqual
Call hhwtqual
Call hhnoqual
Call rtpest
Call rthpest
Call rtbact
Call irr_rch – Call irrigate
Call rchuse
Call rtout
Call Routres
Call resinit
Call irr_res–call irrigate
Call res
Call resnut
Call lakeq
Call Transfer
Call Addh
Call Rechour
Call Recmon
Call Recyear
Call Save
Call Recday
Call Reccnst
Call Structure
Call Saveconc
Call Autocal
Call varinit
Call albedo
Call solt
Call surface
Call percmain
Call etpot
Call Ee
Call etact
Call Expo
Call wattable
Call fert
Call confert
Call conapply
Call graze
Call crpmd
Call nminrl
Call nitvol
Call pminrl
Call gwmod
Call apply
Call Erfc
Call washp
Call decay
Call pestlch
Call enrsb
Call pesty
Call orgn
Call psed
Call nrain
Call nlch
Call solp
Call subwq
Call bacteria
Call urban
Call sweep
Call pothole
Call latsed
Call gwnutr
Call gw_no3
Call surfstor
Call filter
Call buffer
Call wetlan
Call hrupond
Call pond
Call irrsub
Call irrigate
Call autoirr
Call irrigate
Call watuse
Call watbal
Call sumv
Call virtual
Call hruday
Call impndday
Call subday
Call canopyint
Call snom
Call crackvol
Call dailycn
Call volq
Call surq_daycn
Call surq_greenampt
Call crackflow
Call surfst_h2o
Call alph
Call pkq
Call tran
Call eiusle
Call percmacro
Call percmicro
Call sat_excess
Call Operatn
Call Plantop – Call curno
Call Dormant
Call Harvkillop – Call curno
Call Harvestop
Call Killop
Call Tillmix – Call curno
Call SWU (Soil Water Uptake)
Call Grow (Plant Growth)
Call tstr (Temp stress)
Call nup (Nitrogen uptake)
Call Nfix/Call Nuts
Call npup (Phosphorus uptake)
Call Nuts
Call anfert (Autofert)