Investigating Phosphorus Reduction Strategies in the Wigle Creek Watershed Using Hydrologic and Water Quality Modelling

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Abstract

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In recent decades, the quality of the Great Lakes ecosystems has deteriorated due to non-point source pollution caused by agricultural activity. As agricultural activity continues, as do the issues that plague the water quality of the Great Lakes. Though it is easy to determine sources of pollution (point sources), it is difficult to assess the pollution from agricultural activities (non-point sources); modeling, however, can provide reasonable assessment of such pollution.

The Soil & Water Assessment Tool (SWAT), a continuous simulation model, was selected to model hydrology of the Wigle Creek Watershed. Initial setup of the model was to implement currently practiced Best Management Practices (BMP), and to calibrate it with the available data. The Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and Coefficient of Determination (R^2) statistics were used to evaluate the model's performance in representing the measured values for flow, sediment yield, and phosphorus yield. Calibration and validation were performed on a daily time step, for the data available between the start of 2016 to mid-2017, as a result of an insufficient availability of data.

Flow calibration of the model was found to be satisfactory, with an NSE of 0.52, a PBIAS of 6.71%, and a R^2 of 0.56. Calibration of sediment yield did not provide satisfactory results for NSE and R^2, with values of 0.3 and 0.31 respectively. PBIAS, on the other hand, was satisfactory at -15.94%. Additionally, sediment concentration was tested based on the calibration results and it did not provide satisfactory results for NSE and R^2; however, the value for concentration PBIAS was much better when compared to the sediment yield PBIAS. Phosphorus calibration was found to be rather poor in all statistical parameters, especially overestimating the output of phosphorus in the watershed. The NSE was calculated to be -0.08, PBIAS as 82.57%, with an R^2 of 0.17. These results imply that the calibrated model was not an accurate estimator for sediment and phosphorus in the Wigle Creek watershed; availability of limited data could have resulted in such outcome.

To determine the effectiveness of the currently implemented BMPs and scenarios, a no BMP scenario was created for comparison. BMPs were then added onto the "No BMP" scenario to examine the reduction from a given scenario.

The best scenario, though not practical, was the retiring of agricultural land to either forest or pasture. The average annual reduction in phosphorus obtained was 74% and 63% for the forest and pasture options, respectively. The effects of minimum tillage and no-till, when applied throughout the watershed, were also included as scenarios. The no-till scenario provided a higher (53%) average annual reduction as compared to minimum-till (36%). Vegetative filter strips were also explored as a BMP in this modelling exercise. The Vegetative filter strips were applied along the edge of a field, based on growing area, in the entire watershed and had a significant effect on the reduction of phosphorus (38%). Cover crops were also evaluated as a BMP, when planted after harvesting winter wheat. Cover crops showed little reduction in phosphorus yield (3%) at the watershed outlet.

Résumé

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Au cours des dernières décennies, la qualité des écosystèmes des Grands Lacs s'est détériorée en raison de la pollution de source non ponctuelle causée par l'activité agricole. Alors que l'activité agricole se poursuit, de même que les problèmes qui nuisent à la qualité de l'eau des Grands Lacs. Bien qu'il soit facile de déterminer les sources de pollution (sources ponctuelles), il est difficile d'évaluer la pollution provenant des activités agricoles (sources diffuses).

L'outil d'évaluation « Soil & Water Assessment Tool » (SWAT), un modèle de simulation continue, a été sélectionné pour modéliser le bassin versant de « Wigle Creek ». La configuration initiale du modèle consistait à mettre en œuvre les BMP utilisés et à les calibrer avec les données disponibles. Les statistiques de l'efficacité de Nash-Sutcliffe (NSE), du pourcentage de biais (PBIAS), et du coefficient de détermination (R^2) ont été utilisées pour évaluer la performance du modèle dans la représentation des valeurs mesurées pour le débit, le rendement en sédiments, et le rendement en phosphore. L'étalonnage et la validation ont été effectués quotidiennement, pour les données disponibles entre le début de 2016 et le milieu de 2017, en raison d'une quantité insuffisante de données.

L'étalonnage du modèle a été jugée satisfaisante, avec un NSE de 0.52, un PBIAS de 6.71% et un R^2 de 0.56. L'étalonnage du rendement en sédiments n'a pas donné de résultats satisfaisants pour NSE et R^2, avec des valeurs respectives de 0.3 et 0.31. PBIAS était satisfaisant à -15.94%. La concentration des sédiments a été vérifiée sur la base des résultats d'étalonnage et a donné de pires résultats pour NSE et R^2, mais la valeur du concentration PBIAS était bien meilleure par rapport au rendement PBIAS. La calibration du phosphore s'est révélée plutôt médiocre pour tous les paramètres statistiques, en particulier la surestimation de la production de phosphore dans le bassin versant. Le NSE a été calculé à -0.08, le PBIAS à 82.57%, avec un R^2 de 0.17. Ces résultats ont démontré que le modèle calibré n'était pas un estimateur précis pour les sédiments et le phosphore du bassin versant de « Wigle Creek ».

Pour déterminer l'efficacité des BMP actuellement mis en œuvre et des scénarios alternatifs, un scénario sans BMP a été créé à des fins de comparaison. Les BMP ont ensuite été ajoutés au scénario « No BMP » pour examiner la réduction par rapport à un scénario donné.

Le meilleur scénario, bien que non pratique, était de retirer les terres agricoles de la forêt ou des pâturages. La réduction de phosphore annuelle moyenne obtenue était de 74% et 63% pour les options de forêt et de pâturage, respectivement. Les effets de labourage minimum et de la culture sans labour lorsqu'il était appliqué dans tout le bassin versant étaient inclus comme scénarios. Le scénario sans labour prévoyait une réduction annuelle moyenne plus élevée (53%) par rapport à labourage minimum (36%). Des bandes filtrantes végétales ont également été explorées en tant que BMP dans cet exercice de modélisation. Les bandes filtrantes végétales ont été appliquées le long d'un champ, en fonction de la superficie cultivée, dans l'ensemble du bassin versant et ont eu un effet significatif sur la réduction de phosphore (38%). Les cultures de couverture ont été évaluées en tant que BMP lorsqu'elles ont été plantées après la récolte du blé d'hiver. Les cultures de couverture après le blé d'hiver ont démontré une très faible réduction (3%) du rendement en phosphore à la sortie du bassin versant.

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Contributions of Authors

The author of this thesis was responsible for the model setup, calibration and validation, and analysis of the data. Dr. Shiv Prasher is the thesis supervisor and gave guidance on model use, and scientific advice, as well as reviewing the thesis. Dr. Prasad Daggupati is the thesis co-supervisor and provided guidance, as well as technical assistance for model use.

Dr. Ramesh Rudra at the School of Engineering, University of Guelph, also provided scientific advice, as well as reviewing the thesis. Dr. Rituraj Shukla, a post-doctoral at the School of Engineering, University of Guelph, performed initial processing of the data prior to use and was also involved in reviewing the thesis.

Dr. Ramesh Rudra and Dr. Prasad Daggupati both contributed the introduction to this thesis. Dr. Rituraj Shukla contributed in the creation of Table 2, section 3.3, and section 3.4.

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List of Abbreviations

AnnAGNPS	Annualized Agricultural Non-Point Source
ANSWERS	Areal Non-point Source Watershed Environment Response Simulation
APEX	Agricultural Policy / Environmental eXtender
BMP	Best Management Practices
DEM	Digital Elevation Model
EPA	Environmental Protection Agency
EPIC	Environmental Policy Integrated Climate
ERCA	Essex Region Conservation Authority
GLASI	Great Lakes Agricultural Stewardship Initiative
HRU	Hydrologic Response Unit
HSPF	Hydrological Simulation Program – Fortran
K	Potassium
N	Nitrogen
NSE	Nash-Sutcliffe Efficiency
P	Phosphorus
PBIAS	Percent Bias
R^2	Coefficient of Determination
SCS	Soil Conservation Service
SUFI-2	Sequential Uncertainty Fitting
SWAT	Soil and Water Assessment Tool
SWAT-CUP	SWAT Calibration and Uncertainty Procedures
WARMF	Watershed Analysis Risk Management Framework
USDA	United States Department of Agriculture

Chapter 1: Introduction

Water quality is constantly deteriorating in our current environment. Industry and other human activities that contribute to the pollution of water quality are categorized as point source or non-point source. A point source is defined as a clearly identifiable point of discharge, such as a conduit. Non-point source pollution comes from many dispersed sources in a much broader area. In comparison to point sources, non-point source pollution is much more difficult to take actions for controlling runoff and the associated pollutants.

The Great Lakes, holding one-fifth of the fresh water on Earth, are an unparalleled treasure for Ontario. Lake Erie is the one of the largest lakes in the world, and "provides habitat for economically, ecologically, and culturally important biota", as well as providing for many people living around it (Watson et al., 2016). In the last few decades, the Great Lakes health is under serious threat due to increased levels of harmful pollutants, especially rising levels of phosphorus. During the 1960's, high phosphorus levels caused blue-green algae (cyanobacteria) growth in Lake Erie, making it a major environmental issue. The Canadian and US governments co-operated to develop a Great Lakes Cleanup Agreement in 1972, which helped to reduce algae levels in Lake Erie. The algae levels began to resurface again in the late 1990's. According to USA Environmental Protection Agency (EPA), in 2011 the algae levels in Lake Erie were 50 times above the World Health Organization limit for safe bodily contact and, in the same year, the levels were 1200 times higher than the limit of safe drinking water. During August 2014, toxic algae resulted in shutting down the Toledo's Drinking Water Treatment Plant for several days, and the Summer of 2015 produced the largest algae bloom in Lake Erie in 100 years.

To reduce the algae problems, Canada and US amended the Great Lakes Cleanup Agreement (signed in 1972) and announced a goal to reduce phosphorus levels by 40 percent by 2025 and an interim reduction goal of 20 percent by 2020. The targets were based upon the phosphorus levels in 2008.

Therefore, there is an urgent need to develop remedial strategies for reducing phosphorus loading in the Lake. Earlier widespread algal blooms (in the 1960's) in the Great Lakes were mainly due to point sources, that had been largely addressed by reductions in point source inputs of phosphorus into the Great Lakes. Recent studies have indicated that the phosphorus loadings in recent decades (i.e., after 1990's) are mainly due to runoff, primarily from agricultural areas. To reduce phosphorus losses from agricultural landscape, the Great Lakes Agricultural Stewardship Initiative (GLASI) with Priority Watersheds project is making valiant efforts in selected watersheds to implement Best Management Practices (BMPs) for reducing nutrient losses at the edge-of-field soil and in the receiving water bodies, with a major emphasis on phosphorus. Agricultural producers in the selected watersheds are offered financial support (cost-share) to implement BMPs that will not only be beneficial to the participating farm operations but will also help establish critical information about achieving measurable improvements in water quality through stewardship. As a part of this initiative, various monitoring stations at several locations have been established in these watersheds to monitor water quantity and quality parameters.

The Wigle Creek watershed, one of the priority watersheds under the GLASI project was chosen to be evaluated. The watershed consists of a very flat topography, with a total area of 13.76 km^2. It is located just west/north-west of the city of Kingsville, depositing directly into Lake Erie with phosphorus concentrations in the streams being known to be very high due to the watershed being dominated by agricultural activity, primarily cash-cropping. Extensive tile drainage is present in the watershed, along with the soils consisting mostly of clay. Only the western branch of the Wigle Creek watershed was evaluated in this study.

1.1 Project Objectives

The main objective of this research was to identify the critical areas in the watershed contributing to sediment and phosphorus loading, and to identify the most effective BMPs in alleviating pollution in Great Lakes. The specific objectives were as follows:

1. Set-up a baseline or current condition model, calibrate and validate the model for the Wigle Creek watershed.
    a. Calibrate SWAT model using high resolution spatial and hydro-meteorological datasets and monitored data at the watershed outlet and investigate the effectiveness of currently implemented BMPs in the watershed at the watershed outlet.
2. Perform a scenario analysis by simulating different possible BMPs and evaluate their effectiveness to identify BMP(s) for pollution control.

Chapter 2: Literature Review

2.1 Hydrologic Models

Understanding the natural processes found in watersheds leading to varying issues in water quantity and water quality has been a challenge for scientists and engineers (Borah and Bera, 2004). As a result, mathematical models were developed as useful analysis tools that provide a means of simplifying and simulating complex natural processes to further our comprehension and to find solutions (Borah and Bera, 2004).

Hydrologic and water quality models have been increasingly used to evaluate the quantity and quality of land and water resources and must be calibrated and validated prior to applying them in research (Bicknell et al., 2001; Moriasi et al., 2012). There are many different models to choose from with differing input requirements, as well as varying approaches, equations, and capabilities when simulating data.

As such, a literature review of some commonly used watershed models was done. This includes models such as the Annualized Agricultural Non-Point Source model (AnnAGNPS) (Bosch et al., 1998); the Areal Non-Point Source Watershed Environment Response Simulation model (ANSWERS) (Beasley et al., 1980; Bouraoui and Dillaha, 1996); the Agricultural Policy/Environmental eXtender model (APEX) (Gassman et al., 2009; Gassman et al., 2010; Wang et al., 2012); the Hydrological Simulation Program – Fortran model (HSPF) (Bicknell et al., 2001); the MIKE SHE model (Refsgaard and Storm, 1995); the Watershed Analysis Risk Management Framework model (WARMF) (Herr and Chen, 2012); and the Soil and Water Assessment Tool model (SWAT) (Arnold et al., 1998).

2.1.1 AnnAGNPS

AGNPS was initially developed as a single-event model, which was later recognized as a serious model limitation. Further development in the early 1990's was done by a team of ARS and NRCS scientists, with the Annualized Agricultural Non-Point Source (AnnAGNPS) (Bosch et al., 1998) model being the result of the development of an annualized continuous-simulation version of AGNPS.

The AnnAGNPS model performs calculations on a daily time step simulating water, sediment, nutrients, and pesticide transport. These calculations are performed at the cell and watershed levels, where cells are subdivided segments of homogenous land areas in the watershed based on soil type, land use, and land management (Bosch et al., 1998). Daily input data is required, with the model capable of outputting on a daily, monthly, annual, or event basis (Licciardello et al., 2007). Surface runoff in the model is calculated by using the SCS curve number and extended TR55 methods. The RUSLE (Revised Universal Soil Loss Equation) method is used when calculating sheet and rill erosion from simulated storm events daily (Licciardello et al., 2007). The HUSLE (Hydrogeomorphic Universal Soil Loss Equation) method is used to simulate the total sediment volume delivered from the field to the channel after sediment deposition (Licciardello et al., 2007).

One major limitation of AnnAGNPS is that the model routes all the load generated in a given day (runoff, sediment, nutrients, and pesticide) to the outlet of the watershed before simulating the following day (Bosch et al., 1998; Upadhyay et al., 2018). This limitation is likely to have very little effect on smaller watersheds where the case may be close to reality and could pose a greater problem for scenarios in larger watersheds (Upadhyay et al., 2018). Another limitation of AnnAGNPS is that surface runoff and subsurface flow produced by cells will merge before being loaded into the reaches and is therefore “not possible to simulate scenarios with artificially drained cells that represent reality” (Upadhyay et al., 2018).

2.1.2 ANSWERS

The ANSWERS (Areal Nonpoint Source Watershed Environment Response Simulation) (Beasley et al., 1980) model is a distributed parameter, event based, watershed model. ANSWERS-2000 (Bouraoui and Dillaha, 1996) model was derived from the base ANSWERS model and added an improved infiltration model as well as simulating soil processes in a homogenous soil layer (Bouraoui and Dillaha, 1996). The original ANSWERS model used the Holtan’s equation for infiltration which was considered a major limitation due to the difficulty in estimating the required input parameters (Bouraoui and Dillaha, 1996). Holtan’s equation was replaced by the Green-Ampt equation in ANSWERS-2000 due to the ease and availability of the required parameters.

Mousavizadeh (1998) linked the GIS program SPANS to ANSWERS-2000, as well as improving the ANSWERS code. This was performed to improve the model performance, minimize user interaction and time requirement, as well as providing a visualized output in SPANS.

Not much data is readily available regarding the use and ability of the ANSWERS model, with many sources regarding its use being dated.

2.1.3 APEX

The Agricultural Policy/Environmental eXtender (APEX) (Gassman et al., 2009) model is a flexible and dynamic tool used to estimate land management and climatic impacts for whole farms and small watersheds (Gassman et al., 2009; Gassman et al., 2010; Wang et al., 2012). Functioning on a daily time step, and capable of performing long term simulations, the APEX model is used to estimate environmental indicators such as water quantity, erosion, nutrient cycling and loss, tile drainage, as well as other indicators (Wang et al., 2012). The APEX model is essentially a multi-field version of the Environmental Policy Integrated Climate (EPIC) model (Gassman et al., 2009; Gassman et al., 2010), where APEX extends the EPIC modeling functions to a spatially distributed model (Wang et al., 2012). The APEX model has the capability of simulating key landscape processes by segmenting a study area into landscape units called subareas (Wang et al., 2012. These subareas are used to “capture the land use, soil, and management variability” of the study area, with these components being the same between the APEX and EPIC models (Wang et al., 2012).

The APEX model requires some improvements that are listed in Gassman et al. (2010) and Wang et al. (2012). One of the suggested modifications is the inclusion of improved subsurface tile drainage algorithms to allow for a broader range of tile drainage scenarios (Gassman et al., 2010). Another suggestion is the modification of the RCN technique and/or adaptation of more complex physically based routines, such as the SWAT curve number modifications, to improve the APEX hydrologic interface (Wang et al, 2012).

2.1.4 HSPF

The Hydrological Simulation Program – Fortran (HSPF) (Bicknell et al., 2001) is a continuous watershed model capable of simulating sub-hourly data. The model can simulate any period, from a few minutes to common ranges of 5 to 20 years or more (Duda et al., 2012). HSPF has many applications, being able to simulate pollutant loadings in streams and lakes, as well as simulating the hydrologic and water quality processes of pervious and impervious land surfaces (Duda et al., 2012; Javan et al., 2015).

The model is a process-based, continuous model that utilizes subroutines that each perform a task during simulation. These subroutines are organized in a hierarchy and provide the model with a modular design, allowing it to be "readily adapted to special applications designed by the user" (Duda et al., 2012). The output of the model is a time history of the water quantity and quality at any point in a watershed and uses the results to simulate stream processes (Duda et al., 2012). HSPF incorporates hundreds of algorithms and can calculate a very large number of hydrologic and water quality aspects (Duda et al., 2012).

There are limitations that are stated by Duda et al. (2012) with the use of HSPF. One of the limitations due to the large number of algorithms is that there are thousands of model parameters that can be modified, which may prove to be complex. Additionally, some parameters are not fully distributed and grouped between multiple aspects of a watershed. Other major limitations include: the inability to model agricultural tile drainage processes, certain BMPs being difficult to implement, inability to model wetland processes, and channel hydraulics being simulated with a simplified routing technique (Duda et al., 2012).

2.1.5 MIKE SHE

Originally developed from the Système Hydrologique Européen (SHE), MIKE SHE (Refsgaard and Storm, 1995) is a distributed, physically based model. The model consists of modules for calculating water movement and water quality (Zhou et al., 2013).

Various water movement modules that are simulated in the MIKE SHE model includes: interception and evapotranspiration, unsaturated zone flow, overland flow, saturated zone flow, and channel and river flow. In MIKE SHE, these processes are simulated through different methods and equations available to each module: evapotranspiration (Kristensen and Jensen model/two-layer water balance); unsaturated flow (1-D Richards equation); overland flow (Saint-Venant equations/Manning's equation); saturated zone flow (3-D Darcy equation); channel and river flow (MIKE 11) (Jaber and Shukla, 2012).

