Evaluation of Best Management Practices to Reduce Phosphorus and Sediment Loading in Gully Creek Watershed using SWAT

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Abstract

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The Great Lakes hold over 20% of the earth's surface fresh water. Due to intense agricultural practices, the ecosystems of the Great Lakes have deteriorated. As the water pollution caused by agricultural activity is non-point source pollution, it is much harder to assess the pollution as compared to point sources of pollution where we can identify the sources of pollution easily. With the help of mathematical modeling, we can make a reasonable assessment of such pollution as well as provide different options (best management practices (BMPs)) for mitigating the problem. The Soil & Water Assessment Tool (SWAT) was selected to model the hydrology of the Gully Creek watershed in Ontario. SWAT is a watershed scale, continuous simulation model. Available data were used to calibrate and validate the model, and the Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBIAS), and Coefficient of Determination (R^2) statistics were used to evaluate the model's performance for simulating flow, sediment yield, and phosphorus yield. Due to the scarcity of observed data, calibration was performed for flow, sediment, and phosphorus between the start of 2011 and 2013. Flow calibration of the model was found to be satisfactory, with an NSE of 0.5, a PBIAS of 24.8%, and an R^2 of 0.53. Calibration of sediment yield did not provide satisfactory results for NSE, PBIAS, and R^2, with values of -0.75, 33.8%, and 0.14, respectively. Additionally, total phosphorus load was tested based on the calibration results, and it too did not provide satisfactory results. A "no BMP" scenario was created to evaluate the effectiveness of current and potential BMPs. "Retire to Forest" and "Retire to Pasture" reduced the total phosphorus load the most. Compared to the present practice, "Retire to forest" reduced phosphorus loss by 90%, compared to 73% under "pasture retirement." Conservation tillage BMPs could reduce the phosphorus burden. No-till BMP reduced phosphorus by 23% annually and 16% during the growing season, while minimum tillage reduced it by 8% annually and 1% during the non-growing season. Vegetated filter strips (VFS) at field boundaries reduced phosphorus loss (61%). The cover crop BMP was found to reduce annual phosphorus loss by 13%, whereas during spring, it shows a considerable reduction (29%). This study demonstrates how BMPs and hydrological modeling using SWAT will assist planners in controlling soil and water pollution at the watershed scale. The current study demonstrates conservation methods and offers practical guidance on how to choose the best BMPs for agricultural watersheds.

Résumé

Maîtrise ès sciences **Génie des bioressources**

Les Grands Lacs contiennent plus de 20 % des ressources en eau douce en surface. En raison de pratiques agricoles intenses, les écosystèmes des Grands Lacs se sont détériorés. Comme la pollution de l'eau causée par l'activité agricole est une pollution diffuse, elle est beaucoup plus difficile à évaluer que la pollution à sources ponctuelles, dont on peut aisément identifier les sources. Avec l'aide de la modélisation mathématique, on peut faire une évaluation raisonnable de cette pollution et proposer différentes options [pratiques exemplaires de gestion (PEG)] pour atténuer le problème. Le Soil & Water Assessment Tool (SWAT) a été choisi pour modéliser l'hydrologie du bassin versant du Gully Creek en Ontario. SWAT est un modèle de simulation continue à l'échelle du bassin versant. Les données disponibles servirent à calibrer et valider le modèle. La statistique d'efficacité de Nash-Su cliffe (NSE), le pourcentage de biais (PBIAS) et du coefficient de détermination (R^2) servirent à évaluer la performance du modèle pour la simulation du débit, et des apports en sédiments et phosphore. Faute de données exhaustives, la calibration fut effectuée pour le débit, et les apports en sédiments et phosphore entre le début de 2011 et 2013. La calibration du modèle pour le débit s'est avérée satisfaisante, avec un NSE de 0,5, un PBIAS de 24,8 % et un R^2 de 0,53. Cependant, la calibration de l'apport en sédiments n'a pas donné de résultats satisfaisants pour l'NSE, le PBIAS et le R2, avec des valeurs de -0,75, 33,8 % et 0,14, respectivement. De même, l'exactitude des valeurs simulées de la charge en phosphore totale s'avéra in satisfaisante. Un scénario " sans PEG " fut créé pour évaluer l'efficacité des PEG actuels et potentiels. La charge totale de phosphore fut réduite le plus sous les scénarios "Retirer en forêt" et "Retirer en pâturage," soit de 90 % et 73 % par rapport au système d'exploitation présent. Les PEG de travail de conservation du sol pourraient aussi réduire la charge de phosphore. Les PEG sans labour ont réduit le phosphore de 23 % par an, et, en particulier de 16 % pendant la saison de croissance. Comparativement, un travail minimum du sol l'a réduit de 8 % par an, mais seulement 1 % hors saison. Les bandes de végétation filtrantes (BVF) aux limites des champs ont réduit les pertes de phosphore de 61 %. Une culture de couverture a permis de réduire les pertes annuelles de phosphore de 13 %, avec une réduction considérable (29 %) au printemps. Cette étude démontre comment les PEG et la modélisation hydrologique à l'aide de SWAT peut aider les planificateurs à contrôler la pollution du sol et de l'eau à l'échelle du bassin versant. L'étude actuelle démontre diverses méthodes de conservation et offre des conseils pratiques sur la façon de choisir les meilleures PEG pour les bassins versants agricoles.

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List of Abbreviations

ABCA	Ausable Bayfield Conservation Authority
AGNPS	AGricultural Non-Point Source Pollution Model
AnnAGNPS	Annualized Agricultural Non-Point Source
ANSWERS	Areal Non-point Source Watershed Environment Response Simulation
AVSWAT2000	Arc View Soil and Water Assessment Tools-2000
BASINS	Better Assessment Science Integrating Point and Nonpoint Sources
BMPs	Best management practices
BOD	Biochemical oxygen demand
CASC2D	CASCade 2 Dimensional SEDiment
CSAs	Critical Source Areas
DEM	Digital elevation model
DWSM	Dynamic Watershed Simulation Model (hydrology)
EPA	Environmental Protection Agency
ET	Evapotranspiration
GIS	Geographic Information System
HRU	Hydrological response unit
HSPF	Hydrological Simulation Program – Fortran
KINEROS	Kinematic runoff and erosion model
MUSCLE	Modified Universal Soil Loss Equation
N	Nitrogen
NPS	Nonpoint source
NSE	Nash-Sutcliffe Efficiency

OMAFRA	Ontario Ministry of Agriculture, Food, and Rural Affairs
P	Phosphorus
PBIAS	Percent Bias
PRMS	Precipitation-Runoff Modeling System
R^2	Coefficient of Determination
SUFI-2	Sequential Uncertainty Fitting-2
SWAT	Soil and Water Assessment Tool
SWAT-CUP	SWAT Calibration and Uncertainty Procedures
VFS	Vegetative Filter Strips
WASCoBs	Water and Sediment Control Basins
WBBE	Watershed Based BMP Evaluation

Chapter 1: Introduction

The worsening of water pollution around the world since the 1990s poses more significant risks to human health and the environment (du Plessis, 2022) increasingly. Moreover, through increased extreme weather events, climate change may further challenge the relationship between agricultural activities and water quality (Skidmore et al., 2022). Climate change impacts are projected to be more assertive in regions with cold and temperate climates, which are characterized by severe winter temperatures, frozen ground, freeze-thaw cycles, accumulation and melting of snowpacks, and mixed precipitation patterns (Callesen et al., 2007). On a global scale, agricultural practices (*e.g.*, tillage, artificial drainage, application of fertilizers, animal manure, and pesticides) contribute to a large quantity of nonpoint source (NPS) pollutants (*e.g.*, sediments, nutrients, pesticides, and pathogens) reaching surface waters and groundwater bodies through surface runoff and natural or tile-drain-enhanced leaching (Maringanti et al., 2009; Singh et al., 2007). Excess loading of NPS pollutants like nitrogen (N) and phosphorus (P) into the freshwater and coastal marine ecosystems can cause rapid and excessive aquatic plant and algal growth, followed by a die-off. This is followed by rising biochemical oxygen demand (BOD) and alkalinization associated with eutrophication, a leading cause of impairment in many aquatic ecosystems (Chislock et al., 2013). Consequently, many species of commercial importance or key to environmental sustainability may disappear. Moreover, drinking water drawn from such sources can have an unacceptable taste and/or odor, and be difficult to treat. In waters subject to eutrophication, many algae, toxic to both animals and humans, may bloom to the extent that water bodies may become unfit for recreational purposes, let alone drinking, due to potential health issues. It is, therefore, necessary to mitigate or eliminate eutrophication by limiting the transport of nutrients and sediments from agricultural lands through runoff and subsurface drainage waters; this is particularly critical for P, which can be lost in both soluble and sediment-bound forms and is often the primary limiting nutrient in aquatic ecosystems. Implementation of best management practices (BMPs) within an agricultural watershed can minimize pollutant transport to water bodies (Carpenter et al., 1998).

The Great Lakes are the largest group of freshwater lakes on earth, the second largest by total volume, containing 21% of the world's surface fresh water. In the last few decades, the Great Lakes' health has been subject to a severe threat from farmland producing excessive phosphorusrich runoff. Lake Huron is a large, deep, oligotrophic lake (Berst and Spangler, 1972) and is bounded on the west by Michigan (U.S.) and on the north and east by Ontario (Canada). It provides drinking water, recreation, livelihood, and food to approximately 3 million people in Canada and the U.S. (https://greatlakes.guide/watersheds/huron). Discharging directly into Lake Huron and therefore affecting lakeshore water quality, southern Ontario's environmentally sensitive Gully Creek watershed is in urgent need of pollution control measures being adopted within the watershed. According, the efficacy in pollution control of implementing different BMP schemes at sites across the watershed must be evaluated. Given practical considerations, modeling is preferred over field experiments as a method to select and spatially allocate various BMPs for reducing sediment and phosphorus transport.

