

**Microbial contamination assessment with SWAT in a tile-drained
rural watershed**

A Thesis
Presented to
The Faculty of Graduate and Postdoctoral Studies
Of
The University of Ottawa

by
Claudia Fall

In partial fulfillment of the requirements
for the degree of
Master of Science
March, 2011

ABSTRACT

Microbial contamination assessment with SWAT in a tile-drained rural watershed

Microbial contamination of drinking water poses an important health risk which causes severe illnesses and epidemics. In order to improve surface and drinking water quality, the understanding of fecal pathogen contamination processes including their prevention and control needs to be enhanced. The watershed model soil water assessment tool (SWAT) is commonly used to simulate the complex hydrological, meteorological, erosion, land management and pollution processes within river basins. In recent years, it has been increasingly applied to simulate microbial contamination transport at the watershed scale. SWAT is used in this study to simulate *Escherichia coli* (*E.coli*) and fecal coliform densities for the agriculturally dominated Payne River Basin in Ontario, Canada. Unprecedented extensive monitoring data that consist of 30 years of daily hydrological data and 5 years of bi-weekly nutrient data have been used to calibrate and validate the presented model here. The calibration and validation of the streamflow and nutrients indicate that the model represent these processes well. The model performs well for periods of lower *E. coli* and fecal coliform loadings. On the other hand, frequency and magnitude of higher microbial loads are not always accurately represented by the model.

ACKNOWLEDGEMENT

The successful completion of this research project would not have been possible without the generous support of several people. I would like to take this occasion to thank my graduate advisor, Dr. Mike Sawada, who not only provided sound technical guidance and practical help, but was always full of encouragement. I am also very thankful for his invaluable assistance towards my professional career.

My very special thanks go to Agriculture and Agri-Food Canada for facilitating my research and foremost Dr. David Lapen, for master minding the project objectives, his scientific guidance and for providing any possible support that a graduate student could need. He and his team made my time as a Research Affiliate at Agriculture and Agri-Food Canada a great experience. I wish to thank Graham Wilkes for his help with field work, data acquisition and numerous discussions, Ed Topp for providing very useful bacteria data, Mark Sunohara for providing tile drain and nutrient management information, and Natalie Gottschall, Che Zhenuang, Patricia Bolton, Mark Edwards and Emilia Craiovan for technical and moral support. Furthermore, I would like to extend my appreciation to all Eastern Cereal and Oilseed Research Centre (Agriculture and Agri-Food Canada) employees who supported me and my work in one way or another. To name just a few, thank you to Dr. Ted Huffman, Dr. Rainer DeJong, David Kroetsch, Dirk Anderson, Bahram Daneshfar, Brent Corrigan for their expert advice on land use, modeling, soil, climate, GIS and livestock management. Moreover, I want to thank Ken Ross (Canadian Wildlife Service, Environment Canada) for his very much appreciated help on the estimation of geese numbers for the study area. Finally, I would like to thank my family for their patience and precious support. It would certainly not have been possible without you!

Table of Contents

ABSTRACT	i
ACKNOWLEDGEMENT	ii
Table of Contents	iii
List of Tables.....	iv
List of Figures	v
List of Abbreviations	vi
1. Introduction	1
1.1 Purpose and Objectives.....	3
1.2 Organisation of Thesis	4
2. Background	5
2.1 Sources of microbial contamination	5
2.2 Survival of bacteria in manure, soil and water	7
Manure	8
Soil	9
Water	10
2.3 Transport characteristics	11
Overland Transport	12
Subsurface Transport	13
In stream Transport	14
2.4 Modeling of microbial contaminant transport.....	18
SWAT Model	24
3. Model Development	30
3.1 Study Area.....	30
3.2 Data and Model Setup	31
Soil	34
Land Use Data	36
Land Management	39
Bacteria parameter	48
Observed Data	50
4. Model Calibration and Validation	52
4.1 Sensitivity	52
4.2 Calibration and Validation	54
Flow	56
Sediment.....	58
Nutrients.....	58
Bacteria	60
5. Discussion	62
6. Summary and Conclusion	67
7. Recommendations.....	68
8. References	70
Appendix A SWAT Input Parameter (Neitsch et al. 2004)	82
Appendix B Soil Properties.....	89

List of Tables

TABLE 1	EXAMPLES OF FECAL COLIFORMS AND CONCENTRATIONS IN DIFFERENT MEDIA	6
TABLE 2	BACTERIA DIE-OFF COEFFICIENTS WITHIN THE LITERATURE	8
TABLE 3	COMPARISON OF WATERSHED MODELS AND THEIR CAPABILITIES	20
TABLE 4	DATA SOURCES USED FOR THE SWAT MODEL	32
TABLE 5	CLIMATE STATIONS AND DATASETS EMPLOYED IN THE MODEL.....	34
TABLE 6	CROP DISTRIBUTION BASED ON CENSUS OF AGRICULTURE 1991, STATISTICS CANADA.....	39
TABLE 7	LIVESTOCK NUMBERS AND MANURE PRODUCTION IN 2006.....	41
TABLE 8	CATTLE AND GRAZING CATTLE IN THE PAYNE RIVER CATCHMENT	42
TABLE 9	GEESE ESTIMATIONS.....	42
TABLE 10	MUSKRAT ESTIMATIONS.....	43
TABLE 11	SEPTIC SYSTEMS.....	44
TABLE 12	MANURE APPLICATION RATES AND POINT SOURCE LOADINGS ESTIMATED WITHIN THE STUDY AREA.....	45
TABLE 13	LAND MANAGEMENT PARAMETERS.....	46
TABLE 14	FCs AND <i>E. COLI</i> CONCENTRATIONS IN LIVESTOCK AND WILDLIFE FECES, STORED MANURE AND SEPTIC EFFLUENT	49
TABLE 15	SENSITIVITY ANALYSIS RESULTS FOR FLOW AND NUTRIENTS.....	53
TABLE 16	CALIBRATION AND VALIDATION PARAMETERS.....	54

List of Figures

FIGURE 1 ARCSWAT MAIN INPUTS AND OUTPUTS (GOLLAMUDI 2006).....	25
FIGURE 2 CONCEPTUAL MODEL OF THE SWAT PATHOGEN TOOL.....	27
FIGURE 3 PAYNE RIVER WATERSHED, EASTERN ONTARIO, CANADA.....	31
FIGURE 4 SOIL MAP OF THE AREA (CANSIS).....	35
FIGURE 5 LAND USE CLASSIFICATIONS DERIVED FROM REMOTELY SENSED IMAGERY FROM 2004 TO 2007.....	36
FIGURE 6 GENERAL LAND USE GROUPS.....	37
FIGURE 7 RESULTING GENERATED LAND USE MAP.....	38
FIGURE 8 WATERSHED MODEL CALIBRATION PROCEDURE (MORIASI ET AL. 2007).....	55
FIGURE 9 OBSERVED VERSUS SIMULATED DISCHARGE FOR THE CALIBRATION PERIOD.....	57
FIGURE 10 OBSERVED AND SIMULATED TOTAL NITROGEN LOADS.....	59
FIGURE 11 OBSERVED AND SIMULATED TOTAL PHOSPHORUS LOADS.....	60
FIGURE 12 OBSERVED AND SIMULATED <i>E. COLI</i> LOADINGS.....	61
FIGURE 13 OBSERVED AND SIMULATED <i>E. COLI</i> LOADINGS.....	62
FIGURE 14 OBSERVED BACTERIA LOADINGS IN RELATION TO MODELED TILE FLOW CONTRIBUTIONS (129 OBSERVATIONS).....	64
FIGURE 15 OBSERVED BACTERIA LOADINGS IN RELATION TO OBSERVED TILE FLOW CONTRIBUTIONS (67 OBSERVATIONS).....	65

List of Abbreviations

AAFC	Agriculture and Agri-Food Canada
ALPHA-BF	Baseflow Alpha Factor
BACTKDDDB	Bacteria Partition Coefficient
BACTKDQ	In-Stream Bacteria Partition Coefficient
BACTMX	Bacteria percolation coefficient
BACTPDB	Concentration of Bacteria in Manure
CANMX	Maximum Canopy Storage
CanSIS	Canadian Soil Information System
CH-K	Effective Hydraulic Conductivity in the Channel Alluvium
CH-K2	Effective Hydraulic Conductivity in the Main Channel Alluvium
CH-N	Manning's Roughness Coefficient for Channels
CH-N2	Manning's Roughness Coefficient for the Main Channel
CN2	Initial SCS Runoff Curve Number for Moisture Condition II
DEM	Digital Elevation Model
<i>E.coli</i>	<i>Escherichia coli</i>
EPCO	Plant Uptake Compensation Factor
ESCO	Soil Evaporation Compensation Factor
FC	Fecal Coliform
GW-DELAY	Delay Time for Aquifer Recharge
GWQMN	Threshold Depth of Water in the Shallow Aquifer for Return Flow to Occur
GW-REVAP	Groundwater Revap Coefficient
HRU	Hydrological Response Unit
LH-OAT	Latin Hypercube Sampling
N	Nitrogen
NPERCO	Nitrate Percolation Coefficient
NRVIS	Natural Resources and Values Information System
NSE	Nash-Sutcliffe Efficiencies
NUPDIS	Nitrogen Plant Uptake
OV-N	Manning's Roughness Coefficient for Overland Flow
P	Phosphorus
PCR	Polymerase Chain Reaction
PHOSKD	Phosphorus Soil Partitioning Coefficient
PPERCO	Phosphorus Percolation Coefficient
PUPDIS	Phosphorus Plant Uptake
RCHRG-DP	Deep Aquifer Percolation Coefficient
REVAPMIN	Threshold Depth of Water in the Shallow Aquifer for "revap" or Percolation to the Deep Aquifer to Occur
RT-PCR	Real Time Polymerase Chain Reaction
SFTM	Snow Fall Temperature Threshold
SHALLST	Initial depth of water in shallow aquifer
SLSUBBSN	Average Slope Length (Distance for Sheet Flow Runoff)
SMFMN	Minimum Melt Factor
SMFMX	Maximum Melt Factor

SMTMP	Snowmelt Base Temperature
SOL-AWC	Available Water Capacity of the Soil Layer
SOL-K	Saturated Hydraulic Conductivity
SOL-ALB	Moist Soil Albedo
SOLNO3	Initial NO ₃ Concentration in the Soil Layer
SOLORGN	Initial Organic N Concentration in the Soil Layer
SOLORGP	Initial Organic P Concentration in the Soil Layer
SOL-Z	Soil Depth
SURLAG	Surface Runoff Lag Coefficient
SWAT	Soil Water Assessment Tool
THBACT	Temperature adjustment factor for bacteria die-off/ growth
TIMP	Snow Pack Temperature Lag Factor
TMDL	Total Maximum Daily Load
TSS	Total Suspended Solids
WDLPQ	Die Off Factor for Less Persistent Bacteria in Soil Solution at 20°C
WDLPRCH	Die Off Factor for Less Persistent Bacteria in Streams (Moving Water) at 20°C
WDLPRES	Die Off Factor for Less Persistent Bacteria in Water Bodies (Still Water) at 20°C
WDLPS	Die Off Factor for Less Persistent Bacteria Adsorbed to Soil Particles at 20°C
WDPQ	Die Off Factor for Persistent Bacteria in Soil Solution at 20°C
WDPRCH	Die Off Factor for Persistent Bacteria in Streams (Moving water) at 20°C
WDPRES	Die Off Factor for Persistent Bacteria in Water Bodies (Still Water) at 20°C
WDPS	Die Off Factor for Persistent Bacteria adsorbed to Soil Particles at 20°C

1. Introduction

Microbial contaminations of drinking water pose a health risk that causes severe illnesses and epidemics. As seen in 2002 in Walkerton, Ontario, the occurrence of bacteria *E.coli* O157:H7 and *Campylobacter jejuni* in drinking water caused the infection of 2300 people with gastroenteritis and led to several deaths (Locas et al. 2007). That outbreak alerted the public to the health risks posed by pathogens. The detection of potentially pathogenic microorganisms in water resources and drinking water supplies along with the resistance of *Cryptosporidium* to conventional drinking water treatment (filtration, chlorination) (Marshall et al. 1997, King & Monis 2006) reveal the necessity to reduce human exposure to these pathogens through more efficient source protection strategies.

Fecal pathogens of concern excreted by animals and humans comprise bacteria (*E.coli*, *Campylobacter*, *Salmonella enterica*), protozoa (*Cryptosporidium*, *Giardia*), and viruses (rotavirus, norovirus). Contamination by fecal pathogens can be caused by point and non-point sources. Point sources (direct entry of contaminants into the water resource) can be usually better identified and controlled than non-point source contaminations. While non-point source pollution with fecal pathogens can be derived from spatially dispersed and multifaceted sources (human, agricultural livestock, wildlife), agricultural activities (especially animal manure applications) have been identified as main contributors to non-point source pollution with fecal pathogens (and nutrients) (USEPA 2007, Jamieson 2004). In order to improve surface and drinking water quality, the understanding of fecal pathogen contamination processes including their prevention and control needs to be enhanced. For

example, research needs to be conducted at each level, starting with effective livestock infection control to reduce pathogen shedding rates. Pathogen concentrations in manure need to be controlled through manure management and treatment. Best management practices for manure application and grazing have to be developed, improved, and implemented in order to decrease surface and groundwater contamination. Furthermore, efficient water treatment methods need to be studied in order to provide the public with pathogen free drinking water.

Watershed models are commonly used to simulate the complex hydrologic, meteorologic, erosion, land management and pollution processes within river basins. Models have been proven to be an efficient tool to inform sensible water management, design and test best management practices, and forecast environmental impacts on the watershed. Moore et al. (1983) developed a model to estimate the level of fecal coliform (FC) in runoff. Subsequently, new models have been introduced (Ferguson et al. 2007). Additionally, hydrological watershed models have been extended to simulate microbial transport (Dorner et al. 2004a, Tian et al. 2002) such as the soil water assessment tool (SWAT) microbial sub-model (Sadeghi & Arnold 2002). SWAT has been extensively used for water quality assessments in diverse watershed conditions (Gassman et al. 2007). However, since the introduction of its microbial sub-model, few applications of bacterial transport in agricultural and forested watersheds have been published (Coffey et al. 2010, Chin et al. 2009, Parajuli et al. 2009, Baffaut & Benson 2008). Although these studies have significantly contributed to our knowledge of microbial transport in watersheds and its simulation, they are based on limited calibration and validation data due to the high temporal and spatial variability of pathogenic contaminants and the cost associated with their analysis. Therefore, a need for microbial transport simulations calibrated and validated with long-term field data is

fundamental. This thesis presents research conducted in the Payne River Basin of Ontario, Canada to determine if SWAT can simulate the transport of nutrients (nitrogen (N), phosphorus (P)) and fecal bacteria (FC and *E. coli*) and the degree to which these simulation results agree with observed long-term field data. This research enhances our understanding of sources as well as surface transport mechanisms of microbial contaminants at the watershed scale.

1.1 Purpose and Objectives

The wealth of data generated through detailed field observations and water quality sampling programs enables us to draw an accurate picture of the present situation and processes that occur within watersheds. However, in order to forecast future scenarios and deepen the understanding of these complex environmental interactions, watershed models are necessary tools. Since 2004, the Agriculture and Agrifood Canada research group led by Dr. D. Lapen has carried out an extensive water quality sampling program on several streams within the South Nation River Basin. The Payne River Basin is a sub-basin of the South Nation River. Long term hydrological data from the Environment Canada gauging station Payne River near Berwick (02LB022) are available in addition to water quality observations. These are the most important prerequisites for a robust and reliable model design and calibration. It is therefore a natural choice to use these long-term observations for simulation purposes and achieve the following objectives:

1. to simulate the transport of nutrients (N, P) and fecal bacteria (FC and *E. coli*) for the years of 2004-2008;

2. to parameterize the model by using geospatial data and in situ field analyses;
3. to determine to which degree these simulation results agree with observed long-term field data in the Payne River Basin of Ontario, Canada; and
4. to enhance our understanding of sources as well as surface transport mechanisms of microbial contaminants at the watershed scale.

1.2 Organization of Thesis

This thesis is in the form of an enriched manuscript that contains several chapters which contribute to achieve the above stated thesis objectives. A review of the existing literature on sources of microbial contamination, survival of bacteria in manure, soil and water, their transport characteristics and the modeling of microbial contaminant transport is presented in Chapter 4. The subsequent chapter describes in detail the model development, including model parameterization and quantification of sources of microbial contamination in the watershed. A sensitivity analysis, and calibration and validation of the model for discharge, sediment and water quality (nutrients and bacteria) are presented in Chapter 6. Chapter 7 discusses in detail, the model results, which is followed by a summary of the most important results of this study as well as conclusions and recommendations drawn from this thesis.

2. Background

The following literature review has been performed with the purpose of better understanding the mechanisms that drive microbial contamination in agricultural watersheds. A discussion of the sources of microbial pollution, including FC and *E. coli* concentrations in feces, stored manure and septic effluent, will be followed by a review of bacteria survival, transport characteristics and modeling approaches at the watershed scale.

2.1 Sources of microbial contamination

Common sources of water pollution with pathogens are fecal matters of livestock (e.g., cattle, horses, goats, sheep), wildlife (deer, waterfowl, muskrat, raccoon, and beaver), humans and pets. These sources are distributed either as point or most commonly as non-point sources throughout the watershed depending on the actual land use (urban, water, cropland, and forest). Point sources include mostly waste water treatment plants and straight pipe sewage discharges of older houses. Non-point sources are more diverse and consist of manure storage lagoons, manure land application as fertilizer on cropland, feces of grazing livestock (placed on grazing land) and wildlife (placed on agricultural, residential, and forest areas), human fecal matter deposited on land surfaces through failing septic systems as well as livestock, wildlife and human fecal matter directly deposited into streams from individuals or animals with access to streams or recreational use of water bodies. Generally, the amount of pathogens contained in animal waste depends on the species, age, feed, health as well as manure storage and treatment. Feces produced by confined livestock operations (principally

poultry, swine, and dairy) are usually stored (Benham et al. 2004). During dung storage, bacteria might increase, decrease or shift in species diversity (Lu et al. 2005). Examples of FC and *E.coli* concentrations in fresh cattle and wildlife feces, as well as in stored cattle manure and septic effluent, are summarized in Table 1.

Table 1 Examples of fecal coliforms and concentrations in different media

	Fecal Coliform Range		<i>E. coli</i> Range		Units	Source
Beef, fresh	1.74×10^6	6.03×10^6	1×10^6	1×10^7	cfu g ⁻¹ (dry weight)	van Kessel et al. 2007
Cattle Manure	8.48×10^8	2.73×10^7	1×10^5	1×10^8	cfu g ⁻¹ (dry weight)	Guber et al.2009, Trevisan et al. al. 2002
Geese	7×10^4	1.3×10^6			cfu/g (wet weight)	Middleton & Ambrose 2005
Muskrat	2.5×10^5		2.5×10^5		cfu/g (wet weight)	Yagow et al. 2001
Septic System	7×10^4	1.1×10^8	3×10^5	6.2×10^7	cfu l ⁻¹	Sidhu et al. 2009

Concentrations of bacteria that are contained in fecal matter deposited on land surfaces (manure, application, grazing animals) may decline due to dehydration and UV-radiation. Rainfall that results in surface runoff can transport feces and the remaining bacteria into streams or in the case of urban land use (pets) into a storm sewer that directly empties into streams. The intensity and duration of runoff producing rainfall and the proximity to streams control hereby the amount of bacteria that reach the watercourse (Jamieson et al. 2002). Fecal matter and associated bacteria used as fertilizer and applied on cropland might reach subsurface tile drainage systems (Jamieson et al. 2002) that empty into streams. During the downstream transport, additional bacteria die-off can occur (Benham et al. 2004). If fecal matter is directly deposited into streams, bacteria die-off is lower than bacteria deposited on the land. Direct deposits are therefore a major source of water pollution.

The presence of fecal pathogens is usually detected by means of indicator bacteria (such as FC (fecal coliforms) or *Escherichia coli* (*E. coli*)). To reduce fecal contamination of water,

substantial efforts in source tracking and understanding the fate and transport of bacteria are made (Benham et al. 2004).

2.2 Survival of bacteria in manure, soil and water

The survival of pathogens in manure, soil and water depends on multiple factors, including soil type, temperature, moisture, pH, UV radiation, method of waste application, nutrient availability, competition and pathogenic bacterial-protozoa interactions. Pathogen survival has been reviewed by Reddy et al. (1981), Crane et al. (1983), Crane & Moore (1986), Dorner (2004b), Snelling et al. (2006), and King & Monis (2007).

Among all factors that influence bacteria survival in the environment, nutrient availability and temperature seem to be the most essential (Van Elsas et al. 2011). Foppen & Schijven (2006) evaluated numerous studies on environmental inactivation of *E.coli* in solution and attached to sediment, and concluded that despite the variety of experimental conditions, a positive relationship between temperature and die-off coefficients is apparent. The average *E. coli* die-off coefficient at 20° was found to be 0.5 d⁻¹ (with values ranging between 0.08 and 1.1). Furthermore, predation/antagonism seems to increase the die-off rate by 1 log-unit on average.

The range of bacteria deactivation rates found in the literature is summarized in **Table 2**. The table clearly shows that die-off coefficients vary with the bacteria host medium. In the following, bacteria die-off in manure, soil and water will be discussed.

Table 2 Bacteria Die-Off Coefficients within the Literature

	Die-Off coefficients				Condition	Source
	Fecal Coliform		<i>E. coli</i>			
	day ⁻¹	day ⁻¹	day ⁻¹	day ⁻¹		
manure	0.169	0.225	0.205	0.23	Field	van Kessel et al. 2007
amended soil			0.0581	0.0995	Field	Soupir et al. 2008
			0.05	0.06	Field	Sinton et al. 2007
			0.016		Field	Muirhead 2009
	0.028	0.066			Field	Crane & Moore 1986
		0.054	0.096	Laboratory	Oliver et al. 2006	
	0.071		0.08	Laboratory (21 C)	van Kessel et al. 2007	
fresh water			0.19	0.33	Laboratory	Oliver et al. 2006
			0.288	0.99	Laboratory (20 C)	Crane & Moore 1986

Manure

E. coli and pathogen survival in manure is, according to Himathongkham et al. (1999), most importantly influenced by temperature, pH, solid content, microbial content, oxidation-reduction potential and time. The authors determined best survival rates for *E. coli* at a temperature of 4° C and characterized bacteria decay as a first order reaction. On the other hand, protozoan pathogens can persist for extended periods in the environment.

Nicholson et al. (2004) conducted research in Nottinghamshire, UK and mixed fecal matter with *E. coli* O157, *Listeria monocytogenes*, *Campylobacter jejuni* and *Salmonella*. Dairy slurry and dirty water were then stored in 20 m³ above-ground circular steel tanks, solid manures (dairy cattle and pig farmyard manure (FYM), and broiler litter) in 10 m³ turned (composted) and unturned heaps. Their results indicate that *E. coli* O157, *Salmonella* and *Campylobacter* survived in stored slurries and dirty water up to three months, and *Listeria* up

to six months. On the other hand, in solid manure heaps with temperatures $>55^{\circ}\text{C}$, pathogens survived for less than one month.

E.coli and FC die-off rates in cowpats under field and laboratory incubation conditions were compared by Van Kessel et al. (2007). In both settings, FC and *E. coli* concentrations increased during the first week and subsequently decreased. Generally, the die-off rates of *E. coli* and FC are higher under field conditions and highest in non-shaded cowpats.

Soil

The survival of pathogens in agricultural soil systems varies importantly (mean first order die-off rate constants: FC - 1.14 d⁻¹, fecal streptococci - 0.41 d⁻¹, *Salmonella* - 1.33 d⁻¹, *Shigella* - 0.68 d⁻¹ (Sjogren 1994)) and is mostly influenced by moisture content, soil type, temperature and pH, nutrient availability and competition (Jamieson 2002). Reddy et al. (1981) estimated survival times in soil for *E. coli* 20.7 to 23.3 months. According to Jamieson (2002), various studies suggest that water saturation controls the survival of enteric bacteria in soil (low moisture content \rightarrow low bacteria survival rate). Soil properties, like particle size distribution and organic matter content influence moisture and nutrient retention in soils (high fine particle and organic matter content \rightarrow high moisture and nutrient retention capacity) and therefore bacteria survival (Garzio-Hadzick et al. 2010). According to Garzio-Hadzick et al. (2010), higher fine particle and organic carbon content in sediments leads moreover to lower sensitivity of the bacteria inactivation to temperature. Habitually, higher temperatures increase bacteria mortality independently of their medium (Foppen & Schijven 2006). A pH between 6 and 7 was found to be optimal for bacteria survival (Jamieson 2002). Nutrient availability and competing micro-organisms (competition for essential nutrients and water) limit the survival of pathogens in soil (Jamieson 2002).