The MIKE SHE model calculates the transport of pollutants using the QUICKEST method discussed in Leonard (1979) between the various water movement modules (Jaber and Shukla, 2012). However, the model is limited when simulating nitrogen and phosphorus cycling, but can be improved by coupling the DAISY model to MIKE SHE specifically for water quality calculations (Jaber and Shukla, 2012)

Jaber and Shukla (2012) state that due to the lack of simplified and lumped processes, MIKE SHE can have a rather time-consuming learning curve as well as requiring users to have advanced knowledge of hydrologic processes. Additionally, the number of parameters available to users provides another issue where the calibration process may take much longer than desired.

2.1.6 WARMF

The Watershed Analysis Risk Management Framework (WARMF) model is a distributed watershed model that is a decision support system for stakeholders (Herr and Chen, 2012). WARMF was designed to provide tools for stakeholders to meet water quality criteria and develop management plans with a GIS based graphical user interface (Herr and Chen, 2012).

The WARMF model divides river basins into various segments and catchments (compartments) with their boundaries based on their maximum extent (Herr and Chen, 2012). Though each compartment is comprised of subcompartments with their own characteristics based on land use, the outputs are lumped (Herr and Chen, 2012). The model is capable of dynamically simulating several hydrologic and water quality components by default such as pH, snow water depth, coliform bacteria, algae, and mercury cycling (Herr and Chen, 2012). The model contains many parameters which cannot be modified all at one and includes an autocalibrator for hydrology (Herr and Chen, 2012). WARMF contains built-in BMPs and is capable of simulating both point and non-point source pollutions for several water quality constituents, with the model using a "physically based approach for water quality modeling based on geochemistry and mass balance" (Congdon et al., 2014).

One of the limitations of the WARMF model is that it is unable to simulate agricultural tile drains or wetlands that may be found in some watershed or as a BMP (Congdon et al., 2014). Additionally, the model does not simulate deep groundwater interactions or lateral groundwater flow below the soil layers, as well as the model simplifying the groundwater system (Congdon et al., 2014).

2.1.7 SWAT

The Soil and Water Assessment Tool (SWAT) is a continuous, semi-distributed, physically-based watershed model developed by Arnold et al. (1998) (Arnold et al., 2012). The SWAT model was developed for the USDA Agricultural Research Service (ARS) and incorporates components from both USDA-ARS models such as EPIC, GLEAMS, and CREAMS (Arnold et al., 2012), as well as non-USDA models.

SWAT operates on a daily time step and is capable of "continuous simulation over long time periods" (Arnold et al., 2012) to evaluate the impact of current and alternative management practices on water resources in large watersheds (Arnold et al., 2012; Congdon et al., 2014).

SWAT divides a watershed into multiple subbasins, which are divided further into hydrologic response units (HRUs). HRUs are created based on the subbasin they are in, as well as their soil type, land management, and slope class defined by the user. HRUs may not be spatially identified as they can lump multiple areas within the subbasin if the landuse, soil, and slope are the same (Arnold et al., 2012). Area thresholds can be set for the creation of HRUs to include or remove certain soils or land managements, as well as lowering the number of slope classes if the user wishes to simplify the watershed they are working on at the sacrifice of accuracy.

Water balance is the driving force behind the watershed processes in SWAT, being separated into two major parts: land phase and routing phase (Arnold et al., 2012). These phases are responsible for controlling the amount and movement of water quantity and quality through the watershed and channels (Arnold et al., 2012).

One of the limitations as stated prior with the SWAT model is that HRUs typically do not have spatial reference (Arnold et al., 2012; Daggupati et al., 2011). This limitation can be overcome by setting only 1 slope class as well as setting the area thresholds to 0% for soil and landuse (Daggupati et al., 2011). However, it should be noted that the specific landuse and soil HRU combinations will still be separated by the subbasin boundaries. In comparison to WARMF, SWAT shares many capabilities, with the advantage of SWAT being able to simulate groundwater below the soil and being able to simulate wetlands (Congdon et al., 2014). The limitation of the SWAT model is the lack of visualization capabilities for the model but can be overcome with addons such as VIZSWAT (Arnold et al., 2012; Congdon et al., 2014). SWAT-CUP (Abbaspour et al., 2007) is a calibration tool that can be used to autocalibrate a watershed, as manual calibration may be difficult in large-scale applications (Arnold et al., 2012). Caution should be taken when performing autocalibration, as input parameters are physically-based, and ranges set by the user should be kept within realistic ranges (Arnold et al., 2012).

2.2 Hydrologic Processes in SWAT

The SWAT model was chosen for this study. The equations regarding surface runoff, sediment, and phosphorus are explored further in this section. The equations and text are adopted closely from the SWAT theoretical documentation by Neitsch et al. (2011) for completeness sake.

2.2.1 Flow

The hydrologic cycle simulated by SWAT is based on the water balance equation:

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

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

Snow melt is included with rainfall in the calculations of runoff and percolation in SWAT. For erosion calculations, rainfall energy from the snow melt fraction is set to zero, with the water released from snow melt assumed to be evenly distributed over a given day's 24-hour period (Neitsch et al., 2011).

Snow melt is calculated as a linear function of the difference between the average snow pack-maximum air temperature and the base or threshold temperature for snow melt in SWAT.

The snow melt equation is defined as:

$$SNO_{mlt} = b_{mlt} \cdot sno_{cov} \cdot \left[\frac{T_{snow}+T_{max}}{2} - T_{mlt}\right] \tag{2.2}$$

Where SNO_{mlt} is the amount of snow melt on a given day (mm), b_{mlt} is the melt factor for the day (mm/day-°C), sno_{cov} is the fraction of the HRU area covered by snow, T_{snow} is the snow pack temperature on a given day (°C), T_{max} is the maximum air temperature on a given day (°C), and T_{mlt} is the base temperature above which snow melt is allowed (°C).

2.2.2 Surface Runoff and Infiltration

In SWAT, the surface runoff can be estimated from two methods: the modified SCS curve number method (SCS, 1972), or the Green & Ampt infiltration method (Green and Ampt, 1911).

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

$$Q_{surf} = \frac{(R_{day}-I_a)^2}{(R_{day}-I_a+S)} \tag{2.3}$$

Where Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), I_a is the initial abstractions which includes surface storage, interception and infiltration prior to runoff (mm), and S is the retention parameter (mm).

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

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \tag{2.4}$$

Where *CN* is the curve number for the day.

The SCS curve number is a function of the soil's permeability, land use, and soil water conditions (Neitsch et al., 2011).

The Initial abstractions, I_a, is commonly approximated as 0.2S, which changes the SCS curve number becomes:

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \tag{2.5}$$

The alternative method for surface runoff calculation in SWAT is the Green & Ampt equation. The Green & Ampt equation was developed to predict infiltration, assuming excess water at the surface always (Green and Ampt, 1911). The soil profile is considered homogenous, with antecedent moisture being uniformly distributed in the profile (Neitsch et al., 2011).

Mein and Larson (1973) developed a methodology for determining ponding time with infiltration using the Green & Ampt equation, but requires sub-daily precipitation data (Neitsch et al., 2011).

The Green-Ampt Mein-Larson infiltration rate is defined as:

$$f_{inf,t} = K_e \cdot \left(1 + \frac{\Psi_{wf} \cdot \Delta\theta_v}{F_{inf,t}}\right) \tag{2.6}$$

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

For each time step, SWAT calculates the amount of water entering soil. The water that does not infiltrate into the soil becomes surface runoff (Neitsch et al., 2011).

2.2.3 Sediment

The Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975; Williams, 1995) is used to estimate erosion and sediment yield for each HRU in SWAT and is defined as:

$$sed = 11.8 \cdot \left(Q_{surf} \cdot q_{peak} \cdot area_{hru}\right)^{0.56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG \quad (2.7)$$

Where sed is the sediment yield on a given day (metric tons), Q_{surf} is the surface runoff volume (mm/ha), q_{peak} is the peak runoff rate (m^3/s), $area_{hru}$ is the area of the HRU (ha), K_{USLE} is the USLE soil erodibility factor (0.013 ton m^2 hr/m^3 ton cm), C_{USLE} is the USLE cover and management factor, P_{USLE} is the USLE support practice factor, LS_{USLE} is the USLE topographic factor, and $CFRG$ is the coarse fragment factor.

Additionally, SWAT accounts for the effect of snow coverage on erosion from rain and runoff for sediment yield:

$$sed = \frac{sed'}{exp\left(\frac{3 \cdot SNO}{25.4}\right)} \quad (2.8)$$

Where *sed* is the sediment yield on a given day (metric tons), *sed'* is the sediment yield calculated with MUSLE (metric tons), and *SNO* is the water content of the snow cover (mm)

The Bagnold equations (Bagnold, 1977) are simplified and used to determine the sediment carrying capacity of the channel as a function of channel slope and peak channel velocity (Neitsch et al., 2011). The peak channel velocity, $v_{ch,pk}$, is defined as:

$$v_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}} \quad (2.9)$$

Where $q_{ch,pk}$ is the peak flow rate (m^3/s) and A_{ch} is the cross-sectional area of flow in the channel (m^2)

The peak flow rate is defined as:

$$q_{ch,pk} = prf \cdot q_{ch} \quad (2.10)$$

Where prf is the peak rate adjustment factor, and q_{ch} is the average rate of flow (m^3/s)

Therefore, the maximum amount of sediment that can be transported from a reach segment is calculated:

$$conc_{sed,ch,mx} = c_{sp} \cdot {v_{ch,pk}}^{spexp} \quad (2.11)$$

Where $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by the water (ton/m^3 or kg/L), c_{sp} is a coefficient defined by the user, $v_{ch,pk}$ is the peak channel velocity (m/s), a *spexp* is an exponent defined by the user.

In the case of deposition or degradation in the reach segments, the dominant process is dependent on whether the initial sediment concentration or maximum concentration of sediment that can be transported by water is larger (Neitsch et al., 2011).

Deposition in the reach segment is defined as:

$$sed_{dep} = \left(conc_{sed,ch,i} - conc_{sed,ch,mx}\right) \cdot V_{ch} \tag{2.12}$$

Where sed_{dep} is the amount of sediment deposited in the reach segment (metric tons), $conc_{sed.ch.i}$ is the initial sediment concentration in the reach (kg/L or ton/m^3), $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by water (kg/L or ton/m^3), and V_{ch} is the volume of water in the reach segment (m^3).

Degradation in the reach segment is defined as:

$$sed_{deg} = \left(conc_{sed,ch,mx} - conc_{sed,ch,i}\right) \cdot V_{ch} \cdot K_{CH} \cdot C_{CH} \tag{2.13}$$

Where sed_{deg} is the amount of sediment reentrained in the reach segment (metric tons), $conc_{sed,ch,mx}$ is the maximum concentration of sediment that can be transported by water (kg/L or ton/m^3), $conc_{sed.ch.i}$ is the initial sediment concentration in the reach (kg/L or ton/m^3), and V_{ch} is the volume of water in the reach segment (m^3), K_{CH} is the channel erodibility factor, and C_{CH} is the channel cover factor.

The amount of sediment transported out of the reach is then calculated:

$$sed_{out} = sed_{ch} \cdot \frac{V_{out}}{V_{ch}} \tag{2.14}$$

Where sed_{out} is the amount of sediment transported out of the reach (metric tons), sed_{ch} is the amount of suspended sediment in the reach (metric tons), V_{out} is the volume of outflow during the time step (m^3), V_{ch} is the volume of water in the reach segment (m^3).

2.2.4 Phosphorus

The organic P as well as mineral P attached to sediments loading from HRUs is estimated using a formulation of McElroy et al. (1976) as adapted by Williams and Hann (1978) and is a function of respective P concentrations in the top soil layer, enrichment ratio and sediment yield (Neitsch et al, 2011).

The equation for the phosphorus transported with sediment is defined as:

$$sedP_{surf} = 0.001 \cdot conc_{sedP} \cdot \frac{sed}{area_{hru}} \cdot \varepsilon_{P:sed} \tag{2.15}$$

Where $sedP_{surf}$ is the amount of phosphorus transported with sediment to the main channel in surface runoff (kg P/ha), $conc_{sedP}$ is the concentration of phosphorus attached to sediment in the top 10 mm (g P/metric ton soil), sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and $\varepsilon_{P:sed}$ is the phosphorus enrichment ratio.

"The enrichment ratio is defined as the ratio of the concentration of phosphorus transported with the sediment to the concentration of phosphorus in the soil surface layer" (Neitsch et al., 2011). The enrichment ratio is calculated as a logarithmic function of sediment yield and surface runoff described by Menzel (1980).

The phosphorus enrichment ratio, $\varepsilon_{P:sed}$, is calculated:

$$\varepsilon_{P:sed} = 0.78 \cdot \left(conc_{sed,surq}\right)^{-0.2468} \tag{2.16}$$

Where $conc_{sed,surq}$ is the concentration of sediment in surface runoff (Mg sed/m^3 H_2O).

The concentration of sediment in surface runoff is calculated:

$$conc_{sed,surq} = \frac{sed}{10 \cdot area_{hru} \cdot Q_{surf}} \tag{2.17}$$

Where sed is the sediment yield on a given day (metric tons), $area_{hru}$ is the HRU area (ha), and Q_{surf} is the amount of surface runoff on a given day (mm).

SWAT also accounts for the interaction with solution phosphorus in the top 10 mm of soil due to the low mobility of solution phosphorus (Neitsch et al., 2011). The amount of solution P transported in surface runoff is:

$$P_{surf} = \frac{P_{solution,surf} \cdot Q_{surf}}{\rho_b \cdot depth_{surf} \cdot k_{d,surf}} \tag{2.18}$$

Where P_{surf} is the amount of soluble phosphorus lost in surface runoff (kg P/ha), $P_{solution,surf}$ is the amount of phosphorus in solution in the top 10 mm (kg P/ha), Q_{surf} is the amount of surface runoff on a given day (mm), ρ_b is the bulk density of the top 10 mm (Mg/m^3) (assumed to be equivalent to bulk density of first soil layer), $depth_{surf}$ is the depth of the "surface" layer (10 mm), and $k_{d,surf}$ is the phosphorus soil partitioning coefficient (m^3/Mg).

2.3 Best Management Practices (BMPs) Applications with SWAT

Agricultural activity is known to create diffuse/nonpoint source pollution and is a major global contributor in pollutant loss and degradation of water resources (D'Arcy and Frost, 2000; Rao et al., 2009; Liu et al., 2018). The runoff from these activities is comprised of nutrients/fertilizer, primarily phosphorus and nitrogen, and is a major issue for the environment, the aquatic environment in particular (D'Arcy and Frost, 2000). To address/minimize the impacts of agricultural activities on soil and water systems, practical and affordable approaches, BMPs, are adopted. BMPs can be classified as structural and non-structural BMPs. Structural BMPs are defined as permanently constructed structures or physical devices such as water and sediment control structures. Non-structural BMPs are agricultural practices that have no construction and are based on programs or the modification of current practices or procedures such as cover crops or alternative forms of tillage.

BMPs were historically designed and implemented by farmers to reduce soil erosion and sediment entering the streams and channels (Rao et al., 2009). This also reduced nutrients entering the streams, however the BMPs did not target dissolved nutrients and only reduced sediment bound phosphorus and nitrogen (Rao et al., 2009). Current implementation of BMPs focus on reducing the amount of dissolved nutrients "along with traditional erosion control BMPs" for greater effect (Rao et al., 2009). Farmers may also be more inclined or motivated to apply BMPs to their land with financial incentives which often come in the form of government subsidies (Liu et al., 2018).

Some of the BMPs that are commonly practiced in Ontario as well as similar U.S. watersheds that flow into Lake Erie includes buffer strips, conservation tillage (mulch tillage, reduced tillage, no-till), irrigation management, nutrient management plan, winds strips, and winter cover crops (oats, cereal rye, red clover) (Liu et al., 2016; Merriman et al., 2018a; 2018b).

Uribe et al. (2018) evaluated the effects of conservation tillage on nitrogen and phosphorus losses in the Fuquene watershed in Colombia using the SWAT model. The watershed explored in this study is an estimated 16,933 ha with four stream gauging stations. The SWAT model was built on a daily time step with data ranging from 2006 to 2013. Streamflow calibration was performed on a monthly basis, with three of the four gauging stations having satisfactory results for NSE, and one unsatisfactory (0.54, 0.32, 0.58, 0.61) (Uribe et al., 2018). Calibration and validation were found to be affected by a lack of information available for a reservoir located upstream, with an overprediction of peak flows when information was lacking. No values were given for statistical indicators regarding nutrient and sediment calibration, though Uribe et al. (2018) stated that the calibration results were considered acceptable.

Uribe et al. (2018) applied conservation tillage by changing the tillage implementation for potato and Italian (annual) ryegrass from "Bedder shaper" to "Chisel Plow Gt2ft-vertical" and "Rotovator-bedder" to "Bedder shaper" respectively. Fertilizer amounts were also reduced for potatoes from 1400 kg/ha to 1000 kg/ha in the conservation tillage scenario (Uribe et al., 2018). Conservation tillage was initially investigated at the field level comparing to the baseline results on an average monthly basis. When extrapolated to the watershed scale, surface runoff and sediment yield were found to have a reduction of approximately 11% and 26% respectively. Phosphorus losses decreased at the watershed level, with organic phosphorus showing an 8% decrease, soluble phosphorus a 38% decrease, with overall phosphorus having a decrease of 18% (Uribe et al., 2018).

Liu et al. (2016) used the SWAT model to evaluate BMPs in the Grand River watershed in Southern Ontario. The Grand River watershed has a drainage area of approximately 6800 km^2 (680,000 ha) and flows into Lake Erie. The flow from the watershed makes up 10% of the lake's total Canada/U.S. drainage area. In addition to the non-point source pollution from agricultural activities, the watershed receives wastewater from communities in the area. The model was initially calibrated using SWAT-CUP, followed by manual calibration for 8 monitoring stations. The monitoring stations were given equal weighting during the auto-calibration process to get an overall calibration of the watershed. After manual calibration, the daily NSE was calculated for all the monitoring stations, with the values representing satisfactory results in flow simulation ranging from 0.48 to 0.91, with monthly and yearly NSE showing better simulation results (Liu et al., 2016). Water quality data, including sediment, total phosphorus, and total nitrogen, were not simulated as satisfactorily as flow, with phosphorus and nitrogen being less accurate.

Liu et al. (2016) applied BMP scenarios in the Grand River watershed includes nutrient management, buffer strips, cover crops, and wetland restoration. In the case of nutrient management, N and P applications were reduced by approximately 10% (low), 20% (medium), and 50% (high), while maintaining management operation times and tillage practice. Three scenarios were given to buffer strip application, with carrying strips widths of 3m, 5m, and 10m. Cover crops were simulated by planting red clover after harvesting winter wheat and growing until plowed prior to seeding corn. The wetland restoration scenario was applied by identifying subbasins containing crop HRUs and restoring wetlands from the cropland. The scenario targeted 2% and 4% of wetland surface area in the watershed for evaluation. Additionally, two BMP combination scenarios were created. The first scenario included nutrient management with an approximate 20% reduction in N and P fertilizer, the 3 m buffer strip, and the inclusion of cover crops. The second multiple BMP scenario included the same nutrient management of a 20% reduction, 3m buffer strip, cover crop, and the 2% surface area wetland restoration.