Policy makers must know in advance which management practices should be adopted to achieve the desired reduction in a water body's pollutant loads. Although studies suggest that BMPs can reduce pollutant transport, no clear information exists on the optimal selection and placement of BMPs in the watershed.

In 2010, the Ontario Ministry of Agriculture, Food, and Rural Affairs (OMAFRA) established the Watershed Based BMP Evaluation (WBBE) project, which includes the Gully Creek watershed and Ridgeway and Zurich watersheds. The BMPs to be examined include tillage practices, nutrient management planning, cover crops, and Water and Sediment Control Basins (WASCoBs). Such monitoring will help model the effectiveness of different BMPs on a watershed scale.

Located along the shoreline of Lake Huron, the Gully Creek watershed, one of the priority watersheds under the WBBE project, was selected for evaluation. The study area covers 14 km^2 within the larger north Gullies study area. Gully Creek discharges directly into Lake Huron, so it can potentially directly influence nearshore water quality. This watershed has been classified as an environmentally sensitive area (Brock et al., 2010; Veliz et al., 2007). About 70% of the land is dedicated to agricultural production, and 25% of the area is in natural vegetation, which includes trees, shrubs, and grasses. The topography of the watershed is undulating, with an average slope of 6%. Clay loam soils dominate the watershed's upper reaches, while sandy loam soils dominate the lower reaches.

Although there are many watershed-scale hydrologic models [*e.g.*, AGricultural Non-Point Source Pollution Model (AGNPS), the Annualized Agricultural Non-point Source Pollutant

(AnnAGNPS), Areal Nonpoint Source Watershed En-vironment Response Simulation (ANSWERS), ANSWERS–Continuous, the CASCade 2 Dimensional SEDiment (CASC2D), Dynamic Watershed Simulation Model (DWSM), Hydrological Simulation Program - FORTRAN (HSPF), kinetic run-off and erosion model (KINEROS), MIKE SHE, Precipitation-Runoff Modeling System (PRMS), and Soil and Water Assessment Tool (SWAT)], DWSM stands out as a storm event model (Borah and Bera, 2003). In contrast, SWAT and HSPF were more suitable for predicting yearly flow volumes, sediment losses, and nutrient loads (Borah and Bera, 2004). However, HSPF has extensive data requirements, and comprehensive guidance regarding parameter settings is lacking (Liu et al., 2007). In the present study, the SWAT model was selected for BMP evaluations on the Gully Creek watershed.

1.1 Objectives

The study's primary objective was to use the SWAT model to examine the water quantity and quality effects of BMP implementation on the Gully Creek watershed. The specific objectives were to:

1. Set up the SWAT model for the Gully Creek watershed,
2. Calibrate SWAT using available data, and
3. Examine the effectiveness of different BMPs on water quantity and quality for pollution control in the Gully Creek watershed.

Chapter 2: Literature Review

2.1 Sediment and P losses from agricultural watersheds

Excessive P-concentration is the most common cause of eutrophication in freshwater lakes, reservoirs, streams, and estuarine systems. Eutrophication increases BOD, which depletes dissolved oxygen in the aquatic ecosystem and adversely affects marine life. These problems are caused by how natural aquatic ecosystems react when they receive excess nutrients; eutrophication causes a wide range of issues with freshwater and marine ecosystem water quality (Liu et al., 2019b; Schindler et al., 2016; Smith and Schindler, 2009). Many commercially important faunal and floral species can be decimated, and environmental sustainability compromised. Moreover, drinking water from such sources can have an unacceptable taste and/or odor and be challenging to treat. In waters subject to eutrophication, many algae, toxic to both animals and humans, may bloom to the extent that water bodies may become unfit for recreational purposes, let alone drinking, due to potential health issues. It is, therefore, necessary to control eutrophication by limiting the transport of nutrients, especially phosphorus, and sediment loads from agricultural lands. Implementing best management practices (BMPs) in the watershed can minimize pollutant transport to water bodies (Carpenter et al., 1998). While P is a critical nutrient in causing blooms, recent studies of Lake Erie suggest that N may have a growing role in causing them (Davis et al., 2015; Gobler et al., 2016; Hellweger et al., 2022).

Most excessive contributions of P to soil and water system are contributed by anthropogenic sources (Zhou et al., 2022). Phosphorus inputs are provided to agricultural systems in the form of manure or concentrated P fertilizers to support crop yield (Hopkins and Hansen, 2019). However, most of these P inputs continue to build in the soil as residual P, accumulating over a multi-year to the decadal timeline (Rowe et al., 2016). Each year, nearly 35% (6.30 ± 3.20 Mt/a of P (megatons per year of phosphorus)) of P fertilizer is delivered from the soil to surface waters through surface runoff (Cordell and White, 2014), with 75-90% of P being transported from farmed land in water-borne particulate form (Sharpley et al., 1995). One of three essential plant nutrients, P, is present in the soil in various organic and inorganic forms. Organic P is readily available as undecomposed plant residues and microbes in soil and stable compounds of the soil organic matter. Conversion of organic P to its plant-available soluble form is a slow process, and therefore organic P alone may sometimes not be sufficient to support proper crop growth. In many soils about 50 to 75% of P exists in an inorganic form. Inorganic P may originate from easily soluble fertilizers, slowly soluble calcium phosphate, or bound to stable Fe and Al oxides. Readily available P can be converted to a stable form by its adsorption to soil. Up to 90% of inorganic P may be fixed within 2 to 4 weeks after its application to soils.

On the other hand, inorganic P in a stable form can be converted to readily available forms; however, the conversion process is usually slow. Notably, P fertilizers are applied early in the growing season to satisfy crop needs. Generally, the P content of topsoil is high as P tends to become fixed on soil and only slowly moves downward. Upon amendment of the soil with crop residues, phosphorus taken up by a previous crop is recycled. Fertilizer addition also builds up P in the soil's surface layers. Cultivation redistributes P in soil, whereas no-till cropping promotes build-up in the soil's uppermost layer.

Surface runoff and subsurface drainage flow lead to P transport. The upper 30 to 50 mm layer of soil harbors a very high P concentration. The P is released from this layer into the runoff in soluble and particulate forms. Although soluble P percolates down to some extent, it is fixed mainly by the soil it meets. However, some may also leach down and be transported off-site through drainage water, especially in highly permeable soils or soils that have become P-saturated through years of manure application.

Easily transported to water bodies, soluble P, mainly in the form of orthophosphate, is readily available for uptake by algae. Sediment-bound P transported from the soil is more slowly available to algae but remains a long-term source. Most of the P transported from agricultural lands is sediment-bound. Thus, management practices for erosion control are critical in reducing P losses from agricultural land, although they may not be sufficient alone.

2.2 Hydrologic Models

It has been difficult for scientists and engineers to fully comprehend the complex natural processes that occur in watersheds and cause a variety of water quantity and quality problems (Borah and Bera, 2004). Mathematical models were created as practical analysis tools to help us better understand and solve problems by simplifying and simulating complicated natural phenomena.

Hydrologic and water quality models must be calibrated and verified before being used in research to assess the amount and quality of land and water resources (Moriasi et al., 2012). There are numerous models to pick from, each with varied input specifications, techniques, equations, and capacities for data simulation.

Some watershed models include (i) soil and water assessment tool, SWAT (Arnold et al., 1998); (ii) agriculture non-point source pollution, AGNPS (Young et al., 1989); (iii) annualized version of the AGNPS, AnnAGNPS (Bingner et al., 2003); (iv) better assessment science integrating point & non-point sources, BASINS (EPA, 2015); and (iv) the GIBSI modelling system (Quilbé and Rousseau, 2007). The SWAT model was selected as a long-term continuous simulation model as it can simulate a variety of BMPs being applied within a watershed and support continuous simulation.

2.3 The SWAT model

A watershed-scale model that operates on a daily time step (Arnold et al., 1998), SWAT can be used to predict the impact of management practices on the hydrology, sediment yield, and water quality on an un-gauged watershed. The model's major components include a weather generator and hydrology, sediment, crop growth, nutrient, and pesticide subroutines (Arnold et al., 1998). The SWAT model requires specific information about weather, soil properties, topography, vegetation, ponds or reservoirs (if present), groundwater, the main channel, and land management practices to simulate water quantity and quality at the watershed scale (Neitsch et al., 2002a, 2002b). In the GIS-assisted version, AVSWAT2000 (Di Luzio et al., 2002), specific inputs, such as soil type, land use, elevation, streams, outlets, and gauges, are introduced as ArcView files (shapes and grids). The model then simulates the watershed by dividing it into sub-basins, which are further divided into hydrologic response units (HRUs). These HRUs are the product of overlying soils, land use, and topography.

The processes are lumped at the HRU level, and no interaction occurs between HRUs within a sub-basin. SWAT runs on a daily time step and computes, for each HRU in every sub-basin, the soil water balance, groundwater flow, lateral flow, evapotranspiration (ET), crop growth and nutrient uptake, pond and wetland balances, soil pesticide degradation, and in-stream transformations of nutrients and pesticides (Vazquez-Amábile and Engel, 2005). The discharge of the sub-basins is routed through the stream network to the main channel and from the main channel to the basin outlet (El-Nasr et al., 2005).

The model's hydrologic components include surface runoff, infiltration, ET, lateral flow, tile drainage, percolation/deep seepage, consumptive use through pumping, shallow aquifer contribution to streamflow for a nearby stream (base flow), and recharge by seepage from surface water bodies (Neitsch et al., 2002a, 2002b). More detailed descriptions of the model are provided by Arnold et al. (1998) and Neitsch et al. (2002a).