The influence of nutrient availability on bacteria survival was documented by Estrada et al. (2004). FCs and *E. coli* numbers in soil treated with waste water treatment plant sludge declined over time under open-air and laboratory conditions, but considerably increased in the presence of chemical fertilizers. These findings are supported by observations from Franz et al. (2008), who found *E. coli* O157:H7 to show prolonged survival in soil with increasing levels of dissolved organic carbon per unit biomass carbon DOC/biomC. Furthermore, the type of manure seems to impact bacteria survival as shown by Unc & Goss (2006), who detected higher initial *E. coli* densities in soils treated with solid beef cattle manure, but faster bacteria decline than those treated with liquid swine manure.

On the other hand, the existence of “naturalized” *E. coli* strains in soils is being discussed in the literature. Ishii et al. (2010) found *E. coli* to be able to grow and survive long-term in soils as long as soil temperature, moisture, and nutrient conditions are tolerable. According to Brennan et al. (2010), *E. coli* would lose its value as an indicator of recent fecal contamination if it can be proven that *E. coli* recovered in subsurface water (tile and groundwater) is primarily mobilized from naturalized populations that reside within the soil profile.

Water

E. coli is commonly considered to decline in a natural aquatic environment. When faced with low nutrient concentrations and other environmental stresses, *E. coli* will enter a starvation state and eventually die-off (Rozen & Belkin 2001). *E. coli* die-off rates in freshwater under laboratory conditions will range from 0.19 to 0.99 d⁻¹ (Oliver et al. 2006, Crane & Moore 1986). Different microorganisms will show diverse persistence and in situ inactivation rates. Lendrum (2006) found first order die-off kinetics of *Cryptosporidium* in ponds to be

significantly different than those of *E. coli* and *Enterococcus*. *Cryptosporidium* (0.314 day^{-1}) decayed much more slowly than *E. coli* (0.0671 day^{-1}) or *Enterococci* (0.0540 day^{-1}). On the other hand, DeLoyde et al. (2007) showed that *Giardia* can survive up to 2.8 months in river water at $<10^{\circ}\text{C}$ and ~ 1 month in lake water at $15\text{-}20^{\circ}\text{C}$. However, Vital et al. (2008) provided evidence of the ability of *E. coli* O 157 to grow in sterile freshwater at low carbon concentrations.

In addition to the water column itself, natural aquatic environments provide opportunities for bacteria reservoirs in biofilms and bottom sediments. Balzer et al. (2010) found total coliforms, *E. coli* and *Enterococci* concentrations in biofilms to be two magnitudes higher than those in river water. Whereat, Garzio-Hadzick et al. (2010) determined that *E. coli* survives in sediments much longer than in overlaying water. Sediments that act as reservoirs of *E. coli* will affect microbiological stream water quality during high flow events (Sinclair et al. 2009, Garzio-Hadzick et al. 2010).

2.3 Transport characteristics

Reviews on pathogen transport have been published by Mawdsley et al. (1994), Jamieson et al. (2002), Ferguson et al. (2003), and Unc & Goss (2004). Soil type, soil water content, soil pH, plant roots, surface properties of microorganisms, micro-and meso-faunal activities, topography, climatic conditions, temperature, water infiltration, volume and type of manure have been found to influence pathogen transport in overland flow, subsurface flow and streams.

Overland Transport

If pathogens are applied to land surfaces, they can either travel overland with runoff or infiltrate (subsurface transport). The entrainment and suspension of pathogens depends on the kinetic energy of the runoff and the physical characteristics (diameter, mass) of the microorganisms. Sediment-microorganism associations change the physical characteristics of the particles and influence their settling velocity.

Overland transport of *Cryptosporidium* oocysts from experimental plots has been assessed by Tate et al. (2000). It was found that oocyst concentrations recovered downstream largely depend on the volume of overland flow and pathogen supply.

Mishra et al. (2008) assessed bacterial transport in runoff from cropland. One and two days after manure application (dairy manure, poultry litter) rainfall simulators were used to stimulate surface runoff. Manure was either superficially applied or incorporated. They concluded that manure application based on agronomic P rates result in significant bacterial loadings (bacteria-FC, *Escherichia coli*, and *Enterococcus*) if rainfall occurs soon after manure application. Different manure application techniques did not result in significant different bacterial loadings.

Interestingly, the results of Muirhead et al. (2006a) indicate that *Escherichia Coli* in runoff from cowpats do not attach to dense particle or flocks, and are predominantly transported as individual cells. Furthermore, laboratory scale experiments conducted by Muirhead et al. (2006b) show that *E.Coli* are mainly transported by advection in overland flow over saturated soils. They attach predominantly to small particles (<2 µm) which do not attenuate bacteria transport like particles >45 µm. Oliver et al. (2007) conducted batch sorption

experiments on clay loam soil and found 65% of *E.Coli* associated with particles $<2 \mu\text{m}$ as well as a preferential attachment to 16-30 μm fraction for the remaining bacteria.

Subsurface Transport

Bacterial transport to subsurface tile systems largely depends on soil moisture content (at manure application time) and precipitation (up to 2-3 weeks after application) (Jamieson et al. 2002). While soils with a high content of silt and clay can retain moisture and nutrients and filter bacteria (0.2 - 5 Wm) successfully (in case of matrix flow), they are predisposed to shrink or crack, and therefore offer preferential flow opportunities in macropores (non matrix flow). Macropores have been found to be the dominant transport pathway for fecal pathogens. They are formed by soil fauna (size: 1 - 50 mm, near the soil surface), cracks and fissures, plant roots (near the soil surface), and subsurface flow erosion (Jamieson et al. 2002). Akhand et al. (2006) simulated liquid biosolids and precipitation induced tile flow with the program MACRO and found that 97% of the total tile drain flux originate in macropores. In addition, 7% of *E.Coli* O157H applied to grazing land reach tile drains during rainfall events (Fenlon et al. 2000)

Ouellet et al. (2007) affirmed that earthworm activity is an indicator of groundwater and tile drainage contamination risk, and investigated in their study, the relationship between earthworm biomass, physical and hydraulic soil properties, and land management. Tillage practice and surface residue cover were found to most importantly influence earthworm activity. Higher biomass contents were found in no till and conventionally tilled fields with high surface residue covers. Tillage interrupts worm channels and integrates surface organic residues into the soil, which is less favourable for earthworms. Surface residue covers offer food supply and protection to earthworms and therefore create a favourable environment.

Worm biomass could be an indicator of preferential flow, but is too sensitive to soil temperature and humidity. Instead, soil saturated air-entry tension (AEV) that represents continuous pore networks and strongly related to field saturated hydraulic conductivity (K_{fs}) could be used as an indicator of burrowing activity. With a regression trees analysis, robust indicators of macropore flow (high K_{fs} , low AEV and high earthworm biomass) have been identified. Quillet et al. (2008) conducted their study in Eastern Ontario and collected data on physical soil properties (soil texture, clay, silt, sand content, organic matter, bulk density, water content, soil temperature, K_{fs} , AEV, earthworm biomass) and management parameters (tillage, vegetation cover, residue cover) on 78 fields (59 conventionally tilled, 19 long term (>5 a) no-tillage).

Liu (2007) studied the influence of biofilm presence on *E.coli* transport in porous media. Experiments in glass bead packed columns with and without a biofilm coating were conducted and resulted in the following conclusions. High biofilm thicknesses enhance bacteria cell adhesion. *E.coli* attached to biofilm coated media is able to grow to form an integral part of the biofilm bacteria and persist in the filter media even under a low nutrient supply. It was concluded that biofilm sloughing mostly influences the fate of *E.coli* over the experimental period.

The potential movement of pathogens in ground water, including viruses, bacteria, *Cryptosporidium* and *Giardia*, was reviewed by Robertson and Edberg (1997).

In stream Transport

Pathogenic microorganisms reach streams from their overland sources or are directly deposited into water bodies. Within streams, they are transported by advection and dispersion processes (Jamieson et al. 2004). The pathogen attachment to sediment or organic

particles influences its settling characteristics. According to Jamieson et al. (2005a), bacteria adsorption can be modeled as an irreversible process in freshwater environments.

Searcy et al. (2005 and 2006a) studied the transport of *Cryptosporidium parvum* in surface water under laboratory conditions in flow cell system, settling column and flume experiments. *Cryptosporidium parvum* oocysts were found to attach to inorganic and organic particles (under typical surface water chemical conditions). The attachment on its part increased oocyst settling velocities, so that the rate of oocyst deposition to the river bed increases in the presence of suspended particles. Additionally, Searcy et al. (2006b) studied the influence of biofilms on *Cryptosporidium parvum* oocyst attachment with flow cell experiments. Surfaces covered by *Pseudomonas aeruginosa* biofilms would demonstrate greater deposition of *Cryptosporidium parvum* oocysts than abiotic surfaces. They concluded that the interaction of oocyst with sediment and biofilm reduces oocyst concentration under low flow conditions and produces a resuspendable in-stream reservoir (at higher flows). Angles et al. (2007) pointed out the need to further assess the possible extended infectivity of biofilm-associated *Cryptosporidium* and their re-suspension mechanism.

Moghadam (2006) studied the settling characteristics of *Cryptosporidium* and *Giardia* in filtered tap water in a column. It was concluded that *Cryptosporidium* settles faster than *Giardia*. Their settling velocity increases with rising temperatures. Furthermore, the settling velocities of inactive *Cryptosporidium* and *Giardia* (oo)cysts are higher than those of active (oo)cysts.

Cryptosporidium parvum oocyst surface macromolecules significantly hinder oocyst attachment (Kuznar and Elimelech 2006). They investigated viable oocyst attachment

efficiencies to quartz surfaces with a radial stagnation point flow system and compared them to those of oocyst with removed surface macromolecules (digestive enzyme treatment (proteinase K)). Low deposition rates and attachment efficiencies of viable oocyst are explained with “electrosteric” repulsion between the oocyst surface macromolecules and the quartz surface (both surfaces are negatively charged). After removal of surface macromolecules, the *Cryptosporidium parvum* oocyst showed increased attachment efficiencies and demonstrated the typical behaviour of colloidal particles.

Jolley (2005) studied the interactions of (bacteria indicator) FC and sediments in two fresh water streams in South Carolina. In base flow conditions 10-10000 times higher, FC counts were observed in bottom sediments than in the water column. Furthermore, during storm flows, FC counts in water were found to be higher than at base flow conditions. This confirms the statement by Jamieson et al. (2004) that resuspension of pathogens from bottom sediments into a water column could be the result of storm flow, human or animal induced disturbances to the riverbed. However, the amount of bacteria available for resuspension in bottom sediments seems to be finite, as the supply is depleted on the rising limb of the storm hydrograph (Jamieson et al. 2005b).

Surbeck et al. (2006) characterized the relationships between streamflow and concentration of fecal pollution (fecal indicator bacteria and F+ coliphages viruses infecting *E. coli*) or total suspended solids (TSS) in stormwater runoff from the Santa Ana River watershed (California). During three storms, 4 samples per hour (peak flow) to 2 samples per day (end of a storm) were taken at three locations with dominant residential, commercial and minor agriculture land uses. Samples were analyzed for TSS (Standard Method 2540D), *E.coli* and total coliform (Colilert test), *enterococci* bacteria (Enterolert test), fecal indicator viruses (F+

Coliphage) (two-step enrichment method and plaque-forming unit assay) and 15 samples for the presence of human *adenovirus* (nested PCR protocol) and human *enterovirus* (RT-PCR procedure). Streamflow rates were obtained from the U.S. Geological Survey and Orange County Water District. Log-log plots of fecal pollutant concentration versus streamflow revealed little dependence between both variables and therefore, the flow independent nature of fecal indicator bacteria and F+ coliphages. On the other hand, log-log plots of TSS versus streamflow display a very strong dependence. These differences are explained by the authors with different sources and transport pathways for stormwater constituents. Fecal pollutants are ubiquitously present on the surface of urban landscapes and can be rapidly transported into the surface water under rainfall conditions. In contrast, TSS represents shear-induced erosion of drainage areas and channel bed sediments.

Characklis et al. (2005) demonstrated that pathogens do not exclusively exist as free (unattached) organisms. They investigated microbial partitioning of several bacterial, protozoan and viral indicator organisms to settleable particles in stormwater in three urban streams under storm and dry weather conditions. Microorganisms associated with settleable particles were estimated through the use of a centrifugation technique (calibration with suspensions of standard glass, latex particles). An average of 20%–35% of bacterial indicator organisms (FCs, *E.coli*, *enterococci*) were attached to settleable particles in background samples and 30%–55% in storm samples. *Clostridium perfringen* spores showed the highest association level under storm conditions (50% to 70%). *S. coliphage* partitioning varied between 20–60% during storms.

2.4 Modeling of microbial contaminant transport

In order to characterize catchment processes and pathogen transport at a watershed scale, different mathematical models have been developed in recent years. Several reviews that compare the performances of these models have been published by Borah & Bera (2003 & 2004), Jamieson et al. (2004), Shoemaker et al. (2005), Coffey et al. (2007), and Migliaccio & Srivastava (2007). Catchment models are generally based on the hydrological cycle, and simulate water yield as well as sediments, nutrients, and in some cases, pathogen transport. Current microbial modeling approaches for watersheds are summarized in Table 1. They include the Hydrologic Simulation Program (HSPF, Bicknell et al., 2000), Loading Simulation Program in C++ (LSPC, Tetra Tech, Inc. & USEPA, 2002), SWAT (Arnold et al. 1998, Arnold et al. 2005, Neitsch et al. 2004), Storm Water Management Model (SWMM, Donigian & Huber, 1991), Watershed Assessment Model with an ArcView Interface (WAMView, SWET, 2006) linked to a bacteria model developed by Tian et al. (2002), Watershed Modeling System (WMS, Dellman et al. 2002), Watershed Analysis Risk Management Framework (WARMF, Chen et al. 1999), MWASTE (Moore et al., 1989), Coli (Walker et al. 1990), a model developed by Dorner et al. (2004a), and a model developed by Ferguson et al. (2007).

HSPF was designed to simulate hydrological and pollutant transport in complex watersheds. It is included in the USEPA supported BASINS model. Bacteria are modeled as free floating contaminants with no sediment association (Bicknell et al. 2000). According to Coffey et al. (2007), HSPF has been extensively applied to simulate bacteria transport and evaluate total maximum daily loads (TMDL). HSPF is a process based model which relies on many empirical relationships to represent physical processes. It includes model features like

surface and groundwater, stream routing, and sediment, nutrient, pollutant, pesticide and bacteria transport. Simulation time steps are user-defined and vary between minute and daily. Disadvantages of the model include the lack of a tile drain component as well as the high level of model expertise, time and data needed (Shoemaker et al. 2005).

LSPC was designed to handle very large watersheds (≥ 100 sub-watersheds). It is based on HSPF and uses its algorithm to model hydrological, sediment, nutrient, pollutant, FC and bacteria transport processes on land, in the subsurface and streams (Tetra Tech, Inc. & USEPA 2002). LSPC is a process based model which relies on many empirical relations to represent physical processes. It does not include tile drainage features and requires extensive calibration, data, time, and a high level of expertise for application (Shoemaker et al. 2005).

Table 3 Comparison of Watershed Models and their Capabilities

Software	Process based	Surface + GW	Stream routing	Nutrients	Bacteria	Time steps	Tile drainage	Experience	Time need	Data need	Cost
HSPF	Yes	Yes	Yes	Yes	Yes	Minutely to Daily	No	Substantial Training	High	High	No
<i>Hydrologic Simulation Program— FORTRAN, EPA</i>											
LSPC	Yes	Yes	Yes	Yes	Yes	Minutely to Daily	No	Substantial Training	High	High	No
<i>Loading Simulation Program in C++, EPA and Tetra Tech, Inc.</i>											
SWAT	Yes	Yes	Yes	Yes	Yes	Daily	Yes	Moderate Training	Med.	Med.	No
<i>Soil and Water Assessment Tool, USDA-ARS</i>											
SWMM	Yes	Yes	Yes	Yes	Yes	Hourly	No	Substantial Training	High	High	>500 \$
<i>Storm Water Management Model, EPA</i>											
WAM View	Yes	Yes	Yes	Yes	Yes	Hourly	No	Moderate Training	Very High	High	No
<i>Watershed Assessment Model with an ArcView Interface, Soil and Water Engineering Technology, Inc. (SWET), EPA, Bacteria model by Tian et al.2002</i>											
WARMF	Yes	Yes	Yes	Yes	Yes	Daily	No	Moderate Training	High	Med.	No
<i>Watershed Analysis Risk Management Framework, Systech Engineering, Inc.</i>											
WMS	Yes	Yes	Yes	Yes	Yes	Hourly	No	Substantial Training	High	High	>500 \$
<i>Watershed Modeling System, Environmental Modeling Systems, Inc.</i>											
MWASTE		Surface water	No		Yes			Moderate Training	?	Med.	?
<i>Moore et al.1989</i>											
Coli		Surface water	No		Yes			Moderate Training	?	Med.	?
<i>Walker et al. 1990</i>											
Model	Yes	Yes	Yes	No	Yes	Hourly	No	?	?	?	No
<i>Dorner et al. 2004a</i>											
Model	Yes	Surface water	Yes	No	Yes		No	?	?	?	?
<i>Ferguson et al. 2007</i>											

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 (Gassmann et al. 2007). SWAT is a process-based model which simulates sediment, nutrient, pollutant, pesticide, and bacteria transport on land, in interflow, groundwater and streams. It simulates daily time steps and is therefore not designed for single storm events. Its microbial sub-model was developed by Sadeghi and Arnold (2002) and allows the partitioning of bacteria into adsorbed and non adsorbed fractions. The SWAT linkage to ArcGIS with graphic interfaces was introduced by Di Luzio et al. (2004). SWAT has been extensively applied to model hydrology, TMDL and non-point source pollution (Shoemaker et al. 2005, Parajuli et al. 2007). It is one of the few watershed models which include a tile drainage component (Du et al. 2005). Model experience, time and data needed for SWAT applications are moderate (Shoemaker et al. 2005).

SWMM was developed for the analysis of surface runoff and flow routing through complex urban sewer systems. It is a process based model which includes surface and groundwater, stream routing, and nutrient and bacteria transport features. Single-event or long-term simulation by using various time steps are possible (Donigian & Huber 1991). SWMM is primarily applied to urban areas. It is associated with substantial training, time and data as well as high software costs (Shoemaker et al. 2005).

WAMView allows the user to assess the water quality of surface and groundwater based on land use, soils and weather. WAMView is a process based model which is linked to a bacteria model developed by Tian et al. (2002). It includes surface and groundwater, streamrouting, and nutrient and bacteria transport features (SWET, 2006). The microbial

component was developed to assess the pollution potential of surface water with *E. coli* (Tian et al. 2002). According to Shoemaker et al. (2005), the model has proven to work well for wetlands, but has a very elevated time and data need.

WARMF was designed to evaluate water quality management alternatives for river basins and is capable of calculating the TMDL of pollutants (Chen et al., 1999). It simulates daily time steps and includes surface and groundwater, and nutrient and bacteria transport components. Tile drainage is not supported. Other limitations include that the model can not account for individual source contributions and the user has to contact Systech to setup and calibrate the model (Shoemaker et al. 2005).

WMS simulates all phases of watershed hydrology and hydraulics. The model is process based, but relies on many empirical relations to represent physical processes (Dellman et al. 2002). It includes surface and groundwater, and nutrient and bacteria transport components. Tile drainage is not supported. It is associated with substantial training, time and data as well as high software costs (Shoemaker et al. 2005).

MWASTE simulates waste generation and bacterial concentrations in surface runoff from agricultural areas and was developed by Moore et al. (1989). It estimates bacterial (FC and fecal streptococci) surface transport with empirical equations. Limitations include the missing groundwater, tile drain and stream routing components (Coffey et al. 2007).

Coli was developed by Walker et al. (1990) to predict FC bacteria concentration of runoff from agricultural lands with Monte Carlo simulation. The surface transport of bacteria is assumed to be associated with soil particles and therefore, computed by using a modified

universal soil loss equation (Jamieson 2004). Limitations include the lack of groundwater, tile drain and stream routing components (Coffey et al. 2007).

Dorner et al. (2004a) developed a watershed pathogen transport model based on the hydrologic model WATFLOOD/SPL. The model simulates pathogen transport from non-point and point sources in overland flow, subsurface flow and stream routing. It is a process based model, but does not include nutrient transport and tile drain components.

The pathogen budget model developed by Ferguson et al. (2007) was designed for the Wingecarribee catchment, Sydney, Australia, to predict and rank *Cryptosporidium*, *Giardia* and *E.coli* loads exported from a catchment. It quantifies pathogen generation and transport processes, and includes surface water, stream routing and bacteria transport components, but no tile drain and nutrient features.

All these programs have their own strengths and weaknesses. HSPF and SWAT are useful for long term continuous simulation and assessment of hydrological changes and watershed management practices according to Borah & Bera (2003). While SWAT is suited for predominantly agricultural watersheds and simulates well agrochemical and agricultural management scenarios, HSPF is able to model the impact of urbanization and can be employed in mixed agricultural and urban watersheds. Both models were found to be suitable for predicting yearly and monthly flow volumes, and sediment and nutrient loads. On the other hand, daily simulation results were poor in applications reviewed by Borah & Bera (2004).

Only SWAT simulates tile drainage flow which is important in agricultural dominated watersheds. Other models can simulate subsurface drainage by altering interflow parameters,

but are not originally designed to include tile drain components (Migliaccio & Srivastava 2007). Furthermore, the authors characterized SWAT as a good choice for watersheds where streamflow is dominated by groundwater recharge (Migliaccio & Srivastava 2007).

SWAT, HSPF and LSPC have been classified by Coffey et al. (2007) as the three best choices among 13 microbial modelling approaches for watersheds. All three pathogen models account for the input categories of soil, hydrological cycle, meteorological conditions, bacterial loadings, non-point sources, land management, nutrients, and water channel systems, and their applications have been published. However, Coffey et al. (2007) stated that SWAT is the software with the greatest potential for high-level analyses. This is because of the significant amount of data, empirical parameters, time, and modeling experience needed to develop and calibrate HSPF and LSPC watershed models.

SWAT Model

SWAT is a physically based continuous-time watershed scale model that is designed to predict the effect of land management practices on water, and sediment and crop yields in large watersheds. Each watershed is divided into several sub-basins and hydrological response units (HRU). HRUs are areas with unique combinations of slope, soil, land use, and management practices. The required input parameters are numerous and include data on soil, hydrological conditions, meteorological conditions, bacterial loadings, non-point sources, land management, nutrients, water channel systems within the HRUs, sub-basins, ponds/reservoirs, groundwater, and the channel itself (Arnold et al. 1989) (see Appendix A).

The general model inputs and main outputs are displayed in Figure 1.

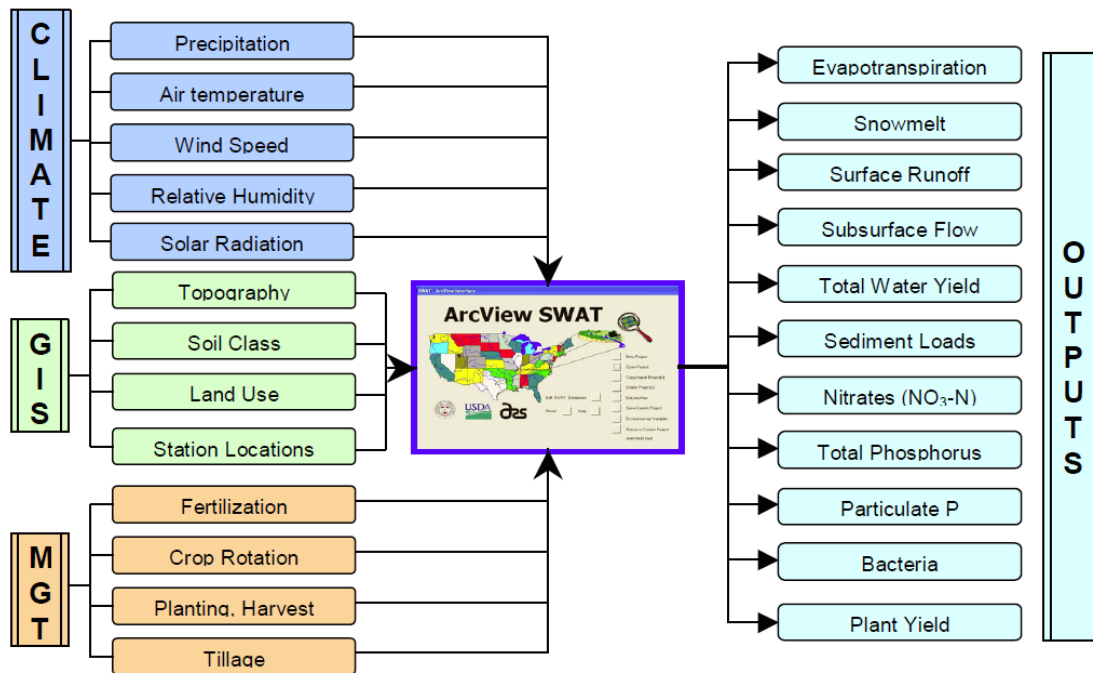


Figure 1 ArcSWAT Main Inputs and Outputs (Gollamudi 2006)

The most important equation that governs SWAT hydrological simulations is the water balance equation:

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

The final soil water content (SW_t in mm H_2O) is computed by summing the initial soil water content (SW_0) and the amount of precipitation (R_{day}) less the amount of surface runoff Q_{surf} , the amount of evapotranspiration (E_a), amount of water that exits the soil to the vadose zone from the soil profile (w_{seep}) and amount of return flow (Q_{gw}).