For the varying nutrient management fertilizer reductions, Liu et al. (2016) found reductions in TP of 8.92%, 17.72%, and 37.18% for the low, medium, and high scenario respectively. The varying buffer strips scenarios had very little reduction in sediment, ranging from 0.66% to 1.2%. Reductions in TP for these scenarios were approximately 6.28%, 7.12%, and 8.8% for the 3m, 5m, and 10m cases. Cover crops, in the form of red clover, when compared to the baseline scenario had a sediment reduction of 1.73% and a TP reduction of 12.59%. The wetland restoration scenarios displayed total phosphorus reductions of 8.8% and 15.11% for 2% and 4% wetland surface areas, respectively. The multiple BMP scenarios had the highest reductions in both sediment and total phosphorus. The reductions for the first combination scenario were 1.79% and 35.7% for sediment and phosphorus respectively. The second combination scenario had greater reductions than the first, with a sediment yield reduction of 4.35% and a TP reduction of 41.32% (Liu et al., 2016).

Merriman et al. (2018a) evaluated BMPs in Alger Creek, Michigan using SWAT. The Alger Creek watershed, approximately 50 km^2 (5000 ha) in area, is part of the Saginaw River basin and flows into Lake Huron. Alger Creek is mostly flat with a slope of 1.3%, having only 41m of relief (Merriman et al., 2018a). Data from three gauging stations were available for use; with one that gauged approximately 93% being used for streamflow, sediment, and nutrients calibration. The weather generator implemented in SWAT was used to calculate daily values for solar radiation, wind speed, and relative humidity. The model was calibrated based on currently implemented BMPs in the watershed and at a monthly time step, with daily data being used to assist with calibration of timing parameters. Calibration results were considered very good based on criteria from Moriasi et al. (2015), with the validation period results also being good. NSE values for flow during the calibration and validation periods were 0.9 and 0.83. Sediment was also quite good for the calibration period at 0.79 NSE, and satisfactory for the validation period with a value of 0.54. Total phosphorus results were better than sediment for both the calibration and validation period at 0.87 and 0.73, with PBIAS being unsatisfactory during the validation period (Merriman et al., 2018a).

Four BMPs were implemented in the Alger Creek watershed: cover crops, nutrient management plan, reduced till, and no-till (Merriman et al., 2018a). The cover crop implemented in the model was cereal rye, which was planted on 1 November and killed on 1 April. The cereal rye was not planted if winter wheat was being grown during the period but was planted the following summer after harvesting the winter wheat. The nutrient management plan was implemented by reducing fertilizer application rates by 10%. Reduced-till and no-till were similarly implemented in the model, where the tillage operations were changed to “Generic No-till” in the management. Reduced-till modified Manning’s overland ‘n’ value to 0.2, reduced the curve number at the time of tillage operation (CNOP) by 2, and changing the biomix efficiency to 0.4. In the case of the no-till BMP, tillage operations were set to “Generic No-Till” in the management, the overland ‘n’ value was set to 0.3, the CNOP was reduced by 5, and biomix efficiency was set to 0.5 (Merriman et al., 2018a). Two additional BMPs were simulated by Merriman et al. (2018a) in hypothetical scenarios, which included conservation crop rotation and filter strips. Conservation crop rotation consisted of a corn-soybean rotation with winter wheat added once every 5 years. Individual fields that received conservation crop rotation were staggered during years 1-5 based on when the wheat was planted to maintain approximately equal areas of wheat fields each year. Filter strips were implemented by using the Scheduled Management Operations (.ops) file. The filter strips were given a ratio of field area to filter strip area of 40, the fraction of the HRU which drains to the most concentrated 10% of the filter strip area was set to 0.5, and the fraction of flow which is fully channelized and not subject to filtering or infiltration effect was set to 0 (Merriman et al., 2018a).

Three scenarios were created as hypothetical levels of BMP implementation: a low scenario, medium scenario, and high scenario. All three scenarios included implementing the trio of cover crops + no-till + nutrient management plan to 40%, 60%, and 100% of the agricultural fields in the watershed (Merriman et al., 2018a). These agricultural field percentages accounted for approximately 21%, 25%, and 42% of the watershed area based on the low, medium, and high scenarios. The low scenario targeted fields that already contained a BMP and included conservation crop rotation. The medium scenario was simply the application of the BMP combination to 60% of the agricultural fields. The high scenario included the application of filter strips to one field in each of the 23 subbasins along with the trio of BMPs on 100% of the agricultural fields. The sediment reductions for the low, medium, and high scenario were approximately 1%, 3%, and 12% respectively. Total phosphorus reductions for these scenarios came to around 11%, 18%, and 31% for the low, medium, and high scenarios respectively (Merriman et al., 2018a).

Similarly to Merriman et al. (2018a), Merriman et al. (2018b) evaluated BMPs in Eagle Creek, Ohio. The Eagle Creek watershed is 125km^2 and is a small subbasin that is part of the larger Maumee River Bain. Much like Alger Creek, Eagle Creek is relatively flat with an approximate slope of 18% and 61m of relief (Merriman et al., 2018b). A 5-year warmup period was given to the model, with BMPs simulated for a period of 10 years between 2005 and 2014. Three stations were used in the calibration process at a monthly time step, with one at the outlet of the watershed, one at the edge of a field, and the other for the tile drain of the same field. Results for the field specific stations varied greatly, with the values for NSE and PBIAS generally being unsatisfactory. For the whole watershed, NSE and PBIAS values were found to be satisfactory, with 0.69 and -4.59% for flow, 0.72 and -19.17% for sediment, and 0.74 and 34.3% for TP respectively (Merriman et al., 2018b).

BMPs that were evaluated by Merriman et al. (2018b) includes cover crops, conservation crop rotation, conservation cover, filter strips, grassed waterways, nutrient management plan, no-tillage, prescribed grazing, upland wildlife habitat management and reduced tillage as well as combinations of the various BMPS. Reduced-till was implemented similarly to the method used in Merriman et al. (2018a), where Merriman et al. (2018b) changed the tillage operation to "Generic Conservation Tillage" for crops other than soybean and modified the curve number in the management files rather than the curve number of the operation during tillage. No-till, filter strips, nutrient management plan were all implemented the same methods as Merriman et al. (2018a). Upland wildlife habitat management was implemented by establishing permanent rangeland. Cover crops in for of cereal rye was planted after tillage following the harvesting of corn. Conservation cover was implemented by permanently establishing switch grass. No information is given as to the parameters set for grassed waterways in the .ops file in the model for implementation.

Merriman et al. (2018b) created 3 hypothetical scenarios that were labelled as low, medium, and high. The low and medium scenarios both implemented crop rotation, nutrient management plan, and no-till BMPs to 25% and 50% of agricultural fields without BMPs. These scenarios accounted for 23.3% and 45.8% of the total watershed area with BMPs. The high scenario included cover crops for any fields that did not have BMPs and came to 76.3% of the watershed area with BMPs.

Reduction percentages stated are not accurate, as the reductions are represented in graphs rather than stated numerically for the scenarios. In the low scenario, the sediment reduction was approximately 2.5% and total phosphorus was reduced by 10%. The medium scenario had reductions of approximately 3% and 15.5% for the sediment and total phosphorus yield respectively. The high scenario reductions were greater than the other hypothetical scenarios, with a sediment reduction of approximately 7%, and a total phosphorus reduction of 23% (Merriman et al., 2018b).

Researches primarily focus on BMPs for field-scale reductions of sediment and nutrient losses in their study watersheds, citing and comparing to other literature values for these reductions if they are similar. This may not be the case and is dependent on several variables including soil, fertilizer use, and crop being grown to name a few. Additionally, BMP combinations are commonly tested at the watershed-scale, without observing and analyzing the results of single BMPs applied at this scale. However, barring the results obtained, SWAT is shown to be capable of handling and simulating several different BMPs. SWAT also contains a specific file for the management and simulation of certain BMPs including filter strips, grassed waterways, and residue management.

Chapter 3: Material and Methods

3.1 Study Area with Climate and Hydrology

In this project, Wigle Creek watershed, has been selected as Priority Watershed (PW) under the Great Lakes Agricultural Stewardship Initiative (GLASI) program, drains into Lake Erie. This section provides a concise geographical description of the Wigle Creek watershed areas, which is the part of Lake Erie watershed, Ontario, Canada. It includes the location, extent, accessibility, and a brief description of the climate and hydrology of the watershed.

3.1.1 Location, Extent & Accessibility

The Wigle Creek watershed has a total area of 3530 ha, with the study watershed lying on the west branch of Wigle Creek with an area of 1949 ha. The study watershed extends from 82° 47’ 30” W to 82° 43’ 30” W longitude, and 42° 07’ 30” N to 42° 03’ 30” W latitude and is located between both Kingsville and Cottam (Figure 1). This agriculture dominated watershed comprises of a very flat topography with Brookston clay soils and cash crop (corn and soybeans) as major land use along with extensive tile drainage system.

Figure 1. Location Map of Wigle Creek Watershed.

3.1.2 Climate & Hydrology

Climate data was gathered from the Jack Miner weather station located within the Wigle Creek watershed. The data gathered from the Jack Miner station included only precipitation data from July 18, 2016 to July 12, 2017. Environment Canada weather data was used as an alternative for the missing climate data, required from 2012 to 2017 including precipitation, temperature and other climatic parameters needed for SWAT buildup. Details of climate data is further explored in section 3.2.2.

The annual observed precipitation for Wigle Creek in 2016 and 2017 was 829.5mm and 930.9mm, respectively. Much higher precipitation can be seen in Spring of 2017, with May having a significantly higher precipitation of 121.4 mm over the 49.4 mm in 2016. The Summer and Fall seasons of 2016 were warmer than 2017, with the Winter transition between 2016 and 2017 being much warmer than the start of 2016 and end of 2017. The yearly average maximum and minimum temperatures for 2016 and 2017 are very similar, showing a decrease of 0.5°C and 0.4°C respectively in 2017 (Table 1).

Table 1. Monthly observed precipitation, maximum and minimum temperature in the Wigle Creek watershed (after including data from the Harrow CDA Auto station).

Year	Month	P (mm)	Tmax (°C)	Tmin (°C)
2016	Jan	39.1	0.8	-5.9
	Feb	53.3	2.9	-5.2
	Mar	135.5	9.1	0.5
	Apr	59.2	11.9	1.4
	May	49.4	20.2	9.4
	Jun	18.3	26.5	14.3
	Jul	101.9	28.5	18.3
	Aug	97.8	28.0	18.5
	Sep	130.9	24.1	14.6
	Oct	57.7	17.4	8.3
	Nov	38.4	11.9	3.5
	Dec	48.0	1.2	-4.2
	Average	69.1	15.2	6.2
2017	Jan	75.4	2.4	-3.6
	Feb	46.6	6.9	-2.0
	Mar	109.2	5.6	-2.3
	Apr	90.4	16.5	6.0
	May	121.4	18.6	9.1
	Jun	81.4	25.8	15.7
	Jul	47.5	26.6	17.0
	Aug	42.7	25.4	14.6
	Sep	66.7	23.6	12.8
	Oct	65.6	17.8	9.1
	Nov	153.6	8.3	0.4
	Dec	30.4	-0.1	-7.1
	Average	77.6	14.7	5.8

3.2 Data Availability and Database Preparation

This section includes a brief description of the available climate data, topography, soil, landuse, water quantity and quality data and land management data (Table 2). It also provides the GIS database preparation of various thematic maps, which were used as an input to the SWAT model.

3.2.1 Data Requirement and Availability

The study requires both water quality and quantity data at primary and secondary levels to arrive at analytical conclusions. Data needed for Wigle creek Watershed, for the modelling exercise, were obtained from the ERCA.

Seven water quality stations are monitored by the ERCA upstream and downstream of locations where BMPs were being implemented, as well as in side drains and in the East branch, with one downstream of the connection of both branches of Wigle Creek. Level loggers installed by the ERCA at three locations (W E9, Wigle 1, and W KLN13) were used to collect bi-weekly, event-based grab samples, and streamflow data. Four additional sampling sites were added in Spring 2016 to monitor water quality but with no level logger or flow measurements. Automated samplers (ISCO) were later installed at Wigle 1 and one of the later added monitoring location for more effective event sampling in addition to the routine grab samples. A modem was also installed at the Wigle 1 (watershed outlet) monitoring point to monitor the water level remotely.

Data gaps were filled by collecting data from nearby and available sources. A complete list of data required for modelling and their availability status is described below in Table 2.

Table 2. Data available for Wigle creek Watershed.

SN	Data	Available Data Description	Remark (Required Data Description)
(A) Spatial Data			
a	Topography	30m x 30m	0.5 x 0.5 m (resolution) Hydro-Enforced DEM (Digital Elevation Model) is available. [Pre-processed or refinement of the DEM resolution is required]
b	Soil	1. A coarse data from Soil Landscapes of Canada (SLC) 2. Only 2 soil types available	A more detailed soil map is desirable with the following properties for each soil layers: 1. Soil Depth 2. Moist Bulk Density 3. Available Water Capacity (AWC)

			4. Saturated Hydraulic conductivity 5. Soil Carbon (%) 6. Percentage of sand, silt and clay 7. Moist soil albedo 8. Soil erodibility factor (K) 9. Soil pH 10. Soil CaCO3 11. Electrical Conductivity
c	Land use	Prepared based on map of the original study area with designated plots and surveys	Not Applicable (NA)
(B) Climatic data			
a	Precipitation	Daily data: July 2016 – July 2017 Jack Miner Weather station data is available a) Precipitation: Duration (18/07/2016 - 12/07/2017). b) Temperature: Duration (18/07/2016 - 12/07/2017).	Data from 2012 to July 2016 and July 2017 to the end of 2017 taken from Harrow CDA Auto Environment Canada weather station. Details are given in section 3.2.2
b	Max and Min Temperature	Data not given	Data from 2012 to 2017 taken from Harrow CDA Auto Environment Canada weather station
c	Relative Humidity	Data not given	Handled by SWAT weather generator
d	Solar Radiation	Data not given	Handled by SWAT weather generator
e	Wind Speed	Data not given	Handled by SWAT weather generator
(C) Crop Management Data			
a	For each field	1. List of crops grown for 2012-2016 for 5-year	For each field: 1. The tillage date (if applicable) 2. Sowing/plantation date 3. Fertilizer application (type and

		survey and 2016-2017 for 2-year windshield survey 2. Till or No Till information for some plots only 3. Some tile drainage information such as tile spacing for 2 fields	rate) 4. Harvesting dates. 5. Tile drainage, the spacing of tiles, and depth of the main and branch lines from surface.
(D) Validation data			
a	Streamflow	Flow data from late 2015 to mid-2017 from Wigle 1: Dec 2015 to May 2017 (not continuous)	1. Starting date of sampling 2. Full and continuous data from the start date to end of 2017
b	Sediment as Total Suspended Solid (TSS) concentration	Sediment data from late 2015 to mid-2017 from Wigle 1: Jan 2016 to Dec 2017 (not continuous)	1. Starting date of sampling 2. Full and continuous data from the start date to end of 2017
C	Water Quality data (Ortho-Phosphate, TP, and Organic Phosphorus)	Phosphorus data from late 2015 to mid-2017 from Wigle 1: Jan 2016 to Dec 2017 (not continuous), details are given in section 3.2.3	1. Starting date of sampling 2. Full and continuous data from the start date to end of 2017
(E) Best Management Practices (BMPs): Details are given in 3.2.4			
a	Cover Crop	Based on survey information and BMP list	For each field, detailed description required, including the species of the cover crop
b	Alternative Phosphorus Application Practices	For some fields: 1. Variable rate application of phosphorus	For each field, if applicable, detailed information regarding: 1. The ratio and amount of phosphorus/fertilizer application 2. Timing of application 3. Spatial application
c	Vegetative Filter/Buffer Strips	1. None	For each field, if applicable, the following information required: 1. Timing of the operation 2. Area of the filter strips

d	Conservation Tillage	1. Spatial information of till or no till available for some fields	The information is required for all fields and if tilled, the timing of the operation and type of instrument used

3.2.2 Climate Data

Climate data for the simulation with SWAT model was obtained from the ERCA for the Jack Miner station. This data was available for the period between July 18, 2016 and July 12, 2017 and did not include temperature. Missing data from 2012 to the end of 2017 was taken from Environment Canada weather stations near Wigle Creek. Two weather stations considered for the missing data were, Kingsville MOE and Harrow CDA Auto, approximately 6.31 km and 11.63 km away, respectively from Wigle creek.

The correlation between the data available from these stations and the Jack Miner station was examined to fill the missing precipitation data. A detailed examination of the data indicated that the Harrow station has a better correlation ($R^2 = 0.79$) with the precipitation data at the Jack Minor station than the Kingsville station ($R^2= 0.11$). Therefore, the Harrow station was used to fill the missing precipitation data (Figure 2.).

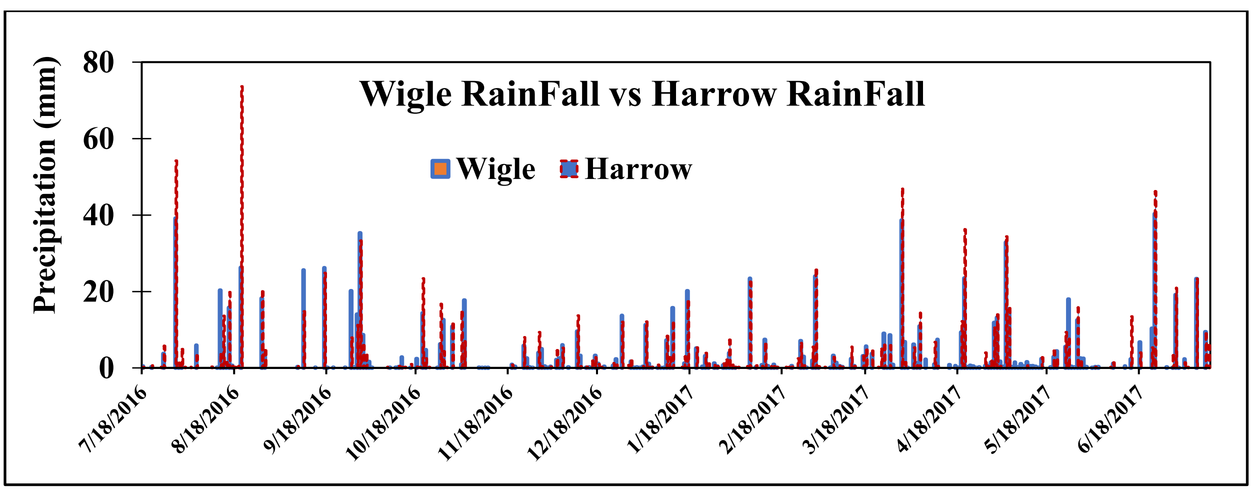


Figure 2. Graphical Comparison of the Precipitation Data Between the Jack Miner and Harrow Stations.

No temperature data was available from the Jack Miner station in the Wigle Creek watershed. Both the Harrow and Kingsville stations were explored as potentials for the missing temperature data. Both these stations have a similar pattern of temperature and a very high correlation (R^2 = 0.955 for Tmin and 0.989 for Tmax). In this case, the Harrow station data was used as it was assumed that temperature would much more accurate, similar to the precipitation data. Data that was not available or missing was not used in the comparisons and later set to a value of -99 to be used with the weather generator in ARC-SWAT.