As it can deplete the soil of nitrogen and phosphorus reserves and thereby affect soil fertility, soil erosion is a cause for concern for both agricultural and environmental professionals. The model computes erosion using the Modified Universal Soil Loss Equation (MUSCLE) (Williams, 1975). In MUSCLE, the use of a rainfall/runoff factor, based on the depth of runoff and peak runoff peak, results in a significant improvement in sediment yield estimation (over the former USLE), mainly since runoff is a function of, among other factors, antecedent soil moisture condition. Therefore, accurate simulation of subsurface and surface hydrology should significantly improve the simulation of soil erosion, sediment, and nutrient loads.

SWAT can simulate the complete nutrient cycle for nitrogen and phosphorus at the HRU level. It can also model the transformation and degradation of any applied pesticides (Neitsch et al., 2011b). The model can also simulate bacterial fate and transport. SWAT considers six soil P pools: three inorganic pools (solution, active and stable) and three organic forms (crop residue and microbial biomass, active and stable organic pools associated with soil humus, and manure application). The inorganic P in the solution pool is assumed to be in rapid equilibrium (days or weeks) with the active pool, while the active pool P is in slow equilibrium with the stable pool. SWAT starts by initializing P levels in each pool. Like nitrogen, mineralization and decomposition of phosphorus are functions of soil water content and temperature. The model considers both fast and slow sorption of inorganic phosphorus to soil, a rapid equilibrium between solution phosphorus and an active mineral pool, and a subsequent slow equilibrium between active and stable mineral pools. In the model, P leaching depends upon the amount of water percolating from the surface into the profile. Nutrient transport from the soil into streams and water bodies is also simulated by SWAT. The transport of P can occur through surface runoff or leaching; the accuracy of simulation of both processes will be affected by improved watershed hydrology simulation. The estimation of soluble phosphorus in surface runoff will also be affected by improvements in subsurface hydrology simulation. Surface runoff may also carry organic and mineral P attached to soil particles.

2.3.1 Hydrologic Processes in SWAT

The hydrological component of SWAT considers precipitation, infiltration, deep aquifer, channel transmission and evapotranspiration (ET) losses, surface runoff (Q_{surf}), and lateral and return flow ($Q_{sub\text{-}surf}$) for its water balance calculations:

$$SW_t = SW_0 + \sum_{i=1}^{i=t}\left(P_i - ET_i - Q_{i,seep} - Q_{i,surf} - Q_{i,gw}\right) \tag{1}$$

Where,

i	is the day counter,
ET_i	is evapotranspiration (mm),
P_i	is precipitation (mm),
$Q_{i,gw}$	is ground water return flow (mm),
$Q_{i,seep}$	is percolation through soil profile (mm),
$Q_{i,surf}$	is surface runoff (mm),
SW_0	is initial soil moisture (mm), and
SW_t	is soil moisture at time t (mm).

SWAT differentiates precipitation as rainfall or snowfall while comparing air temperature with a snowfall temperature parameter (SFTMP). As a result, the model keeps track of the volume and areal extent of snowpack, as well as the corresponding snowmelt (Eqs. 2-3). Snow accumulation and melting are processes that can be spatially varied using elevation bands within a sub-basin.

$$SNO_t = SNO_0 + \sum_{i=1}^{i=t}\left(P_i - E_{i,sub} - SNOMLT_i\right) \tag{2}$$

$$SNOMLT_i = b_{i,mlt}.SNOCOV_i + \left(\frac{T_{i,snow} + T_{i,max}}{2} - SMTMP\right) \tag{3}$$

$$b_{i,mlt} = \left(\frac{SMFMX + SMFMN}{2} + \frac{SMFMX - SMFMN}{2}\right) \cdot sin\left(\frac{2\pi}{365}(i - 81)\right) \tag{4}$$

Where,

$b_{i,mlt}$	is a melt factor (mm $^{o}C^{-1}$ day^{-1}),
$E_{i,sub}$	is the water equivalent of snow sublimation for the i^{th} HRU (mm),

$\boldsymbol{SMFMN}$	is the minimum snow melt rate (mm $^{o}C^{-1}$ day^{-1}),
$\boldsymbol{SMFM}P$	is the snow melt base temperature (^{o}C),
$\boldsymbol{SMFM}X$	is the maximum snow melt rate (mm $^{o}C^{-1}$ day^{-1}),
$\boldsymbol{SNO_0}$	is the initial snow water equivalent (mm),
$\boldsymbol{SNO_t}$	is the snow water equivalent at time *t* (mm),
$\boldsymbol{SNOCOV_i}$	is the fraction of the i^{th} HRU covered by snow (-),
$\boldsymbol{SNOMLT_i}$	is the water equivalent of snowmelt or the i^{th} HRU (mm),
$\boldsymbol{T_{i,max}}$	is the maximum air temperature (^{o}C), and
$\boldsymbol{T_{i,snow}}$	is the snowpack temperature (^{o}C).

The model employs either the SCS curve number or the modified Green-Ampt method to determine the infiltration and runoff volumes for each HRU. Infiltrated water percolates through each soil layer, as estimated using a storage routing technique. SWAT offers a variable storage method or Muskingum method to route the streamflow generated due to runoff coming from each HRUs within the sub-basins (Neitsch et al., 2011b).

2.3.2 Erosion and Sediment Transport Processes

SWAT uses the Modified Universal Soil Loss Equation to estimate soil erosion and sediment yield from each HRUs (Williams and Berndt, 1977).

$$\boldsymbol{sed' = 11.8\left(Q_{surf} * q_{peak} * area_{hru}\right)^{0.56} K_{USLE} * C_{USLE} * P_{USLE} * LS_{USLE} * CFRG} \quad (5)$$

Where,

$\boldsymbol{area_{hru}}$	is the HRU area (ha),
$\boldsymbol{sed'}$	is the sediment yield (Mg),
$\boldsymbol{q_{peak}}$	is the peak runoff (m^3 s-1),
$\boldsymbol{CFRG}$	is the coarse fragment factor (-),
$\boldsymbol{C_{USLE}}$	is the cover and management factor (-),
$\boldsymbol{LS_{USLE}}$	is the topographic factor (-),
$\boldsymbol{K_{USLE}}$	is the soil erodibility factor (0.013 Mg m^2 ha/m^3 Mg cm),
$P_{\boldsymbol{USLE}}$	support practice factor (-), and
$\boldsymbol{Q_{surf}}$	surface runoff (mm ha^{-1}).

SWAT also accounts for the snow coverage effect on erosion (Neitsch et al., 2011a).

$$ed = \frac{sed'}{exp\left(\frac{3 \cdot SNO}{25.4}\right)} \quad (6)$$

Where,

SNO is the water content of the snow cover (mm).

Sediment contribution from lateral and groundwater flows also considered. Once sediments are in the stream, the sediment carrying capacity of the channel is determined using the Bagnold approach (Bagnold, 1977):

$$conc_{sed,ch,mx} = c_{sp} . v_{ch,pk}^{spexp} \quad (7a)$$

Where,

$$v_{ch,pk} = \frac{q_{ch,pk}}{A_{ch}} = \frac{Prf . q_{ch}}{A_{ch}} \quad (7b)$$

Where,

$conc_{sed,ch,mx}$ is the maximum sediment concentration that can be carried in the channel (Mg m^{-3}),

c_{sp} is a coefficient (-),

Prf is the peak rate adjustment factor (-),

q_{ch} is the average channel flow (m^3 s^{-1}),

$spexp$ is an exponent parameter (-),

$v_{ch,pk}$ is the peak channel velocity (m s^{-1}), and

A_{ch} is the cross sectional area of the channel flow (m^2).

The maximum transport carrying capacity is then compared against the initial sediment concentration at the i^{th} reach ($conc_{sed,ch,i}$). If $conc_{sed,ch,i} > conc_{sed,ch,mx}$ then deposition prevails. Otherwise, degradation prevails. The amount of deposition or degradation is computed based on the approach suggested by (Neitsch et al., 2011a).

$$sed_{dep} = \left(conc_{sed,ch,i} - conc_{sed,ch,mx}\right) \cdot V_{ch} \quad (8)$$

$$sed_{deg} = \left(conc_{sed,ch,mx} - conc_{sed,ch,i}\right) \cdot V_{ch} \cdot K_{ch} \cdot C_{ch} \quad (9)$$

Where,

sed_{deg} is the quantity of sediment degraded (Mg),

sed_{dep} is the quantity of sediment deposited (Mg),

C_{ch} is a channel cover factor (-).

K_{ch} is the channel erodibility factor (cm ha^{-1} Pa^{-1}), and

V_{ch} is the volume of water (m^3).

After maintaining the sediment balance on the reach, the sediment concentration at the outlet of the reach is given as (Neitsch et al., 2011a):

$$sed_{out} = sed_{ch} \frac{V_{out}}{V_{ch}} \tag{10}$$

Where,

sed_{ch} is the quantity of sediment in the reach (Mg),

sed_{out} is the quantity of sediment transported out of the reach (Mg),

V_{ch} is the volume of the water in the reach (m^3), and

V_{out} is the volume of water transported out of the reach (m^3);

2.3.3 Phosphorus Cycle

The phosphorus (P) cycling in SWAT is simulated at the HRU level using a single-pool soil organic matter sub-model (Kemanian, 2006). SWAT maintains separate pools for residue and manure P. The P in the pools can undergo decomposition, mineralization, and immobilization. The SWAT traces three forms of the mineral P (solution, active and stable, Figure 1) and three pools of organic P (fresh, active, and stable, Figure 1). The fresh pool of organic P is associated with crop residues and microbial biomass, while the active and stable pools of organic P are associated with soil humus.