The microbial contaminant module allows the simulation of transport, growth and decay of two distinct bacteria species (persistent and less persistent bacteria). The flowchart in Figure 2 displays the different bacteria related processes considered by SWAT. The fate and

transport of bacteria is described through different processes, including the input of bacteria into the stream by point sources or on soil surfaces and foliage via manure application or grazing. Pathogens are then transported by surface runoff into streams or lakes. Specific partitioning coefficients determine the relative amount of bacteria in soluble and adsorbed phases. Bacteria on soil surfaces and transported within streams adsorbed to sediment particles encounter first order die-off as described by Moore et al. (1983) and Walker et al. (1990) as well as re-growth. The equation that describes bacterial die-off according to Chick's Law is as follows:

$$[2] \quad N_t = N_0 * 10^{-\mu t}$$

Here, the number of bacteria at any given time t (N_t in cfu) equals the initial number of bacteria (N_0 in cfu) multiplied with 10 to the power of the negative product of μ (decay constant in day^{-1}) and t (time in days). The bacteria decay is further adapted to environmental conditions by accounting for temperature differences as shown in the following equation:

$$[3] \quad \mu = \mu_{20} * \theta^{T-20}$$

where μ_{20} is the die-off constant at 20°C (day^{-1}), θ is the temperature adjustment factor and T is the given temperature ($^\circ\text{C}$).

In addition to runoff transport, infiltration and incorporation through tillage are considered. Common tillage practices incorporate a portion of the applied bacteria into the soil profile. Infiltrated and incorporated bacteria can not be transported by surface runoff and do not contribute to interflow or groundwater. SWAT considers these bacteria as a loss, even though several studies have shown that the subsurface transport of microorganisms can be

significant (Jamieson et al. 2004), particularly in cases of preferential flow (tile-drain, karst) (Fenlon et al. 2000, Akhand et al 2006).

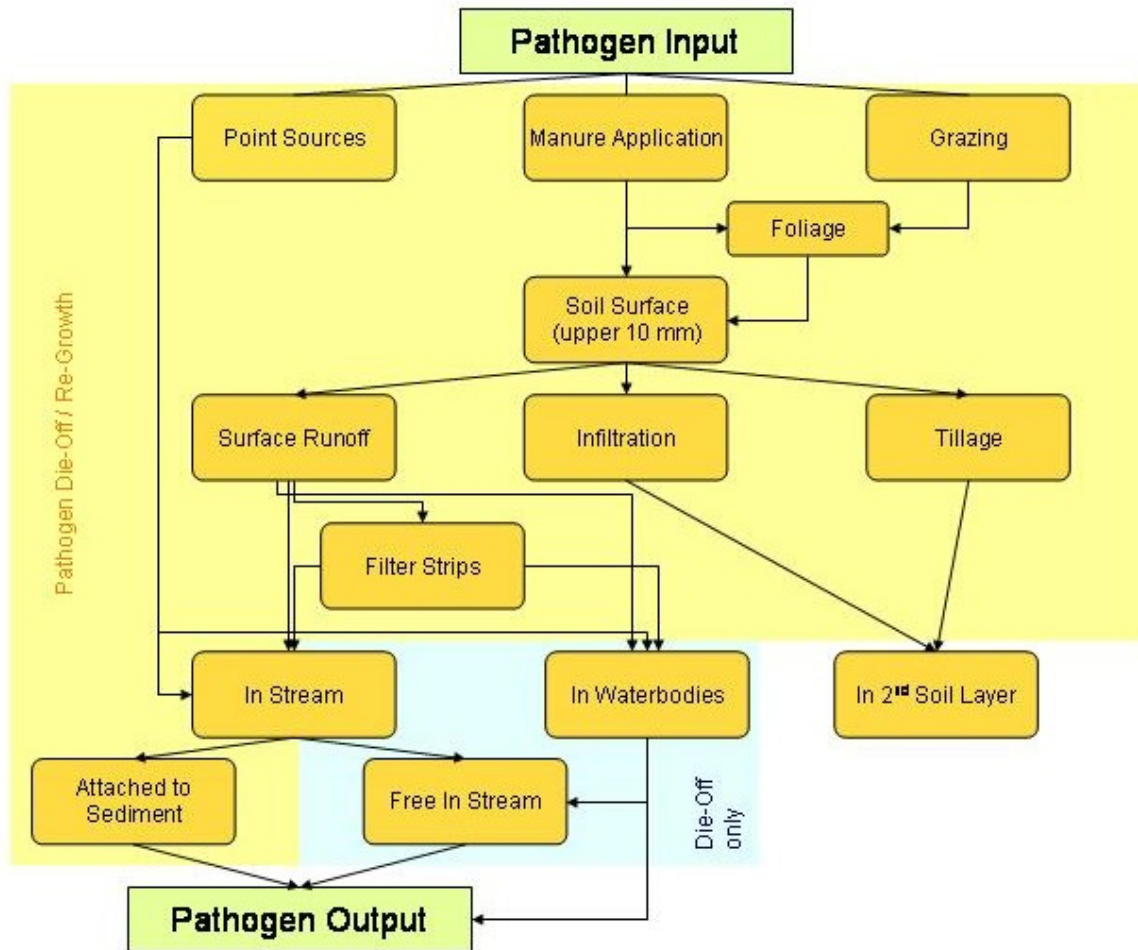


Figure 2 Conceptual Model of the SWAT Pathogen Tool

Applications of bacteria transport modeling are sparse. However, since the introduction of the SWAT microbial sub-model, some applications of bacterial transport in agricultural and forested watersheds have been published.

In his Master's thesis, Mocan (2006) applied SWAT to two small (46 and 74 km²) rural watersheds within the Grand River Basin in Ontario. The models were calibrated by using

six months of field monitoring data, including hourly water level and semi weekly bacteria data (total coliform and *E. coli*). His results indicated the ability of SWAT to capture seasonal *E. coli* trends, but the model fails to accurately represent field conditions during the study period.

Baffaut & Benson (2008) simulated bacteria transport in the 3600 km² large James River Basin in Missouri based on 7 years of occasional bacteria samples at 4 locations (max. 84 samples). Sources of bacterial contamination for this watershed have been estimated based on surveys and include cattle, poultry, wildlife and human wastewater. The model performance was evaluated at Nash-Sutcliffe efficiencies (NSE) = 0.0-0.21.

The 15.6 km² Little River Watershed in Georgia was modeled by Chin et al. (2009). Model calibration was performed on 53 FC samples taken occasionally over a period of 7 years. The dominant land use of this watershed is forest and therefore, wildlife grazing and direct inputs into the stream are the main contamination sources. The authors achieved very good NSE values of 0.73, but relied on bacteria source inputs exclusively estimated through calibration in their modeling approach.

Parajuli et al. (2009) simulated 3 sub-watersheds (51, 75.4 and 152 km²) of the Upper Wakarusa Basin in Kansas. The models include FC inputs from cattle, wildlife, failing septic systems as well as point sources, and were calibrated by using approximately 2 years of weekly (growing season) to monthly (dormant period) samples. Model performances varied between sub-watersheds between NSE=-2.2 and 0.31.

A watershed model for the Fergus catchment (29.05 km²) in Ireland was developed by Coffey et al. (2010). The model was calibrated and validated by using 2 years of

hydrological data and 12 monthly *E. coli* samples. Bacteria loadings include cattle and sheep grazing, as well as manure applications on agricultural fields. The model predicted *E. coli* for the given time frame with satisfactory accuracy (NSE=0.59).

The models discussed here are characterized by very different hydrological conditions, land use settings, contamination sources, model period lengths and number of observed bacteria data used for calibration and validation. The model results are found to be in the range of NSE= -2.2 to 0.73. This may indicate that SWAT has the ability to represent bacteria transport in watersheds with satisfactory accuracy under certain conditions. In order to further enhance our knowledge on microbial transport in watersheds and better understand the strengths and limitations of SWAT, more applications on microbial transport, especially calibrated and validated with long-term field data, are essential.

3. Model Development

In order to simulate bacteria and nutrient transport in the Payne River Basin, a physical-based model capable of simulating processes like loading and movement of runoff, sediment, nutrients, and bacteria to and within the main channel, as well as tile-drainage, had to be chosen. The literature review revealed SWAT, HSPF and LSPC as the three best options among the microbial modeling approaches. SWAT was ultimately chosen for its ability to simulate agrochemical and agricultural management scenarios, the inclusion of a tile drainage component (Du et al. 2005) as well as its microbial sub-model (Sadeghi & Arnold 2002).

1.3 Study Area

The present study focuses on developing a microbial transport model for FC and *E.coli* by using SWAT for the 178 km² Payne River Basin situated in Eastern Ontario, Canada (Figure 3). The watershed is characterized by a generally flat topography with average elevations of 88 m asl and an average slope of 2%. Annual rainfall ranges from 750 to 1220 mm. The main land use is agriculture (58%) followed by forest (39%) and urban areas (2%). Tile drainage and groundwater are important contributors to river flow. Major bacterial contamination sources in the catchment include manure applied to agricultural fields as fertilizer, fresh manure deposited from grazing livestock on pasture and fresh manure directly deposited into the stream or on agricultural areas from avian and other wildlife.

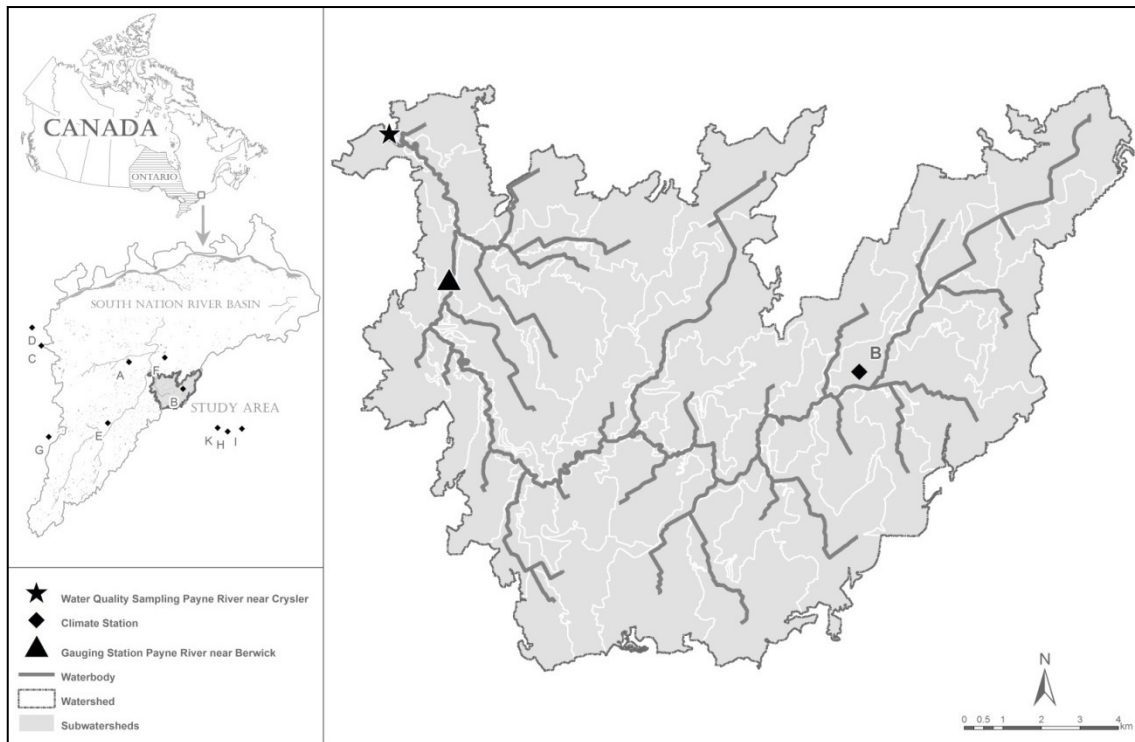


Figure 3 Payne River Watershed, Eastern Ontario, Canada

1.4 Data and Model Setup

The modeling of hydrological processes at a watershed scale with SWAT requires large quantities of detailed climate, topographical, land use, land management, population (human, livestock, wildlife) as well as observed stream flow and water quality data. Data sources used are listed in Table 4. The necessary data have been prepared as geographic information system (GIS) layers and used as input files into the ArcGIS interface (ArcSWAT) of SWAT 2005. Appendix A includes the complete inventory of parameters needed to successfully run SWAT 2005.

Table 4 Data sources used for the SWAT model

Type of Data	Source	Scale/Time Step	Description
Topography	NRVIS- Ontario Ministry of Natural Resources	10 m	Digital elevation model
Hydrography	NRVIS- Ontario Ministry of Natural Resources	1:10 000	Stream network
Soil	CANSIS- Agriculture and Agri-Food Canada	1 :25 000	Soil classification and physical properties
Land use	Agriculture and Agri-Food Canada	30 m	Land-use classification
Land management	Statistics Canada		2006 Census of Agriculture
Climate	Environment Canada, Agriculture and Agri-Food Canada	daily	Precipitation, air temperature, solar radiation, humidity, and wind speed
Hydrology	Environment Canada	daily	Streamflow
Waterquality	Environment Canada, Agriculture and Agri-Food Canada	biweekly	Nutrients (N, P) and bacteria (fecal coliform, <i>E.coli</i>)

To initiate the model setup, a digital elevation model (DEM) from the Natural Resources and Values Information System (NRVIS 2002) with a 10 m resolution was used. DEM resolution affects the stream flow, and sediment and nutrient predictions (Chaubey et al. 2005, Di Luzio 2005) of the model. Elevation data are also critical for SWAT stream networks and watershed delineation. NRVIS flowlines were “burned” into the DEM and a critical source area of 512 ha (2% of the watershed) was defined in order to allow for a realistic stream network definition. Forty five sub-basins were defined (Figure 3) in accordance with a watershed subdivision level of 2% as recommended by Migliaccio & Chaubey (2008) and Jha et al. (2004). This division is required because simulated sediment and nutrient yields are influenced by sub-basin size (Arabi 2006, FitzHugh & Mackay 2000, Bingner 1997). Based

on the digital elevation model described above, the slope was calculated and classified into two groups. The first class contains areas with 0% and 6% slope and the second class with areas steeper than 6%. These slope classes are combined with soil and land use data in order to compute the Hydrological Response Units (HRU). The HRUs represent areas with similar hydrological properties. During HRU definition, no thresholds for land use, soil or slope were defined. For each sub-basin, one point source was created to allow the direct input of human and wildlife contributions to fecal contamination. Furthermore, weather station, soil, land cover, fertilizer and tillage databases were updated; point source loadings as well as sub-basin and watershed data were defined. Parameters that govern tile drainage in SWAT were estimated based on knowledge of the study site. A deep impermeable layer was assumed to be at a depth of 0.8 m for all tile drained fields. Furthermore, subsurface drains were fixed in the model at a depth of 0.9 m. The time to drain the soil to field capacity and the drain tile lag time were estimated to be 48 h and 24 h, respectively. A CANMX value of 2.5 mm was used for all forested HRUs in this study (Hancock & Crowther, 1979). The automatically computed channel depth was multiplied by 2.5

Climate data

Daily climate data were compiled from nine Environment Canada weather stations and one Agriculture and Agri-Food Canada (AAFC) weather station (Figure 3). Long term records for precipitation, temperature, humidity, solar radiation, and wind speed were derived from the closest available weather station. Missing data as well as periods of no records were then substituted with values from other stations. Table 5 lists all consulted climate stations and the data sets used.

Table 5 Climate Stations and Datasets Employed in the Model.

	Name	Latitude	Longitude	Elevation(m)	Data used for Modelling	Period of Record
A	Little Castor River	45° 15.834' N	75° 9.643W	66.5	Precipitation, Temperature, Humidity, Solar Radiation, Wind Speed	2004-2010
B	Avonmore	45° 10.200'N	74° 58.200'W	91.4	Precipitation, Temperature	1976-2006
C	Ottawa Airport	45° 19.200' N	75° 40.200' W	114.0	Humidity, Wind Speed	1953-2010
D	Ottawa CDA	45° 22.800'N	75° 43.200'W	79.2	Solar Radiation	1985-2010
E	Winchester	45° 3.000' N	75° 20.400' W	75.0	Humidity	2003-2007
F	St Albert	45° 16.800' N	75° 3.600' W	70.0	Precipitation, Temperature	1986-2006
G	Kemptville CS	45° 0.000' N	75° 37.800' W	99.4	Precipitation	2001-2010
H	Cornwall 1	45° 1.200' N	74° 45.000' W	64.0	Precipitation, Temperature	1950-2010
I	Cornwall 2	45° 1.800' N	74° 40.800' W	85.0	Humidity	2003-2007
K	Cornwall Ont Hydro	45° 1.800'N	74° 48.000'W	76.2	Solar Radiation	1955-1995

Soil

Soil physical characteristics have a major impact on hydrological processes. Information on soil names, maximum rooting depth of the soil profile, number of soil layers, texture of the soil layer, depth from surface to bottom of soil layer, moist bulk density, saturated hydraulic conductivity of the soil layer, as well as sand, silt, clay, rock and organic carbon content of the soil within the study area were obtained from the Canadian Soil Information System (CANSIS).

The available water capacity of soils was derived from water retention curves published by Schut & Wilson (1987). Moist soil albedo was estimated based on Munsell soil colours and

literature values (Post, 2000). Soil erodibility factors (universal soil loss equation K values) for different soil texture classes and organic matter contents have been calculated by Wilkes (2004). Based on the CanSIS soil map for Eastern Ontario, 19 different soil types are identified within the watershed (Figure 4). For model purposes, soil properties of adjacent soil polygons were afterwards assigned to all areas within river basins identified as eroded in the soil map.

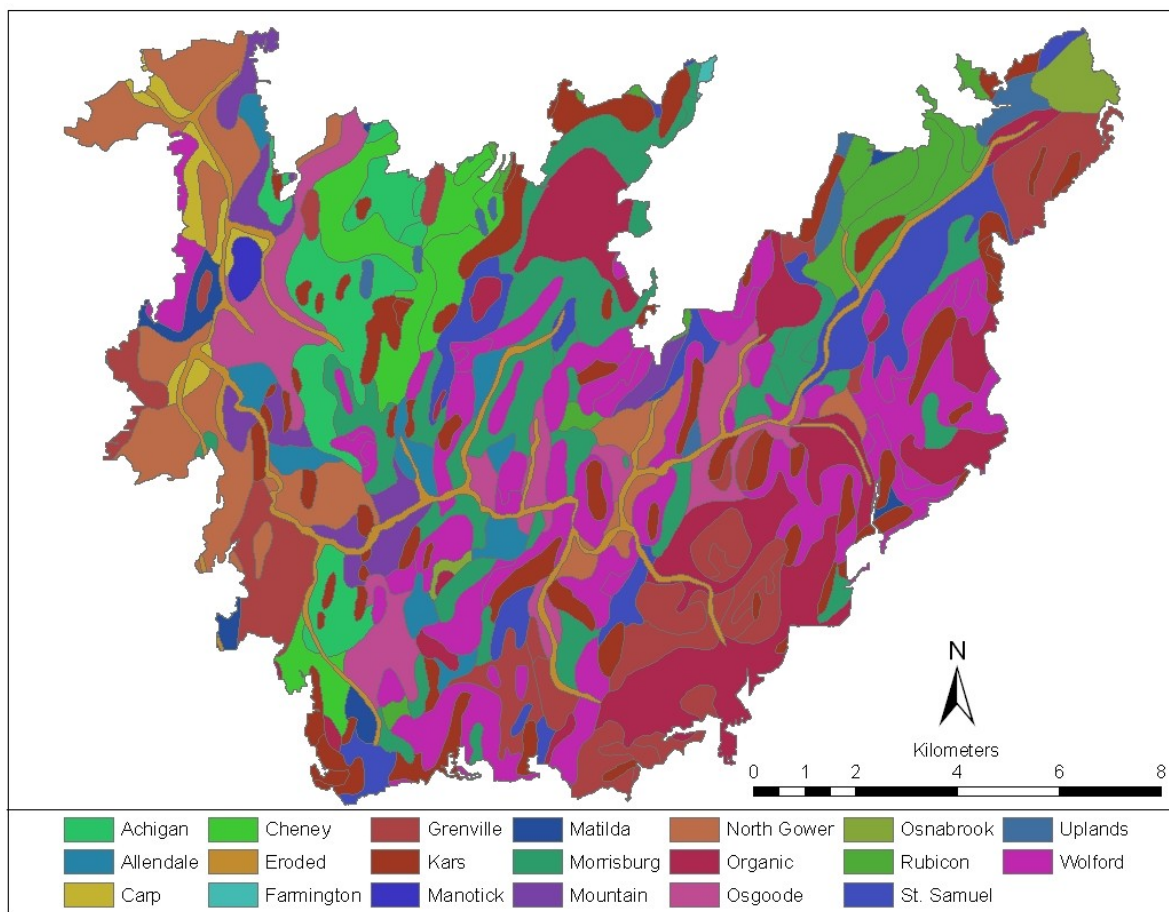


Figure 4 Soil Map of the Area (CanSIS)

Land Use Data

Detailed and consistent land use and management data are of fundamental importance in order to guarantee reliable model results. Data which comprise type and date of management operations, including tillage, fertilizer application, planting, harvest, grazing as well as information on type and amount of fertilizer and manure applied, type of crops, and depth of subsurface drains are required. Land use data for the SWAT model was created by using remotely sensed images (e.g., LANDSAT and SPOT) classifications from 2004-2007 (Figure 5) and agricultural management information extracted from Statistics Canada Census of Agriculture 1991.

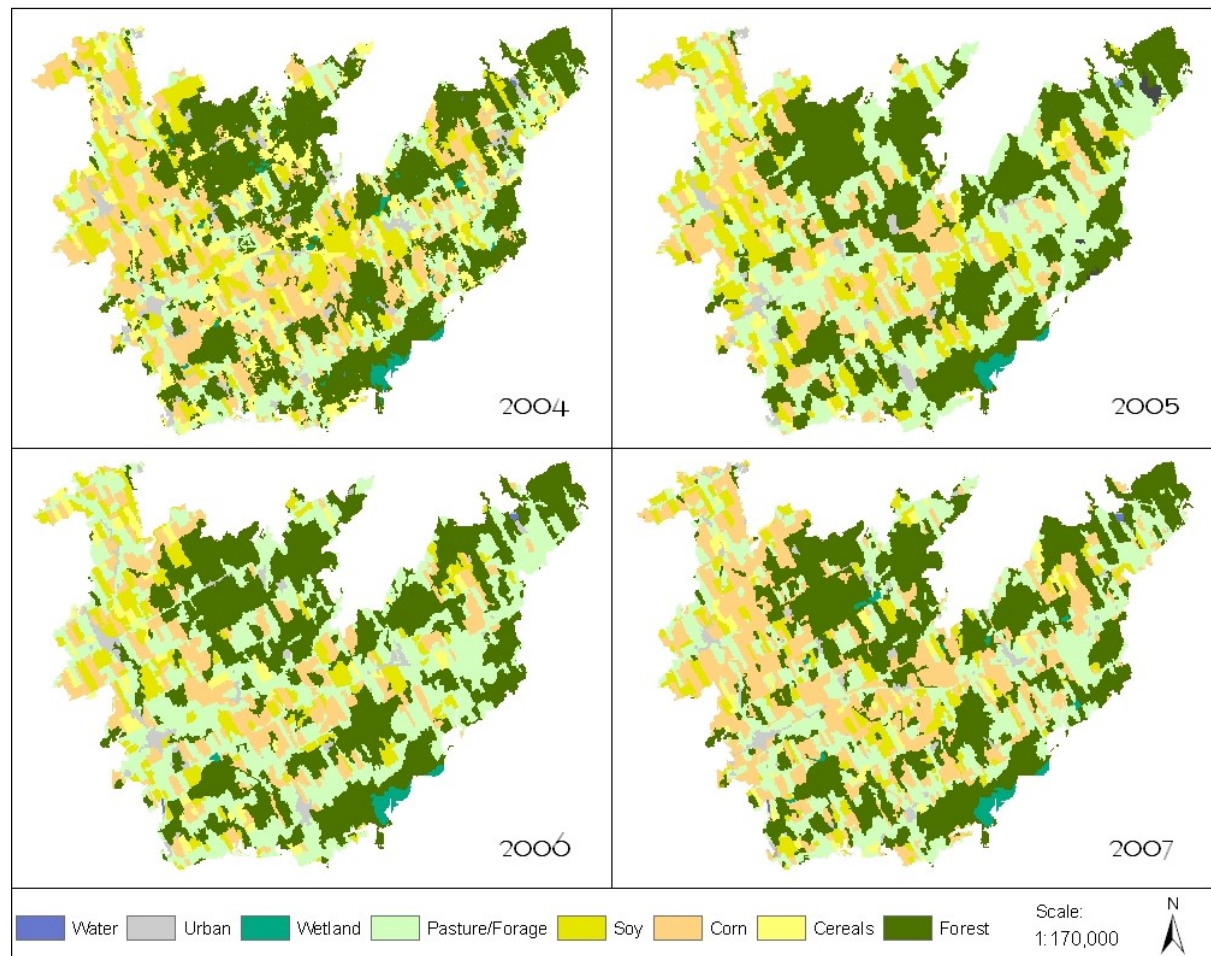


Figure 5 Land Use Classifications Derived from Remotely Sensed Imagery (2004 to 2007)

In order to identify general land use groups and crop rotation types, the four raster images were combined and reclassified based on majority criteria into the following groups: forest, forested wetland, urban, water, crop, grass, and crop - grass rotation. As land use information used in SWAT should not include water, these areas were filled in with classified values of their nearest neighbours. The resultant general land use map was combined with estimated grazing areas (300 m buffer around surveyed cattle farms), manure application areas (700 m buffer around grazing areas) and known tile drain locations (Figure 6). The ArcGIS majority filter was then used to smoothen borders and filter out isolated pixels.