3.2.3 Flow and Water Quality Data

Flow and water quality data were gathered by the ERCA at various points in the Wigle Creek watershed. The data used was from the Wigle 1 station located closest to the outlet of the watershed on the McCain Side Road, North of Road 2. Three other stations had available data for both flow and water quality, being stations WRD6, KLN13, and E9 located North East of Road 6, on Road 2, and on City Road 20 respectively. The other stations were not used as Wigle 1 was the closest to the outlet of the model and was used for calibration of the model. A total of 47 days (based daily) of flow data were available from the Wigle 1 station during the period 2016-17, with some days having multiple points that were averaged. For the same period, the water quality data was also collected at Wigle 1 station which contained datasets for 123 days of data. Likewise, for water quality data, some days had multiple points and were averaged, with most days having values based on instantaneously collected data.

3.2.4 Land Management Data

Land management data was initially collected and detailed by the ERCA based on windshield surveys of the various fields located in the Wigle Creek watershed. Information provided later by the ERCA from 5-year surveys filled out by farmers gave more details as to the management practices that the farmers were doing. This information provided insight on potential fertilizer amounts, planting dates, and harvesting times throughout the rest of the watershed for farmers that did not give information as well as information to the specific field. Some surveys did not provide certain pieces of data including: planting dates, harvesting data, and fertilizing dates. Hence, available information based on survey was given to the SWAT model under management operations to simulate the fields as accurately as possible. An additional file was later given, detailing what BMPs were practiced in specific fields in the watershed. The BMPs that were known to have been practiced by farmers were for the years 2015 to 2017. This file was cross referenced with available data from filled and windshield surveys to include practices into the field management that may have been missing from the surveys.

3.2.5 GIS Database Preparation

Data that was prepared and processed through ARC-GIS includes a) DEM, b) Drainage, c) Soil map, d) land use map, and e) slope map. The soil map, landuse map and slope maps shapefiles were created using ARC-GIS and later were used as inputs in ARC-SWAT to create the HRU (Hydrological response Unit) map of the Wigle Creek watershed.

3.2.5.1 Digital Elevation Model (DEM)

Wigle Creek is a flat watershed, with elevation ranging 185m to 203m above mean sea level (MSL). For the Wigle Creek watershed, two DEMs (Digital Elevation Model) were available to set-up the watershed model. The first DEM was a 0.5x0.5m resolution Hydro-Enforced Dem prepared by the Watershed Nutrient Monitoring (WNM) Technician of the Essex Region Conservation Authority (ERCA, 2016).

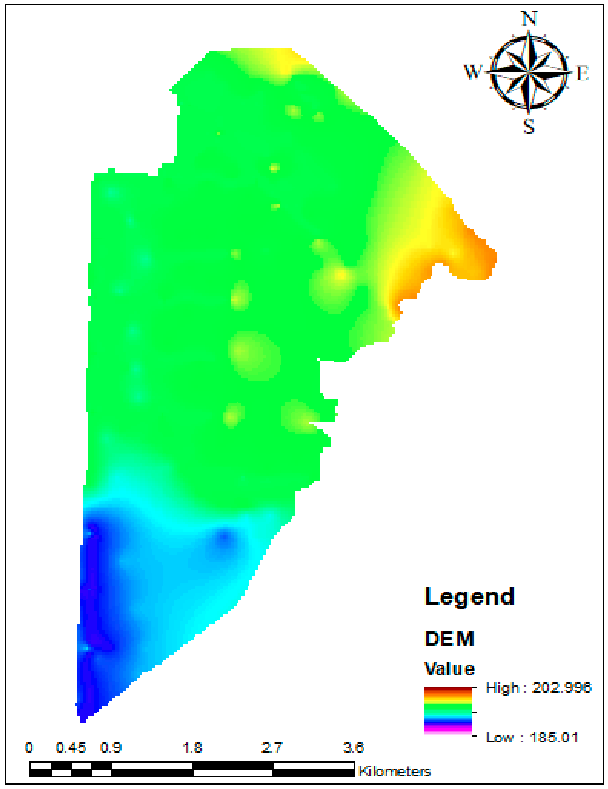


Figure 3. Digital Elevation Model (DEM) map of Wigle Creek Watershed Area (resolution 30x30m).

Some issues with this DEM for SWAT setup are described in section 3.3. These issues resulted in exploring the use of the second DEM. The second DEM is a 30x30m resolution DEM extracted from the South Ontario DEM website, provided by the Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA) shown in Figure 3.

3.2.5.2 Soil Data

In this study, Ontario Soil Databases was used to prepare the input for the SWAT model. It includes the provincial level soil database, the Soil Landscapes of Canada (SLC) version 3.2 (Soil Landscapes of Canada Working Group 2007). The SLC data contains soil map of Canada together with major characteristics of the soil for the whole country. The SLC was compiled at a scale of 1:1 million, and each polygon on the map describes a distinct type of soil and its associated characteristics. Figure 4. Shows the soil map of the Wigle Creek watershed used for the model setup.

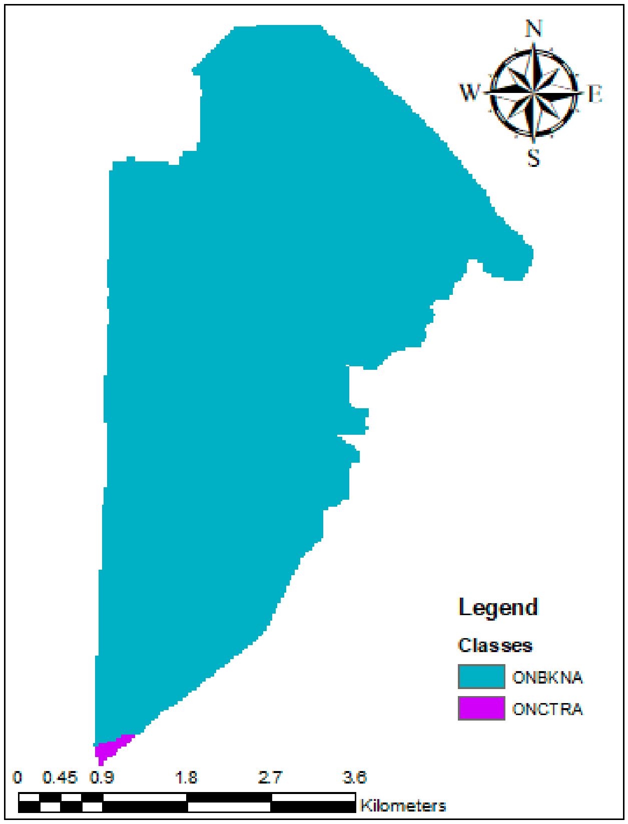


Figure 4. Soils distribution map of Wigle Creek Watershed, Blue color shows Brookston Clay (ONBKNA) and ONCTRA (Caistor Soil).

3.2.5.3 Land use and land cover (LULC)

The preparation of the land use map for the Wigle Creek watershed was done based on the cropping pattern data and windshield survey report provided by the ERCA (Figure 5). Other information, such as tillage type, tillage time, planting times, harvest date, harvest amount, fertilizer use, and application rate for some fields were also available for limited fields from farmer surveys. Table 3 represents land codes based on plot number with their respective area in percentage. Detailed explanation of land codes is available from the author upon request.

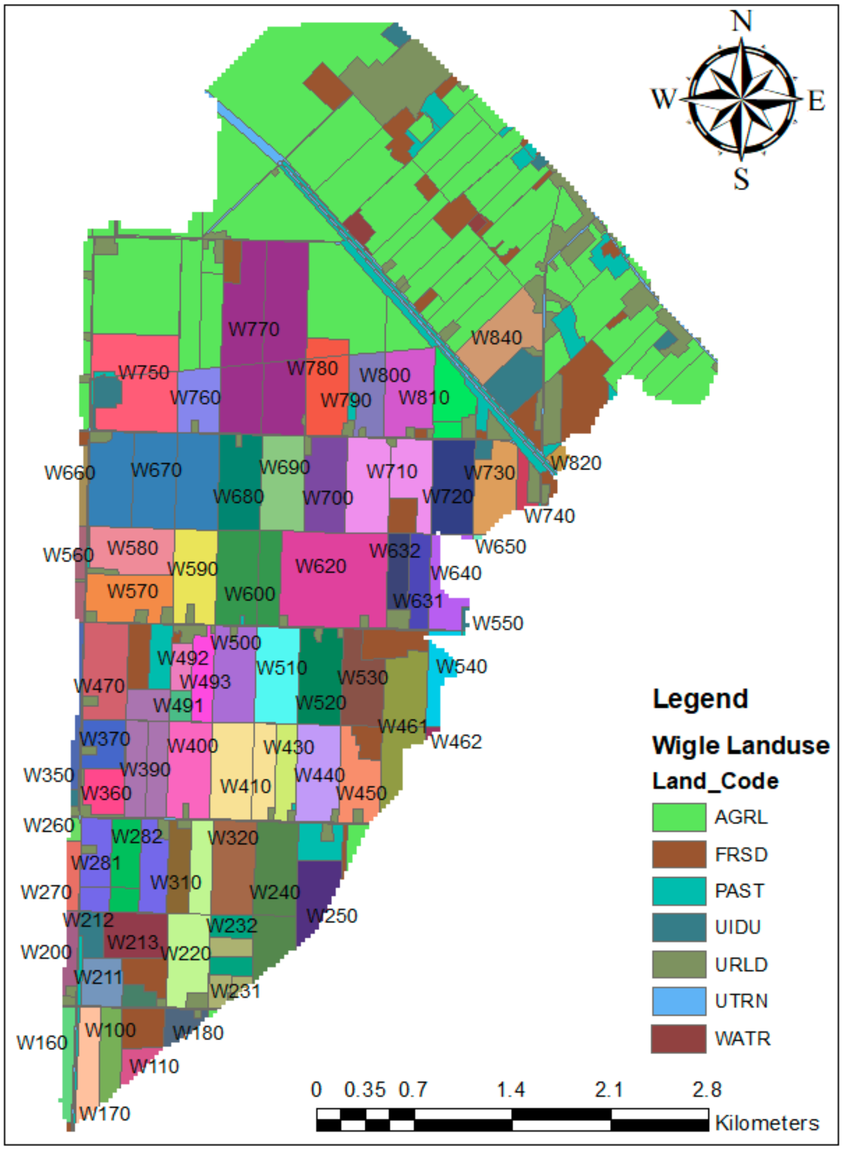


Figure 5. Land management Distribution in the Wigle Creek Watershed Model.

Table 3. Land Codes Based on Plot Number and Respective Area in Percentage

Land Code	Total Area (%)	Land Code	Total Area (%)
AGRL	24.82	W470	1.04
FRSD	5.13	W491	0.18
PAST	2.97	W492	0.25
UIDU	1.56	W493	0.48
URLD	5.29	W500	1.04
UTRN	1.52	W510	1.07
WATR	0.22	W520	1.06
W100	0.5	W530	0.88
W110	0.25	W540	0.43
W160	0.34	W560	0.2
W170	0.66	W570	1
W180	0.28	W580	1.01
W200	0.24	W590	1.02
W211	0.48	W600	1.57
W212	0.16	W620	2.6
W213	0.76	W631	0.48
W220	1.47	W632	0.48
W231	0.43	W640	0.5
W232	0.51	W650	0.01
W240	1.64	W660	0.16
W250	0.73	W670	3.17
W260	0.06	W680	1.04
W270	0.22	W690	1.11
W281	1.35	W700	1.03
W282	0.74	W710	1.85
W310	0.51	W720	1.06
W320	1.03	W730	0.84
W350	0.21	W740	0.19
W360	0.48	W750	1.87
W370	0.52	W760	0.72
W390	1.4	W770	4.06
W400	1.07	W780	1.05
W410	1.65	W790	0.72
W430	0.5	W800	1.03
W440	1.07	W810	0.71
W450	0.79	W820	0.11
W461	1.35	W840	1.06
W462	0.03		

3.2.5.4 Surface Water Hydrology

In this project, drainage maps were prepared from DEM data and then corrected based on field by field manual ground truth. All the fields in the watershed were visited several times to quantify the flow path pattern. The streams are manually prepared and modified based on ground truthing and then overlapped on the 30x30 meter DEM to detect the flow pattern of the drainage network (Figure 6).

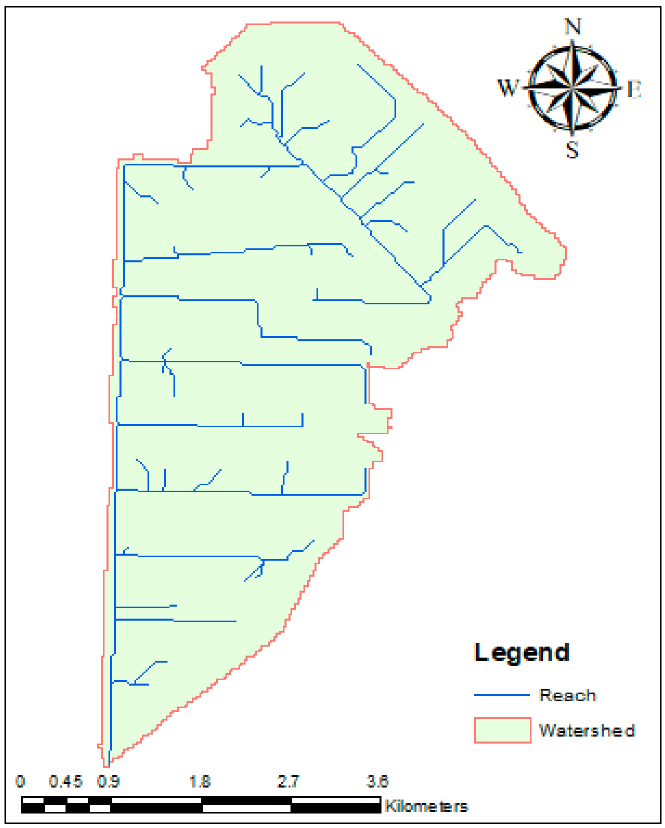
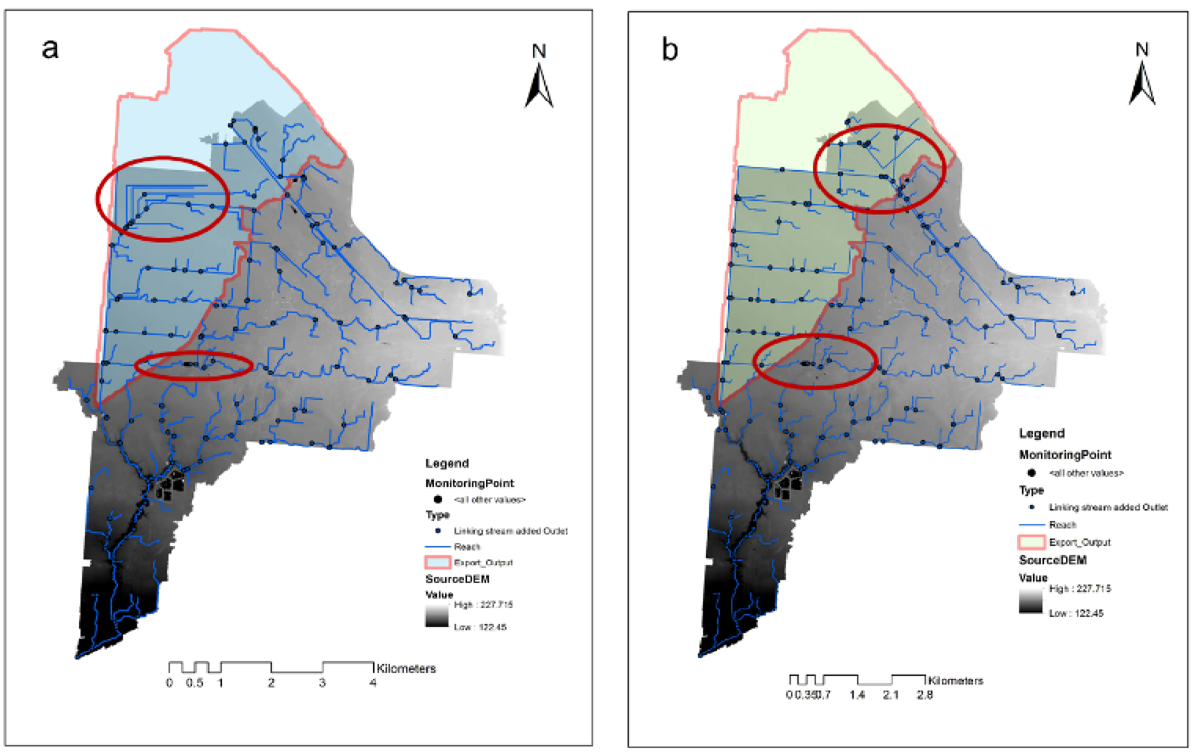


Figure 6. Drainage map of Wigle Creek Watershed.

3.3 Challenges During Model Setup and Delineating the Stream and Sub-watersheds

The 0.5x0.5m Hydro-Enforced DEM was used to develop the change in the drainage network pattern (Figure 7.a). The drainage pattern developed from this DEM was found to be dense throughout the study area due to the high-resolution of the DEM with a 10 ha threshold value. This indicated that the generation of the drainage network would be suitable from the high-resolution

Hydro-Enforced DEM (0.5x0.5m) when the threshold area is smaller. The number of streams and length of the streams are observed to increase when using the high-resolution DEM, as opposed to using the 30m resolution DEM. However, in some areas (particularly the upper middle and upper right side) of the watershed, the drainage formation was not clear; after delineation of the stream network using the 0.5m Hydro-Enforced DEM (Figure 7.a). Therefore, the model was set-up from the manually prepared and modified streams created based on ground truth obtained from field visits. By overlapping the created stream network onto the 0.5x0.5m hydro-Enforced DEM, changes were detected in the pattern of the flow paths. This indicated that the generation of drainage after burning the streams was much more suitable for analysis with the high-resolution DEM (0.5m). However, there were still issues in some areas (upper right side) in the watershed where the drainage formation was not clear (near the highway); after delineation of the stream network by 0.5m Hydro-Enforced DEM (Figure 7.b).



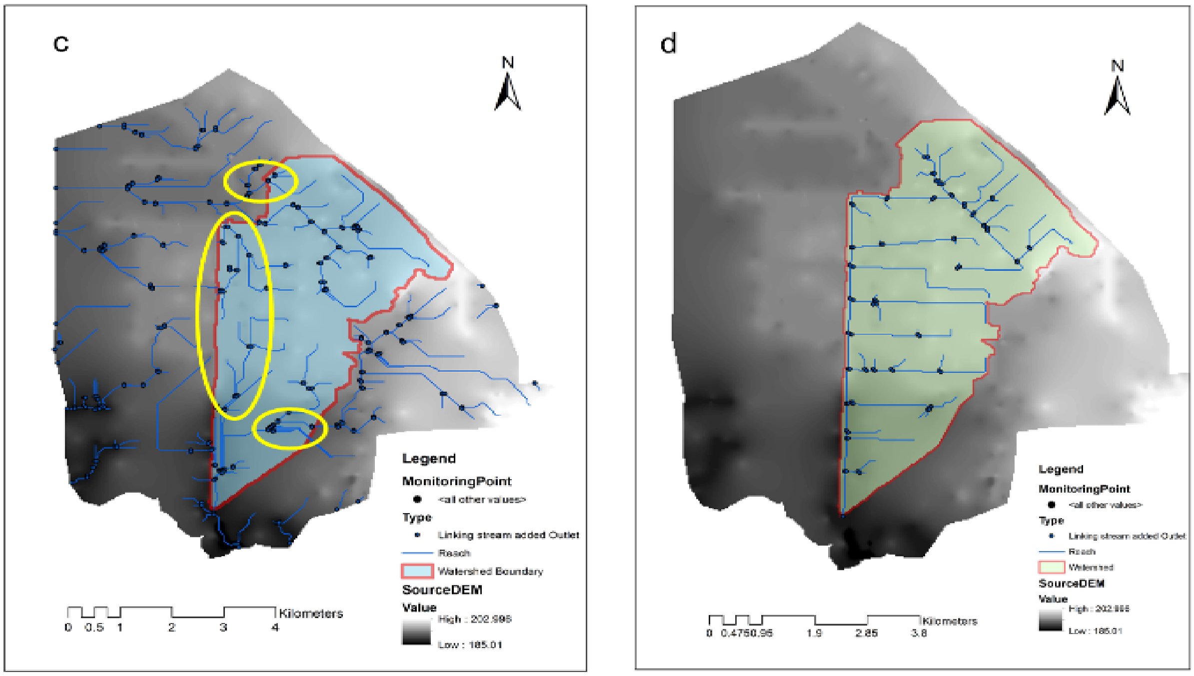


Figure 7. Stream Delineation of the Wigle Creek Watershed: a) Stream Network Generated by the 0.5 x 0.5m Hydro-Enforced DEM; b) Modified Burn-In Stream Network on the 0.5 x 0.5m Hydro-Enforced DEM; c) Stream Network Generated by the 30x30m DEM; d) Modified Burn-In Stream Network on the 30x30m DEM.