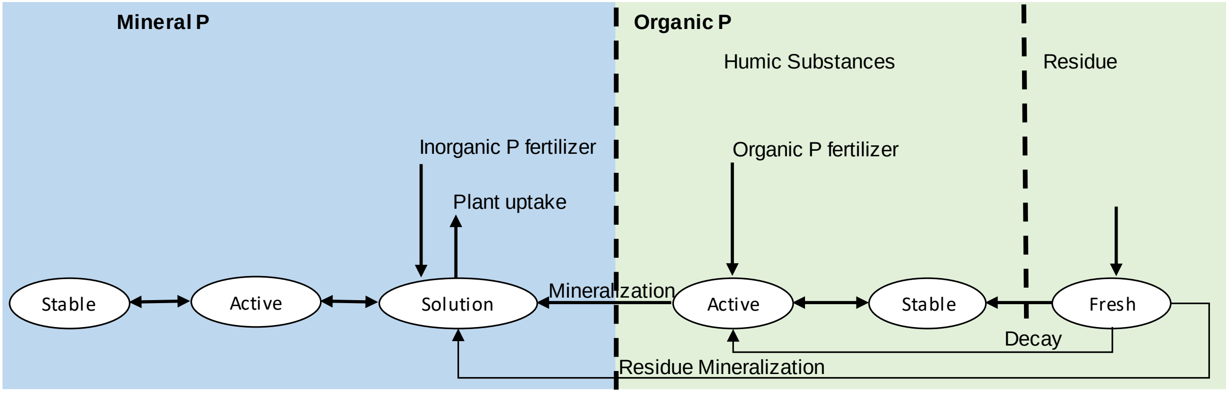

Figure 1. Soil phosphorus pools and processes considered in Soil and Water Assessment Tool (SWAT). (From S.L. Neitsch et al., Soil and Water Assessment Tool theoretical documentation version 2009, available at https://swat.tamu.edu/media/99192/swat2009-theory.pdf).

The organic P (and mineral P attached to sediments) loading from HRUs is estimated according to McElroy (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 (Eqns. 11 & 12). The enrichment ratio is dynamically calculated as a function of sediment yield and surface runoff using the formulation of (Menzel, 1980) or kept fixed:

$$\boldsymbol{OrgP_{surq}} = \frac{\mathbf{0.001} \cdot \boldsymbol{OrgP_{conc}} \cdot \boldsymbol{sed(ERORGP)}}{\boldsymbol{area_{HRU}}} \qquad \textit{(11)}$$

$$\boldsymbol{ERORGP} = \mathbf{0.78} \cdot \left(\frac{\boldsymbol{sed}}{\mathbf{10} \cdot \boldsymbol{area_{HRU}} \cdot \boldsymbol{Q_{surq}}}\right)^{-0.2468} \qquad \textit{(12)}$$

Where,

$\boldsymbol{OrgP_{surq}}$ is the organic P in surface runoff (kg P ha^{-1}),

$\boldsymbol{area_{HRU}}$ is the HRU area (ha),

$\boldsymbol{OrgP_{conc}}$ is the organic P concentration in the topsoil layer (g P Mg^{-1} soil),

$\boldsymbol{sed}$ is the sediment yield (Mg), and

$\boldsymbol{ERORGP}$ is the ratio of P entrainment.

The soluble form of phosphorus transported in surface runoff ($\boldsymbol{P_{surq}}$) is a function of the phosphorus-soil partitioning coefficient, the concentration of soluble phosphorus in the topsoil layer and surface runoff volume is computed as:

$$\boldsymbol{P_{surq}} = \left(\frac{\boldsymbol{P_{solution,surq} \cdot Q_{surq}}}{\boldsymbol{\rho_b \cdot depth_{surq} \cdot PHOSKD}}\right) \tag{13}$$

$$\boldsymbol{sedP_{surq}} = \left(\frac{\boldsymbol{0.001 \cdot sedP_{conc} \cdot sed \cdot ERORGP}}{\boldsymbol{area_{HRU}}}\right) \tag{14}$$

Where,

$\boldsymbol{depth_{surq}}$	is the depth of surface layer (which SWAT assumes as 10 mm),
$\boldsymbol{P_{solution,surq}}$	is the amount of phosphorus in solution (kg P ha^{-1}),
$\boldsymbol{P_{surq}}$	is the amount of soluble phosphorus in surface runoff (kg P ha^{-1}),
$\boldsymbol{PHOSKD}$	is the phosphorus soil partitioning coefficient (-), and
$\boldsymbol{\rho_b}$	is the bulk density of the soil layer (Mg m^{-3}).

2.4 BMPs for NPS pollution control

Best management practices (BMPs) are those combinations of methods or techniques, drawing upon optimum resources and inputs, which prove most effective in optimizing crop production while preventing or minimizing pollution. Thus, BMPs are practical techniques adopted to obtain optimum production yet reduce the potentially adverse impacts of production-related activities on water resources and the environment. BMPs have been widely used to address hydrology and water quality issues in agricultural and urban areas (Andrews et al., 2013; Gilroy and McCuen, 2009; Liu et al., 2015; Liu et al., 2017; Mwangi et al., 2015).

Despite the widespread use of BMPs, concerns remain about their effectiveness and the appropriate combination of practices for achieving particular objectives. To measure BMP efficiency and help in their selection and implementation, numerous empirical studies of specific techniques have been carried out (Ahmed et al., 2015). Considering their cost-effectiveness, the practicality of their application at a given site, and their social acceptability, BMPs are the best pollution control technologies for NPS pollution. Use of appropriate BMPs can significantly improve the quality of runoff and subsurface drainage waters from agricultural lands, as well as waters from forested and residential areas. Accordingly, BMPs are routinely used to reduce NPS pollution resulting from farming activities and improve the quality of runoff and subsurface drainage waters. Different BMPs can include conservation tillage systems, vegetated filter strips, cover crops, reduced rates of fertilizer and pesticide application, reduced areal extent of chemical application on the landscape, constructed wetlands, irrigation, and subsurface drainage practices, to name a few.

2.4.1 Tillage Management

Besides increasing soil erosion from a field, tillage also heightens sediment and nutrient transport. Compared to conservation tillage, plowing increases runoff volume, as well as sediment and nutrient loads in the runoff, whereas no-till management produces the lowest runoff volume and pollutant losses. Tillage could change the physical properties of the soil that control drainages, such as evaporation, infiltration, aeration, water holding capacity, pore connectivity, and preferred flow paths (Hess et al., 2018; Morris et al., 2010; Strudley et al., 2008). Generally, granular fertilizers are applied broadcast under conservation tillage, so nutrient losses are high (Seta et al., 1993). In contrast, runoff volume under conservative tillage exceeds that under conventional tillage. However, suspended solids in runoff are lesser under conservation tillage. Soluble-P concentrations are higher (Gaynor and Findlay, 1995) ; (Kimmell et al., 2001) observed that tillage practices and phosphorus fertilizer application methods (e.g., placement, chemical form, timing) greatly influenced nutrient losses. Conservation tillage is a BMP that effectively reduces the loss of many surface water pollutants, including sediment, pesticides, and nutrients. Upon implementing no-till, filter strips, and nutrient management in the Nomini Creek watershed, (Inamdar et al., 2001) found 26% and 41% reductions in mean annual loads and flow-weighted concentrations of N, respectively, and equivalent reductions in total phosphorus of 4% and 24%. They also observed higher streamflow in spring and winter than in summer or fall; however, they did not evaluate the impact of variation in runoff over seasons on nutrient transport. Kirsch et al. (2002) investigated the effect of BMPs on P losses using SWAT, estimating a 20% reduction in P losses through improved tillage practices, especially conservation tillage. In the Fuquene Lake watershed, conservation tillage showed a decrease in sediment output and surface runoff of 26% and 11%, respectively, with an increase in TN and TP of 2% and 18%, respectively (Uribe et al., 2018). When conservation and zero-tillage operations were used, sediment yield went down by 2%, but TN and TP went up by 25% at the watershed scale (Risal and Parajuli, 2022). Even though conservation tillage is a good BMP for reducing nutrient loss, more BMPs will be needed, and in some cases, tillage practices may need to be changed.

In a study on short-term impacts of tillage (0–3 months) on soil and hydrological responses in fig orchards located in Croatia, Telak et al. (2020) found that the sediment concentration (SC) was significantly greater 3 months after tillage than it had been during the previous monitoring periods, although the sediment loss (SL) and carbon loss (C loss) were much lower immediately after tillage than 3 months after tillage.

2.4.2 Cover crops

After harvesting the crops, the soil surface is usually left bare until the next crop is planted. During this interim period, before a new plant canopy is established, the soil is susceptible to soil erosion and nutrient losses in runoff or snowmelt in cold climates. This soil erosion can be reduced by protecting the soil surface, either by providing cover with growing plants or crop residues. Cover crop minimizes the impact of raindrops so that soil particles are not as easily dislodged and transported. The cover crop also hinders flow and reduces the runoff velocity, reducing the transport of soil particles and associated nutrients and other pollutants. Cover crop roots stabilize soil aggregates, enhance infiltration, reduce runoff volume, and add organic matter, which, in turn, increases the soil's water holding capacity. The crop cover also acts as a layer of insulation atop the soil, modifying changes in soil temperature and mitigating its impacts during the freeze-thaw cycle. Accordingly, cover crops are generally established in the fall season and remain over the winter. In the spring, the cover crop may be killed, leaving residues on the surface under conservation tillage or incorporating cover crop residues into the soil under conventional tillage. Cover crops may also take up available P, making it less likely that soluble P will be lost through leaching. Cover crops help water soak into the soil, which cuts down on soil runoff. In much of the eastern United States, for soils with moderate infiltration rates, runoff reductions in the range of 20 to 25% can be expected when implementing cover crops (Baker and Laflen, 1983). Studies focused on the development of legume cover crops after cereals have found significant N supply to a subsequent corn crop (Stute and Posner, 1995). However, grain maize production responses to increased nitrogen fertilizer continue to be observed in some conditions and management regimes (Hesterman et al., 1992). In a study done in southcentral Ontario, Vyn et al. (2000) found out that after red clover (Trifolium pratense L.), regardless of tillage practice, the highest maize yields without N fertilizer were consistently seen, irrespective of the tillage method. In research with cover crops, Singer and Kaspar (2006) found that the total amount of phosphorus could be cut by between 54% and 94%. The cultivation of ryegrass (Lolium multiflorum Lam.) cover crop led to a significant reduction in sediment and nitrate losses compared to the conventional practice of leaving dryland fields fallow after harvesting the main crop (Maharjan et al., 2016). Even though a rye cover crop could lower corn yields by changing the amount of nitrogen in the soil (Pantoja et al., 2015) and by making corn seedlings more susceptible to disease (Bakker et al., 2016), the early removal of the rye before planting corn seems to have lessened this effect. A reduction ranging from 66% to 99% in sediment and Ptot loading were observed at the subwatershed level after the conversion of croplands to Conservation Reserve Program (CRP) grasslands in subwatersheds identified as critical source area (CSAs) (Lamba et al., 2016). Red clover interseeding with winter wheat offers several ecological functions by diversifying cropping systems and lowering the likelihood of crop failure due to drought stress (Gaudin et al., 2015). In a study done in northwest Missisippi, no matter what time of year it was, using cover crops with minimum tillage cut the amount of total P in surface runoff by 27% (Badon et al., 2022). Red clover is a commonly used cover crop in Ontario, Canada. Research on phosphorus reduction was not always the same, and reductions were not always made.