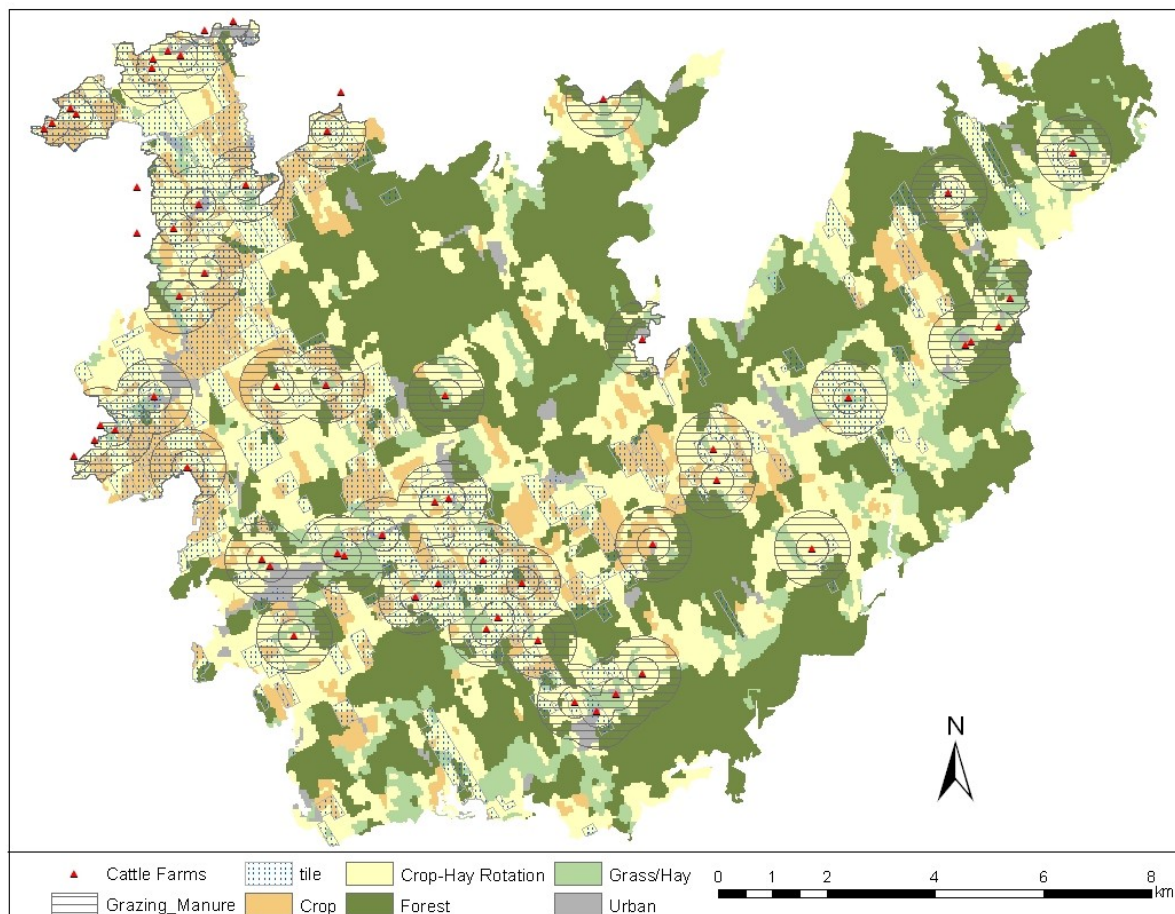


Figure 6 General Land Use Groups

By using statistical data from the Census of Agriculture 1991, Statistics Canada (Table 6), and field boundaries, the dataset was then populated with detailed crop information by using random distribution. The resulting land use map shown in Figure 7 sufficiently reflects the 1991 crop distribution characteristics for the North Stormont County as well as crop management practices required for SWAT inputs.

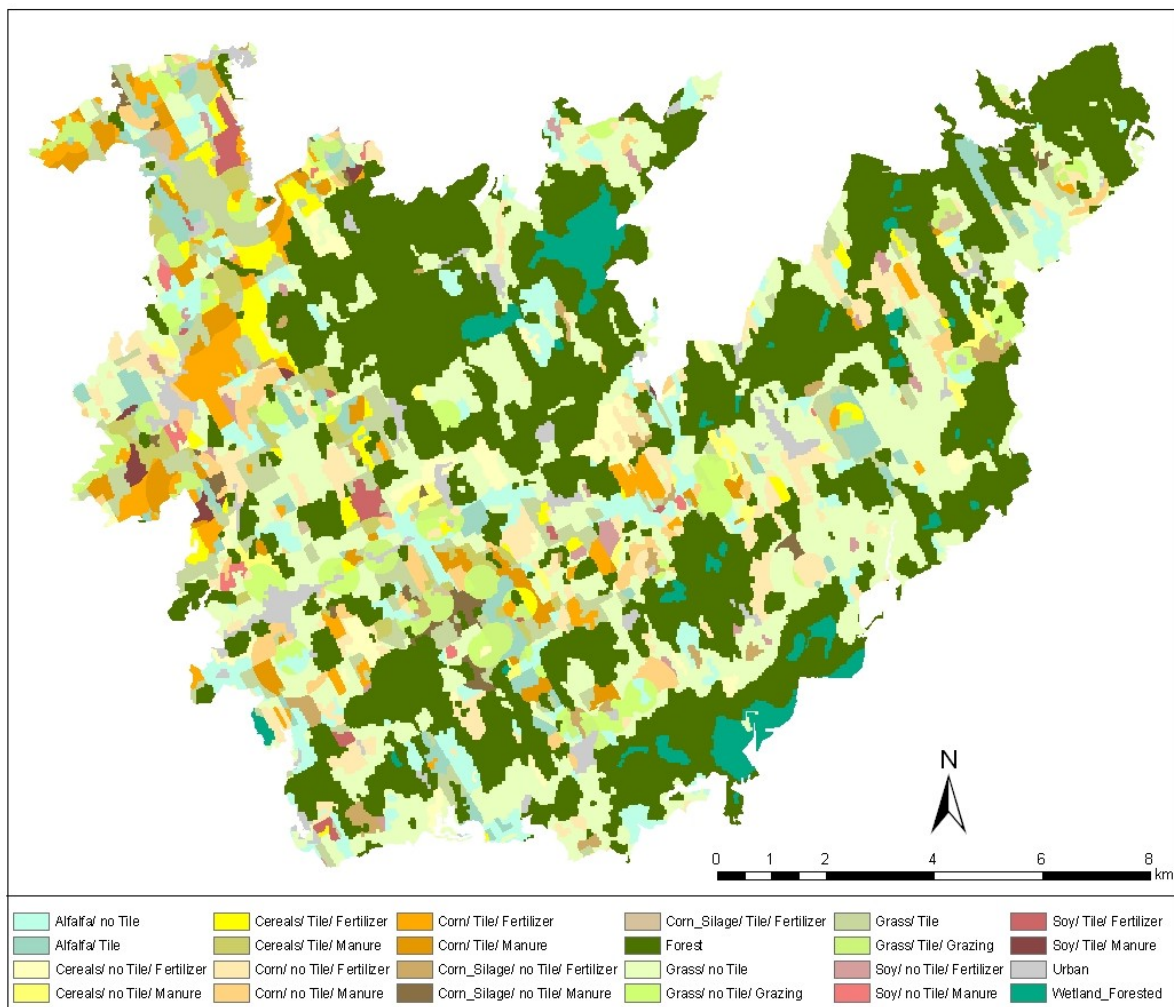


Figure 7 Resulting Generated Land Use Map

Table 6 Crop distribution based on Census of Agriculture 1991, Statistics Canada

	1996
	% of Agricultural Land
Soy	4
Corn grain	22
Corn silage	5
Cereals (Wheat, Barley, Rye...)	11
Alfalfa	14
Hay	44

Land Management

SWAT requires detailed land management information for each land use/ land cover class. General land cover classes like corn have to be divided into subclasses that represent specific land management practices, for example, corn/tile/manure for tile drained areas that grow corn and use manure as a fertilizer.

Manure is commonly used as a natural fertilizer. Besides its beneficial effects, manure also constitutes a source of bacterial contamination. In the model, five different sources of manure are being used. These sources are applied either in fields and pasture areas (cattle manure stored in lagoons, fresh manure from grazing livestock, geese droppings) or directly into the water course (muskrat droppings, failing septic systems).

Detailed management scenario information is listed in Table 13. In order to determine tillage, timing, fertilizer application rates, manure properties and tillage practices, the following assumptions and estimations are made.

- *Tillage:* Cereal and corn fields receive generic spring and fall tillage, whereas soy is only tilled during spring.

- *Timing*: Dates of planting, fertilizer application and harvest have been based on provincial recommendations (OMAFRA 2009).
- *Mineral fertilizer*: In spring, all designated crop areas (corn, cereal and soy) receive mineral fertilizer treatments according to Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) recommendations (OMAFRA 2009) and local knowledge (personal communication Mark Sunohara, South Nation Conservation Authority). Cereal crops receive 70 kg of mineral nitrogen, corn, 170 kg and soy, 7 kg. Additionally, all three crops are fertilized with 20 kg of mineral phosphorus (Table 13) in accordance with average measured 2008 soil phosphorus levels of about 14-16 ppm (Sunohara et al. 2010).
- *Manure*: Cattle manure is applied on cereals and corn in the spring and on cereal, corn and soy in the fall. Only areas identified as potential manure application areas within the 300 to 700 m buffer zone around the cattle farms receive manure applications. Manure application rates have been calculated based on the estimated manure production for 2006 (Table 7) less the amount of manure applied during grazing.

Table 7 Livestock numbers and manure production in 2006

	Dry Manure kg/year (dry weight)	Total Heads	Total Dry Manure kg/year (dry weight)
Calves	511	,1031	526,841
Heifers	1,351	1,284	173,4042
Dairy	3,249	1,946	6,321,581
Beef, Steers,			
Bulls	2,409	544	1,310,496
Σ		4,805	9,892,960

- *Livestock Grazing*: The number of grazing cattle on pasture areas was estimated based on agricultural census data and a typical density of one cow per hectare. In Eastern Ontario, beef cows, steers, bulls and heifers usually graze from the end of May to the end of October for about 150 days. Dairy cows commonly stay inside their freestyle operations. However, each day, about 30% of the milk cows will spend some time outside on exercise yards (personal communication Brent Corrigan, Supervisor Farm Operations, Canada Agriculture Museum). Assuming a density of one grazing cow per hectare of pasture area, the number of grazing animals within the study area has been estimated based on the availability of pasture areas. Based on these estimations, the number of grazing cattle has dropped from 4610 heads in 1976 to 971 in 2006 (Table 8).

Table 8 Cattle and Grazing Cattle in the Payne River Catchment

	Unit	1976	2006	Source
Cattle	heads	7313	4805	Agricultural Census
Cattle, estimation	heads		4534	Land Survey
Pasture Area	ha	4609.6	971	Agricultural Census
Grazing Cattle	heads	4610	971	Estimation (density:1 cow/ha)

- *Avian Wildlife Grazing:* Every year, thousands of Canada geese migrate through Eastern Ontario. Based on personal communication from Ken Ross, Head Population Management Unit, Canadian Wildlife Service Ontario, Environment Canada, geese densities of 50-500 head/km² (0.5 to 5 geese ha⁻¹) between late March and early May (\approx 6 weeks) and 50 to 250 head/km² from mid September to mid October (\approx 10 weeks) are estimated. Geese are assumed to be present on all crop and pasture areas with total numbers between 5203 and 26018 for the entire watershed (Table 9). Given a manure production of approximately 250 grams per geese (Hussong 1979), application rates of 0.18 to 1.75 kg ha⁻¹ day⁻¹ (Table 12) have been estimated.

Table 9 Geese estimations

Land Use	Area (km ²)	Time of presence	Duration (weeks)	Geese Densities (head/ km ²)	Total Geese (head)
Cropland, Grassland	104	Late March - Early May	6	50 - 500	5,203 - 52,030
		Early September - Mid November	10	50 - 250	5,203 - 26,018

- *Rodent Direct Water Input:* The muskrat (*Ondatra zibethicus*) has been shown to be a non-negligible source of *Giardia* and *Cryptosporidium* in perennial streams (Ruecker et al. 2007). One of the reasons might be the direct deposition of feces into the watercourse. Therefore, muskrat contribution to bacterial loadings to the watercourse have been estimated and implemented as point sources into the model (lone management option for direct deposition into the stream). According to Allen & Hoffmann (1984), muskrats prefer still or low velocity water, water depths between 0.46 – 1.2 m, and streams bordered by agricultural crops (55 animals km⁻¹ water course). Furthermore, cattail banks are preferred over those without vegetative cover (Kadlec et al. 2007) or forested areas. Nadeau (1995) found muskrat burrow densities of 37.4 per km in farm ditches in southwestern Quebec. The home ranges of this large field mouse are less than 2.5 ha (Marinelli and Messier 1993). Consequently, given the size of the study area, a conservative estimate of 3600 muskrats is made based on the watercourse size as well as the area of land use (Table 10). As a result, an estimated 360 kg day of muskrat manure is applied to the watershed (Table 12).

Table 10 Muskrat Estimations

Land Use	Category	Length km	Animals / km	Total Muskrat
			Watercourse	
Crop, Pasture	Payne River	26	20	520
	Tributaries	53	35	1855
	Very small ditch	111	5	553
Forest, Forested	Payne River	16	7	112
	Tributaries	39	12	468
Wetland, Urban	Very small ditch	92	1	92
	Σ			3600

- *Human direct waste water input:* According to Petersen et al. (2009), 1-35% of septic systems fail. Therefore, the impact of human waste on microbial water quality might be significant and has to be considered in the model. Septic effluent could rise to the soil surface and be considered in the model as a fertilizer input. On the other hand, effluent could directly flow into the stream and be considered a point source. Parajuli et al. (2009) showed that only the impact of direct input of septic effluent into the stream is significant. Therefore, only direct waste water input will be considered in the model. A number of 38 out of 671 private septic systems (road side survey, Census of Agriculture 2006) in the basin are located in close (30 m) proximity to the stream. In the model 20% of these 38 private septic systems are assumed to fail, and therefore directly discharging $3 \text{ m}^3\text{day}^{-1}$ of sewage effluent into streams and ditches of the Payne River Basin (Table 11).

Table 11 Septic Systems

Payne Basin	Dwellings with Septic Systems	Average Number of Habitants per Dwelling	Total Number of Habitants Contributing to Septic System	Average Residential Water Use ($\text{l} \cdot \text{day}^{-1} \cdot \text{person}^{-1}$)	Sewage Effluent ($\text{m}^3 \cdot \text{day}^{-1}$)
Houses with Septic Systems	671	2.7	1812	160	290
Septic Systems within 30 m distance from reach	38	2.7	103	160	16
Failing Septic Systems (20 %)	7.6	2.7	21	160	3

Table 12 Manure Application Rates and Point Source Loadings Estimated within the Study Area

	Time (days)	SWAT Area (ha)	Number of Point Sources	Animals/ Failing Septic Systems	Total Manure / Effluent	Units	Density (head /ha)	Application Rate	Units	Operation	Application Area
Cattle	150	801		971	775,545	kg/150 days (dry weight)	1	6.5	kg×ha ⁻¹ ×day ⁻¹	Grazing	Pasture
	1	1,166			4,946,480	kg/application (dry weight)		4,241	kg×ha ⁻¹	Spring Fertilizer Application	Cropland (Corn, Cereals)
	1	1,261			4,170,935	kg/application (dry weight)		3,308	kg×ha ⁻¹	Fall Fertilizer Application	Cropland Corn, Cereals, Soy)
Geese	42	10,400		5,203 - 52,030	54,632 -546,315	kg/ 42 days (wet weight)	0.5 - 1	0.13 - 1.25	kg×ha ⁻¹ ×day ⁻¹	Grazing	Crop- and Grassland
	70	10,400		5,203 - 26,018	91,053 - 455,4315	kg/70 days (wet weight)	0.5 - 2.5	0.13 - 0.63	kg×ha ⁻¹ ×day ⁻¹	Grazing	Crop- and Grassland
Muskrat	240		40	3,600	86,400	kg/ 240 days (wet weight)	1-20 (head / km)	9	kg×day ⁻¹ ¹ ×point source ⁻¹	Point Sources	Reach
Septic Systems	240		40	8	720,000	l/ 240 days (wet weight)		75	l×day ⁻¹ ×point source ⁻¹	Point Sources	Reach

Table 13 Land Management Parameters

Land use	Date (HU)	Management	Grazing (days)	Fertilizer (kg/ha)	Min. N (kg/ha)	Min.P (kg/ha)	Org.N (kg/ha)	Org. P (kg/ha)	Fecal Coliform (cfu/ha)	E.coli (cfu/ha)	
Alfalfa	01-Mar (0.015)	Graz Geese	42	1/day	0	0	0	0	1.53×10^8	1.43×10^8	
	18-Apr (0.04)	Planting									
	12-Jun (0.6)	Harvest									
	19-Jul (1.2)	Harvest									
	01-Sep (1.9)	Graz Geese	70	0.55/day	0	0	0	0	8.42×10^7	7.86×10^7	
Cereal	27-Mar (0.015)	Graz Geese	41	1/day	0	0	0	0	1.53×10^8	1.43×10^8	
	11-Apr (0.029)	Tillage									
	12-Apr (0.03)	Planting									
	07-Aug (1.2)	Harvest+Kill									
	02-Sep (1.6)	Tillage									
	02-Sep (1.6)	Graz Geese	70	0.55/day	0	0	0	0	8.42×10^7	7.86×10^7	
	Option 1: 16-Apr - 10-May	Manure			4241	42.4	12.7	131.5	12.7	4.07×10^{13}	4.03×10^{13}
	08-Aug - 1-Sep	Manure			3308	33.1	9.9	102.5	9.9	3.18×10^{13}	3.14×10^{13}
	Option 2: 12-Apr (0.03)	Min. Fertilizer				35	10				
	15-May (0.1)					35	10				
Corn	27-Mar (0.015)	Graz Geese	42	1/day	0	0	0	0	1.53×10^8	1.43×10^8	
	28-April (0.09)	Tillage									
	06-May (0.1)	Planting									
	30-Sep (1.17)	Harvest+Kill									
	09-Oct (1.2)	Tillage									
	02-Sep (0.97)	Graz Geese	70	0.55/day	0	0	0	0	8.42×10^7	7.86×10^7	
	Option 1: 01-May –25-May	Manure			4241	29.7	21.2	131.5	12.7	4.07×10^{13}	4.03×10^{13}
	06-May (0.1)	Min. Fertilizer				7					
	01-Oct - 25-Oct	Manure			3308	23.2	16.54	102.5	9.9	3.18×10^{13}	3.14×10^{13}
	Option 2: 06-May (0.1)	Min. Fertilizer				85	10				
06-Jun (0.3)	Min. Fertilizer				85	10					

Land use	Date (HU)	Management	Grazing (days)	Fertilizer (kg/ha)	Min. N (kg/ha)	Min.P (kg/ha)	Org.N (kg/ha)	Org. P (kg/ha)	<i>Fecal Coliform</i> (cfu/ha)	<i>E.coli</i> (cfu/ha)	
Grass	27-Mar (0.015)	Graz. Geese	42	1/day	0	0	0	0	1.53×10 ⁸	1.43×10 ⁸	
	12-Apr (0.03)	Planting									
	02-Sep (1.06)	Graz. Geese	70	0.55/day	0	0	0	0	8.42×10 ⁷	7.86×10 ⁷	
	Option 1: 26-May (0.17)	Graz. Cattle	150	6.5/day	0.065	0.026	0.195	0.05	7.54×10 ⁹	6.89×10 ⁹	
	Option 2: 16-Jul (0.6)	Harvest									
	06-Sep (1.1)	Harvest									
Soy	27-Mar (0.015)	Graz. Geese	42	1/day	0	0	0	0	1.53×10 ⁸	1.43×10 ⁸	
	01-May (0.09)	Tillage									
	17-May (0.15)	Planting									
	07-Oct (1.17)	Harvest+Kill									
	02-Sep (0.96)	Graz. Geese	70	0.55/day	0	0	0	0	8.42×10 ⁷	7.86×10 ⁷	
	Option 1: 08-Oct – 1-Nov	Manure			3308	23.2	16.5	102.5	9.9	3.18×10 ¹³	3.14×10 ¹³
	Option 2: 01-May (0.09)	Min. Fertilizer			7		20				

Bacteria parameter

Aside from defining manure application rates and point source contributions, in order to simulate microbial water quality, initial bacteria concentration, bacteria die-off, the bacteria partition coefficient and the temperature adjustment factor are most sensitive on bacteria model output (Coffey et al. 2010, Parajuli et al. 2009). Bacteria related parameter estimations are explained below.

- *Initial bacteria concentration*: bacteria concentrations in manure depend on several factors, including animal species, animal age, feed, health as well as manure storage and treatment. Examples of FCs and *E.coli* concentrations in fresh beef, muskrat, geese feces, stored cattle manure and septic effluent are summarized in Table 14. In the model, FC concentrations of 9.6×10^6 cfu/g (beef), 1.16×10^6 cfu/g (cattle manure), 1.53×10^5 cfu/g (geese), 2.5×10^5 cfu/g (muskrat), 1×10^8 cfu/l (septic effluent) and *E.coli* concentrations of 9.5×10^6 cfu/g (beef), 1.06×10^6 cfu/g (cattle manure), 1.43×10^5 cfu/g (geese), 2.5×10^5 cfu/g (muskrat), 6×10^7 cfu/l (septic effluent) are assumed.
- *Bacteria die-off*: some values on bacteria die-off exist within the literature, but their magnitude significantly varies, especially between laboratory and in situ field studies. Die-off values between 0.016 and 0.23 day^{-1} for manure and manure amended soil have been observed in the literature. Therefore, model parameters with regards to *E. coli* and FC adsorbed to soil particle die-off (WDPS, WDLPS) are set to 0.03 day^{-1} . Within water, bacteria decay more rapidly and values range from 0.19 to 0.99 day^{-1} (Table 2). The SWAT parameters, WDPQ, WDL PQ (bacteria in soil solution),

WDPRCH, and WDLPRCH (bacteria in moving water) are set to 0.3 day⁻¹ and WDPRES, WDLPRES (bacteria in still water) to 0.4 day⁻¹.