In the third case, the SWAT model was set-up using the 30x30m resolution DEM to observe the changes in the pattern of the stream network. The stream density was observed to have decreased with increased threshold values for area (Figure 7.c). Hence, the drainage pattern was found to disappear in the middle and upper part of the watershed, which is draining towards the left side (Cadar creek watershed), due to the low-resolution of 30x30m DEM (Figure 7.c). This indicates that the generation of the drainage network would not be suitable for the low-resolution DEM (30m), when the threshold area is smaller. The number of streams and length of the streams visibly decreased when comparing the low-resolution DEM to the high-resolution DEM. In the fourth case, the model was set-up with the 30m DEM using the modified burn-in streams from ground truthing. In this case the drainage network pattern was found to be realistic in the middle part of the watershed after burning the streams. Most of the streams on the left-side and upper part of watershed were found to drain towards the outlet (Figure 7.d). Therefore, the fourth option was selected for the set-up of SWAT model for Wigle Creek watershed.

3.4 Model Performance Evaluation

Several statistics can be used for model performance evaluation. To evaluate and conduct a qualitative rating of the model results, this study focused on coefficient of determination (R^2), the percentage of bias (PBIAS), and the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970). Different ranges of these statistics, suggested by Moriasi et al. (2015) and used in this study are given in Table 4. Furthermore, many researchers, e.g. Abbaspour (2005) have favoured stochastic model calibration, over traditional deterministic calibration. Their study also used two such statistics in conjunction with an uncertainty analysis, as described earlier: the p- and r-statistics. The p-statistics (p-stat) indicates the percentage of observations bracketed by the 95% prediction uncertainty band, while the r-statistics (r-stat) reflects the width of the band. Ideally, one would prefer all observations (p-statistics = 1) bracketed in a very narrow band (r-statistics = 0). It should be noted that higher p-statistics could be obtained with an increased r-factor (Abbaspour et al., 2004).

Table 4. Statistics for model performance evaluation and range of values for a qualitative rating (Moriasi et al., 2015).

Variables	Statistics	Qualitative Ratings			
		Very Good	Good	Satisfactory	Unsatisfactory
Streamflow (D-M-A)	R^2	> 0.85	0.75 to 0.85	0.6 to 0.75	< 0.6
	PBIAS	< 5%	5 to 10%	10 to 15%	> 15%
	NSE	> 0.8	0.7 to 0.8	0.5 to 0.7	< 0.5
Sediment (M)	R^2	> 0.80	0.65 to 0.80	0.4 to 0.65	< 0.4
	PBIAS	< 10%	10 to 15%	15 to 20%	> 20%
	NSE	> 0.8	0.7 to 0.8	0.45 to 0.7	< 0.45
Phosphorus (M)	R^2	> 0.80	0.65 to 0.80	0.4 to 0.65	< 0.4
	PBIAS	< 15%	15 to 20%	20 to 30%	> 30%
	NSE	> 0.65	0.5 to 0.65	0.35 to 0.5	< 0.35
D: Daily; M: Monthly; A: Annual					

Chapter 4: Model and Scenario Setup

4.1 Watershed Delineation

The first step to set up SWAT model was to delineate the watershed or basin using a digital elevation model (DEM) and watershed characteristics (soil and land use). The delineation can be performed either by using a preprocessed stream and boundary or through automatic delineation. In this project, predefined streams were used in the delineation. As indicated earlier, the predefined streams were created from ground truth of the watershed channels and waterways. The stream definition for flow direction and accumulation was handled by the DEM based on the predefined streams and gave the defined area of the Wigle Creek watershed model. With the delineation, the watershed was divided into 78 sub-basins with a cumulative area of approximately 19.49 km^2.

4.2 Soil Characterization

Wigle Creek is composed of two soils, Brookston Clay and Caistor Soil. Based on the watershed delineation, the Brookston clay covers approximately 99.7% of the watershed. Both soils consist of 3 layers, and are composed primarily of silt and clay, with less than 20% sand. The Brookston clay belongs to soil group C and is referred to a clay loam, whereas the Caistor soil belongs to soil group B and is classified as a silt loam.

4.3 Land Management

Land management data was obtained from the survey of farmers conducted by ERCA. The surveys detail the crop grown, tillage practices, amount of fertilizer used, application method, harvesting efficiency, including dates for these operations for 2012. About 29% farmers in this watershed participated in the survey and the response was incomplete. There was no information about the timings for various operations, as some data for the plots were not available from the local survey with some landuse data was extracted from the 2 years windshield survey provided by ERCA. Data related to timing of operation such as planting, tillage operation, fertilizer application, and harvesting etc., were taken from Jeannettes Creek's datasets (Table 5). The fields/plots with no data in the watershed model were assigned a standard corn-soybean rotation according using available information.

4.3.1 Planting Operations

The primary crops grown in the Wigle Creek watershed during the study period were corn, soybean, and winter wheat with very small percentage of fields under alfalfa and hay. The management operations data for the primary crops are given in Table 5. No data was available for alfalfa and hay from the surveys, so alternative sources were used to collect such data.

Table 5. Management Operations Times Based on Observations and Time from Jeannettes Creek for Corn, Soybean, and Winter Wheat.

Crop	Corn	Soy	Winter Wheat	
Year	1	1	1	2
Tilling	25-Oct	12-May	24-Oct	
Planting	2-May	15-May	25-Oct	
Fertilizer 1	2-May	15-May	25-Oct	
Fertilizer 2	29-May			25-Apr
Harvest and Kill	20-Oct	12-Oct		20-Jul

4.3.2 Fertilizer and Manure Application

Some data related to fertilizer amount and application methods were only defined within the 5-year surveys. For fertilizer with an undefined application method, it was assumed that the fertilizer was banded into the soil. Similarly, liquid fertilizer with no specified application method was assumed to be sprayed onto the field. Fertilizer use, and application were assumed based on the 5 year-surveys as the 2-year survey did not give enough details.

Crops which required fertilizer amounts and ratio of nutrients are soybean, corn, and winter wheat. The fertilizers used in the 5-year surveys were carefully examined to select the fertilizer amount and nutrient ratio closer to the average values. For soybean, the chosen fertilizer amount and ratio was 56 kg/ha of 11-52-00 (N-P-K) fertilizer. In the case of corn, two fertilizers, in the liquid form, were commonly used during each growing season. The first fertilizer with a ratio of 15-15-03 was applied at a rate of 243 kg/ha. The second fertilizer was applied at a rate of 608 kg/ha with nutrient ratio 28-0-0. Winter wheat was also found to use two types of fertilizer application, one fertilizer with a nutrient ratio of 11-52-0 was plied at a rate of 95 kg/ha. The second applied at a rate of 510 kg/ha with a ratio of 28-0-0 was in liquid form.

In SWAT, the parameter FRT_SURFACE determines the fraction of fertilizer applied to the top 10 mm of the soil. The default FRT_SURFACE is 0 for the "Fertilizer application" operation, which was used for banded fertilizer and injected liquid fertilizer. In the case of surface broadcasted fertilizer and sprayed liquid fertilizer, FRT_SURFACE was set to 1.

4.3.3 Tillage Operations

Tillage operations were extracted from the 5-year and 2-year surveys. The most observed tillage operation in the Wigle Creek watershed was in the form of conventional Tillage and conservation tillage, primarily no-till. Most of the cases of conservation tillage were being practiced on fields for which the farmers participated in the 5-year surveys or in the case of the windshield survey, when growing soybean for 2-year rotations. Only 3 cases of minimum tillage were found from the 2-year windshield survey report. In the 5 years survey many farmers did not specify yearly tillage operations. Any unspecified form of tillage in the 5-year surveys was assumed to be no-till, which corresponded to a list of BMPs practiced in Wigle Creek between years 2015 and 2017.

4.4 Tile Drain Characterization

Not enough information regarding tile drainage was available for the Wigle Creek watershed; however, it is known that most fields have tile drainage. For this study, tile drainage was simulated for all agricultural fields in the watershed using the recommended values for depth to drain (DDRAIN) from the SWAT IO documentation, the drain tile lag time (GDRAIN) and time to drain soil to field capacity (TDRAIN) reported by Merriman et al. (2018a) was used. Based on these documents the depth to drain was assumed to be 900 mm for all fields in the watershed. The time to drain soil to field capacity and lag time were assumed to be 48 hours and 24 hours, respectively

(Table 6). However, these values can very spatially, and more detailed characterization of tile drain can be setup in SWAT if more detailed data are available.

Table 6. Tile drainage parameter values for SWAT setup.

Soil type	Depth to surface drain (mm)	Time to drain soil to field capacity (hour)	Tile drain lag time (hour)
ONBKNA	900	48	24
ONCTRA	900	48	24

4.5 HRU Formation

After watershed delineation, SWAT develops HRUs based on soil, landuse, and slope (DEM) inputs, and uses the HRUs to compute landscape processes. SWAT provides the ability to set thresholds for soil, landuse, and slope layers based on the amount of area a class takes up. Any class' area under the threshold then get distributed to the remaining types. Daggupati et al. (2011) used a zero threshold for soil, landuse and slope to represent each field as its own HRU. This method was followed to control and maintain each field's management. However, it should be noted that fields may have sub-basin boundaries split them into multiple HRUs, as is the case in the Wigle Creek watershed model. These HRUs, though having different values based on the sub-basin they are in, will maintain the same unique characteristics and management.

4.6 Characterization of BMPs

This section describes the BMPs used in the Wigle Creek watershed.

4.6.1 Conservation Tillage

Conventional tillage refers to traditional, mechanized crop production systems seedbed preparation that consists of several field operations (Lobb et al., 2007). These field operations include, mouldboard ploughing to turn the soil, breaking sod, incorporating crop residues, and aerating and warming the soil. Conservation tillage refers to any tillage practice that aims to reduce the amount of soil erosion through fewer and less disruptive operations. Types of tillage considered to be a form of conservation tillage are replacements for mouldboard plough including: chisel plough, disc plough, blade plough or sweep plough (Lobb et al., 2007). Conservation tillage also retains most of the crop residue on the surface. This lowers soil erosion by water and wind by absorbing the impact of rainfall, slowing water flow over the soil surface, and maintaining soil stability. The residue protects the surface structure and porosity of the soil, retaining the soil's infiltration capacity while also decreasing runoff (Lobb et al., 2007). In the Wigle Creek watershed, most tillage is primarily done using a mouldboard plough, with some fields practicing conservation tillage in the form of minimum tillage or no-till.

4.6.2 Cover Crops

Though multiple cover crops are used in Ontario such as cereal rye and red clover, an ERCA representative stated that oats and radish are the common cover crops used in the Wigle Creek watershed. Oats were chosen for the cover crop to use for scenarios in the model as they were the cover crop defined in some of the surveys (Table 7). Based on information given by the ERCA, the oats grown in Wigle Creek are winterkilled, with the Sustainable Agriculture Research & Education Program (SARE) stating that they are often seeded for USDA hardiness zones 7 or colder.

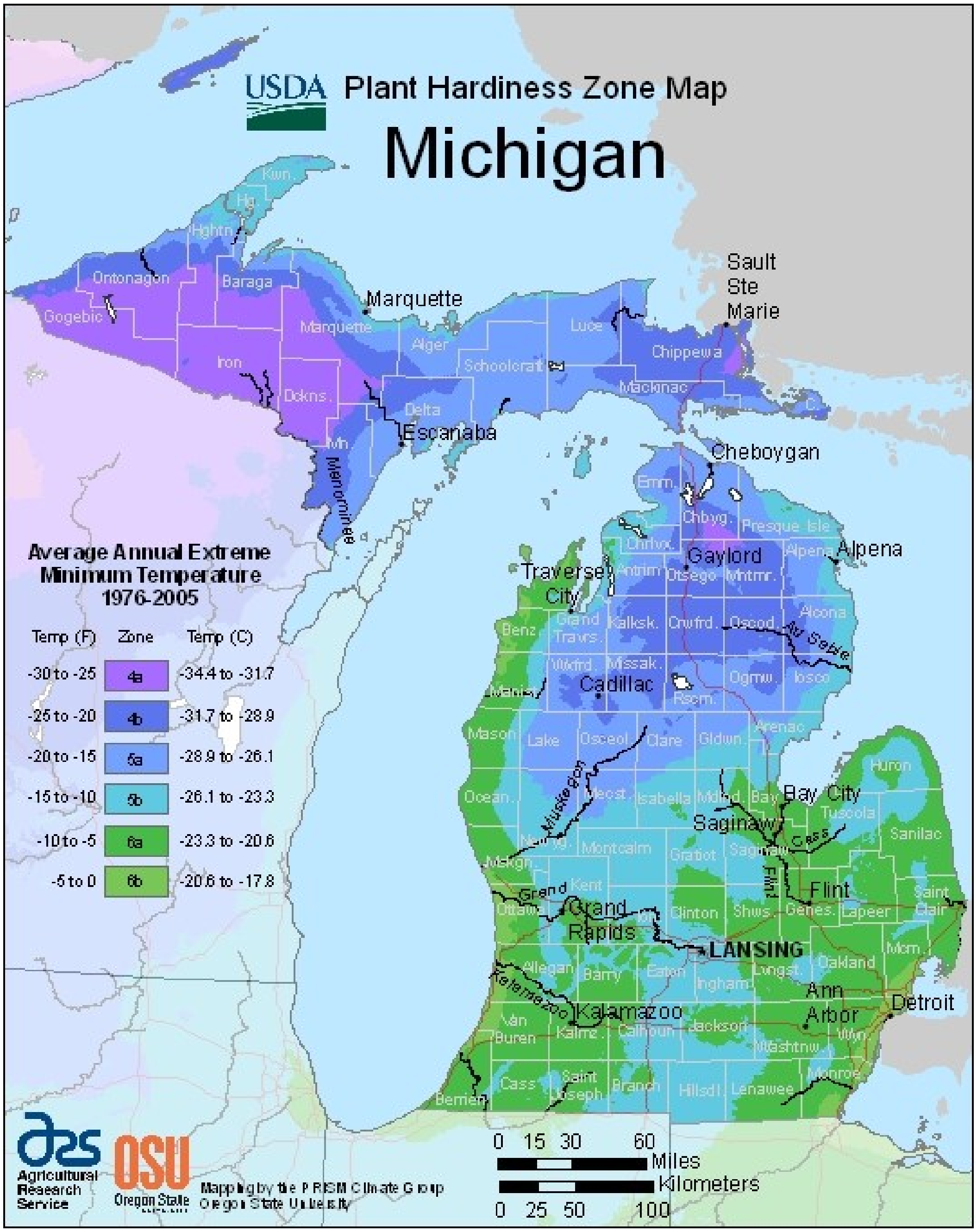


Figure 8. USDA Plant Hardiness Zone Map of Michigan (Source: 2012 report, Agricultural Research Service, U.S. Department of Agriculture).

Wigle Creek is close to the US border, located South-East of Detroit on the edge of Lake Erie. From the USDA hardiness zone map of Michigan, the region is predominantly hardiness zone 5 and 6, which fits the description of winterkilled oats for those zones (Figure 8). Oats suffer serious cold damage at around and below 20°F (-7°C) and completely die off at 6°F (-17°C), reported in the article "Growing for Market" (2016). It can be assumed that they die off at the lower temperature, as well as an ERCA representative stating that the oats in Wigle Creek generally winterkill at the start of January.

Table 7. Cover Crop Management Operations.

Crop	**Oats**	
Year	1	2
Tilling	24-Aug	
Planting	25-Aug	
Harvest and Kill		1 -Jan

4.6.3 Retiring Agricultural Land

Retiring of agricultural land is the cessation of agricultural activities either for specific fields, particularly marginal lands, or of a larger area. The land is restored to its previous environment of either grassland, pasture, forest, or a mixture of these (flora of the Southern Ontario region). This represents the best-case scenario for reduction of phosphorus loads as there is no tillage practices, fertilizer applications, or harvesting of crops.

4.6.4 Vegetative Filter Strips

Vegetative filter strips are gently sloping, bands of planted indigenous vegetation. Filter strips provide localized erosion protection as well as filtering to reduce sediment and phosphorous and other pollutants from agricultural runoff. As vegetative filter strips have low installation and maintenance costs, as well as their perceived effectiveness in removing pollutants, conservation and regulatory agencies are encouraging their use (Dillaha et al., 1989). However, the riparian buffer length, width and slope were characterized in SWAT to simulate riparian buffer effects.

4.7 Definition of BMP Scenarios

The following section describes the scenarios that were tested in the Wigle Creek watershed.

4.7.1 Current BMPs

The "Current BMP" scenario covers all the existing BMPs applied in the Wigle creek watershed during 2016-17 (Figure 9). Most of the BMPs practiced in the Wigle Creek watershed are non-structural BMPs. It includes no-till, minimum tillage, cover crops, phosphorus management, variable rate fertilizer application, and in-field erosion control structures. Some of these BMPs that did not have enough data or information regarding their application or locations include phosphorus management, variable rate fertilizer application, and in-field erosion control structures.

4.7.2 No BMPs

The "No BMPs" scenario is the retiring of all BMPs from the "Current BMPs" scenario. This is to be used as a comparison to all scenarios to calculate the effectiveness of the varying BMPs implemented in the model.

4.7.3 Current Min-Till

The "Current Min-Till" scenario was created by removing all other BMPs that are currently implemented in the watershed ("existing BMPs" scenario). This can help to determine the effectiveness of the other BMPs.