In cold climates, cover crops and crop residues generally stop soil erosion and the loss of particle-bound P during the off-season in erodible landscapes, but they tended to increase dissolved P loss in nonerodible soils. Their effect on total P loss was different from one study to the next, and soil, climate, and management factors made things even more complicated (Liu et al., 2019a).

2.4.3 Vegetative Filter Strips (VFS)

One of the most widely implemented BMPs is vegetative buffer strips (VFS), or buffers, which have become ubiquitous and even required in agricultural landscapes worldwide. Buffers are a popular BMP due to their low cost, relative ease of implementation, and demonstrated effectiveness in decreasing the movement of nutrients into surface waters. VFS is often employed in the United States to improve the quality of stream ecosystems and has emerged as a significant best management practice (BMP) to control pollution transfer by stormwater runoff (Boyd et al., 2003; Chaubey et al., 1994; Schellinger and Clausen, 1992). In their study of feedlot runoff, Dickey and Vanderholm (1981) discovered that VFS can remove up to 95 percent (on a mass basis) of nutrients and oxygen-demanding compounds with concentration reductions of up to 80 percent. (Lammers-Helps et al., 1991) concluded that buffer strips are ineffective when water collects in natural drainage routes before crossing the buffer strips. Chaubey et al. (1994) found that a 4.6-m wide filter strip reduced the amount of total suspended solids (TSS) and total phosphorus (TP) in surface runoff by 66 and 27%, respectively.

Studies from temperate regions and some cold climates throughout the world have demonstrated that buffers can efficiently filter soluble and particulate P, lowering burdens by up to 90 percent in some instances Barfield et al. (1998). While buffer strips can decrease the amount of water entering a stream and reduce erosion and P-particle movement, water traveling through bare or sparsely vegetated areas can enhance bank and streambed erosion.

Schmitt et al. (1999) suggested that VFS were more successful in reducing the concentration of particle pollutants but less efficient in reducing the concentration of soluble pollutants. They evaluated the efficacy of various filter strip widths and discovered that filter strips of 7.5 and 15m could achieve silt removal efficiency of 76 and 93 percent, respectively. Oelbermann and Gordon (2000) investigated the effectiveness of the VFS by comparing the concentrations of pollutants in runoff at the VFS's inlet and exit. They concluded that, if correctly installed and maintained, VFS can remove at least 75% of sediments and sediment-bound contaminants from farm runoff. Lee et al. (2000) discovered that, generally, the concentration-based removal efficiency of sediment-bound nutrients (N and P) followed the same patterns as total suspended sediments. Furthermore, Abu-Zreig et al. (2003) discovered that the sediment removal efficiency of VFS varied directly with filter strip width and inversely with runoff flow rate. In a study done in northeast Kansas to investigate the efficiency of various lengths of VFS used at the edge of fields to diminish non-point source pollution, the greatest reduction of sediment was 25% after the VFS adoption (Parajuli et al., 2008). Chiang et al. (2012) found that vegetative filter strips (VFS) were the most significant management methods in lowering pollutant losses, and a smaller VFS ratio (ratio of the drainage area to VFS area) led to better pollutant reduction. It was found that a 10-foot-wide strip had removal efficiency close to 100 percent for both dissolved nutrient and suspended sediment output from a given field (Bodah et al., 2016). The addition of vegetated filter strips to all farmland lowered phosphorus loads by 11 percent at the upland scale and by 12 percent at the watershed size (Almendinger and Ulrich, 2017). When the SWAT model was used to analyze a field-scale watershed in Michigan, it was discovered that VFS could lower phosphorus and sediment production (Merriman et al., 2018b). In a study done in Mississippi River alluvial plain, Risal and

Parajuli (2022) found out that at a watershed scale, VFS reduced sediment yield, total nitrogen, and total phosphorus by 12 to 38 percent, 29 to 87 percent, and 42 to 99 percent, respectively.

Although there are several non-structural BMPs for reducing pollutant losses, BMPs such as tillage management, cover crop, and VFS are generally more effective in pollution control; however, their effectiveness is specific to agro-climatic conditions.

The SWAT filter strip algorithm was based on work by White and Arnold (2009). Filter strips reduce sediment, nutrients, bacteria, and pesticides, but they don't change the amount of water that runs off the surface in SWAT. The following equation shows the sediment reduction model:

$$S_R\% = 79.0 - 1.04S_L + 0.213R_R \quad \textbf{\textit{(15)}}$$

Where,

S_R is the predicted sediment reduction (%),

S_L is sediment loading (kg/m^2), and

R_R is the runoff reduction (%).

The model for total phosphorus was made using 63 observations, which is more data than any other nutrient model.

$$TP_R = 0.90S_R \quad \textbf{\textit{(16)}}$$

Where,

TP_R is the total phosphorus reduction (%), and

S_R is the sediment reduction (%).

Soluble Phosphorus model is given below:

$$DP_R = 29.3 + 0.51R_R \quad \textbf{\textit{(17)}}$$

Where,

DP_R is the dissolved phosphorus reduction (%), and

R_R is the runoff reduction (%).

Chapter 3: Materials and methods

3.1 SWAT Model

The Soil and Water Assessment Tool (SWAT) model has been widely used and has produced satisfactory results in simulating the control of water, soil, and nutrient loss through the implementation of BMPs (Arabi et al., 2006; Himanshu et al., 2019; Kirsch et al., 2002; Merriman et al., 2018a; Santhi et al., 2001; Wu et al., 2022). For example, the field scale SWAT model was used to evaluate how BMPs affected the Black Kettle Creek subwatershed of the Arkansas River watershed (Daggupati et al., 2011). The SWAT model requires various spatial and hydro-meteorological input data, as described below.

3.1.1 Selection of Study Watershed

When developing a continuous as well as event-based model, it is essential to have access to a variety of spatial datasets, including digital elevation model (DEM), soil and land-use/land-cover (LULC), meteorological datasets like precipitation and temperature, crop, and land-management data of individual fields, and any existing BMPs. Due to the lack of ongoing monitoring data, particularly for water quality indicators, a through model's calibration is frequently hampered once it has been established (e.g., sediment, nitrogen, and phosphorus). Using these two crucial criteria as a basis, Gully Creek watershed, an agricultural watershed was selected.

3.1.2 Location

The Gully Creek watershed is a representative of several small watersheds in the lakeshore area of the Lake Huron catchment, located in southern Ontario, Canada. The study area covers about 1408 ha (14 km^2). The location of the study area is shown in Figure 2.