Table 14 FCs and *E. coli* Concentrations in Livestock and Wildlife Feces, Stored Manure and Septic Effluent

	Fecal Coliform		<i>E. coli</i>			Units	Source	
	Average	Range	Average	Range				
Beef, fresh	9.6×10⁶		9.5×10⁶			cfu g⁻¹ (dry weight)	Model Assumption	
		1.74×10 ⁶	6×10 ⁶	1×10 ⁶	1×10 ⁷	cfu g ⁻¹ (dry weight)	van Kessel et al. 2007	
			1.78×10 ⁷	1.16×10 ⁵	8.63×10 ⁷	cfu g ⁻¹ (dry weight)	Soupir et al. 2008	
			6.61×10 ⁵	5	2.5×10 ⁷	cfu g ⁻¹ (dry weight)	Moriarty et al. 2008	
Cattle, stored manure			2.2×10 ⁶	2.2×10 ⁵	3×10 ⁶	cfu g ⁻¹ (dry weight)	Sitton et al. 2007	
	1.16×10⁶		1.06×10⁶			cfu g⁻¹ (dry weight)	Model Assumption	
		8.48×10 ⁸	3.39×10 ⁶			cfu g ⁻¹ (dry weight)	Guber et al. 2009	
		2.73×10 ⁷		1×10 ⁵	1×10 ⁸	cfu g ⁻¹ (dry weight)	Hodgson et al. 2009	
Geese			3.55×10 ¹⁰			cfu g ⁻¹ (dry weight)	Trevisan et al. 2002	
						cfu g ⁻¹ (dry weight)	Unc & Goss 2003	
	1.53×10⁵		1.43×10⁵			cfu/g (wet weight)	Model Assumption	
	3.6×10 ⁴					cfu/g (wet weight)	Hussong et al. 1979	
Muskrat	1.53×10 ⁴	4.5×10 ³				cfu/g (wet weight)	Alderiso & DeLuca 1999	
	6.6×10 ⁵	7×10 ⁴	1.3×10 ⁶			cfu/g (wet weight)	Middleton & Ambrose 2005	
Septic System	2.5×10⁵		2.5×10⁵			cfu/g (wet weight)	Model Assumption	
	2.5×10 ⁵		4.8×10 ⁷			cfu/g (wet weight)	Yagow et al. 2001	
	1.90×10 ⁶		7×10 ⁷	3.6×10 ⁴	8.9×10 ⁷	cfu/g (wet weight)	MapTech Inc. 2000	
				9.3×10 ⁶	1.47×10 ⁷	cfu l ⁻¹	Peterson et al. 2009	
						cfu l ⁻¹	Ferguson et al. 2009	
						cfu l ⁻¹	Geldreich 1996	
Septic System	3.4×10 ⁷	7×10 ⁴	1.1×10 ⁸	1.5×10 ⁷	3×10 ⁵	6.2×10 ⁷	cfu l ⁻¹	Sidhu et al. 2009
	2.88×10 ⁶						cfu l ⁻¹	Map Tech INC 2000
	1.17×10 ⁶						cfu l ⁻¹	Weiskel et al. 1996

- *Bacteria partition coefficient*: for the bacteria partition coefficient, BACTKDDB, a value of 0.5 was chosen as studies suggest the high attachment rates of bacteria to soil particles. Recent studies found about 30% to 50% of *E.coli* in runoff, and river and storm water to be particle associated (Soupir et al. 2010, Garcia-Arminsen & Servais 2009, Krometis et al. 2009).
- Default values are used for the bacteria percolation coefficient, BACTMX (10), soil partitioning coefficient, BACTKDQ (175), and temperature adjustment factor, THBACT (1.07).

Observed Data

Discharge data (m^3s^{-1}) were obtained from the Environment Canada gauging station Payne River near Berwick (02LB022). Flow data spanned from 1976 to 2008. The records were split into periods used for model warm up, calibration and validation. Model warm up includes the years 1976 to 1978. The calibration period includes daily discharge data between April 1979 to March 1989, and January 2004 to October 2006. The model was validated by using streamflow data between April 1989 to March 1997, and November 2006 to December 2008. The base flow contribution to total observed flow as well as the base flow recession constant (Alpha_BF) were estimated by using the baseflow filter program developed by Arnold and Allen (1999).

Water quality was monitored biweekly by AAFC, Ottawa, Ontario, for 5 years (2004 – 2008) at the basin's outlet (Payne River near Chrysler, ca. 5.6 km downstream of gauging station Payne River near Berwick). Surface water grab samples were collected bi-weekly at approximately 1 m depth of the water profile by using sterile 1 L bottles. Samples were then cooled and shipped within 24 hours to the AAFC laboratory (London, Ontario) and the

Robert O. Pickard Environmental Center (ROPEC, Ottawa, Ontario) for determination of total P, total N, FC, and *E. coli* analyses.

Nitrate and ammonia/ammonium were colourimetrically analysed with a TrAAcs 800 autoanalyzer (Bran and Luebbe Analyzing Technologies, Inc., Elmsford, NY, USA) by using the cadmium reduction method for nitrate and the phenate method for ammonia. Total P was analyzed with a SMART Spectro spectrophotometer from LaMotte Company (Chestertown, MD, USA) by using the ascorbic acid method, preceded by a persulfate digestion.

For microbial enumeration, a series of sterile GN-6 membranes (Pall–Gelman, VWR, Mississauga, Ontario) was placed onto a series of selective differential media. FCs were enumerated on mFC agar (Difco) following incubation for 18–20 h at 44.5°C by counting colonies that produce a distinctive indigo blue color. For *E. coli* enumeration, colonies that generated a characteristic blue color which indicates b-glucuronidase activity were counted on an mFC basal medium (Difco) supplemented with 3-bromo-4-chloro-5-indolyl-b-D-glucuronide (100 mg l⁻¹, Med-Ox Diagnostics, Ottawa, Ontario) after 18–24 h of incubation at 44.5°C (Wilkes et al., 2009).

4. Model Calibration and Validation

Model setup, input parameters and data sources for the SWAT model have been discussed in Chapter 3. This chapter will discuss the sensitivity analysis performed to identify model parameters that are most influential on predicted flow, sediment and nutrient model results. Furthermore, the calibration and validation approach used to increase the ability of the model to accurately model replicate watershed processes will be described.

4.1 Sensitivity

A Latin hyper-cube one-at-a-time (LH-OAT) sensitivity analysis (van Griensven et al. 2006), of parameters related to flow and nutrient simulation was carried out in order to understand their influence on model results and to select calibration parameters. Table 15 shows the 16 hydrological and 10 nutrient transport parameter used for the sensitivity analysis as well as their respective sensitivity ranks and sensitivity values. The soil evaporation compensation factor (ESCO), the initial SCS runoff curve number for moisture condition II (CN2), and soil depth (SOL-Z) have been identified by the sensitivity analysis as the most influential parameters for flow simulation. Furthermore, the effective hydraulic conductivity in the main channel alluvium (CH-K2), available water capacity of the soil layer (SOL-AWC), threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur (REVAPMIN) as well as the threshold depth of water in the shallow aquifer for return flow to occur (GWQMN) have shown some influence on discharge outputs. Nutrient simulation results show highest sensitivity towards the deep aquifer percolation fraction (RCHRG-DP), snow pack temperature lag factor (TIMP), nitrate percolation coefficient (NPERCO) as well as phosphorus soil partitioning coefficient (PHOSKD) (Table 15).

Table 15 Sensitivity Analysis Results for Flow and Nutrients

Rank	Discharge	Mean	Total N	Mean	Total P	Mean
1	ESCO	0.0860	RCHRG-DP	0.443	RCHRG-DP	0.501
2	CN2	0.0771	TIMP	0.42	TIMP	0.464
3	SOL-Z	0.0529	NPERCO	0.114	PHOSKD	0.0761
4	CH-K2	0.0164	PHOSKD	0.0156	NPERCO	0.0258
5	SOL-AWC	0.0155	PPERCO	0.00499	PPERCO	0.012
6	REVAPMN	0.0124	SHALLST-N	0	SHALLST-N	0
7	GWQMN	0.0108	SOL-LABP	0	SOL-LABP	0
8	GW-REVAP	0.0088	SOLNO3	0	SOLNO3	0
9	CH-N2	0.0035	SOL-ORGN	0	SOL-ORGN	0
10	EPCO	0.0016	SOLORGP	0	SOLORGP	0
11	ALPHA-BF	0.0015				
12	SURLAG	0.0005				
13	SLOPE	0.0005				
14	GW-DELAY	0.0005				
15	SOL-K	0.0002				
16	SLSUBBSN	0.0002				

4.2 Calibration and Validation

The field data described in Chapter 5 were used to calibrate and validate the presented model here. Data sources are summarized in Table 16.

Table 16 Calibration and Validation Parameters

SWAT Basin Output		Field Monitoring Data	
Average daily stream flow out of reach during time step	[m ³ /s]	Daily streamflow Gauging station Berwick	1976-2008
Total sediment concentration	[mg/kg]	9 suspended sediment samples Gauging station Berwick	May 1993 – November 1994
Total nitrogen transported with water out of reach	[kg N]	bi-weekly, Agriculture & Agri-Food Canada	May - December 2005 to 2008
Total phosphorus transported with water out of reach	[kg P]	bi-weekly, Agriculture & Agri-Food Canada	May - December 2005 to 2008
Number of persistent bacteria transported out of basin	[#cfu/100 ml]	bi-weekly <i>E coli</i> , Agriculture & Agri-Food Canada	May - December 2005 to 2008
Number of less persistent bacteria transported out of basin	[#cfu/100 ml]	bi-weekly fecal coliform, Agriculture & Agri-Food Canada	May - December 2005 to 2008

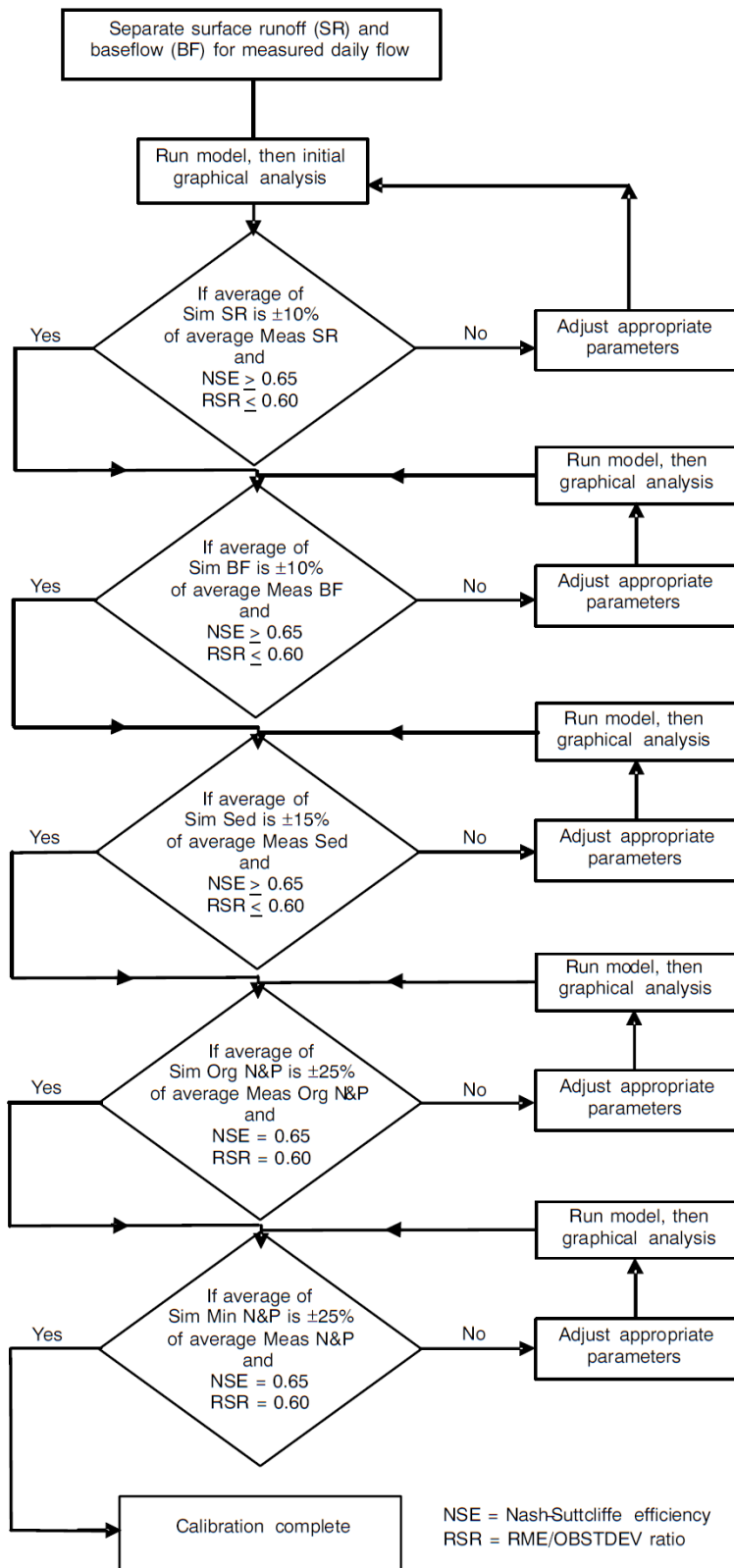


Figure 8 Watershed Model Calibration Procedure (Moriassi et al. 2007)

Flow

Calibration was conducted by using the procedure by Moriasi et al. (2007), and Santhi et al. (2001) (

Figure 8 Watershed Model Calibration Procedure (Moriasi et al. 2007). In the first step, model results were compared to yearly meteorological (snowfall) and hydrological (surface runoff, baseflow, deep aquifer recharge) budget averages. Daily discharge simulation results were then manually calibrated based on a visual inspection of daily hydrographs and NSEs. The soil evaporation compensation factor (ESCO), Manning's roughness coefficient for channels (CH-N), effective hydraulic conductivity in the channel alluvium (CH-K), curve number (CN2), delay time for aquifer recharge (GW-DELAY), threshold depth of water for return flow to occur (GWQMIN), groundwater revap coefficient (GWREVAP), threshold depth of water for revap or percolation to occur (REVAPMN), Manning's roughness coefficient for overland flow (OV-N) as well as slope and slope length have been used to calibrate daily discharge. This selection was later extended to snow related parameters, as their importance in northern climates has been shown by Levesque et al. (2008). Therefore, the parameter snowfall temperature threshold (SFTM), snowmelt base temperature (SMTMP), maximum melt factor (SMFMX), minimum melt factor (SMFMN), and snowpack temperature lag factor (TIMP) have been included in the calibration procedure. The automatic model calibration option was computationally burdensome because of the complexity of our model and was therefore abandoned. The simulation time required is explained by the large number of HRUs required in order to implement detailed land management practices in our basin.

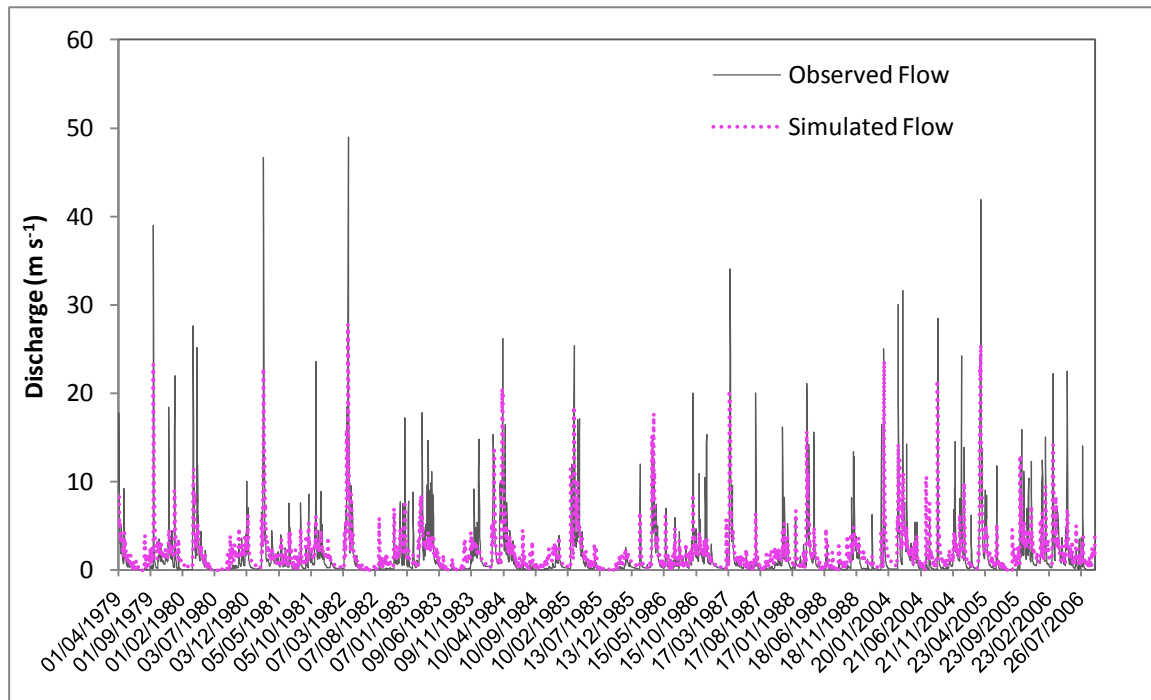


Figure 9 Observed versus simulated discharge for the calibration period.

The model predicted flow for the calibration period (April 1979 to March 1989, and January 2004 to September 2006) and showed good agreement between observed and simulated values. Even though high flow is generally underpredicted by the model, baseflow conditions are very well represented (Figure 9). The Nash-Sutcliffe Efficiencies (NSE) for the calibration period is 0.61 and the coefficient of determination (R^2) is 0.62. The model results were validated with observed daily discharge values between April 1989 to March 1997, and October 2006 to December 2008. During this period, the underprediction of high flow peaks is more accentuated than during calibration. However, the performance criteria of $NSE=0.45$ and $R^2 = 0.45$ indicate that the model generates a reasonably good agreement between the observed and simulated series. Therefore, it can be concluded that the model is able to

simulate hydrological and especially baseflow processes that occur in the watershed with adequate precision.

Sediment

Due to restricted data availability on sediment data in the Payne River (nine analyses of suspended sediment between 1993 and 1994), the model was only partially calibrated and not validated for this parameter. The calculated NSE of 0.52 indicates that sediment transport simulated by the model sufficiently reflects the limited number of observations available and is doubtless in the same order of magnitude as in field conditions.

Nutrients

Total N and P were calibrated for the period of January 2004 to October 2006 by using field data. Total daily N and P loads were calculated by using N and P concentrations and simulated discharge values for the sampling point. Parameters used for total N calibrations include the deep aquifer percolation coefficient (RCHRG-DP), snowpack temperature lag

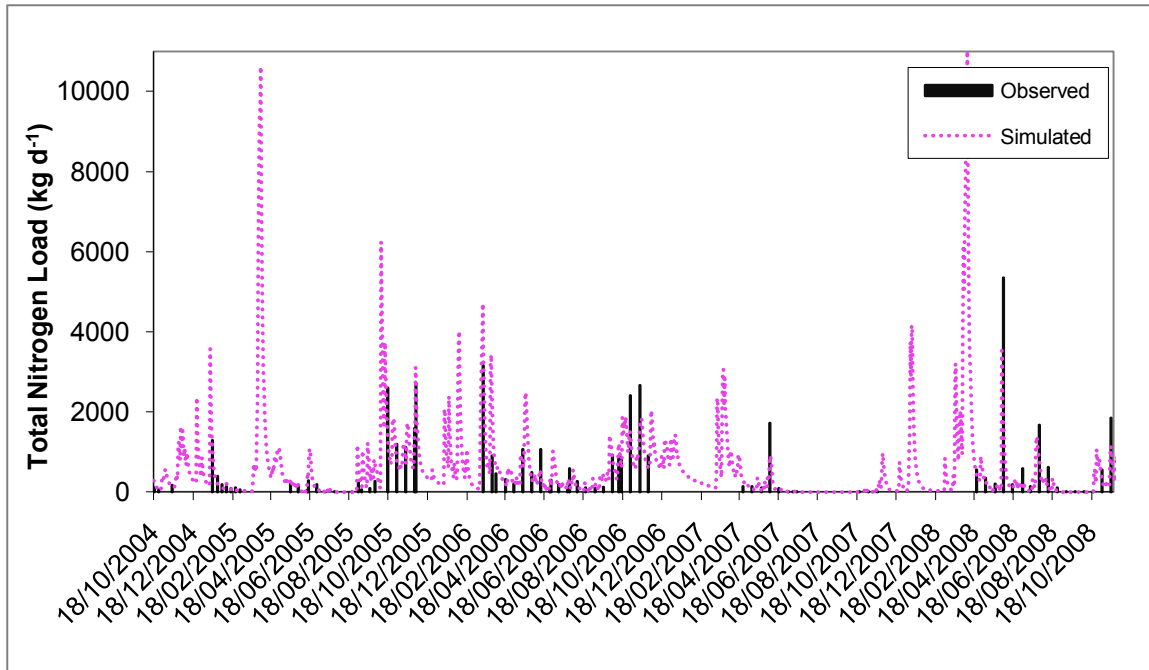


Figure 10 Observed and Simulated Total Nitrogen Loads

factor (TIMP), nitrogen percolation coefficient (NPERCO) and nitrogen plant uptake (NUPDIS). Calibrated total N loads are slightly underpredicted for high flow situations. On the contrary, loads in the middle and lower ranges are well represented. NSE values of 0.62 for calibration and 0.59 for validation illustrate a good agreement between observed and simulated total N loads achieved by the model.

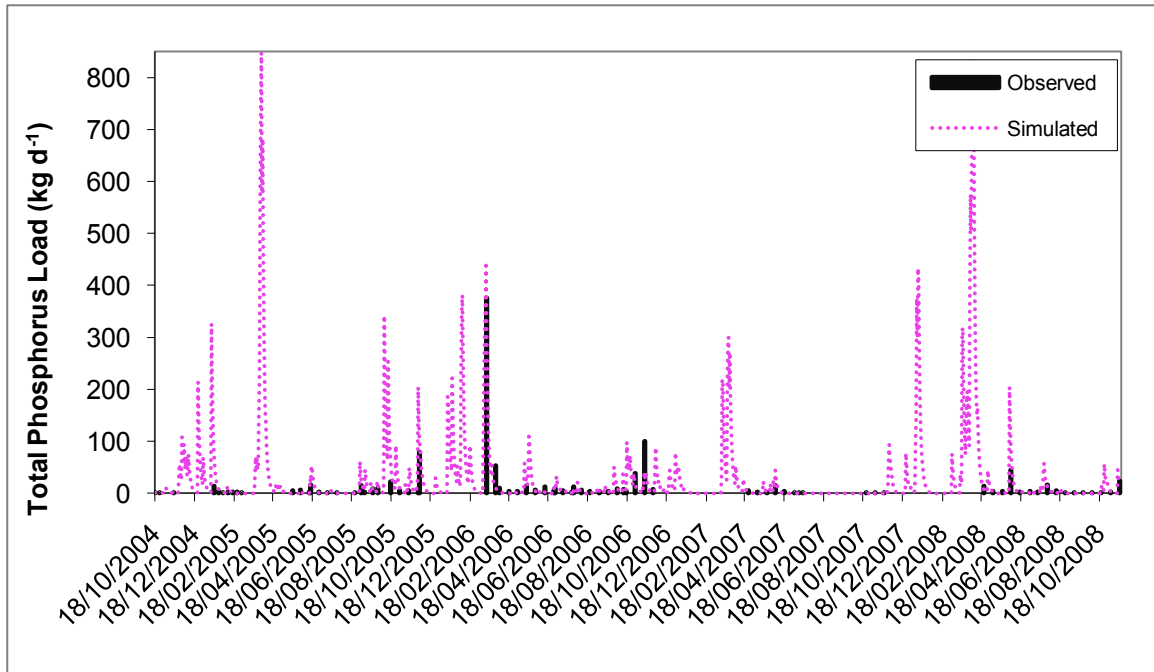


Figure 11 Observed and Simulated Total Phosphorus Loads

Total P was calibrated by using a deep aquifer percolation fraction (RCHRG-DP), snow pack temperature lag factor (TIMP), phosphorus soil partitioning coefficient (PHOSKD), phosphorus percolation coefficient (PPERCO), and phosphorus plant uptake (PUPDIS). The model performed very well during calibration, but overpredicted higher total P loads. NSEs of 0.88 for calibration and 0.73 for validation indicate the model accuracy for total P (Figure 11).

Bacteria

E.coli and FCs were calibrated for the same period as nutrients. Bacteria concentrations analysed from bi-weekly field samples were assumed to be daily averages and multiplied by the predicted daily discharge values in order to calculate daily bacteria loads. Calibration parameters used include initial bacteria concentration, bacteria die-off, and bacteria partition

coefficient (BACTKDDDB). The resulting model predicts *E.coli* and FC loads generally well for periods of lower loadings. It is able to capture many of the high load peaks, but not always their magnitude. Model performance statistics reflect these results. FC simulation yields in NSE values of 0.18 for calibration and 0.01 for validation. *E.coli* simulation performance is better with NSE values of 0.3 for calibration and 0.05 for validation.