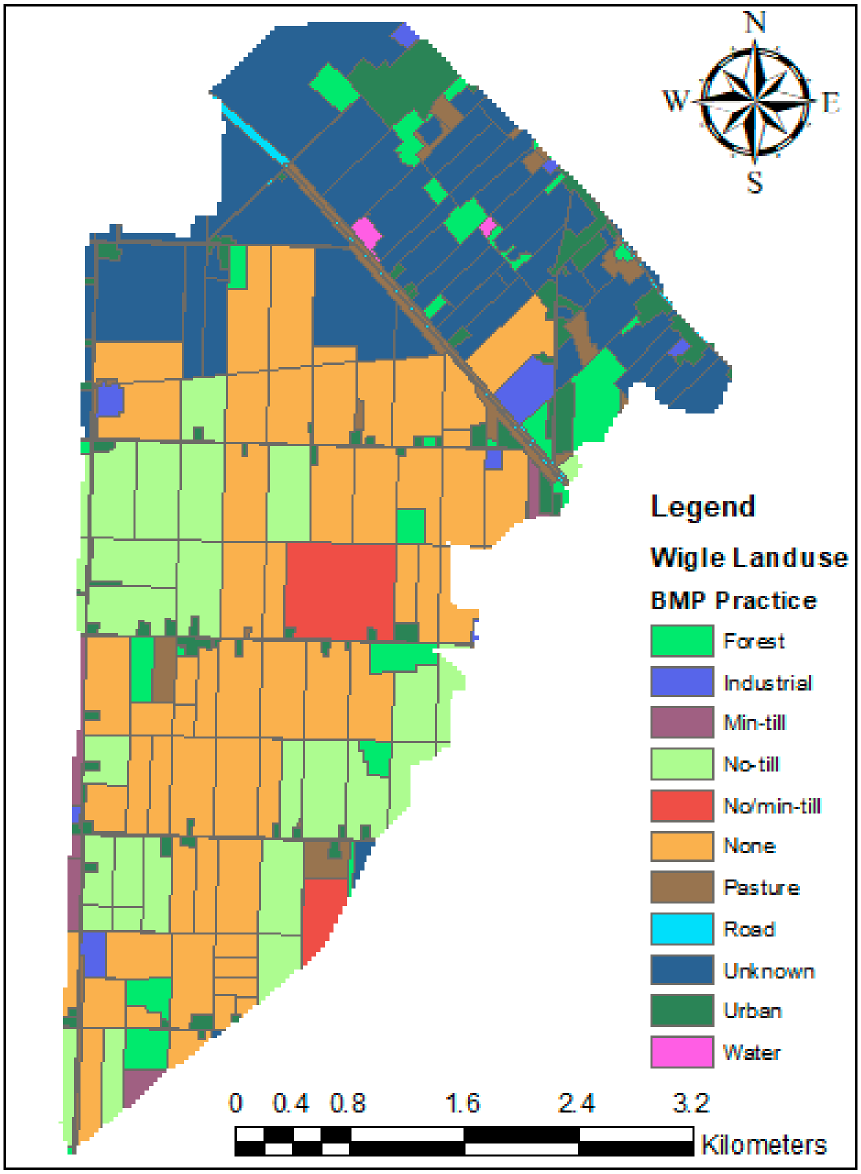


Figure 9. Current BMPs and Locations in the Wigle Creek Watershed.

4.7.4 All Fields Min-Till

In "No BMPs" scenario, the minimum tillage was applied to the fields, this is done by modifying the tillage operations in the management file. In the case of soybean, the tillage operation is set to "Generic No-Till Mixing", while other crops had the tillage operation set to "Generic Conservation Tillage". For this scenario, all curve number (CN2) of the crops were reduced by 2 in the tillage operation's curve number of the operation (CNOP). Both parameters BIOMIX.mgt and OV_N.hru were also changed to 0.4 and 0.2 respectively based on the approach used by Merriman et al. (2018a) and Merriman et al. (2018b).

4.7.5 All Fields under No-Till

Similarly, as the "All Fields Min-Till" scenario is based on the "No BMPs" scenario, the "All Fields No-Till" scenario changes all tillage operations in the management to the "Generic No-Till Mixing" option. In this scenario, all curve number (CN2) values were reduced by 5 for the CNOP for the tillage operations in the management file. Both parameters BIOMIX.mgt and OV_N.hru changed to 0.5 and 0.3, respectively based on the approach used by Merriman et al. (2018a).

4.7.6 Retire Agriculture Fields (Pasture)

The "Retire Agricultural Fields (Pasture)" scenario removes all agricultural management operations and replaces them with the PAST (pasture) management schedule. All agricultural fields also had their CN2.mgt modified based on soil group and OV_N.hru changed to 0.15 based on the land cover database values for PAST.

4.7.7 Retire Agriculture Fields (Forest)

The "Retire Agricultural Fields (Forest)" scenario removes all agricultural management operations and replaces them with the FRSD (deciduous forest) management schedule. All agricultural fields also had their CN2.mgt modified based on soil group and OV_N.hru changed to 0.1 based on the land cover database values for FRSD.

4.7.8 Cover Crops after Winter wheat

The "Cover Crops" scenario was used to determine the effectiveness of cover crops after winter wheat when reducing phosphorus for Winter months/non-growing season. Oats were planted in late Summer and winterkilled at the start of January based on information given by an ERCA representative.

4.7.9 Vegetative Filter Strips

In this scenario, filter strips were applied by activating the .ops file and applying the vegetative filter strips at the edge of all agricultural fields. The parameters for the filter strips operations and their values are as follows: VFSI was set to 1, VFSRATIO was set to 40, VFSCON was left at the default 0.5, and VFSCH was set to 0 as outlined in Merriman et al. (2018a).

Chapter 5: Model Calibration

5.1 Flow Calibration

The ERCA monitored flow data from a sampling station named "Wigle1" and is located at the outlet of the watershed. The data collected was primarily instantaneous, with some days having multiple points of sampling which were averaged for those specific days. Only 47 days of monitored data were available between the period from the start of 2016 and middle of 2017. Calibration was performed by keeping 4 years (2012-2015) as warmup period, and 2 years (2016-17) as a calibration period.

Streamflow calibration in the Wigle Creek watershed focused on improving model performance for the estimation of flow at watershed outlet. Table 8 represents listed various parameter related to flow hydrology (viz, snow and snowmelt-related parameters, groundwater parameters and relative parameters like CN2, SOL_K, SOL_ALB, and SOL_AWC, etc.) which may have spatial patterns that vary from HRU to HRUs at field level. Hence, these parameters were selected for stream flow model calibration, and the final specified parameter values and ranges are listed in Table 8. However, for the final values, the parameter ranges are given in SWAT-CUP, to run for 1000 simulations, with a uniform prior distribution of the parameters based on the upper and lower limits as given in Table 8. Further runs were conducted, if required, as per the 'new parameter sets', recommended by the SUFI-2 algorithm. The statistical indicators used for flow calibration and subsequent calibrations were the Nash-Sutcliffe Efficiency (NSE) and Percentage of Bias (PBIAS). The values calculated for NSE and PBIAS for flow are approximately 0.52 and 6.71%, respectively (Table 8 and Figure 10). The value for NSE falls within the range of 0.5 to 0.7 and is considered satisfactory, with the value for PBIAS falling into the range of ±5% to ±10%, being considered good for flow as displayed in the final evaluation performance criteria in Moriasi et al. (2015).

Table 8. Parameters Used in Flow Calibration.

Parameter Type	Parameter	File Type	Description	Default Value	Model Range	Wigle Creek
Snow	SMTMP	.bsn	Snow melt base temperature (°C)	0.5	-5 to 5	0.97
Snow	SFTMP	.bsn	Snowfall temperature (°C)	1	-5 to 5	-1.93
Snow	SMFMX	.bsn	Maximum melt factor for snow on June 21 (mm H2O $°C^{-1}$ day^{-1})	4.5	1.4 to 6.9	4.14
Snow	SMFMN	.bsn	Minimum melt factor for snow on December 21 (mm H_2O $°C^{-1}$ day^{-1})	4.5	1.4 to 6.9	2.61
Snow	SNOCOVMX	.bsn	Minimum snow water content that corresponds to 100% snow cover (mm H_2O)	1	0 to 500	4.85
Snow	SNO50COV	.bsn	Fraction of snow volume that corresponds to 50% snow cover	0.5	0.01 to 0.99	0.18
Snow	TIMP	.bsn	Snow pack temperature lag factor	1	0.01 to 1	0.91
Hydrology	ESCO	.hru	Soil Evaporation compensation factor	0.95	0 to 1	0.66
Hydrology	EPCO	.hru	Plant uptake compensation factor	1	0 to 1	0.76
Hydrology	CH_N2	.rte	Manning's coefficient for the main channel	0.014	-0.01 to 0.3	0.083
Hydrology	CH_K2	.rte	Effective hydraulic conductivity in main channel alluvium (mm/hr)	0	-0.01 to 500	1.6
Hydrology	SURLAG	.hru	Surface runoff lag coefficient	2	0 to 24	2.6
Hydrology	GWQMN	.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	1000	0 to 5000	859
Hydrology	RCHRG_DP	.gw	Deep aquifer percolation fraction	0	0 to 1	0.24
Hydrology	GW_DELAY	.gw	Groundwater delay time (days)	31	0 to 2000	31.5
Hydrology	GW_REVAP	.gw	Groundwater "revap" coefficient	0.02	0.02 to 0.2	0.084
Hydrology	ALPHA_BF	.gw	Baseflow alpha factor	0.048	0 to 1	0.041
Hydrology	REVAPMN	.gw	Threshold depth of water in the shallow aquifer for “revap” or percolation to the deep aquifer to occur (mm H_2O)	750	200 to 500	416.75
Hydrology	SOL_AWC	.sol	Available water capacity of the soil layer (mm H_2O/mm soil)	Varies	-0.1 to 0.1*	0.09*
Hydrology	SOL_K	.sol	Saturated hydraulic conductivity (mm/hr)	varies	-0.1 to 0.1*	-0.06*
Tile Drainage	DEP_IMP	.hru	Depth to impervious layer in agricultural fields (mm)	6000	0 to 6000	2100
Tile Drainage	DEP_IMP	.hru	Depth to impervious layer in non-agricultural fields (mm)	6000	0 to 6000	6000
Tile Drainage	DDRAIN	.mgt	Depth to drains (mm); must be >0 to initiate tile drainage	0	0 to 2000	900
Tile Drainage	TDRAIN	.mgt	Time to drain soil to field capacity (hours)	0	0 to 2000	48
Tile Drainage	GDRAIN	.mgt	Drain tile lag time (hours)	0	0 to 2000	24

*Relative changes based on % (-0.1 to 0.1 is a relative change of -10% to +10% of the parameter value)

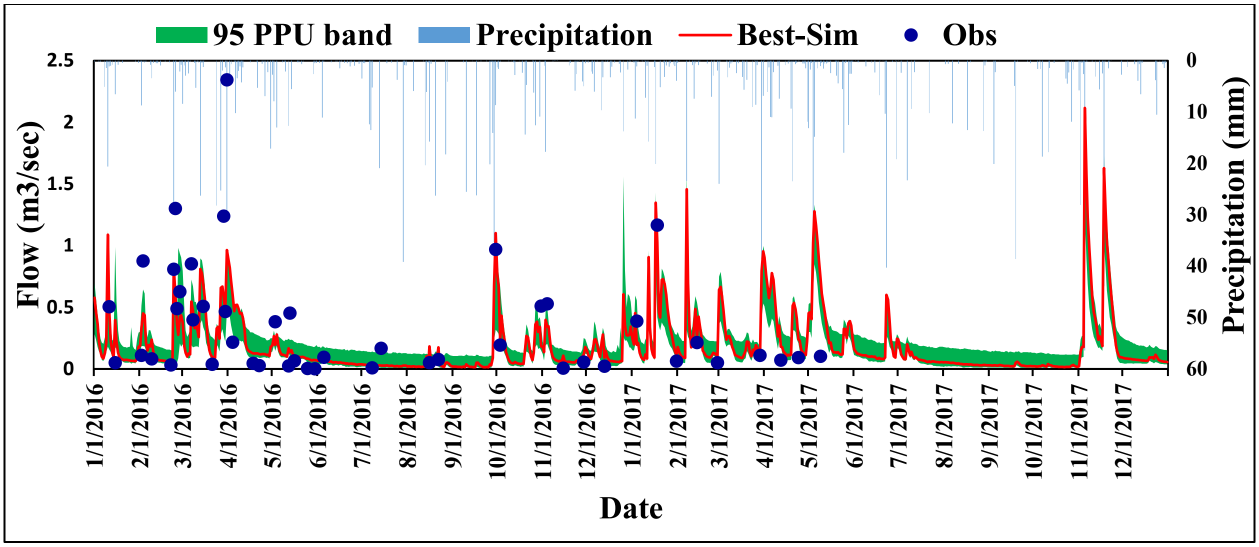


Figure 10. Observed precipitation, and comparison of observed streamflow with simulated streamflow with PPU Band during the period of 2016-17.

Table 9. Model Performance for Flow Simulation at the Outlet.

Station	Period	Samples	Bias	R^2	Daily NSE
Watershed outlet	1/2016 – 5/2017	47	6.71%	0.56	0.52

In addition, an average annual hydrology represents the average water balance for 2016 and 2017 (Table 10). Snow represents a very small amount of precipitation, only being around 3% annually. Typical snow percentage in Ontario is around 10-15%, however an ERCA representative had also stated that there was very little snow in the Wigle Creek watershed area during the simulation period. Climate inputs also displayed minimum temperatures that were commonly well above zero during winter months, leading to more precipitation in the form of rain. Evapotranspiration should typically be around 50% of precipitation, but the model results displayed a slightly higher value. Similarly, the simulated tile drainage (or subsurface runoff) accounts for 25% of the precipitation, which is higher, but within range of the expected 20%.

Table 10. Average Annual Hydrology of Wigle Creek Watershed.

Average Annual Hydrology								
Month	**P (mm)**	**Snow (mm)**	**PET (mm)**	**ET (mm)**	**SR (mm)**	**SUBSR (mm)**	**TR (mm)**	**SED (t/ha)**
1	57.3	4.24	16.68	13.02	13.58	24.225	37.805	0.03
2	49.02	1.62	25.63	17.46	8.12	16.505	24.625	0.03
3	122.45	7.68	47.9	33.49	4.07	38.2	42.27	0.01
4	74.85	0.1	74.66	43.94	0.34	36.145	36.485	0
5	85.4	0	97.03	55.1	0.62	27.3	27.92	0
6	56.83	0	133.58	66.38	0.31	5.045	5.355	0
7	76.62	0	163.2	95.27	0.04	2.5	2.54	0
8	70.2	0	139.79	65.01	0	1.205	1.205	0
9	102.54	0	124.66	59.43	0.62	4.635	5.255	0
10	61.7	0	75.2	28.9	0	16.44	16.44	0
11	96.05	0.1	39.38	22.92	7.36	40.4	47.76	0.2
12	39.25	15.42	18.72	11.6	4.2	9.825	14.025	0
Yearly	892.21	29.16	956.43	512.52	39.26	222.425	261.685	0.11
%	1.00	0.03	1.07	0.57	0.04	0.25	0.29	----------
P is the precipitation, PET is the potential evapotranspiration, ET is the evapotranspiration, SR is the surface runoff, SUBSR is the subsurface runoff, TR is the total runoff, and SED is the sediment yield								

Crop yields were compared after flow calibration to determine whether the simulated yields were acceptable or not, based on the calibrated parameters (Table 11). Data used for the comparison of yields were taken from the five-year surveys report from the ERCA and they are based on a given crop and year and were averaged across the entire watershed, including generic fields. The crop yields simulated from 2012 are higher than the yields obtained by farmers, with winter wheat being lower, but closer to the observed farmer value. The values from 2013 are the opposite of 2012, with simulated yields being closer to the previous year's observed yields, and significantly lower than the current year's observed yields. Only soybean yields were available in 2014, with the simulated value being approximately 12% less than the observed yield. The simulated yields for soybean in 2015 follow the same trend, with the simulated results displaying an approximate reduction of 10% from the observed value, while corn displays an increase of around 3%. In 2016, simulated soybean yields displayed an increase of 11% over the observed value.

Table 11. Average Annual Crop Yield from 2012 to 2016.

Average Annual Yield (kg/ha)						
	Winter wheat		Soybean		Corn	
Year	Observed	Simulated	Observed	Simulated	Observed	Simulated
2012	4202	4038	2297	2863	6170	9985
2013	-----------	------------	2745	2248	8812	6533
2014	-----------	------------	2690	2434	-----------	------------
2015	-----------	------------	3194	2807	9492	9801
2016	-----------	------------	2465	2742	-----------	------------

5.2 Sediment Calibration

The calibration for sediment was performed after flow calibration. The calibration was done through SWAT-CUP, comparing the simulated sediment concentration and loads to the measured concentration and loads keeping 4 years (2012-2015) as warmup period, and 2 years (2016-17) as calibration period. In auto calibration, the best values of selected sediment transport parameters used are shown in Table 12. However, special attention was given to the calibration for high flow periods during which large sediment loads were produced. Hence, the data for sediment was gathered from the same sampling station as the flow data. The data collected for sediment is similar to that of the flow data (Wigle 1, gauging station), where most of the data points are instantaneous, with few points having multiple samples per day (Figure 11). In this case, 127 days of sediment concentration data were available. For the calibration of sediment, sediment load (TSS) data was used. Computation of sediment loads requires flow and sediment concentration data. Therefore, only 47 days of days of data was available for sediment calibration.

Table 12. Parameters Used in Sediment Calibration.

Parameter Type	Parameter	File Type	Description	Default Value	Model Range	Wigle Creek
Sediment	SPCON	.bsn	Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing	0.0001	0.0001 to 0.01	0.0006
Sediment	SPEXP	.bsn	Exponent parameter for calculating sediment reentrained in channel sediment routing	1	1.0 to 1.5	1.27
Sediment	ADJ_PKR	.bsn	Peak rate adjustment factor for sediment routing in the subbasin (tributary channels)	1	0.5 to 2	0.97
Sediment	PRF_BSN	.bsn	Peak rate adjustment factor for sediment routing in the main channel	1	0 to 2	1.54
Sediment	CH_COV1	.rte	Channel erodibility factor	0	-0.05 to 0.6	0.41
Sediment	CH_COV2	.rte	Channel cover factor	0	-0.001 to 1	0.51
Sediment	CH_ERODMO (1-12)	.rte	Monthyl channel erodability factor	0	0 to 1	Varies
Sediment	USLE_K	.sol	USLE equation soil erodibility (K) factor	Varies	-0.1 to 0.1*	0.028*
Sediment	USLE_C	.plant.dat	Minimum value of USLE C factor for water erosion applicable to the land cover/plant	Varies	-0.1 to 0.1*	-0.04*

*Relative changes based on % (-0.1 to 0.1 is a relative change of -10% to +10% of the parameter value)

The calibration statistics for the simulation of sediment is given in Table 13. These results indicate that PBIAS is satisfactory for the simulation of sediment loads and concentration. (Moriasi et al., 2015). However, based on the NSE and R^2, the model performance is unsatisfactory. The model performs slightly better to predict sediment loads than sediment concentration.

Table 13. Model Performance for Sediment Simulation at the Outlet.