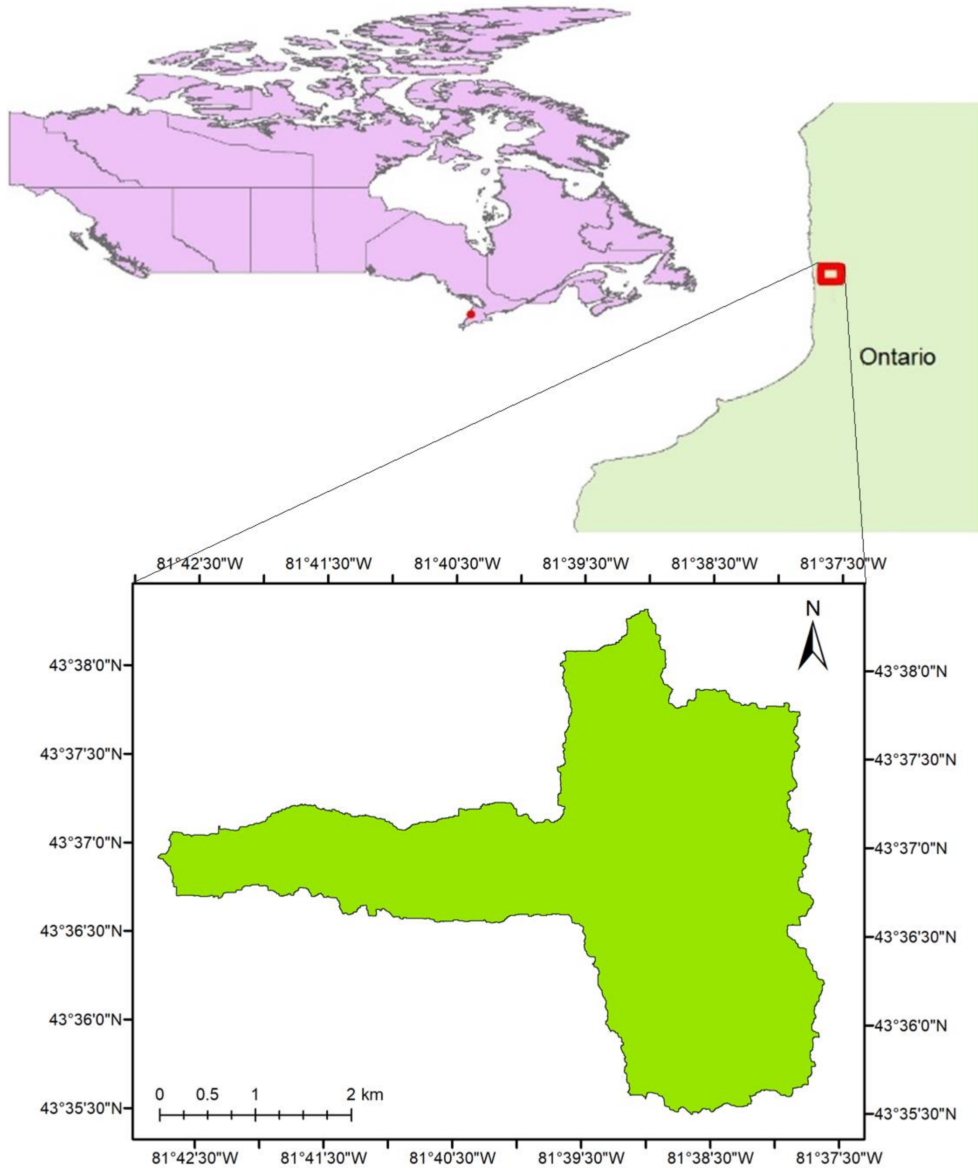

Figure 2. Location of the study area.

3.1.3 Topography, soil, and land use

The watershed has an undulating landscape, with an average slope of 6%. It has been classified as an Environmentally Sensitive Area (Brock et al., 2010; Veliz et al., 2007). Streamflow from the Gully Creek watershed drains directly into Lake Huron; therefore, it has a great impact on the lake's shore water quality. A DEM with 5mx5m spatial resolution, resampled from a 1mx1m LIDAR DEM, was used (Figure 3). It shows the watershed's upper reaches to be characterized by rolling lands, while the lower reaches are relatively flat. Although the average land slope is 6%, it varies from 0% in flat areas to 95% in incised gully areas.

The distribution of different soil types in the watershed is presented in Figure 4. Various soil types and their areal extents are enumerated in Table 3. Clay loam is the dominant soil type in the upper reaches, while the lower reaches are primarily sandy loam.

The land use map of the Gully Creek watershed for the year 2011 is presented in Figure 5. Roughly 68% of the area is comprised of agricultural land planted with corn [*Zea mays* L.], soybean [*Glycine max* (L.) Merr.] or winter wheat [*Triticum aestivum* L.]. These crops are planted in different crop rotations. The remaining areas are covered by forest, pasture, and residential areas. There are 114 agricultural farms in the Gully creek watershed, as shown in the land use map. The different land use codes, based on plot number, along with their respective areas in percentage, are given in Table 1. The management operations for ten years, starting from 2008 until 2018 for farm number F007 is given in Table 2. Similarly, for other farms, the management operations data is prepared and used as input for the model setup.

The DEM file, soil map, and land use map were provided by Ausable Bayfield Conservation Authority (ABCA).

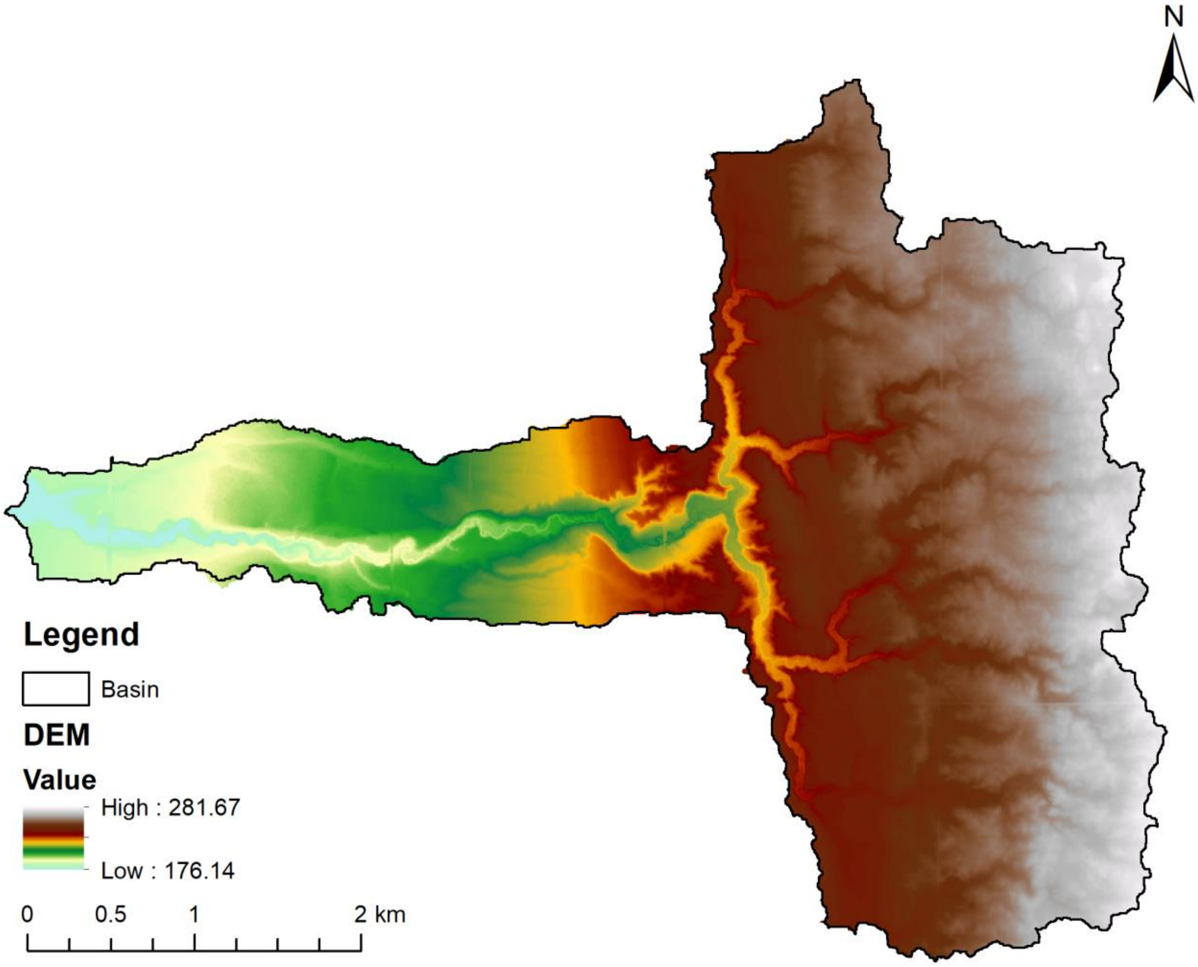

Figure 3. Digital elevation model of the Gully Creek watershed.

Table 1. Land use Codes Based on Plot Number and Respective Area in Percentage

Land use code	Area (ha)	Total Area (%)	Land use code	Area (ha)	Total Area (%)
F071	6.73	0.48	F034	1.53	0.11
F072	4.56	0.32	F038	9.85	0.7
F068	26.42	1.88	F028	3.10	0.22
F070	18.20	1.29	F036	4.03	0.29
F069	17.88	1.27	F037	3.00	0.21
F113	93.47	6.64	F035	13.52	0.96
F115	0.83	0.06	F041	2.25	0.16
F116	2.03	0.14	F032	0.81	0.06
F118	0.36	0.03	F027	1.12	0.08
F119	15.57	1.11	F039	0.09	0.01
F121	0.24	0.02	F040	0.13	0.01
F131	7.81	0.55	F046	0.40	0.03
F120	2.84	0.2	F030	11.35	0.81
F141	1.67	0.12	F128	6.51	0.46
F073	18.98	1.35	F020	1.62	0.12
F063	8.50	0.6	F094	3.44	0.24
F064	23.07	1.64	F095	1.99	0.14
F114	2.06	0.15	F097	0.22	0.02
F112	0.63	0.04	F099	5.82	0.41
F117	0.51	0.04	F101	0.41	0.03
F125	1.25	0.09	F029	11.35	0.81
F111	19.85	1.41	F091	4.58	0.33
F057	15.03	1.07	F089	3.25	0.23
F062	0.94	0.07	F093	6.50	0.46
F065	0.96	0.07	F086	11.01	0.78
F109	1.39	0.1	F018	3.21	0.23
F110	2.80	0.2	F133	4.87	0.35
F050	13.90	0.99	F088	11.39	0.81
F107	0.94	0.07	F084	32.57	2.31
F108	0.92	0.07	F129	7.05	0.5
F137	8.62	0.61	F134	4.64	0.33
F051	1.21	0.09	F017	2.57	0.18
F058	2.13	0.15	F019	2.45	0.17
F047	16.79	1.19	F090	0.64	0.05
F048	5.03	0.36	F098	0.28	0.02
F049	7.40	0.53	F014	16.15	1.15
F053	14.94	1.06	F006	40.94	2.91
F056	1.85	0.13	F007	0.36	0.03

Table 1 Continued

F138	6.95	0.49	F009	0.55	0.04
F139	1.74	0.12	F011	8.17	0.58
F054	12.37	0.88	F013	2.18	0.15
F059	12.98	0.92	F143	7.89	0.56
F060	8.95	0.64	F085	16.58	1.18
F044	25.80	1.83	F012	9.75	0.69
F102	12.59	0.89	F081	16.54	1.17
F043	4.98	0.35	F008	3.71	0.26
F096	1.81	0.13	F010	0.71	0.05
F045	8.89	0.63	F144	7.70	0.55
F136	4.14	0.29	F078	31.33	2.22
F100	6.81	0.48	F079	16.47	1.17
F106	0.01	0	F080	12.35	0.88
F127	4.99	0.35	F082	1.15	0.08
F042	1.31	0.09	F083	1.04	0.07
F052	3.11	0.22	F142	6.54	0.46
F092	30.44	2.16	F003	9.97	0.71
F126	20.97	1.49	F132	15.22	1.08
F033	8.39	0.6	F077	4.67	0.33