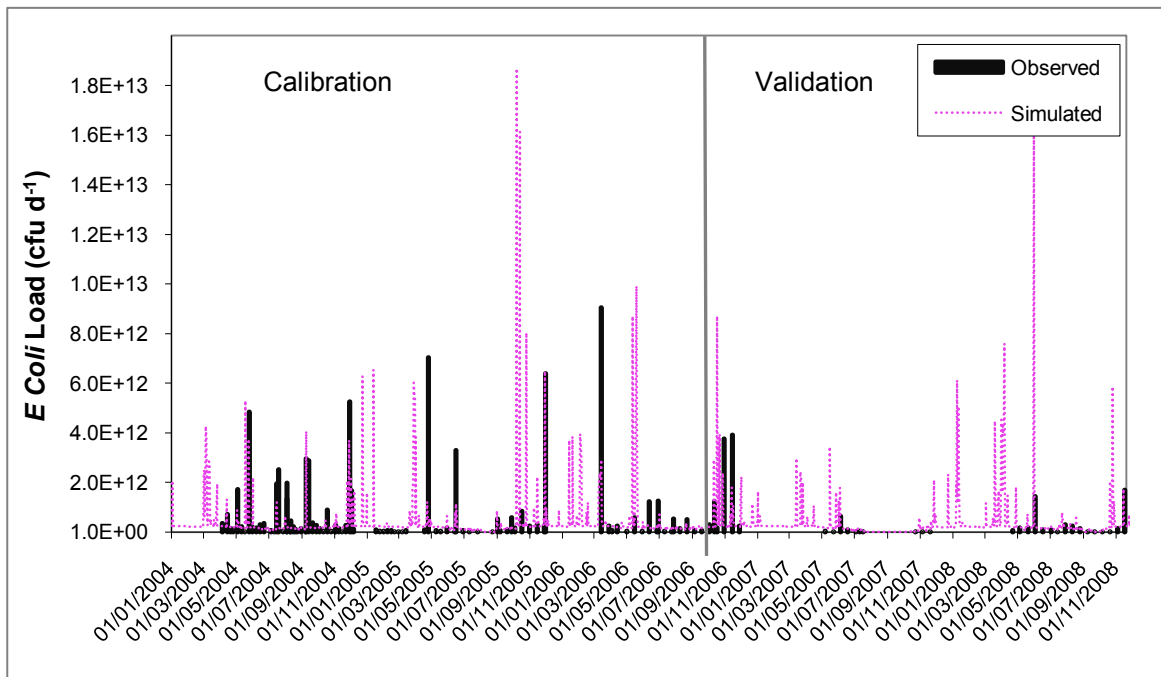


Figure 12 Observed and Simulated *E.coli* Loadings

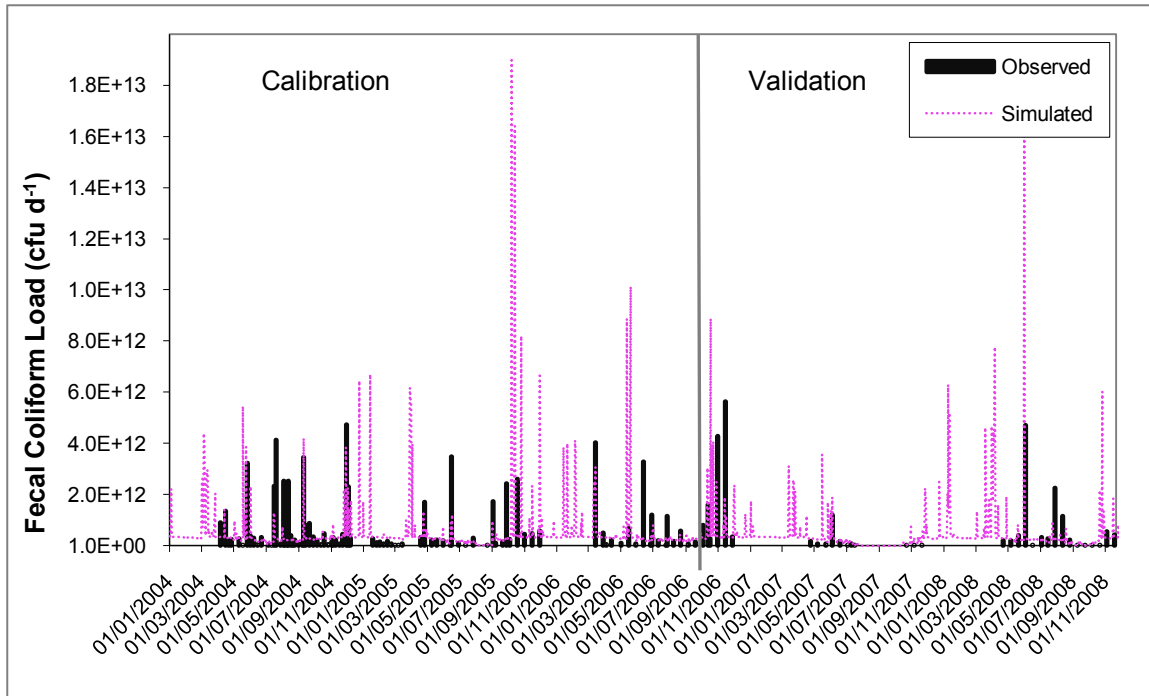


Figure 13 Observed and Simulated *E.coli* Loadings

5. Discussion

The overall model results for the Payne River catchment indicate good performances for hydrological and nutrient transport. The model is able to simulate these processes and the application of this model for future predictions would be suitable. Furthermore, simulation of sediment transport could be improved by calibrating the model to more frequent field data. Nevertheless, the model performance indicates that simulated sediment transport is in the same order of magnitude as observed values. The suitability of our model to simulate hydrological, sediment and nutrient transport processes builds a strong foundation for bacteria transport simulations. SWAT was able to account for human, wildlife and livestock sources of bacterial contamination. It was observed that lower *E.coli* and FC loading simulations are mostly driven by point source inputs. Without these constant daily loadings, only separate high bacteria loadings are predicted and the simulated bacteria level falls

immediately back to zero after each peak. SWAT simulated these lower bacteria loadings generally well and it can be concluded that the detailed estimation of point source inputs from human, wildlife and livestock sources is crucial for meaningful simulation results.

On the other hand, higher FC and *E.coli* loadings were temporally consistent with observations, but their magnitude was not always captured and some observed high bacteria loads were not predicted by the model. The reasons for the lack of definition in the high loading range might include the following factors:

- *tile drain contribution*: SWAT assumes bacteria transported within the subsurface to be lost from the system. However, several studies have shown that the rapid subsurface transport of microbial contaminants may be significant (Akhand et al. 2006, Fenlon et al. 2000, Jamieson et al. 2002, Ouellet et al. 2007). In this context, it is important to observe that 85% of all observed FC and 81% of *E.coli* loads $> 1 \times 10^{12}$ cfu day⁻¹ occurred during periods when the model simulated tile flow contribution to streamflow (Figure 14). Since Student's t-tests (two tailed, unequal variance) on log normalized bacteria loads resulted in p-values of 2.37×10^{-9} for FC and 2.9×10^{-10} for *E.Coli*, it can be concluded that the means of the observed FC loads or *E.Coli* loads that occur during tile flow episodes are significantly different from those observed during modeled no tile flow periods.

This is supported by observed tile flow occurrences in a neighbouring sub-basin of the South Nation River Basin. It was found that 78% of all FC and 87% of *E.coli* loads $> 1 \times 10^{12}$ cfu day⁻¹ observed in the Payne River Basin occur when tiles of the neighbouring watershed were flowing (Figure 15). P values of 1.82×10^{-2} for FC loads and 4.38×10^{-2} for *E.Coli* loads indicate once more that the means of bacteria loads

observed during tile flow episodes are significantly different during no tile flow periods.

Improving this aspect of the SWAT model and allowing bacteria transport through tile drains may improve the performance of the SWAT microbial sub-model.

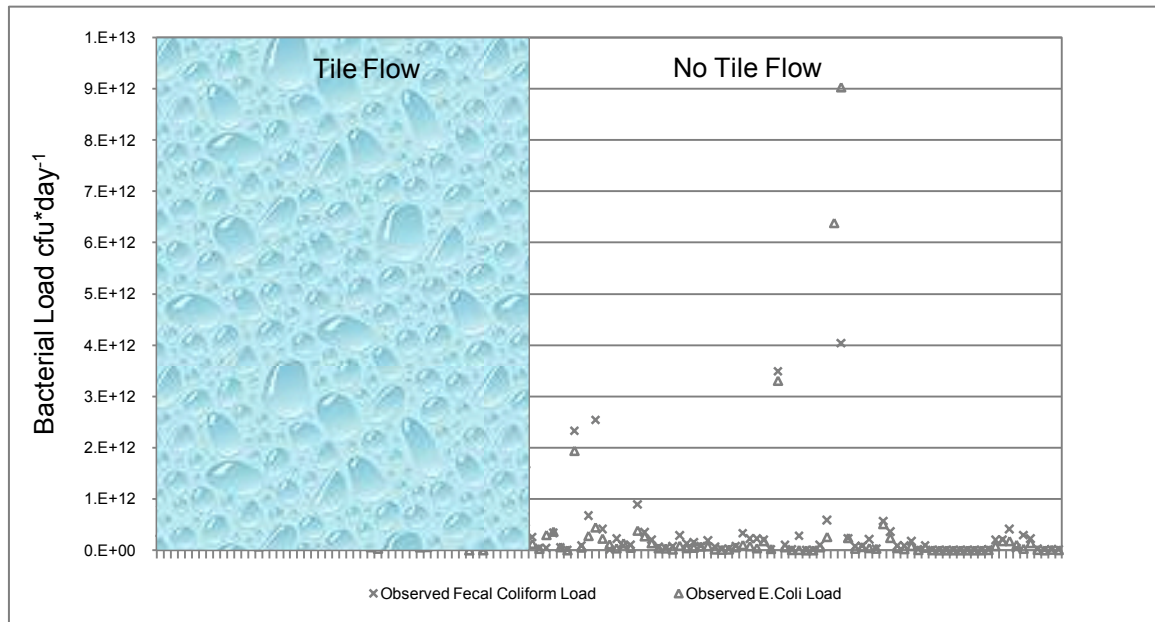


Figure 14 Observed Bacteria Loadings in Relation to Modeled Tile Flow Contributions
(129 Observations)

- *Input uncertainties:* High spatial and temporal diversity is a characteristic for contaminants like bacteria, viruses and parasites. It is therefore difficult to precisely define contaminant sources and model inputs have high associated uncertainties. Great care has to be applied to the quantification of human, wildlife and livestock populations and their manure or septic effluent production. More research and field data are needed to better quantify bacteria concentrations and their ranges in manure. Furthermore, knowledge of contaminant deposition characteristics need to be improved (direct deposition of feces into streams, failing septic systems, farm yard

our model assumes no bacteria re-growth. More research is clearly needed to define bacteria re-growth and die-off in order to improve model performance.

- *Sediment*: The re-suspension of settled bacteria attached to sediment within the water course has been identified by Jamieson et al. (2005) as an important and unaccounted source of water quality impairments. He et al. (2007) showed that FC levels in river or lake sediments can be even higher than those in water. For ponded waters, it is 70-160000 cfu per 100 ml compared to 220-90000 cfu g⁻¹ (dry weight) in bottom sediments and for flowing water conditions, the FC level is 2 to 1300 cfu per 100 ml in contrast to 5000 cfu g⁻¹ (dry weight) in sediment. Therefore, it is likely that some of the high *E.coli* and FC levels that were observed in the field, but measurements that were not accurately simulated by the model, are probably linked to bacteria re-suspension.
- *Soil*: The existence of microbial contaminant reservoirs in soils has been described by Texier et al. (2008) as naturalized *E. coli* populations that became part of the natural soil community. Moreover, Avery et al. (2004) observed *E. coli* survival on grass for at least 5-6 months. Consequently, further data on the influence of soil bacteria levels on water contamination should be acquired.

6. Summary and Conclusion

This study responds to the need for microbial transport simulations that are calibrated and validated with long-term field data. The objective of this study is to determine if SWAT calibrated with 30 years of hydrological data and 5 years of water quality data can accurately simulate the impact of fecal contamination on the Payne River Basin. The model results confirm the reasonable performance of SWAT for discharge and nutrients. *E. coli* and FC simulations demonstrate satisfactory results for base-conditions and low microbial loadings. The magnitude of higher loadings is not always accurately represented because of the extremely high spatial and temporal variability of microbial contaminants. However, the modification of SWAT to allow bacteria transport in tile drains could improve model performances for higher bacteria loading events. Furthermore, even though major efforts have been made to parameterize the model, there are still high uncertainties associated with bacteria inputs. Since model results are only as good as the model inputs, wildlife contributions should be estimated from wildlife surveys, bacteria concentrations in manure need to be better quantified, and understanding of bacteria processes (decay, re-growth, re-suspension) needs to be enhanced.

Overall, SWAT has been proven to be a proficient tool to inform prudent water management strategies. It sufficiently predicts the influence of fecal contamination on water quality for base flow conditions and helps to determine the range of bacteria loads expected during high flow conditions. It has therefore the potential to predict river pathogenity, thereby contributing to landscape management policies and the protection of drinking water resources for human health.

7. Recommendations

Based on the experience with this research investigation, the following opportunities to improve the data collection and modeling procedure have been identified.

- In the beginning of the model development phase, the most reliable and continuously monitored discharge data was available from the Environment Canada gauging station Payne River near Berwick (02LB022). This data allowed the long term calibration and validation of the flow component of the model. However, since the research group is now continuously monitoring water level at the watershed outlet, it is recommended to additionally include this data for calibration and validation purposes in additional model efforts.
- In order to further validate the findings about bacteria occurrence during modeled tile flow events, it is recommended to either monitor tile flow within the study area or peruse modeling activities in areas that are already monitoring tile flow.
- Furthermore, calibration and validation of the model could be improved by increasing the number of samples on bacterial concentrations during peak flow conditions, especially during the spring.
- Moreover, it is advisable to conduct a detailed wildlife survey in the study area to improve model inputs on wildlife grazing.
- Ideally, a collection of manure and wildlife feces within the study region to determine locally typical bacteria concentrations in these mediums is advised and should be able to facilitate more precise bacteria model input estimations.

- The presented model here now constitutes a tool for water quality management within the study area. It is therefore recommended to simulate several management scenarios in order to determine effective microbial pollution control mechanisms.
- Finally, the author recommends the evaluation of the usability of the presented watershed model to simulate the transport of other pathogens of concern, like *Giardia* and *Cryptosporidium*.

8. References

- Akhand, N.A., Lapen, D.R., Topp, E., Edwards, M.J., Sabourin, L., Ball Coelho, B.R., Duenk, P.W., Payne, M., 2006, Prediction of liquid biosolid and precipitation induced tile flow in a Southern Ontario agricultural field using MACRO. *Agricultural Water Management*, 83, 37-50
- Alderiso, K.A., DeLuca, N., 1999, Seasonal Enumeration of Fecal Coliform Bacteria from the Feces of Ring-Billed Gulls (*Larus delawarensis*) and Canada Geese (*Branta canadensis*) *Applied and Environmental Microbiology*, 65 (12), 5628-5630
- Allen, A.W., Hoffmann, R.D., 1984, Habitat Suitability Index Models: Muskrat. *U.S. Fish and Wildlife Service*, FWS/OBS-82/10.46
- Angles, M.L., Chandy, J.P., Cox, P.T., Fisher, I.H., Warnecke, M.R., 2007, Implications of biofilm-associated waterborne *Cryptosporidium* oocysts for the water industry. *Trends in Parasitology*, 23(8)
- Arabi, M., Govindaraju, R.S., Hantush, M.M., Engel, B.A., 2006, Role of watershed subdivision on modeling the effectiveness of best management practices with SWAT. *Journal of the American Water Resources Association*, 42 (2), 513-528
- Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998, Large area hydrologic modeling and assessment part I: Model development. *Journal of the American Water Resources Association*, 34 (1), 73-89
- Arnold, J.G., Allen, P.M., 1999, Automated methods for estimating baseflow and groundwater recharge from streamflow records. *Journal of the American Water Resources Association*, 35(2), 411-424
- Arnold, J.G., Fohrer, N., 2005, SWAT2000: Current capabilities and research opportunities in applied watershed modeling. *Hydrological Processes*, 19 (3), 563-572
- Avery, S.M., Moore, A., Hutchison, M.L., 2004, Fate of Escherichia coli originating from livestock faeces deposited directly onto pasture. *Letters in Applied Microbiology*, 38 (5), 355-359.
- Baffaut, C. and Benson, V.W., 2008, Possibilities and challenges for modeling flow and pollutant transport in a karst watershed with SWAT. *American Society of Agricultural and Biological Engineers Annual International Meeting 2008*, 5, 2668-2679.
- Balzer, M., Witt, N., Hemming, H.-C., Wingender, J., 2010, Faecal indicator bacteria in river biofilms. ; 2010, *Water Science & Technology*; 61 (5), 1105-1111

- Benham, B., Zeckoski, R., Estes, C., Carroll, B., 2004, Fate and transport of fecal Bacteria in the Environment, College of Agriculture and Life Science, Retrieved from www.ahnrit.vt.edu/learning/flash/fatetransport/fatetransport.swf
- Bicknell, B.R., Imhoff, J.C., Kittle, J.L., 2000, Hydrologic Simulation Program-Fortran. *User's Manual* Version 12, Computer program manual, AQUA TERRA Consultants, Mountain View, CA, USA
- Bingner, R.L., Garbrecht, J., Arnold, J.G., Srinivasan, R., 1997, Effect of watershed subdivision on simulation runoff and fine sediment yield. *Transactions of the American Society of Agricultural Engineers*, 40 (5), 1329-1335
- Borah, D. K., & Bera, M., 2003, Watershed-scale hydrologic and nonpoint-source pollution models: Review of mathematical bases. *Transactions of the American Society of Agricultural Engineers*, 46(6), 1553-1566
- Borah, D. K., & Bera, M., 2004, Watershed-scale hydrologic and nonpoint-source pollution models: Review of applications. *Transactions of the American Society of Agricultural Engineers*, 47(3), 789-803
- Brennan, F.P., O'Flaherty, V., Kramers, G., Grant, J., Richards, K.G., 2010, Long-term persistence and leaching of escherichia coli in temperate maritime soils. *Applied and Environmental Microbiology* 76 (5), 1486-1496
- Characklis, G. W., Dilts, M. J., Simmons III, O. D., Likirdopulos, C. A., Krometis, L. - H., & Sobsey, M. D., 2005, Microbial partitioning to settleable particles in stormwater. *Water Research*, 39(9), 1773-1782
- Chaubey, I., Cotter, A.S., Costello, T.A., Soerens, T.S., 2005, Effect of DEM resolution on SWAT output uncertainty. *Hydrological Processes*, 19, 621-628
- Chin, D.A., Sakura-Lemessy, D., Bosch, D.D., Gay, P.A., 2009, Watershed-scale fate and transport of bacteria. *Transactions of the ASABE*, 52 (1), 145-154.
- Chen, C. W., J. Herr, L. Ziemelis, R. A. Goldstein, and L. Olmsted., 1999, Decision support system for total maximum daily load. *Journal of Environmental Engineering*, American Society of Civil Engineers, 125(7), 653-659.
- Chow, V.T., 1959, *Open-Channel Hydraulics*. McGraw-Hill, New York
- Coffey, R., Cummins, E., Cormican, M., Flaherty, V. O., & Kelly, S., 2007, Microbial exposure assessment of waterborne pathogens. *Human and Ecological Risk Assessment*, 13(6), 1313-1351
- Coffey, R., Cummins, E., Bhreathnach, N., Flaherty, V.O., Cormican, M., 2010, Development of a pathogen transport model for Irish catchments using SWAT. *Agricultural Water Management*, 97 (1), 101-111

- Crane, S. R., Moore, J. A., Grisher, M. E., Miner, J. R., 1983, Bacterial pollution from agricultural sources - a review. *Transactions - American Society of Agricultural Engineers*, 26(3), 858-866
- Crane, S. R., Moore, J. A., 1986, Modelling enteric bacterial Die off: A Review. *Water, Air and Soil Pollution*, 27, 411-439
- Dellman, P.N., Ruiz, C.E., Manwaring, C.T., Nelson, E.J., 2002. Watershed Modeling System Hydrological Simulation Program; Watershed Model User Documentation and Tutorial. Engineer Research and Development Center, Environmental Lab, Vicksburg, MS.
- DeLoyde, J. L., 2007, Removal of MS2 Bacteriophage, *Cryptosporidium*, *Giardia* and Turbidity by Pilot-Scale Multistage Slow Sand Filtration. Master Thesis, University of Waterloo, Canada
- Di Luzio, M., Srinivasan, R., Arnold, J.G., 2004, A GIS-Coupled Hydrological Model System for the Watershed Assessment of agricultural Non-point and Point sources of pollution. *Transactions in GIS*, 8(1), 113-136
- Di Luzio, M., Arnold, G.A., Srinivasan, R., 2005, Effect of GIS data quality on small watershed stream flow and sediment simulations. *Hydrological Processes*, 19, 629-650
- Donigian, A.S., Jr., Huber, W.C., 1991, Modeling of nonpoint source water quality in urban and non-urban areas. EPA/600/3-91/039. U.S. Environmental Protection Agency, Environmental Research Laboratory, Athens, GA.
- Dorner, S.M., Huck, P.M., Slawson, R.M., 2004a, Estimating potential environmental loadings of *Cryptosporidium spp.* and *Campylobacter spp.* from livestock in the Grand River Watershed, Ontario, Canada. *Environmental Science and Technology*, 38 (12), 3370-3380.
- Dorner, S.M., 2004b, Waterborne Pathogens: Sources, Fate, and Transport in a Watershed used for Drinking Water Supply. PhD Thesis, University of Waterloo
- Du, B. Arnold, J.G., Saleh, A. Jaynes, D.B., 2005, Development and application of SWAT to landscapes with tiles and potholes. *Transactions of the American Society of Agricultural Engineers*, 48 (3), 1121-1133
- Estrada, I.B., Aller, A., Aller, F., Gómez, X., Morán, A., 2004, The survival of *Escherichia coli*, faecal coliforms and enterobacteriaceae in general in soil treated with sludge from wastewater treatment plants. *Bioresource Technology*, 93 (2), 191-198.
- Fenlon, D.R., Ogden, I.D., Vinten, A., Svoboda, I., 2000, The Fate of *Escherichia coli* and *E coli* O157 in cattle slurry after application to land. *Journal of Applied Microbiology*, 88, 56-149

- Ferguson, C., De Roda Husman, A.M., Altavilla, N., Deere, D., Ashbolt, N., 2003, Fate and transport of surface water pathogens in watersheds. *Critical Reviews in Environmental Science and Technology*, 33 (3), 299-361
- Ferguson, C.M., Croke, B.F.W., Beatson, P.J., Ashbolt, N.J. & Deere, D.A., 2007, Development of a process-based model to predict pathogen budgets for the Sydney drinking water catchment. *Journal of Water and Health*, 5 (2), 187-208
- Ferguson, C.M., Charles, K., Deere, D.A. (2009) Quantification of Microbial Sources in Drinking-Water Catchments. *Critical Reviews in Environmental Science and Technology*, 39 (1), 1 - 40
- FitzHugh, T.W., Mackay, D.S. (2000) Impacts of input spatial aggregation on an agricultural nonpoint source pollution model. *Journal of Hydrology*, 236, 35-53
- Foppen, J.W.A. & Schijven, J.F., 2006, Evaluation of data from the literature on the transport and survival of *Escherichia coli* and thermotolerant coliforms in aquifers under saturated conditions. *Water Research*, 40 (3), 401-426
- Franz, E., Klerks, M.M., De Vos, O.J., Termorshuizen, A.J., Van Bruggen, A.H.C., 2007, Prevalence of Shiga toxin-producing *Escherichia coli* stx1, stx2, eaeA, and rfbE genes and survival of *E. coli* O157:H7 in manure from organic and low-input conventional dairy farms. *Applied and Environmental Microbiology*, 73 (7), 2180-2190
- Garcia-Armisen, T., Servais, P. (2009) Partitioning and fate of particle-associated *E. coli* in river waters. *Water Environment Research*, 81 (1), 21-28.
- Garzio-Hadzick, A., Shelton, D.R. ; Hill, R.L. ; Pachepsky, Y.A. ; Guber, A.K. ; Rowland, R. , 2010, Survival of manure-borne *E. coli* in streambed sediment: Effects of temperature and sediment properties. *Water Research*, 44 (9), 2753-2762
- Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G., 2007, The soil and water assessment tool: Historical development, applications, and future research directions. *Transactions of the ASABE*, 50(4), 1211-1250
- Geldreich, E.E., 1996, Pathogenic agents in freshwater resources. *Hydrological Processes*, 10 (2), 315-333
- Gollamudi, A., 2006, Hydrological and water quality modeling of agricultural fields in Quebec. MSc Thesis, McGill University, Canada
- Guber, A.K., Yakirevich, A.M., Sadeghi, A.M., Pachepski, Y.A., Shelton, D.R., 2009, Uncertainty Evaluation of Coliform Bacteria Removal from Vegetated Filter Strip under Overland Flow Condition. *Journal of Environmental Quality*, 38, 1636–1644

- Hancock, N.H., Crowther, J.M., 1979, A technique for the direct measurement of water storage on a forest canopy, *Journal of Hydrology* 41 (1-2), 105-122
- He, L.-M. Lub, J., Shib, W., 2007, Variability of fecal indicator bacteria in flowing and in southern California: Implications for bacterial TMDL development and implementation. *Water Research*, 41, 3132 – 3140
- Himathongkham, S., Bahari, S., Riemann, H., & Cliver, D., 1999, Survival of *Escherichia coli* O157:H7 and *Salmonella typhimurium* in cow manure and cow manure slurry. *FEMS Microbiology Letters*, 178(2), 251-257
- Hodgson, C.J., Bulmer, N., Chadwick, D.R., Oliver, D.M., Heathwaite, A.L., Fish, R.D., Winter, M., 2009, Establishing relative release kinetics of faecal indicator organisms from different faecal matrices. *Letters in Applied Microbiology* 49, 124–130
- Hussong, D., Damare, J.M., Limpert, R.J., Sladen, W.J.L., Weiner, R.M., Colwell, R.R., 1979, Microbial Impact of Canada Geese (*Branta Canadensis*) and Whistling Swans (*Cygnus columbianus columbianus*) on Aquatic Ecosystems. *Applied and Environmental Microbiology*, 37 (1), 14-20
- Ishii, S., Yan, T., Vu, H., Hansen, D.L., Hicks, R.E. Sadowski, M.J., 2010, Factors controlling long-term survival and growth of naturalized *Escheria coli* populations in temperate field soils. *Microbes and Environments*, 25 (1), 8-14
- Jamieson, R. C., Gordon, R. J., Sharples, K. E., Stratton, G. W., Madani, A., 2002, Movement and persistence of fecal bacteria in agricultural soils and subsurface drainage water: A review. *Canadian Biosystems Engineering / Le Genie Des Biosystems Au Canada*, 44
- Jamieson, R., Gordon, R., Joy, D., & Lee, H., 2004, Assessing microbial pollution of rural surface waters: A review of current watershed scale modeling approaches. *Agricultural Water Management*, 70(1), 1-17
- Jamieson, R., Joy, D. M., Lee, H., Kostaschuk, R., & Gordon, R., 2005a, Transport and deposition of sediment-associated *Escherichia coli* in natural streams. *Water Research*, 39(12), 2665-2675
- Jamieson, R. C., Joy, D. M., Lee, H., Kostaschuk, R., & Gordon, R. J., 2005b, Resuspension of sediment-associated *Escherichia coli* in a natural stream. *Journal of Environmental Quality*, 34(2), 581-589
- Jha, M., Gassman, P.W., Secchi, S., Gu, R., Arnold, J., 2004, Effect of watershed subdivision on swat flow, sediment, and nutrient predictions. *Journal of the American Water Resources Association*, 40 (3), 811-825
- Johnson, K.H., 1977, A predictive method for ground water levels. Master's Thesis, Cornell University, Ithica, N.Y.