Station	Period	Item	Samples	Bias	R^2	Daily NSE
Watershed Outlet	1/2016 – 12/2017	Concentration	123	-1.19%	0.13	0.13
Watershed Outlet	1/2016 – 5/2017	Loading (Calculated)	47	-15.94%	0.31	0.30

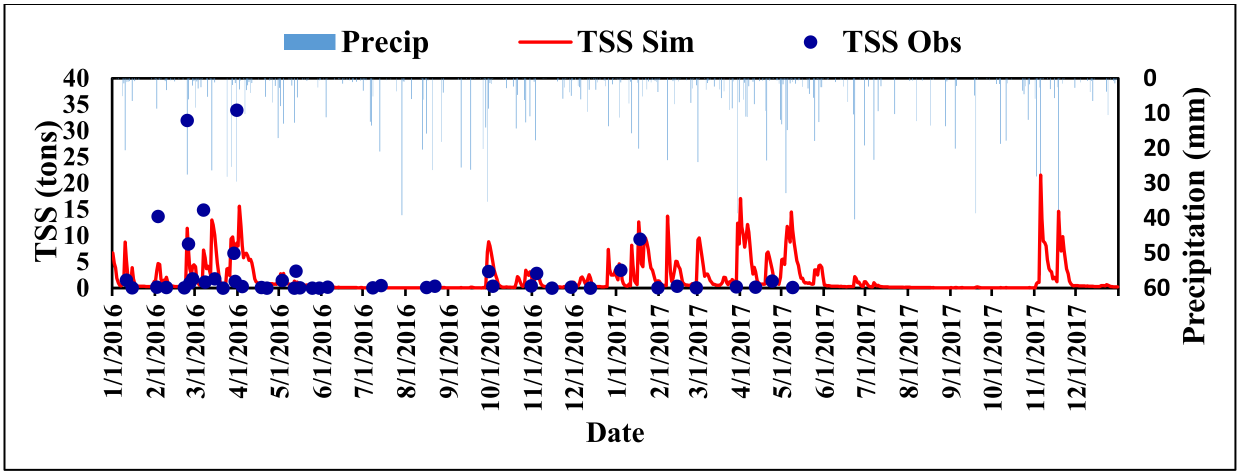


Figure 11. Observed precipitation, and comparison of observed sediment with simulated sediment loads during the period of 2016-17.

5.3 Phosphorus Calibration

After calibration for streamflow and sediment, SWAT model was calibrated for phosphorus for Wigle Creek watershed, keeping 4 years (2012-2015) as warmup period, and 2 years (2016-17) as calibration period using SWAT-CUP. After several runs, a final parameter range of phosphorus related parameters were obtained and used for calibration and uncertainty analysis (Table 14). Following the same sampling and data gathering process as sediment concentration, 127 days of phosphorus concentration were available. This data was of the same quality as the sediment concentration data, instantaneous with few days having multiple points of sampling. The total phosphorus load was calculated from the concentration using the monitored flow data (Figure 12), which was available for 47 days. The calibration statistics are given in Table 15. The value for NSE is below 0.35 and the PBIAS is well above/below ±30%, both of which are not satisfactory based on criteria given by Moriasi et al. (2015).

Table 14. Parameters Used in Phosphorus Calibration.

Parameter Type	Parameter	File Type	Description	Default Value	Model Range	Wigle Creek
Phosphorus	SOL_P_MODEL	.bsn	Soil Phosphorus Model (0=original; 1 = new soil P model)	0	0 or 1	1

Table 15. Model Performance for Phosphorus Simulation at the Watershed Outlet.

Station	Period	Item	Samples	Bias	R^2	Daily NSE
Outlet	1/2016 – 5/2017	Loading (Calculated)	47	82.57%	0.17	-0.08

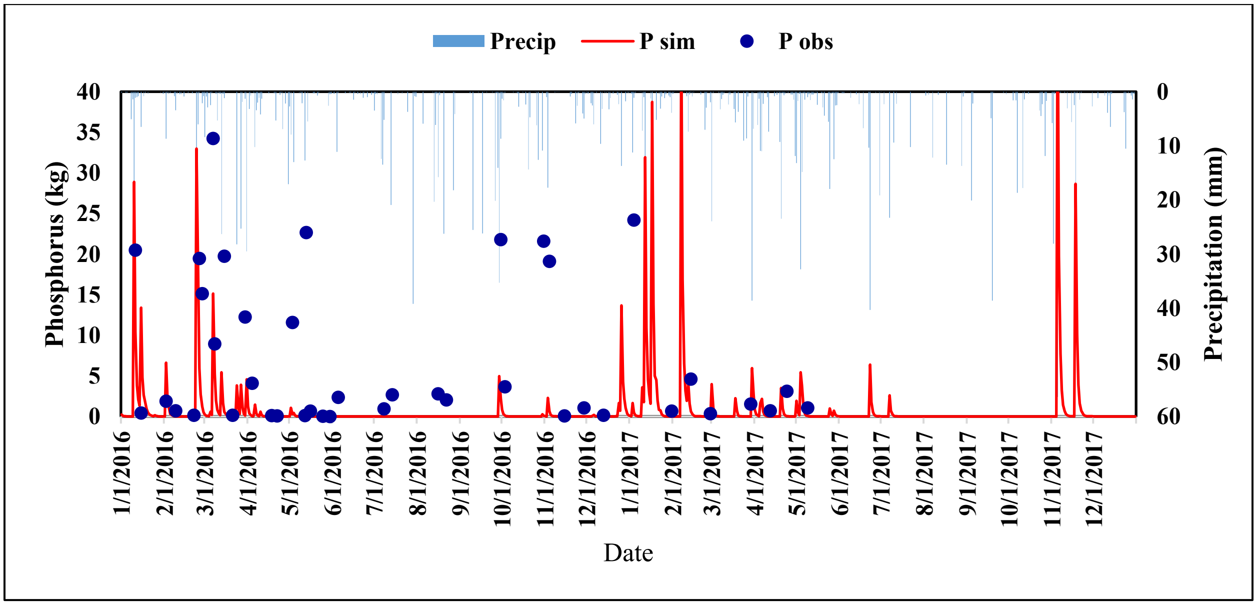


Figure 12. Observed precipitation, and comparison of observed phosphorus with simulated phosphorus loads during the period of 2016-17.

Several efforts were made to improve the phosphorus calibration of the model by adjusting different parameters, including phosphorus uptake (P_UPDIS).bsn, percolation (PPERCO), partitioning (PHOSKD.bsn), availability index (PSP.bsn), enrichment ratio (ERORGP.hru), as well as many of the algae related parameters in the .wwq file; however, these attempts did not improve the model calibration. In some cases, adjusted parameters also affected the flow prediction, which had an additional effect on the TSS and phosphorus loads. Only one calibrated parameter, SOL_P_MODEL.bsn, was found to significantly increase the accuracy without affecting flow and sediment results (Table 14). However, Table 16 represents the best simulated average annual result of the flow, sediment, and phosphorus loads for the Wigle creek watershed for the existing conditions.

Table 16. Average annual Flow, Sediment, and Phosphorus of the Watershed Model.

Year	Average Flow (m3)	Sediment (ton)	Phosphorus (kg)
2016	0.1578	527.5	239.2
2017	0.222	746.5	413.9

5.4 Model Limitations

All the data used in the calibration of the model was instantaneous data, with few days having an average of multiple samples. The days that have multiple samplings did not uniformly spread the times at which observations were taken. This ultimately skews the observed data and affects calibration due to poor data quality. Also, the quantity of data available was limited. The comparison was made between the continuous simulated results and instantaneous observation. Poorer model performance needs to be kept in mind while interpreting the results of BMP simulations. It is expected that better results would have been obtained had data been available for more events per year and for more years.

Chapter 6: BMP Scenario Results

6.1 Effectiveness of Currently Implemented BMPs

In this study, the calibrated SWAT model was used to assess the effectiveness of current BMPs. The current scenario consists of past land management practices such as, minimum-till and no-till. To achieve this, existing BMPs were removed from the calibrated model to determine the phosphorous load at the watershed outlet. Results of BMP scenarios were analyzed on both yearly and seasonal (non-growing and growing season) bases to observe the effectiveness in phosphorus load reduction in the Wigle Creek watershed. The non-growing season includes the period from November to April, when most crops are not growing. The growing season includes the months from May to October. In this study, all scenarios were compared to the "No BMPs" scenario.

The results for the change in phosphorus loads to existing BMPs are presented in Figure 14 and Table 17. The current BMPs implemented in the Wigle Creek watershed show an annual reduction of approximately 1.05% and 4.01% in 2016 and 2017 respectively. Based on the growing and non-growing season, the phosphorus reductions are higher during late Fall to mid-Spring (non-growing season) as presented in Figure 14. The reduction in total phosphorus is primarily from the reduction of organic phosphorus, with a smaller increase in mineral phosphorus. The current BMP implementation of Wigle Creek shows no significant increase or decrease in either flow or sediment yield at the outlet (Table 17).

Table 17. Effectiveness of existing BMPs at the watershed outlet during 2016-2017.

Existing BMPs Reductions (%)						
Year	**Season**	**Flow**	**TSS**	**P Organic**	**P Mineral**	**P Total**
2016	Non-Growing	-0.47	-1.01	-4.69	0.70	-2.57
	Growing	2.13	3.74	11.55	100.22	43.56
	Year	0.25	-0.11	-4.07	3.66	-1.05
2017	Non-Growing	0.16	0.36	-11.69	9.49	-4.29
	Growing	0.99	1.23	0.00	-0.04	-0.03
	Year	0.41	0.58	-11.12	8.45	-4.01

* Negative numbers represent a reduction whereas positive numbers are an increase

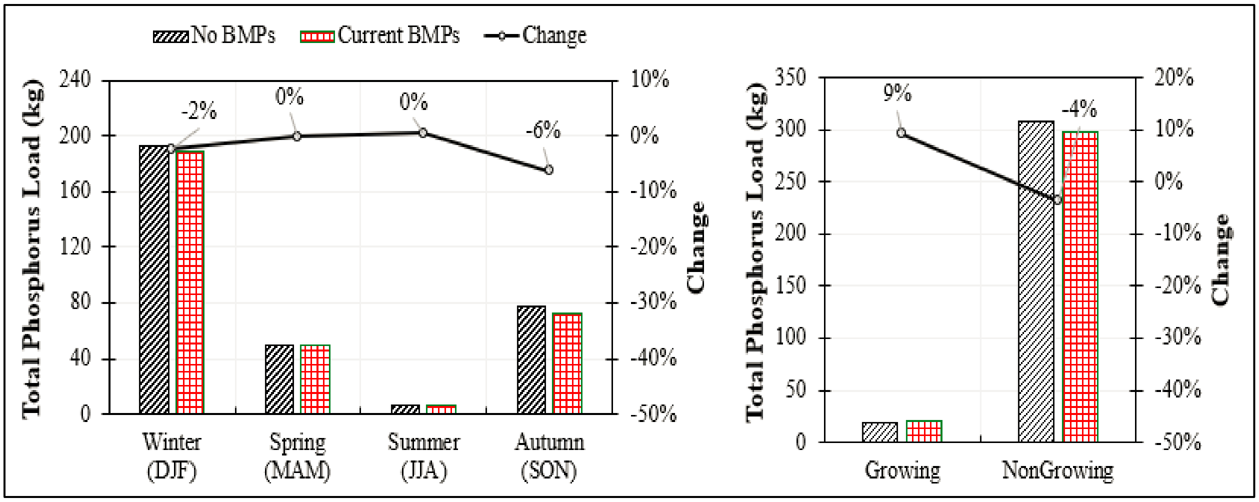


Figure 13. Seasonal and growing/non-growing annual total phosphorus load exported to watershed outlet with existing BMPs.

6.2 Effectiveness of Possible BMPs

After examining the effectiveness of existing BMPs, the calibrated model was used to evaluate the effectiveness of possible BMPs (Minimum tillage, No-tillage, Retiring Land scenario, Cover crop after winter wheat, Vegetative Filter Strips). These BMPs were applied in all the fields in the Wigle Creek watershed and the total phosphorus load exported out of the watershed outlet in each scenario case was compared with the "No BMP" scenario, and their effectiveness was computed in various temporal scales (e.g., annual, conventional seasons, and growing/non-growing seasons).

6.2.1 Minimum Tillage Scenario

This tillage scenarios include the modification of all agricultural fields in the watershed area using "All min-till" for all tillage operations and compared with "No BMP" model. The phosphorus reduction for the "All Min-Till" scenario is consistent, showing reductions greater than 40% and 30% on annual loads, during the 2016-17 period (Table 18). However, this is not much of an issue considering that the amount of phosphorus loads during the growing periods is small. Reduced surface runoff decreases soil erosion rate and organic phosphorus transport to the streams. The reductions in total phosphorus can largely be attributed to reductions in organic phosphorus loads at the outlet (Table 18). However, the reductions for mineral phosphorus under this scenario are also considerable and contribute to the overall reduction of phosphorus at the outlet. Thus, sediment yields are also observed to increase or decrease alongside flow; however, these increases can be considered minimal (Table 18). In addition, seasonal results indicate that the reduction in total phosphorus loads during Winter, Spring, Summer and Fall seasons were 40%, 23%, 7% and 33%, respectively (Figure 14). The "all min-till scenario" resulted 11% and 37% reduction in total phosphorus respectively during the growing season and non-growing seasons annually.

Table 18. Effectiveness of All Min-Till Scenario at the watershed outlet during 2016-2017.

All Min-Till Reductions (%)						
Year	**Season**	**Flow**	**TSS**	**P Organic**	**P Mineral**	**P Total**
2016	Non-Growing	1.99	2.71	-50.17	-25.90	-40.59
	Growing	0.37	-0.17	-40.61	-28.32	-36.17
	Year	1.58	2.16	-49.82	-25.97	-40.43
2017	Non-Growing	0.54	0.53	-46.18	-12.25	-34.35
	Growing	0.50	0.57	-3.55	-3.87	-3.74
	Year	0.54	0.55	-44.08	-11.38	-32.21

* Negative numbers represent a reduction whereas positive numbers are an increase

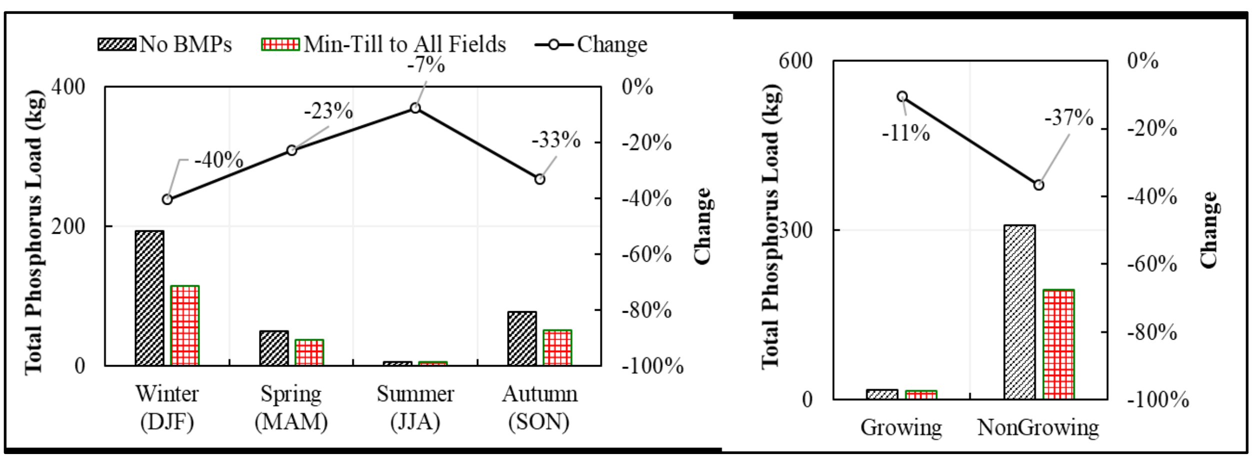


Figure 14. Seasonal and growing/non-growing annual total phosphorus load exported to watershed outlet in the Min-Tillage scenario.

6.2.2 No Tillage Scenario

In this scenario, the results display that no-till practices over the entire watershed provide a 50% annual reduction to phosphorus loads (Table 19 and Figure 15). Like the previous "All Min-Till" scenario, the growing season for 2017 does not show any major reduction in phosphorus. However, the amount of phosphorus loads during this period is relatively small in comparison to the non-growing season loads and may not have a significant impact. Sediment yields under this scenario are greater than the previous ones, though phosphorus yield is greatly reduced. Following the trend of minimum-tillage being applied throughout the entire watershed, no-till provides high reductions in phosphorus yield at the outlet (Figure 15). However, the annual total phosphorus loads reduction in 2016 and 2017 was found to be 57% and 50% respectively at watershed outlet (Table 19). The reduction pattern of total phosphorus in non-growing seasons (54%) was more effective than growing (15%) seasons. However, results indicate the maximum reduction (59%) was during Winter followed by Spring (23%), Fall (58%) and Summer (8%) (Figure 16).

Table 19. Modelling results shows effectiveness of the No-Tillage Scenario at the watershed outlet during 2016-2017.

All No-Till Reductions						
Year	**Season**	**Flow**	**TSS**	**P Organic**	**P Mineral**	**P Total**
2016	Non-Growing	2.24	4.00	-65.87	-42.29	-56.55
	Growing	0.34	-0.02	-64.01	-48.41	-58.38
	Year	1.77	3.22	-65.79	-42.47	-56.61
2017	Non-Growing	0.46	1.30	-64.24	-32.54	-53.19
	Growing	0.41	0.48	-3.66	-4.11	-3.94
	Year	0.45	1.11	-61.27	-29.54	-49.75

* Negative numbers represent a reduction whereas positive numbers are an increase

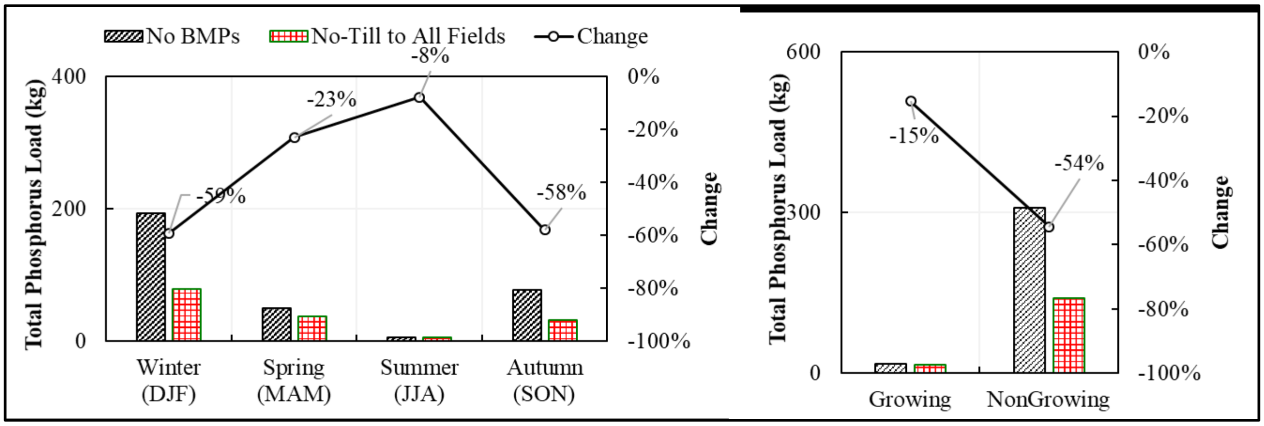


Figure 15. Seasonal and growing/non-growing annual total phosphorus load exported to watershed outlet in the No-Tillage scenario.

6.2.3 Retiring Land Scenarios

The retiring of land scenarios is based on the reintroduction of native flora (trees, shrubs, grasses, etc.,) to agricultural land that is not very practical or profitable. As the data for Wigle Creek watershed was lacking to determine the fields that are not profitable, the operations were given to all agricultural land in the watershed as a best-case scenario. Land retirement may be done by converting it either to pasture or to forest.