Table 2. Ten-year crop rotation management data

Year	Date	Operation	Fertilizer Application Rate
1	26 Apr	Field Cultivator Lt15ft	
1	28 Apr	Plant Corn	
1	1 May	No Till	
1	5 May	Fertilizer application	10 kg N ha^{-1} (inorganic)
1	5 May	Fertilizer application	17 kg P ha^{-1} (inorganic)
1	15 Jun	Fertilizer application	112 kg N ha^{-1} (inorganic)
1	28 Oct	Harvest and kill	
2	6 May	Generic No-till Mixing	
2	8 May	Plant Soybeans	
2	11 May	No Till	
2	28 Sep	Harvest and kill	
2	1 Nov	Fertilizer application	22.45 Mg ha^{-1} Layer-Fresh Manure
3	15 Apr	Fertilizer application	123 kg N ha^{-1} (inorganic)
3	20 Apr	Plant Winter Wheat	
3	25 Jul	Harvest and kill	
3	5 Oct	No Till	
3	10 Oct	No Till	
4	25 Apr	Fertilizer application	9.0 Mg ha^{-1} Layer-Fresh Manure
4	26 Apr	Field Cultivator	

4	28 Apr	Plant Corn	
4	1 May	No Till	
4	3 May	Fertilizer application	124 kg N ha^{-1} (inorganic)
4	28 Oct	Harvest and kill	
5	6 May	Generic No-till Mixing	
5	8 May	Plant Soyabeans	
5	11 May	No Till	
5	28 Sep	Harvest and kill	
5	3 Oct	Fertilizer application	4.5 Mg ha^{-1} Layer-Fresh Manure
6	3 May	Fertilizer application	124 kg N ha^{-1} (inorganic)
6	4 May	Cultivator 1 Row	
6	5 May	Plant Corn	
6	5 May	Cultivator 1 Row	
6	25 Oct	Harvest and kill	
7	3 May	Fertilizer application	124 kg N ha^{-1} (inorganic)
7	4 May	Cultivator 1 Row	
7	5 May	Plant Corn	
7	5 May	Cultivator 1 Row	
7	25 Oct	Harvest and kill	
8	6 May	No Till	
8	11 May	No Till	
8	15 May	Plant Soybeans	
8	28 Sep	Harvest and kill	
8	30 Sep	Fertilizer application	22.450 Mg ha^{-1} Layer-Fresh Manure
9	3 May	Fertilizer application	124 kg N ha^{-1} (inorganic)
9	4 May	Cultivator 1 Row	
9	5 May	Plant Corn	
9	5 May	Cultivator 1 Row	
9	25 Oct	Harvest and kill	
10	6 May	No Till	
10	11 May	No Till	
10	15 May	Plant Soybeans	
10	28 Sept	Harvest and kill	
10	30 Sep	Fertilizer application	22.45 Mg ha^{-1} Layer-Fresh Manure

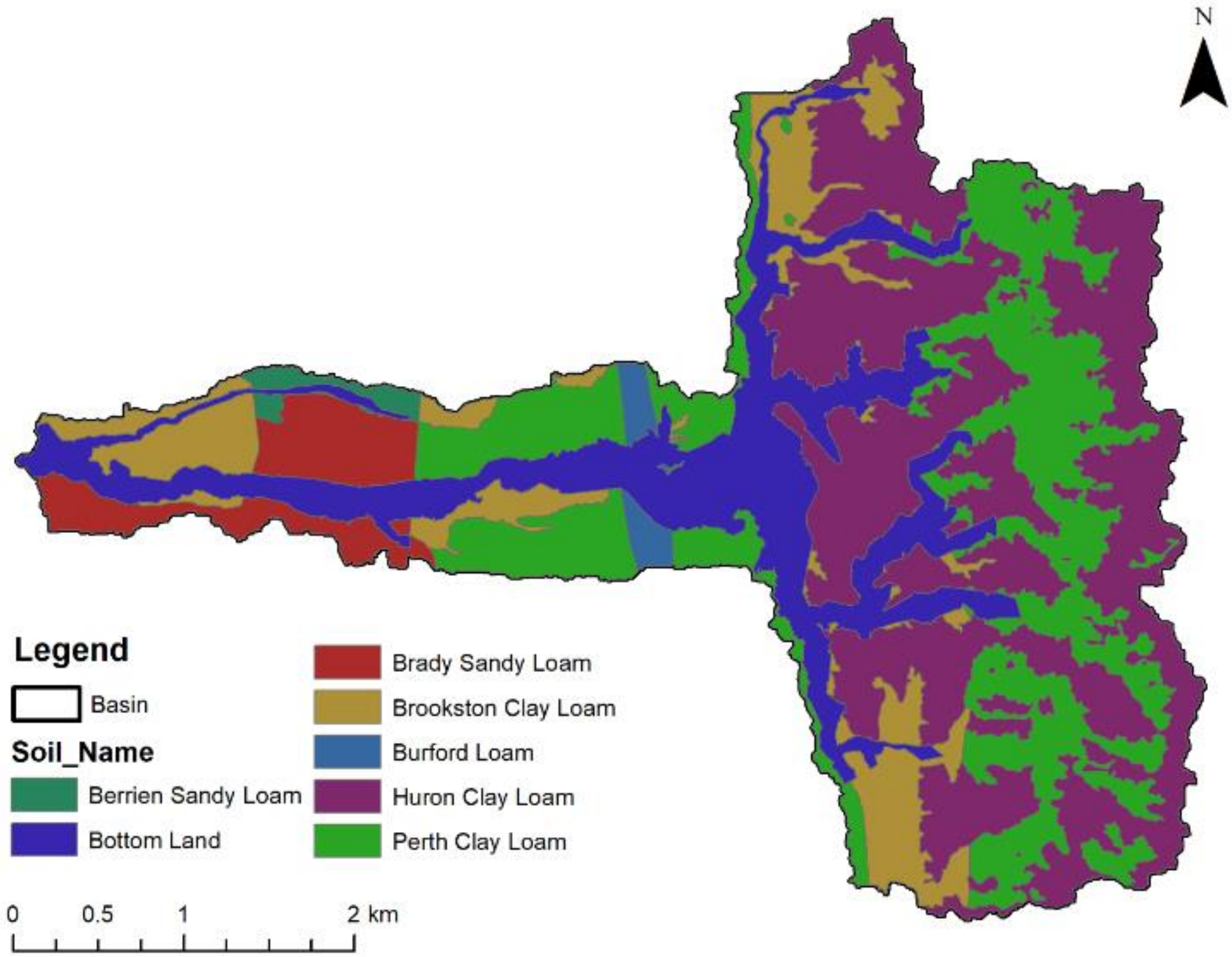

Figure 4. Soil map of Gully creek watershed.

Table 3. Different soil types and their aerial extent of Gully Creek watershed

Name	SWAT Code	Texture	Area (ha)	%
Huron	HUO	Clay Loam	516.1	36.6
Perth	PTH	Clay Loam	362.6	25.8
Bottom Land	ZAL	Sandy Loam	269.3	19.1
Bookton	BKN	Clay Loam	158.4	11.3
Brady	BAY	Sandy Loam	74.4	5.3
Buford	BUF	Loam	15.4	1.1
Bennington	BRR	Sandy Loam	12.0	0.9