- Jolley, L.W., 2005, The Interactions of Indicator bacteria and sediment in Fresh Water Streams. PhD Thesis, Clemson University, USA
- Kadlec, R.H., Pries, J., Mustard, H., 2007, Muskrats (*Ondatra zibethicus*) in treatment wetlands. *Ecological Engineering* 29, 143-153
- King, B.J., Monis, P.T., 2007, Critical Processes affecting *Cryptosporidium* oocyst survival in the environment. *Parasitology*, 137, 309-323
- Krometis, L.-A. H., Patricia N. Drummey, P.N., Gregory W. Characklis, G.W., Sobsey, M.D., 2009, Impact of Microbial Partitioning on Wet Retention Pond Effectiveness. *Journal of Environmental Engineering*, 135 (9), 758-767
- Kuznar, Z.A., Elimelech, M., 2006, *Cryptosporidium* oocyst surface macromolecules significantly hinder oocyst attachment. *Environmental Science and Technology*, 40 (6), 1837-1842
- Lendrum, J.M., 2006, In Situ Environmental Persistence and Differential Survival of Fecally-Derived Indicator Organism and the Protozoan Pathogen, *Cryptosporidium*. PhD Thesis, State University of New York at Albany, USA
- Lévesque, E., Anctil, F.; Van Griensven A.; Beauchamp, N., 2008, Evaluation of streamflow simulation by SWAT model for two small watersheds under snowmelt and rainfall. *Hydrological sciences journal*, 53(5), 961 -976
- Liu, Y., 2007, The Influence of Biofilm and Biofilm EPS on Bacteria Transport and Survival in Porous Media. PhD Thesis, University of Wisconsin-Milwaukee, USA
- Locas, A., Barthe, C., Barbeau, B., Carrière, A., Payment, P., 2007, Virus occurrence in municipal groundwater sources in Quebec, Canada. *Canadian Journal of Microbiology*, 53(6), 688-694
- Lu, Z., Lapen, D., Scott, A., Dang, A., Topp, E., 2005, Identifying host sources of fecal pollution: Diversity of *Escherichia coli* in confined dairy and swine production systems. *Applied and Environmental Microbiology*, 71(10), 5992-5998
- MapTech Inc., 2000, Fecal Coliform TMDL (Total Maximum Load) Development for Upper Blackwater River, Virginia. Report for Virginia Department of Environmental Quality and Virginia Department of Conservation and Recreation
- Marinelli, L., Messier, F., 1993, Space use and the social system of muskrats. *Canadian Journal of Zoology*, 71(5), 869-875.
- Marshall, M. M., Naumovitz, D., Ortega, Y., Sterling, C. R., 1997, waterborne protozoan pathogens. *Clinical Microbiology Reviews*, 10(1), 67-85

- Mawdsley, J.L., Bardgett, R.D., Merry, R.J., Pain, B.F., Theodorou, M.K., 1994, Pathogens in livestock waste, their potential for movement through soil and environmental pollution. *Applied Soil Ecology*, 2, 1-15
- Middleton, J.H., Ambrose, A., 2005, Enumeration and Antibiotic Resistance Patterns of Fecal Indicator Organisms isolated from Migratory Canada Geese (*Branta canadensis*). *Journal of Wildlife Diseases*, 41 (2), 334-341
- Migliaccio, K. W., Srivastava, P., 2007, Hydrologic components of watershed-scale models. *Transactions of the ASABE*, 50(5), 1695-1703
- Migliaccio, K.M., Chaubey, I., 2008, Spatial distributions and Stochastic Parameter Influences on SWAT Flow and Sediment Predictions. *Journal of Hydrologic Engineering*, 13 (4)
- Mishra, A., Benham, B. L., & Mostaghimi, S., 2008, Bacterial transport from agricultural lands fertilized with animal manure. *Water, Air, and Soil Pollution*, 189(1-4), 127-134
- Moghadam, B.Z., 2006, Settling Characteristics of *Cryptosporidium* and *Giardia* under different Environmental Conditions. PhD Thesis, City University of New York, USA
- Mocan, N., 2006, An application of the soil and water assessment tool in modeling pathogen transport through rural watersheds. MSc Thesis, University of Guelph, Canada
- Moore, J.A., Grismer, M.E., Crane, S.R., Miner, J.R., 1983, Modeling dairy waste management systems influence on coliform concentration in runoff. *Transactions of the ASABE*, 26, 1194-1200
- Moore, J. A., Smyth, J. D., Baker, E. S., Miner, J. R., Moffitt, D. C., 1989, Modeling bacteria movement in livestock manure systems. *Transactions of the American Society of Agricultural Engineers*, 32(3), 1049-1053
- Moriarty, E.M., Sinton, L.W., Mackenzie, M.L., Karki, N., Wood, D.R., 2008, A survey of enteric bacteria and protozoans in fresh bovine faeces on New Zealand dairy farms. *Journal of Applied Microbiology*, 105, 2015–2025
- Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007, *Transactions of the ASABE*, 50(3), 885-900
- Muirhead, R. W., Collins, R. P., & Bremer, P. J., 2006a, Numbers and transported state of *Escherichia coli* in runoff direct from fresh cowpats under simulated rainfall. *Letters in Applied Microbiology*, 42(2), 83-87
- Muirhead, R. W., Collins, R. P., & Bremer, P. J., 2006b, Interactions of *Escherichia Coli* and Soil Particles in Runoff. *Applied and Environmental Microbiology*, 72(5), 3406-3411

- Muirhead, R.W., 2009, Soil and faecal material reservoirs of *Escherichia coli* in a grazed pasture. *New Zealand Journal of Agricultural Research*, 52, 1-8
- Nadeau, S. (1995) Muskrat Habitat Use in Quebec. PhD Thesis, McGill University
- Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Srinivasan, R. Williams, J.R., 2004, Soil and Water Assessment Tool Input/Output File Documentation Version 2005. Grassland, Soil and Water Research Laboratory, Agricultural Research Service, Temple, Texas, USA
- Nicholson, F.A., Chambers, B.J., Moore, A., Nicholson, R.J., Hickman, G., 2004, Assessing and managing the risks of pathogen transfer from livestock manures into the food chain. *Water and Environment Journal*, 18, 155–160
- NRVIS, 2002, Provincial Digital Elevation Model Data. [computer file]. The Ontario Ministry of Natural Resources
- Oliver, D.M., Page, T., Heathwaite, A.L., Haygarth, P.M., 2010, Re-shaping models of *E. coli* population dynamics in livestock faeces: Increased bacterial risk to humans? *Environment International*, 36 (1), 1-7
- Oliver, D.M., Haygarth, P.M., Clegg, C.D., Heathwaite, A.L., 2006, Differential *E.coli* Die-Off Patterns Associated with Agricultural Matrices. *Environmental Science & Technology*, 40 (18), 5710-5716
- Oliver, D.M., Clegg, C.D., Heathwaite, A.L., Haygarth, P.M., 2007, Preferential Attachment of *Escherichia Coli* to different Particle Size Fractions an Agricultural Grassland Soil. *Water, Air and Soil Pollution*, 185, 369-375
- OMAFRA, 2009, Fertilizer Recommendation Tables - 2010 Revision. Factsheet, Ontario Ministry of Agriculture, Food and Rural Affairs, Retrieved from <http://www.omafra.gov.on.ca/english/crops/facts/fert-rec-tables-3.htm>
- Ouellet, G., Lapen, D. R., Topp, E., Sawada, M., & Edwards, M., 2007,. A heuristic model to predict earthworm biomass in agroecosystems based on selected management and soil properties. *Applied Soil Ecology*, 39(1), 35-45
- Parajuli, P. B., Mankin, K. R., Barnes, P. L., Green, C. H., 2007, Fecal bacteria source characterization and sensitivity analysis of SWAT 2005. Paper presented at the ASABE Annual Technical Meeting, Technical Papers 6
- Parajuli, P.B., Mankin, K.R., Barnes, P.L., 2009, Source specific fecal bacteria modeling using soil and water assessment tool model. *Bioresource Technology*, 100 (2), 953-963
- Petersen, C.M., Hanadi S. Rifai, H.S., Stein, R., 2009, Bacteria Load Estimator Spreadsheet Tool for Modeling Spatial *Escherichia coli* Loads to an Urban Bayou. *Journal of Environmental Engineering*, 135 (4), 203-217

- Post, D.F., Fimbres, A., Matthias, A.D., Sano, E.E., Accioly, L., Batchily, A.K., Ferreira, L.G., 2000, Predicting Soil Albedo from soil Color and Spectral Reflectance Data. *Soil Science Society of America Journal*, 64, 1027-1034
- Reddy, K. R., Khaleel, R., Overcash, M. R., 1981, Behavior and transport of microbial pathogens and indicator organisms in soils treated with organic wastes. *Journal of Environmental Quality*, 10(3), 255-266
- Robertson, J.B., Edberg, S.C., 1997, Natural protection of spring and well drinking water against surface microbial contamination. I. Hydrogeological parameters. *Critical Reviews in Microbiology*, 23,143-178
- Rozen, Y., Belkin, S., 2001, Survival of enteric bacteria in seawater. *FEMS Microbiology Reviews*, 25(5), 513-529.
- Ruecker, N., Braithwaite, S.L., Topp, E., Edge, T., Lapen, D.R., Wilkes, G., Robertson, W., Medeiros, D., Sensen, C.W., Neumann, N.F., 2007, Tracking Host Sources of *Cryptosporidium* spp. in Raw water for Improved Health Risk Assessment. *Applied and Environmental Microbiology*, 73 (12), 3945-3957
- Sadeghi, A.M., Arnold, J.G., 2002, A SWAT/microbial submodel for predicting pathogen loadings in surface and groundwater at watershed and basin scales. *Total Maximum Daily Load (TMDL) Environmental Regulations, Proceedings of the March 11–13, 2002 Conference, Fort Worth, TX*, 56-63
- Sadeghi, A.M. and Arnold, J.G. (2002) Total Maximum Daily Load (TMDL) Environmental Regulations. 56-63. *ASAE Publication 701Po102*, St.Joseph, Michigan
- Santhi, C., Arnold, J.G., Williams, J.R., Dugas, W.A., Srinivasan, R., Hauck, L.M., 2001, Validation of the SWAT Model on a large River Basin with Point and Nonpoint Sources. *Journal of the American Water Resources Association*, 37 (5), 1169-1188
- Schut, L.W., Wilson, E.A., 1987, The soils of the regional municipality of Ottawa-Carleton. Report No. 58, Ontario Institute of Pedology, Ministry of Agriculture and Food Ontario
- Searcy, K.E., Packman, A.I., Atwill, E.R., Harter, T., 2005, Association of *Cryptosporidium parvum* with suspended particles: Impact on oocyst sedimentation. *Applied and Environmental Microbiology* 71 (2), 1072-1078
- Searcy, K.E., Packman, A.I., Atwill, E.R., Harter, T., 2006a, Deposition of *Cryptosporidium* oocysts in streambeds, *Applied and Environmental Microbiology*, 72 (3), 1810-1816
- Searcy, K.E., Packman, A.I., Atwill, E.R., Harter, T., 2006b, Capture and retention of *Cryptosporidium parvum* oocysts by *Pseudomonas aeruginosa* biofilms. *Applied and Environmental Microbiology*, 72 (9), 6242-6247

- Shoemaker, L., Dai, T., Koenig, J., 2005, TMDL model evaluation and research needs. US Environmental Protection Agency, Retrieved from www.epa.gov/ORD/NRMRL/pubs/600r05149.pdf
- Sidhu, J.P.S., Toze, S.G., 2009, Human pathogens and their indicators in biosolids: A literature review. *Environment International*, 35, 187–201
- Sinclair, A.; Hebb, D. ; Jamieson, R. ; Gordon, R. ; Benedict, K. ; Fuller, K. ; Stratton, G.W. ; Madani, A. , 2009, Growing season surface water loading of fecal indicator organisms within a rural watershed. *Water Research*, 43 (5), 1199-1206
- Sinton, L.W., Braithwaite, R.R., Hall, C.H., Mackenzie, M.L., 2007, Survival of indicator and pathogenic bacteria in bovine feces on pasture. *Applied and Environmental Microbiology*, 73 (24), 7917-7925
- Sjogren, R. E., 1994, Prolonged survival of an environmental *Escherichia coli* in laboratory soil microsomes. *Water, Air, and Soil Pollution*, 75(3-4), 389-403
- Snelling, W.J., Moore, J.E., McKenna, J.P., Lecky, D.M., Dooley, J.S.G., 2006, Bacterial-protozoa interactions; an update on the role these phenomena play towards human illness, *Microbes and Infections*, 8, 578-587
- Soupir, M.L., Mostaghimi, S., Lou, J., 2008, Die off of *E. coli* and Enterococci in Dairy Cowpats. *Transactions of the ASABE*, 51 (6), 1987-1996
- Soupir, M.L., Mostaghimi, S., Dillaha, T., 2010, Attachment of *Escherichia coli* and enterococci to particles in runoff. *Journal of Environmental Quality*, 39 (3), 1019-1027
- Stone, R.P., Hilborn, D., 2000, Universal Soil Loss Equation (USLE). Factsheet, Ministry of Agriculture, Food and Rural Affairs, Retrieved from <http://www.omafra.gov.on.ca/english/engineer/facts/00-001.htm#tab2>
- Sunohara, M., Youssef, M.A., Topp, E., and Lapen, D.R., 2010, Measured Effect of Agricultural Drainage Water Management on Hydrology, Water Quality, and Crop Yield. *9th International Drainage Symposium held jointly with CIGR and CSBE/SCGAB, Québec City Convention Centre, Québec City, QC, Canada, June 13-16, 2010, Paper No. 711P0610e*
- Surbeck, C., Jiang, S., Ahn, J.H., Grant, S., 2006, Flow Fingerprinting Fecal Pollution and Suspended Solids in Stormwater Runoff from an Urban Coastal Watershed. *Environmental Science and Technology*, 40 (14), 4435-4441
- SWET, 2006, Watershed Assessment Model Documentation and User's Manual. Soil and Water Engineering Technology

- Tate, K. W., Atwill, E. R., George, M. R., McDougald, N. K., Larsen, R. E., 2000, *Cryptosporidium parvum* transport from cattle fecal deposits on California rangelands. *Journal of Range Management*, 53(3), 295-299
- Tetra Tech, Inc., US Environmental Protection Agency, 2002, The Loading Simulation Program in C++ (LSPC) Watershed Modeling System-User's Manual, Pasadena, California, USA
- Texier, S., Prigent-Combaret, C., Gourdon, M.H., Poirier, M.A., Faivre, P., Dorioz, J.M., Poulenard, J., Jocteur-Monrozier, L., Moëgne-Loccoz, Y., Trevisan, D. (2008) Persistence of culturable *Escherichia coli* fecal contaminants in dairy alpine grassland soils. *Journal of Environmental Quality*, 37 (6), 2299-2310.
- Tian, Y.Q., Gong, P., Radke, J.D., Scarborough, J., 2002, Spatial and temporal modeling of microbial contaminants on grazing farmlands. *Journal of Environmental Quality*, 31 (3), 860-869.
- Trevisan, D., Vansteelant, J.Y., Dorioz, J.M. (2002) Survival and leaching of fecal bacteria after slurry spreading on mountain hay meadows: Consequences for the management of water contamination risk *Water Research*, 36 (1), 275-283
- Unc, A., Goss, M.J., 2003, Movement of faecal bacteria through the vadose zone. *Water, Air, and Soil Pollution*, 149 (1-4), 327-337
- Unc, A., Goss, M.J., 2004, Transport of bacteria from manure and protection of water resources. *Applied Soil Ecology*, 25, 1-18
- Unc, A., Goss, M.J., 2006, Culturable *Escherichia coli* in soil mixed with two types of manure. *Soil Science Society of America Journal*, 70 (3), 763-769.
- USEPA, 2007, National water Quality Inventory: Report to Congress, 2002 Reporting Cycle, USEPA, Office of Water, Washington, EPA 841-R-07-001, <http://www.epa.gov/305b>
- Van Elsas, J.D., Semenov, A., Costa, R., Trevors, J.T., 2011, Survival of *Escheria coli* in the environment: fundamental and public health aspects. *The ISME Journal*, 5, 173-183
- Van Kessel, J. S., Pachepsky, Y. A., Shelton, D. R., & Karns, J. S., 2007, Survival of *Escherichia coli* in cowpats in pasture and in laboratory conditions. *Journal of Applied Microbiology*, 103(4), 1122-1127
- Van Griensven, A., Meixner, T., Grunwald, S., Bishop, T., Diluzio, M., Srinivasan, R., 2006, A global sensitivity analysis tool for the parameters of multi-variable catchment models. *Journal of Hydrology*, 324 (1-4), 10-23
- Vital, M., Hammes, F., Egli, T., 2008, *Escheria coli* O157 can grow in natural freshwater at low carbon concentrations. *Environmental Microbiology* 10 (9), 2387-2398

- Walker, S., Mostaghimi, S. Dillaha, T., Woeste, F., 1990, Modeling animal waste management practices: Impacts on bacteria levels in runoff from agricultural lands. *Transactions of the American Society of Agricultural Engineers*, 33, 807-817
- Weiskel, P.K, Howes, B.L., Heufelder, G.R. (1996) Coliform Contamination of a Coastal Embayment: Sources and Transport Pathways. *Environmental Science & Technology*, 30 (6), 1872-1881
- Wilkes, G.A., 2004, Utilizing geographic information systems (GIS) for the modelling of warm season soil loss in eastern Ontario, Canada. *Thesis M.A. University of Ottawa*
- Yagow, G. (2001) Fecal Coliform TMDL Mountain Run Watershed Culpeper County, Virginia. Report by Virginia Department of Environmental Quality and Virginia Department of Conservation and Recreation

Appendix A SWAT Input Parameter (Neitsch *et al.* 2004)

	Data	Units	Source	Status
.fig	Watershed configuration			
File.cio	Master watershed file			
.bsn	Basin			
SFTMP	Snowfall temperature	°C	default 1.0, calibration parameter	to obtain
SMTMP	Snow melt base temperature	°C	default 0.5, calibration parameter	to obtain
SMFMX	Melt factor for snow on June 21	mmH2O/ ^o C-day	default 4.5	to obtain
SMFMN	Melt factor for snow on December 21		default 4.5	to obtain
TIMP	Snow pack temperature lag factor		default 1.0	to obtain
SNOCOV MX	Minimum snow water content that corresponds to 100% snow cover (SNOCOVMX)	mmH2O	default 1.00, literature	to obtain
SNO50CO V	Fraction of snow volume represented by SNOCOVMX that correspond to 50% snow cover		default 0.50, literature	to obtain
IPET	Potential evapotranspiration method		Penman Monteith	
ESCO	Soil evaporation compensation factor		Literature, default value 0.95, calibration parameter	to obtain
EPCO	Plant uptake compensation factor		Literature, default value 1, calibration parameter	to obtain
EVLAJ	Leaf Area index at which no evaporation occurs from water surface (depressional areas/potholes)		default value 3	to obtain
FFCB	Initial soil water storage		Result of 2 year equilibrium simulation	to obtain
DEPIMP_B SN	Depth to impervious layer for modeling perched water tables	mm	optional	to obtain
IEVENT	Rainfall runoff routing option		default: daily curve number	to obtain
ICN	Daily curve number calculation method		Calculate CN as function of soil moisture/ as function of plant evapotranspiration	to choose
CNCOEF	Plant ET curve number coefficient		Default 1	to obtain
ICRK	Crackflow code		Default: Do not model crack flow	to obtain
SURLAG	Surface runoff lag coefficient		Default 4, estimate based on sub basin size, calibration parameter	to obtain
ISED_DET	Calculation of daily max. halfhour rain values		Chose option 0: Generate daily value	to obtain
ADJ_PKR	Peak rate adjustment factor for sediment routing		Default 1	to obtain
RTCN	Concentration of nitrogen in rainfall	mg N/L	Default 1	to obtain
CMN	Rate factor for humus mineralization of active organic nutrients (N+P)		Default 0.0003	to obtain
CDN	Denitrification exponential rate coefficient		Default 1.4	to obtain
SDNCO	Denitrification threshold water content		Default 1.10	to obtain
N_UPDIS	Nitrogen uptake distribution parameter		Default 20	to obtain
P_UPDIS	Phosphorus uptake distribution parameter		Default 20.0	to obtain
NPERCO	Nitrate percolation coefficient		Default 0.20	to obtain
PPERCO	Phosphorus percolation coefficient	10 m ³ /mg	Default 10	to obtain
PHOSKD	Phosphorus partitioning coefficient	m ³ /mg	Default 175.0	to obtain
PSP	Phosphorus availability index		Default 0.40	to obtain
RSDCO	Residue decomposition coefficient		Default 0.05	to obtain
ISUBWQ	Subbasin water quality code		Default: do not calculate algae / CBOD loadings	to obtain
WDPQ	Die off factor for persistent bacteria in soil solution at 20°C	[1/day]	Literature	to obtain
WGPQ	Growth factor for persistent bacteria in soil solution at 20°C		Literature	to obtain
WDLPQ	Die off factor for less persistent bacteria in soil solution at 20°C		Literature	to obtain
WGLPQ	Growth factor for less persistent bacteria in soil solution at 20°C		Literature	to obtain
WDPS	Die off factor for persistent bacteria adsorbed to soil particles at 20°C		Literature	to obtain
WGPS	Growth factor for persistent bacteria adsorbed to soil particles at 20°C		Literature	to obtain

	Data	Units	Source	Status
WDLPS	Die off factor for less persistent bacteria adsorbed to soil particles at 20°C		Literature	to obtain
WGLPS	Growth factor for less persistent bacteria adsorbed to soil particles at 20°C		Literature	to obtain
WDPF	Die off factor for persistent bacteria on foliage at 20°C		Literature	to obtain
WGPF	Growth factor for persistent bacteria on foliage at 20°C		Literature	to obtain
WDLPF	Die off factor for less persistent bacteria on foliage at 20°C		Literature	to obtain
WGLPF	Growth factor for less persistent bacteria on foliage at 20°C		Literature	to obtain
BACT_SW F	Fraction of manure applied to land that has active colony forming units.		Literature, default	to obtain
WOF_P	Wash-off fraction for persistent bacteria		Literature	to obtain
WOF_LP	Wash-off fraction for less persistent bacteria		Literature	to obtain
BACTKDQ	Bacteria soil partitioning coefficient	m ³ /Mg	Literature, default	to obtain
BACTMIX	Bacteria percolation coefficient	10 m ³ /Mg	Literature, default	to obtain
THBACT	Temperature adjustment factor for bacteria die-off/ growth		Literature, default	to obtain
BACTMIN LP	Minimum daily bacteria loss for less persistent bacteria	[#cfu/m ²]	Literature, default	to obtain
BACTMIN LP	Minimum daily bacteria loss for persistent bacteria	[#cfu/m ²]	Literature, default	to obtain
WDLPRCH	Die off factor for less persistent bacteria in streams (moving water) at 20°C	[1/day]	Literature	to obtain
WDPRCH	Die off factor for persistent bacteria in streams (moving water) at 20°C	[1/day]	Literature	to obtain
WDLPRES	Die off factor for less persistent bacteria in water bodies (still water) at 20°C	[1/day]	Literature	to obtain
WDPRES	Die off factor for persistent bacteria in water bodies (still water) at 20°C	[1/day]	Literature	to obtain
Reaches				to obtain
IRTE	Channel water routing method		Variable storage or /Muskingum method	to choose
TRNSRCH	Fraction of Transmission losses from main channel that enter deep aquifer (important for arid climate)		Default 0	to obtain
EVRCH	Reach evaporation adjustment factor (important for arid climate)		Default 1	to obtain
IDEG	Channel degradation code		Default 0	to obtain
PRF	Peak rate adjustment factor for sediment routing in the main channel		Default 1	to obtain
SPCON	Linear parameter for calculating sediment reentrained during channel sediment routing		Default 0.0001	to obtain
SPEXP	Exponent parameter for calculating sediment reentrained in channel routing		Default 1.0	to obtain
IWQ	In stream water quality code		Do not model in stream nutrient transformations/ model in stream...	to choose
.sub	Subbasin			
SUB_KM	Area of subbasin	[km ²]	Calculated based on Natural Resources and Values Information System (NRVIS), DEM + Streamlines	existing
SUB_LAT	Latitude of subbasin	[°]	NRVIS, DEM	existing
SUB_ELEV	Elevation of subbasin	[m]	NRVIS, DEM	existing
SNO_SUB	Initial snow water content	Mm H2O	Literature	to obtain
CH_L(I)	Longest tributary channel length in subbasin	[km]	NRVIS Streamlines	to obtain
CH_S(I)	Average slope of tributary channel	[m/m]	NRVIS, DEM	existing