6.2.3.1 "Retire Pasture" Scenario

The phosphorus reduction of the "Retire Pasture" scenario is significantly higher than other scenarios discussed so far. The average annual reduction of phosphorus is above 60%, with higher reductions occurring in the non-growing season (Table 20 and Figure 16). As stated earlier, the retiring of land is a best-case scenario where no crops are grown, no tilling of land, and no fertilizer application to the environment. As a result, the phosphorus is significantly reduced both seasonally and annually well beyond applying minimum till and no-till for tillage operations to all fields. Flow also shows significant reductions overall in both years, with the higher reductions occurring during their respective non-growing seasons. Though overall yearly average flow is also reduced, there is a visible increase during the growing period of each simulated year. This scenario displays tremendous reductions in sediment at the outlet for both years. For flow and phosphorus, the reductions occur primarily during the non-growing season when flow and phosphorus are at their peak rates (Table 20). Figure 16 represents the results of conventional four seasons along with growing and non-growing seasons. The data on the “Retire Pasture” BMPs Scenarios shows that the effectiveness of this scenario was poor during Summer when compared to Winter and Fall seasons. This scenario is displays greater effectiveness during the non-growing season months (66%) compared to growing season months (9%) as shown in Figure 16.

Table 20. Modelling results shows effectiveness of possible BMPs “Retire Pasture” Scenarios at the watershed outlet during 2016-2017.

Retire Pasture Reductions						
Year	**Season**	**Flow**	**TSS**	**P Organic**	**P Mineral**	**P Total**
2016	Non-Growing	-23.73	-82.45	-80.59	-48.99	-68.10
	Growing	19.81	-65.79	-63.90	-17.32	-47.08
	Year	-12.23	-79.26	-80.01	-48.03	-67.41
2017	Non-Growing	-31.77	-84.03	-80.24	-35.01	-64.48
	Growing	36.41	-67.42	-9.97	10.22	1.24
	Year	-12.48	-80.15	-76.81	-30.14	-59.87

* Negative numbers represent a reduction whereas positive numbers are an increase

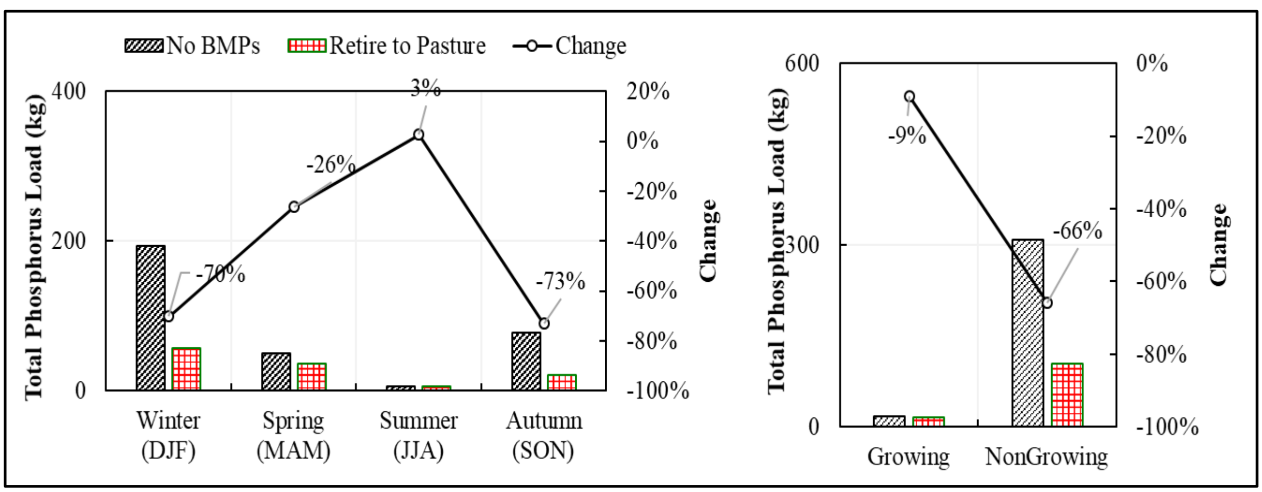


Figure 16. Seasonal and growing/non-growing annual total phosphorus load exported to the watershed outlet in the Retire Pasture scenario.

6.2.3.2 “Retire Forest” Scenario

The “Retire Forest” scenario shows further reductions over the “Retire Pasture” scenario. The average annual reduction of phosphorus under this scenario is above 70% at the outlet, with similar results for the non-growing seasons as seen from the results shown in Table 21 and Figure 17. In terms of flow, the reduction is significant but shows a minimal increase over the “Retire Pasture” scenario. Similar to the comparison of the “Minimum-till” scenario to the “No-Till” scenario, the increase in mineral phosphorus reductions are greater than that of the organic phosphorus, which shows very little improvement. However, the organic phosphorus still accounts for the main factor in total phosphorus reduction. This statement holds true for sediment yield at the outlet under this scenario as well when compared to the previous one. On the seasonal scale, the average annual phosphorous reduction was 78% in non-growing season and 11% for the growing seasons at the watershed outlet (Figure 17).

Table 21. Effectiveness of the Retire Forest scenarios at the watershed during 2016-2017.

Retire Forest Reductions						
Year	**Season**	**Flow**	**TSS**	**P Organic**	**P Mineral**	**P Total**
2016	Non-Growing	-27.53	-83.61	-83.43	-63.89	-75.71
	Growing	25.39	-63.11	-68.53	-46.45	-60.55
	Year	-13.62	-79.70	-82.91	-63.38	-75.21
2017	Non-Growing	-37.03	-85.77	-87.85	-62.72	-79.09
	Growing	40.94	-66.58	-8.59	10.12	1.80
	Year	-14.86	-81.29	-83.98	-54.90	-73.42

* Negative numbers represent a reduction whereas positive numbers are an increase

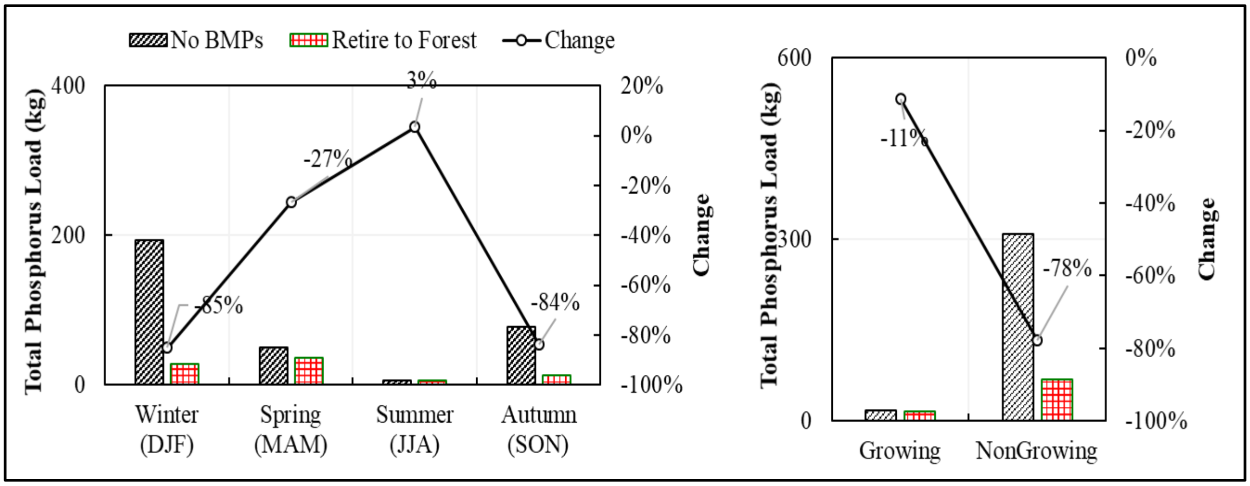


Figure 17. Seasonal and growing/non-growing annual total phosphorus load exported to watershed outlet in the Retire Forest scenario.

6.2.4 Cover crop after Winter Wheat Scenario

The cover crop scenario includes the evaluation of a cover crop after winter wheat based on the "No BMPs" model. As mentioned in section 4.7.8, for the cover crops BMP, oats were chosen based on information from the ERCA. The oats are planted after winter wheat is harvested and are winterkilled at the start of January. In this scenario for the cover crop BMP, the oats planted after winter wheat were applied to all the fields in the Wigle Creek watershed and the simulation results are presented in Figure 18 and Table 22. Unlike the conservation tillage scenarios, cover crops show a decrease in the flow and sediment yield at the outlet of the Wigle Creek Watershed, though remains very small in terms of influence. In addition, the cover crop scenario resulted in a small (3%) reduction in annual total phosphorus loads (Table 22). Cover crops are observed to have some phosphorus reduction, both because of their growth prior to being winterkilled and the residue left during the Winter months. This BMP resulted in a 3% decrease in total phosphorus loads during the non-growing seasons with no change during the growing season. However, the reduction percentages during the non-growing seasons displays a significant effect as compared to the growing season. Most of the reductions in phosphorus load were during the Winter and Fall seasons at watershed outlet, being 4% and 1% respectively (Figure 18).

Table 22. Effectiveness of the Cover Crops scenario at the outlet during 2016-2017.

Cover Crop after Winter Wheat Reductions						
Year	**Season**	**Flow**	**TSS**	**P Organic**	**P Mineral**	**P Total**
2016	Non-Growing	-0.36	-0.20	-2.41	-2.42	-2.41
	Growing	-3.22	-4.01	-0.49	0.08	-0.28
	Year	-1.14	-0.93	-2.28	-2.33	-2.34
2017	Non-Growing	-1.31	-2.24	-3.56	-3.14	-3.41
	Growing	-0.80	-0.71	-0.01	0.01	0.00
	Year	-1.17	-1.86	-3.38	-2.79	-3.17

* Negative numbers represent a reduction whereas positive numbers are an increase

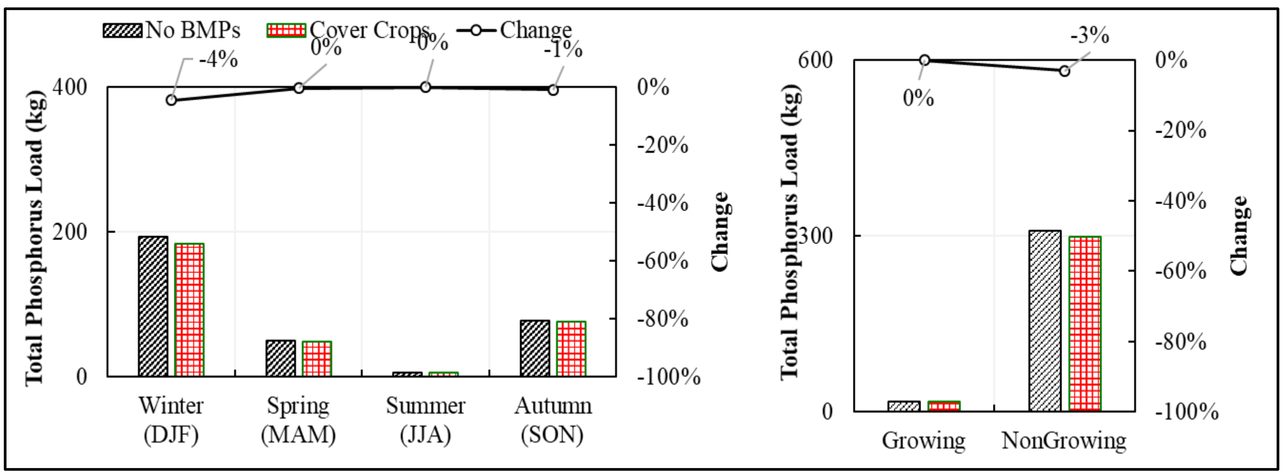


Figure 18. Seasonal and growing/non-growing annual total phosphorus load exported to watershed outlet in the Cover Crops scenario.

6.2.5 Vegetative Filter Strips Scenario

As mentioned in section 4.7.9, the vegetative filter strips (VFS) scenario applies a border to the edge of a field at the sacrifice of seeding area. Based on the parameters used, for every one-unit area of filter strip, there is 40 units of seeding area. As such, the area and width of the filter strips vary based on the size of the HRU they are applied to. Retiring the VFS scenario resulted in a 38% reduction in total annual phosphorus loads at the watershed outlet (Figure 19 and Table 23). The "Filter Strips" scenario shows that filter strips alone provide a significant reduction in the phosphorus runoff. The reductions in both mineral and organic phosphorus are much closer than other scenarios. During Winter, Spring, Summer and Fall seasons the reduction in total phosphorus loads were 45%, 12%, 4%, and 40% respectively (Figure 19). In the case of average annual reductions, a decrease of 8% and 40% is observed in total phosphorus load during the growing season and non-growing season, respectively during simulation period between 2016-17.

Table 23. Effectiveness of the Filter Strips scenario at the watershed outlet during 2016-2017.

Filter Strips Reductions						
Year	Season	Flow	TSS	P Organic	P Mineral	P Total
2016	Non-Growing	0.00	-73.54	-45.56	-33.01	-40.60
	Growing	0.00	-73.57	-35.48	-23.43	-31.14
	Year	0.00	-73.55	-45.20	-32.72	-40.30
2017	Non-Growing	0.00	-73.73	-43.26	-30.77	-38.90
	Growing	0.00	-73.46	-1.91	-1.91	-1.91
	Year	0.00	-73.66	-41.24	-27.68	-36.31

* Negative numbers represent a reduction whereas positive numbers are an increase

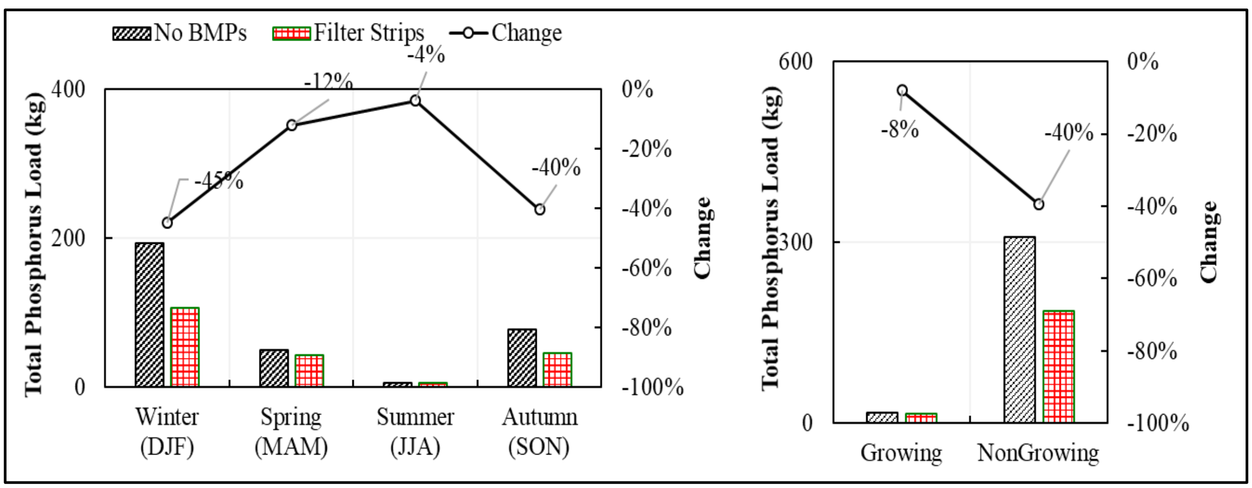


Figure 19. Seasonal and growing/non-growing annual total phosphorus load exported to watershed outlet in the Filter Strips scenario.

Chapter 7: Summary and Conclusions

The SWAT model was built-up and used to simulate possible reductions in phosphorus pollution from the Wigle Creek watershed. The model was calibrated for streamflow, sediment yield, as well as total phosphorus concentration at the watershed outlet. The calibrated model was also used to simulate several possible BMPs and evaluated their effectiveness in reducing total phosphorus export from the watershed.

The simulated average annual phosphorus load at the outlet of the watershed for the current conditions was 326.55 kg. The modelling results show highest reduction in phosphorus loads may be obtained by retiring agricultural fields to either pasture or forest. Retiring to forest had a much higher average yearly reduction in phosphorus loads than retiring to pasture. Conservation tillage throughout the entire watershed resulted in a very large reduction in phosphorus yield at the outlet, with no-till having a greater effect than minimum till practice. When no-till is applied to the whole watershed, the average yearly reduction in phosphorus was approximately 53%, compared to 36% for min-tillage. Vegetative filter strips along the edge of a field in the entire watershed had a significant effect on the reduction (38%) of phosphorus. Cover crops after winter wheat showed very little (3%) reduction in phosphorus yield at the outlet. However, the effects of cover crops after winter wheat are quite clear during the Winter and Non-Growing season.

In this study based on the evaluated BMPs scenarios, the retiring of lands provides the highest reduction of phosphorus loads. However, retiring the lands is also a practically unrealistic option as the agricultural activity in this area is a very significant component of the economy in the region. Application of min-till or no-till to the entire watershed has the potential to significantly reduce the amount of phosphorus loads. This may lead to a dependence on herbicides to control unwanted flora (weeds) and would require investment in land maintenance. This suggests that application of min-till is a possible option as it maintains some of the benefits of conventional tillage while significantly reducing phosphorus loads. Cover crops after winter wheat has very little effect in the reduction of phosphorus loads as cover crops after winter wheat are much more beneficial for nitrogen control. Filter strips along the edge of field provide a significant reduction in phosphorus. This practice however, will reduce the land that available to grow crops resulting in financial loss.

While this study quantified the effectiveness of possible BMPs, the results should be interpreted with caution. The modeling was done based on limited data for calibration and validation; some data used in model was obtained from nearby stations, which may have induced some mismatch and erroneous outputs. All observed data used in model calibration was instantaneous. A significant amount of input data needed was obtained from other sources to fill in the gaps. Precipitation data, though available from nearby stations in the same region, did not show high correlation with the Jack Miner station within the watershed. This can have implications that previous years and the remaining 2017 data, used from the Harrow CDA weather station, may not be an accurate representation for this watershed and may have a significant influence on the simulated results. Similarly, most of the management data was obtained from the Jeannettes Creek watershed, which lies North-East of the Wigle Creek watershed, and may have affected the planting time, and subsequent operations, which can have a significant influence on flow, sediment, and phosphorus loads. Fields without data were assumed to have a simple corn-soy rotation, which may not be true as multiple crops, such as alfalfa, hay, and winter wheat, were also grown in the Wigle Creek watershed. Additionally, data of fertilizer application was missing for some of the fields. The Jeanettes Creek data set used to fill up these gaps also had the same limitations. Runoff from an upstream watershed (ERCA) may have serious ramifications on the quality of flow and water quality modeling as well.

7.1 Future Recommendations

Based on this modelling exercise, several recommendations are made for this watershed: (a) Collection of a full set of meteorological data (such as precipitation, temperature, solar radiation, wind speed and relative humidity) is required for the modelling study. Precipitation data was available from a station within the watershed for a small period, with no temperature data available from the same station. (b) Make a long-term repository of crop and land management data such as crops grown, tillage date and type, plantation date, fertilizer (mineral or organic) application date and rate, crop harvest date and rate, residue management, implementation of any BMPs. (c) More frequent monitoring of flow and water quality data at the watershed outlet. (d) Future monitoring campaigns should also focus on water quality sampling during Winter and early Spring months;

edge-of-field monitoring is recommended to ascertain effectiveness of various BMPs at the field-scale.

Though this study focused on the extrapolation of single BMPs to all agricultural fields, it was found that the areas currently implementing BMPs were not the largest contributors to the phosphorus runoff. Further research in this watershed should focus on the areas which are major contributors to phosphorus losses and apply varying scenarios, both single and combinations of BMPs, to those areas. Applying BMPs to contributing areas would also provide a much more realistic goal when compared to applying practices over a much broader area to achieve desired reductions in nutrient losses.

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