	Data	Units	Source	Status
CH_W(I)	Average width of tributary channel	[m]	Satellite image	existing
CH_K(I)	Effective hydraulic conductivity in tributary channel alluvium	[mm/hr]	Literature	to obtain
CH_N(I)	Manning's roughness coefficient n for tributary channel flow		Literature Chow 1959	to obtain
HRUTOT	Total number of HRU modeled in subbasin (minimum 1)		Based on number of observation points and tributaries	to obtain
.pcp	Precipitation			
Daily				
LATITUDE	Latitude of precipitation recording gage location		Environment Canada Climate Data	existing
LONGITUDE	Latitude of precipitation recording gage location		Environment Canada Climate Data	existing
ELEVATION	Latitude of precipitation recording gage location		Environment Canada Climate Data	existing
YEAR			Environment Canada Climate Data	existing
DATE	Julian Date		Environment Canada Climate Data	existing
PRECIPITATION	Precipitation per day	[mm]	Environment Canada Climate Data, -99 if missing data	existing
.tmp	Temperature			
MAX TEMP	Daily maximum temperature	[°C]	Environment Canada Climate Data, -99 if missing data	existing
MIN TEMP	Daily minimum temperature	[°C]	Environment Canada Climate Data, -99 if missing data	existing
.slr	Solar radiation			
SOL_RAD	Daily total solar radiation	[MJ/m ²]	Agriculture Canada, -99 if missing data	existing
.wnd	Wind			
WND_SP	Daily average wind speed	[m/s]	Environment Canada Climate Data, -99 if missing data	existing
.hmd	Humidity			
RHD	Daily average relative humidity		Environment Canada Climate Data, -99 if missing data	existing
.hru	Hydrological Response Unit			
HRU_FR	Fraction of subbasin contained in HRU	km ² /km ²	NRVIS, DEM + Land use	existing
SLSUBBSN	Average slope length (distance for sheet flow runoff)	m	NRVIS DEM, default 50 (rule: 90 is considered a very long slope length)	to estimate
SLSOIL	Slope length for lateral subsurface flow	m	Default SLSOIL=SLSUBBSN	to obtain
HRU_SLP	Average slope steepness	m/m	NRVIS DEM, GIS sets all HRU to same value if wished it can be varied by soil type and land cover	to obtain
CANMX	Maximum canopy storage	[mm H ₂ O]	Literature	to obtain
OV_N	Manning's roughness coefficient n for overland flow		Literature Chow 1959	to obtain
LAT_TTIME	Lateral flow travel time	day	Default 0	to obtain
POT_FR	Fraction of HRU that drains into pothole		Calculated from land use layer	to obtain
DEP_IMP	Depth to impervious layer in soil profile	[mm]	0 if no perched water table	to obtain
ESCO	Soil Evaporation compensation factor		Default 0.95, calibration parameter	to obtain
EPCO	Plant Uptake Compensation Factor		Default 1, calibration parameter	to obtain
ERORGN	Organic N enrichment ratio for loading with sediment		Default 0	to obtain
ERORGP	Phosphorus enrichment ratio for loading with sediment		Default 0	to obtain
.mgt	Management			
IGRO	Land cover status		No land cover/ land cover growing, land use and time of the year	existing
PLANT_ID	Land cover identification number		SWAT database	existing
LAI_INIT	Initial leaf area index		If land cover growing at begin of simulation	not needed
BIO_INIT	Initial dry weight biomass	kg/ha	If land cover growing at begin of simulation	not needed
PHU_PLT	Total number of heat units needed to bring plant to maturity		If land cover growing at begin of simulation	not needed
BIOMIX	Biological mixing activity		Optional, Default 0.2, calibration parameter	

	Data	Units	Source	Status
CN2	Initial SCS runoff curve number for moisture condition II		Literature (Neitsch <i>et al.</i> , 2004))	to obtain
USLE_P	USLE equation support practice factor		Literature	to obtain
BIO_MIN	Minimum plant biomass for grazing	[kg/ha]	Literature, no grazing unless biomass at or above BIO_MIN	to obtain
URBLU	Type of urban area		Satellite image	existing
DDRAIN	Depth to subsurface drain	[mm]	OMAFRA, 90 mm common	to obtain
TDRAIN	Time to drain soil to field capacity	hours	Literature	to obtain
GDRAIN	Drain tile time lag (Time between water from soil into drain and release into reach)	hours	Calibration parameter	to obtain
NROT	Number of years of crop rotation		Land use, OMAFRA	to obtain
MONTH	of operation		OMAFRA	to obtain
DAY	of operation		OMAFRA	to obtain
MGT_OP	Type of management operation		OMAFRA	to obtain
PLANT_ID	Plant identification number		Land use, SWAT Crop database	existing
CURYR_M AT	Current age of trees	years	to estimate	to obtain
HEAT UNITS	Total heat unit for plant to reach maturity		can be calculated with daily mean temperatures and base temperature of crop in question	to obtain
CNOP	SCS runoff curve number for moisture condition II		Optional, literature, calibration parameter	to obtain
FERT_ID	Type of Fertilizer / manure		OMAFRA	to obtain
FRT_KG	Amount of fertilizer applied	[kg/ha]	OMAFRA	to obtain
FRT_SURF ACE	Fraction of fertilizer applied to top 10 mm of soil		Literature, default	to obtain
MONTH DAY	Date of harvest/kill operation (or Fraction of total base zero heat units at which operation takes place)		OMAFRA	to obtain
MONTH DAY	Date of tillage operation		OMAFRA	to obtain
Till ID	Type of Tillage		OMAFRA	to obtain
MONTH DAY	Date of harvest operation		OMAFRA	to obtain
MONTH DAY	Date of kill operation		OMAFRA	to obtain
MONTH DAY	Date of grazing operation		OMAFRA	to obtain
GRZ_DAY S	Length of grazing operation	[days]	OMAFRA	to obtain
MANURE_ ID	Manure identification		SWAT Fertilizer Database	existing
BIO_EAT	Dry weight of biomass consumed daily	[kg/ha*day]	To estimate based on livestock density	to obtain
MANURE_ KG	Dry weight of manure deposited daily	[kg/ha*day]	To estimate based on livestock density	to obtain
.wus	Consumptive water use			
WUPND(m on)	Average daily water removal from the pond for the month	10 ⁴ m ³ /day	Optional, to estimate based on number of habitans and livestock operations	to obtain
WURCH(m on)	Average daily water removal from reach for the month	10 ⁴ m ³ /day	Optional, to estimate based on number of habitans and livestock operations	to obtain
WUSHAL(mon)	Average daily water removal from shallow aquifer for the month	10 ⁴ m ³ /day	Optional, to estimate based on number of habitans and livestock operations	to obtain
WUDEEP(mon)	Average daily water removal from deep aquifer for the month	10 ⁴ m ³ /day	Optional, to estimate based on number of habitans and livestock operations	to obtain
.sol	Soil			
HYGRP	Soil hydrological group		USDA classification, Infiltration rate, permeability, shrink-swell potential, depth to bedrock, CANSIS	existing
SOL_ZMX	Maximum rooting depth of soil profile	[mm]	CANSIS, default	existing
SOL_CRK	Potential or max. crack volume of the soil profile expressed as fraction of the total soil volume		Optional, if vertisols dominant	???
SOL_Z (layer #)	Depth of soil	[mm]	CANSIS	existing
SOL_BD (layer #)	Moist Bulk Density	[g/cm ³]	CANSIS + Literature, Ouellet <i>et al.</i> 2007	existing

	Data	Units	Source	Status
SOL_AWC (layer #)	Available water capacity of the soil layer	[mm H ₂ O/mm soil]	CANSIS	existing
SOL_K(layer #)	Saturated hydraulic conductivity	[mm/hr]	CANSIS	existing
SOL_CBN(layer #)	Organic carbon content	[% soil weight]	CANSIS	existing
CLAY (layer #)	Clay content	[% soil weight]	CANSIS	existing
SILT (layer #)	Silt content	[% soil weight]	CANSIS	existing
SAND (layer #)	Sand content	[% soil weight]	CANSIS	existing
ROCK (layer #)	Rock fragment content	[% soil weight]	CANSIS	existing
SOL_ALB (layer #)	Moist soil albedo		To estimate based on soil colour	to obtain
USLE_K (layer #)	USLE soil erodibility factor		Literature Wichmeier & Smith (1978), based on soil texture classes and organic matter contents	to obtain
.chm.	Chemical soil characteristics		optional	
.gw	Groundwater			
SHALLST	Initial depth of water in shallow aquifer	[mm H ₂ O]	2 year equilibrium	to obtain
DEEPST	Initial depth of water in deep aquifer	[mm H ₂ O]	2 year equilibrium	to obtain
GW_DELAY	Groundwater delay time (time until water in soil enters shallow aquifer)	[days]	Calculation (Johnson 1977)	to obtain
ALPHA_BF	Baseflow alpha factor	[days]	Calculation ($\alpha = 2.3 / \text{Number of baseflow days}$), Discharge and waterlevel data, AgCan	to obtain
GWQMN	Threshold depth of water in shallow aquifer required for return flow to occur	[mm H ₂ O]	Estimate based on depth of river reach and depth of shallow aquifer, calibration parameter	to obtain
GW_REVA P	Groundwater re-evaporation coefficient		Depend on type of plant cover	to obtain
REVAP_M N	Threshold depth of water in shallow aquifer for re-evaporation or percolation to the deep aquifer to occur	[mm H ₂ O]	Calibration parameter	to obtain
RCHRG_D P	Deep aquifer percolation fraction		Between 0.0-1.0	to obtain
.rte	Physical characteristics of main channel			
CH_W(2)	Average width of main channel at top of bank	[m]	Satellite image	existing
CH_D	Depth of main channel from top of bank to bottom	[m]	Measurements	to obtain
CH_S(2)	Average slope of main channel	[m/m]	NRVIS DEM	existing
CH_L(2)	Length of main channel	[km]	NRVIS Streamlines	existing
CH_N(2)	Manning's n value for main channel		Literature Chow (1959)	to obtain
CH_K(2)	Effective hydraulic conductivity in main channel alluvium	[mm/hr]	Literature, Table in Neitsch <i>et al.</i> 2004	to obtain
CH_EROD	Channel erodibility factor		To estimate based on channel changes seen on aerial photographs	to obtain
CH_COV	Channel cover factor		Ratio of degradation from a channel with a specified vegetative cover to the corresponding degradation from a channel with no vegetative cover (vegetative cover \uparrow causes stream velocity \downarrow and erosive power \downarrow) Satellite Images	to obtain
ALPHA_BNK	Baseflow alpha factor for river bank storage	[days]	If no value entered assumed to be same as alpha factor for groundwater ALPHA_BF	to obtain
.wwq	general water quality for processes modeled uniformly over entire watershed		Only for in stream nutrient cycling modeling	
.swq	Stream water quality for specific reaches		Only for in stream nutrient cycling modeling	
.pnd	Ponds and wetlands			
PND_FR	Fraction of sub basin that drains into ponds		To calculate based on sub basin and pond location	to obtain

	Data	Units	Source	Status
PND_PSA	Surface area when filled to principal spillway	ha	Refers to normal pond storage volume, estimate based on satellite image	to obtain
PND_PVOL	Volume of water stored in ponds when filled to principal spillway	10 ⁴ m ³ H ₂ O	To estimate based on depth and surface of pond	to obtain
PND_ESA	Surface area when filled to emergency spillway	ha	Refers to maximum 1 pond storage volume	to obtain
PND_EVOL	Volume of water stored in ponds when filled to emergency spillway	10 ⁴ m ³ H ₂ O	Refers to maximum pond storage volume	to obtain
PND_VOL	Initial volume of water in ponds	10 ⁴ m ³ H ₂ O	2 year equilibrium period	to obtain
PND_SED	Initial sediment concentration in pond water	mg/l	Literature	to obtain
PND_K	Hydraulic Conductivity through bottom of ponds	mm/hr	To estimate based on soil properties	to obtain
IFLOD1	Beginning month of non-flood season		To define based on wetland characteristics	to obtain
IFLOD2	Ending month of non-flood season		To define based on wetland characteristics	to obtain
NDTARG	Number of days needed to reach target storage from current pond storage		Default 15 days	to obtain
PSETLP1	Phosphorus settling rate in pond for months IPND1 through IPND2	m/year	Literature	to obtain
PSETLP2	Phosphorus settling rate in pond for months other then IPND1 - IPND2	m/year	Literature	to obtain
NSETLP1	Nitrogen settling rate in pond for months IPND1 through IPND2	m/year	Literature	to obtain
NSETLP2	Nitrogen settling rate in pond for months other then IPND1 - IPND2	m/year	Literature	to obtain
CHLAP	Chlorophyll a production coefficient for ponds		Default 1	to obtain
SECCIP	Water clarity coefficient for ponds		Default 1	to obtain
PND_NO3	Initial concentration of NO3-N in pond	mg N/l	2 year equilibrium	to obtain
PND_SOLP	Initial concentration of soluble P in pond	mg P/l	2 year equilibrium	to obtain
PND_ORGN	Initial concentration of organic N in pond	mg N/l	2 year equilibrium	to obtain
PND_ORGP	Initial concentration of organic P in pond	mg P/l	2 year equilibrium	to obtain
IPND1	Beginning month of mid-year nutrient settling season		To define based on wetland characteristics	to obtain
IPND2	Ending month of mid-year nutrient settling season		To define based on wetland characteristics	to obtain
WET_FR	Fraction of subbasin area that drains into wetland		To calculate based on sub basin and pond location	to obtain
WET_NSA	Surface area at normal waterlevel	ha	To estimate based on satellite image	to obtain
WET_NVOL	Volume of water stored at normal waterlevel	10 ⁴ m ³ H ₂ O	to estimate based on depth and surface area	to obtain
WET_MXSA	Surface area at maximum water level	ha	To estimate based on satellite image	to obtain
WET_MXVOL	Volume of water stored at maximum waterlevel	10 ⁴ m ³ H ₂ O	Refers to maximum pond storage volume, to estimate based on depth and surface area	to obtain
WET_VOL	Initial volume of water in wetland	10 ⁴ m ³ H ₂ O	2 year equilibrium period	to obtain
WET_SED	Initial sediment concentration in wetland water	mg/l	2 year equilibrium period	to obtain
WET_N_SED	Equilibrium sediment concentration in wetland water	mg/l		to obtain
WET_K	Hydraulic Conductivity through bottom of wetland	mm/hr	To estimate based on local soil properties	to obtain
PSETLW1	Phosphorus settling rate in wetland for months IPND1 through IPND2	m/year	Literature	to obtain
PSETLW2	Phosphorus settling rate in wetland for months other then IPND1 - IPND2	m/year	Literature	to obtain
NSETLW1	Nitrogen settling rate in wetland for months IPND1 through IPND2	m/year	Literature	to obtain
NSETLW2	Nitrogen settling rate in wetland for months other then IPND1 - IPND2	m/year	Literature	to obtain

	Data	Units	Source	Status
CHLAW	Chlorophyll a production coefficient for wetland		Default 1	to obtain
SECCIW	Water clarity coefficient for wetland		Default 1	to obtain
WET_NO3	Initial concentration of NO3-N in wetland	mg N/l	2 year equilibrium	to obtain
WET_SOL P	Initial concentration of soluble P in wetland	mg P/l	2 year equilibrium	to obtain
WET_ORG N	Initial concentration of organic N in wetland	mg N/l	2 year equilibrium	to obtain
WET_ORG P	Initial concentration of organic P in wetland	mg P/l	2 year equilibrium	to obtain
IPND1	Beginning month of mid-year nutrient settling season		To define based on wetland characteristics	to obtain
IPND2	Ending month of mid-year nutrient settling season		To define based on wetland characteristics	to obtain

Appendix B Soil Properties

Soil	Layer	Hydro Group	Soil Depth (mm)	Depth (mm)	Bulk Density (g/cm ³)	Available Water Capacity (mm/mm)	Saturated Hydraulic Conductivity (mm/h)	Organic Carbon Content (%weight)	Clay (%weight)	Silt (%weight)	Sand (%weight)	Rock (%weight)	Albedo	USLE_K
ACHIGAN	1	B	1000	220	0.9	0.29	53.31	6.3	12	11	77	0	0.05	0.22
	2			450	1.39	0.06	93.64	0.3	1	2	97	0	0.14	0.22
	3			700	1.47	0.07	63.67	0.3	3	4	93	0	0.143	0.22
	4			1000	1.49	0.05	78.17	0.1	1	5	94	0	0.154	0.22
ALLENDALEC	1	C	1000	270	1.32	0.13	43.83	1.5	4	6	90	0	0.03	0.42
	2			410	1.39	0.09	63.98	0.2	4	9	87	0	0.154	0.42
	3			550	1.39	0.16	11.97	0.2	15	10	75	0	0.154	0.42
	4			1000	1.49	0.02	1.97	0.2	54	34	12	0	0.154	0.42
CARP	1	C	1150	280	1.12	0.29	5.68	3.54	26	46	28	0	0.083	0.40
	2			430	1.39	0.17	2.88	0.6	31	48	21	0	0.143	0.40
	3			700	1.39	0.17	2.87	0.3	31	49	20	0	0.143	0.40
	4			950	1.49	0.36	19.32	0.3	33	50	17	0	0.154	0.40
	5			1150	1.49	0.11	2.14	0.2	34	48	18	0	0.154	0.40
CHENEYF	1	B	1110	190	1.2	0.31	54.23	10	10	24	66	0	0.03	0.40
	2			260	1.41	0.08	68.92	1	3	8	89	0	0.03	0.40
	3			310	1.39	0.11	55.49	0.9	5	10	85	0	0.03	0.40
	4			510	1.47	0.06	71.94	0.5	2	2	96	0	0.03	0.40
	5			760	1.47	0.1	44.59	0.3	6	4	90	0	0.03	0.40
	6			1110	1.49	0.05	78.77	0	1	1	98	0	0.03	0.40
FARMINGTONN	1	B	500	210	1.1	0.29	19.69	3.7	12	44	44	0	0.083	0.62
	2			380	1.39	0.15	30.14	3.1	6	45	49	0	0.143	0.62
	3			500	1.61	0.11	19.79	1.3	7	36	57	0	0.143	0.62
GRENVILLES	1	B	1000	370	1.23	0.2	37.65	2.4	8	31	61	4	0.05	0.27
	2			530	1.39	0.17	28.43	1.1	8	33	59	5	0.083	0.27
	3			700	1.61	0.13	15.68	0.6	7	48	45	21	0.143	0.27
	4			1000	2	0.13	15.68	0.6	7	48	45	0	0.143	0.27
KARSP	1	A	1000	200	1.46	0.12	35.37	0.05	6	31	63	0	0.083	0.37
	2			320	1.39	0.14	37.83	0.05	7	25	68	0	0.143	0.37
	3			1000	1.49	0.05	78.17	0.05	1	7	92	0	0.083	0.37

Soil	Layer	Hydro Group	Soil Depth (mm)	Depth (mm)	Bulk Density (g/cm ³)	Available Water Capacity (mm/mm)	Saturated Hydraulic Conductivity (mm/h)	Organic Carbon Content (%weight)	Clay (%weight)	Silt (%weight)	Sand (%weight)	Rock (%weight)	Albedo	USLE_K
MANOTICKSH	1	B	1000	260	1.25	0.14	58.71	2.2	6	15	79	0	0.143	0.32
	2			420	1.39	0.11	47.47	1	6	14	80	0	0.143	0.32
	3			660	1.49	0.08	51.29	0.3	4	15	81	0	0.154	0.32
	4			1000	1.49	0.03	2.03	0.3	52	29	19	0	0.154	0.32
MATILDAZ	1	B	1000	220	1.26	0.23	13.83	2.1	14	39	47	20	0.143	0.40
	2			350	1.39	0.18	23.61	0.4	8	43	49	25	0.143	0.40
	3			1000	1.61	0.12	14.6	0.3	8	44	48	25	0.143	0.40
MORRISBURG	1	C	1000	150	1.16	0.28	10.23	3.1	19	37	44	15	0.083	0.43
	2			280	1.39	0.19	8.9	3.7	15	40	45	20	0.083	0.43
	3			500	1.47	0.16	8.34	0.6	16	35	49	25	0.083	0.43
	4			1000	1.61	0.11	7.02	4	13	38	49	30	0.154	0.43
MOUNTAINS	1	B	1000	190	1.34	0.13	46.22	1.3	7	13	80	0	0.083	0.32
	2			280	1.39	0.11	47.87	0.6	6	14	80	0	0.154	0.32
	3			460	1.39	0.1	54.74	0.2	5	14	81	0	0.154	0.32
	4			660	1.49	0.07	2.16	0.1	44	32	24	0	0.154	0.32
	5			1000	1.49	0.04	1.93	0.1	71	26	3	0	0.154	0.32
NORTHGOWER	1	C	1000	250	1.08	0.31	13.75	3.9	16	41	43	25	0.05	0.45
	2			370	1.47	0.16	7.52	3.3	15	40	45	20	0.143	0.45
	3			1000	1.49	0.2	2.9	0.5	17	63	20	30	0.143	0.45
ORGANIC	1	C	1490	990	0.9	0.2	34.55	10	60	17	23	0	0.05	0.00
	2			1490	1.47	0.08	2.1	0.6	60	17	23	0	0.05	0.00
OSGOODES	1	C	1000	200	1.32	0.23	8.32	1.5	17	42	41	0	0.083	0.40
	2			400	1.39	0.19	5.47	0.3	21	40	39	0	0.154	0.40
	3			700	1.39	0.19	4.54	0.1	23	42	35	0	0.143	0.40
	4			1000	1.49	0.16	3.24	0.1	23	46	31	0	0.143	0.40
OSNABRUCK	1	C	1000	210	1.12	0.29	13.93	3.5	18	31	51	13	0.028	0.37
	2			320	1.47	0.15	16.55	0.9	13	19	68	63	0.154	0.37
	3			1000	1.61	0.13	3.49	0.1	19	43	38	16	0.154	0.37
RUBICON	1	B	900	120	1.16	0.14	76.85	3.1	5	10	85	0	0.083	0.62
	2			300	1.39	0.08	69.27	0.8	3	8	89	0	0.165	0.62
	3			500	1.47	0.09	49.53	0.2	5	7	88	0	0.083	0.62
	4			900	1.49	0.06	68.87	0.2	2	6	92	0	0.143	0.62

Soil	Layer	Hydro Group	Soil Depth (mm)	Depth (mm)	Bulk Density g/cm3	Available Water Capacity (mm/mm)	Saturated Hydraulic Conductivity (mm/h)	Organic Carbon Content (%weight)	Clay (%weight)	Silt (%weight)	Sand (%weight)	Rock (%weight)	Albedo	USLE_K
STSAMUEL	1	B	1000	210	1.2	0.19	43.47	2.7	19	26	55	0	0.143	0.15
	2			390	1.47	0.06	70.51	0.7	2	7	91	0	0.05	0.15
	3			520	1.47	0.05	81.34	0.2	1	2	97	0	0.083	0.15
	4			690	1.49	0.07	61.55	0.1	3	4	93	0	0.154	0.02
	5			1000	1.49	0.05	78.36	0.1	1	3	96	0	0.154	0.15
UPLANDS	1	A	1050	200	1.2	0.11	95.37	2.7	3	8	89	0	0.05	0.23
	2			350	1.39	0.05	93.2	0.5	1	2	97	0	0.143	0.23
	3			650	1.39	0.05	93.75	0.3	1	1	98	0	0.143	0.23
	4			800	1.47	0.05	78.57	1.5	1	5	94	0	0.143	0.23
	5			1050	1.49	0.05	78.45	0.2	1	1	98	0	0.143	0.23
WOLFORD	1	B	1000	300	1.23	0.22	27.58	2.4	9	40	51	0	0.05	0.58
	2			600	1.39	0.18	17.34	0.4	11	37	52	0	0.083	0.58
	3			800	1.39	0.19	13.71	0.3	13	36	51	0	0.154	0.58
	4			1000	1.61	0.13	9.22	0.2	12	38	50	0	0.154	0.58