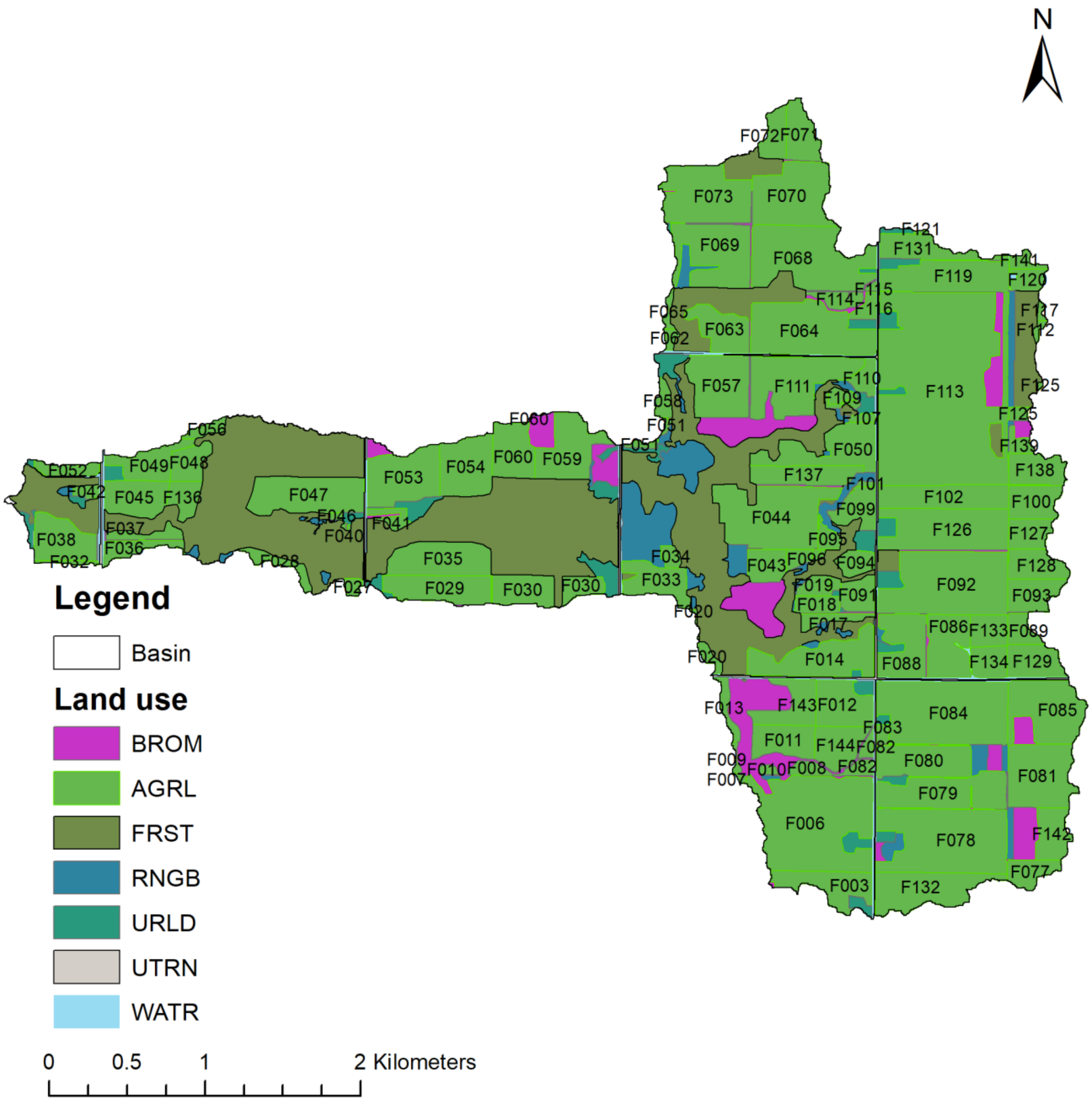

Figure 5. Land use map of the Gully Creek watershed Note: BROM: Meadow Bromegrass; AGRIL: Agricultural Farms; FRST: Forest-Mixed; RNGB: Range-Brush; URLD: Residential-Low Density; UTRN: Transportation; WATR: Water.

3.1.4 Meteorological Data

The SWAT model requires meteorological data in addition to soil, land use, and spatial topography data. It includes daily precipitation, maximum and minimum temperature, wind speed, relative humidity, and solar radiation. The Ausable Bayfield Conservation Authority (ABCA) provided 2005 to 2016 precipitation data from three stations in the Gully Creek Watershed: NGmetVB (on

Orchard Line, Figure 4.4), GULGUL5 (Gully Creek at Porter's Hill Line, Figure 6), and MBVAR1 (Bayfield River at Parr Line, near Varna, not shown on the map). A nonheated tipping bucket rain gauge was used to collect rain data (0.2 mm per tip). Due to equipment failure, some data gaps occurred (Figure 7), *e.g.*, GULGUL5). Temperature data (minimum and maximum) were recorded at the station for the same period (2005-2016). Both sets of daily data were combined to make them compatible with the SWAT model build-up.

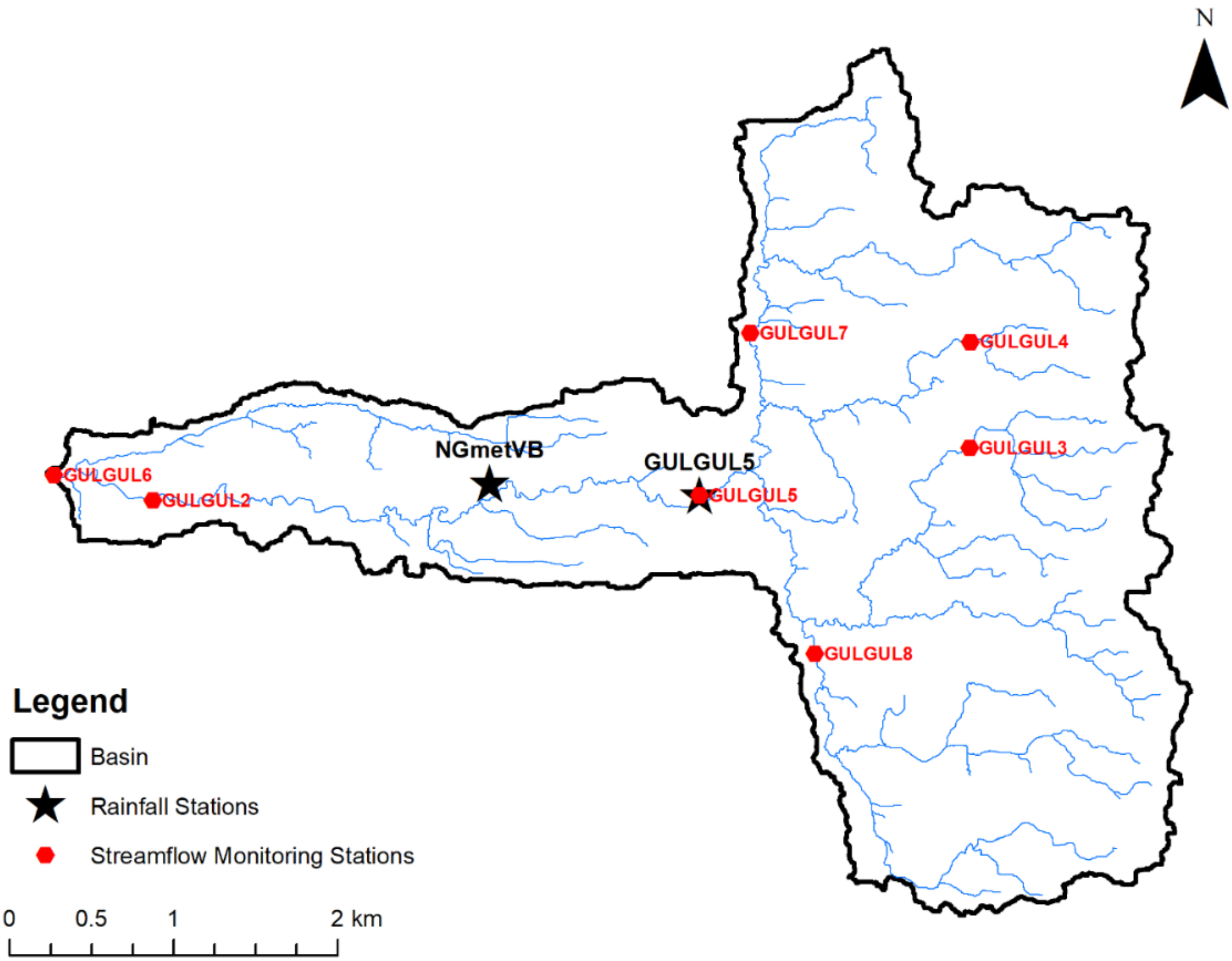

Figure 6. Location of precipitation and streamflow gauging stations of Gully Creek Watershed.

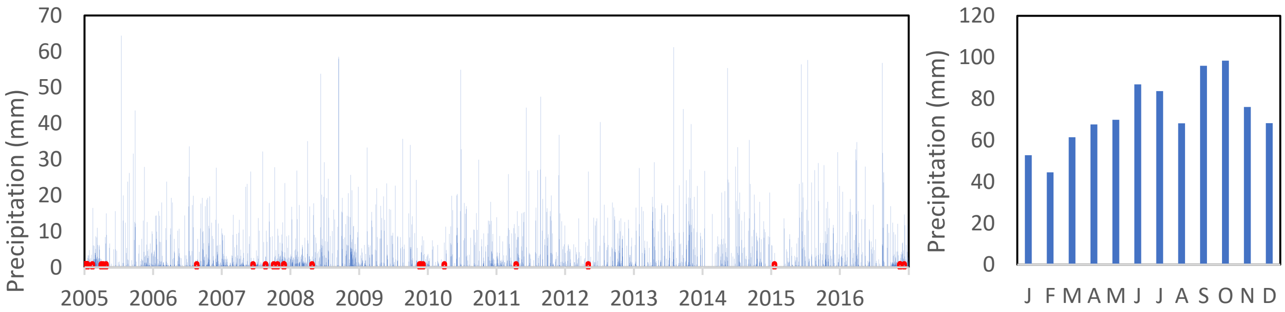

Figure 7. 2005-2016 time series of daily precipitation measured at GULGUL5 station, with monthly average values (left) (right). The absence of precipitation records is indicated by red marks.

3.1.5 Streamflow and Water Quality Data

Streamflow data at multiple locations (Table 4, Figure 6) are available for different periods. The 15-minute streamflow data was collected and maintained by the Ausable Bayfield Conservation Authority (ABCA). The number of available sediment and total phosphorus data for the period of 2011-2015 at Gulgul5 are given in Table 5.

Table 4. Inventory of streamflow data available at Gully creek watershed

Station	Data period
GulGul3	April 2011–March 2014
GulGul4	December 2011–March 2014
GulGul5(outlet)	April 2011–August 2015
GulGul7	September 2012–April 2015
GulGul8	September 2012–December 2014

Table 5. Inventory of (daily averaged) sediment and phosphorus data available at Gully creek watershed

Year	Winter	Spring	Summer	Autumn
2011	1 (1)	11 (9)	9 (11)	9 (10)
2012	4 (5)	4 (8)	3 (6)	8 (7)
2013	20 (20)	16 (17)	36 (36)	21 (21)
2014	4 (4)	15 (15)	30 (30)	18 (18)
2015	4 (4)	22 (22)	14 (14)	26 (26)

3.2 Model Build-up

3.2.1 Watershed Delineation

The process of stream network and sub-basin identification and calculation of their attributes are known as watershed delineation. With a threshold drainage area of 0.25 ha, the DEM-based watershed delineation method was applied in ArcSWAT, the ArcGIS environment's SWAT model builder. Further sub-basin divisions were made by adding an outlet. This process resulted in a total of 100 sub-basins in the Gully Creek watershed and draining a total area of 14.273 km^2. The sub-watershed boundaries and stream network of the selected watersheds are shown in Figure 8.

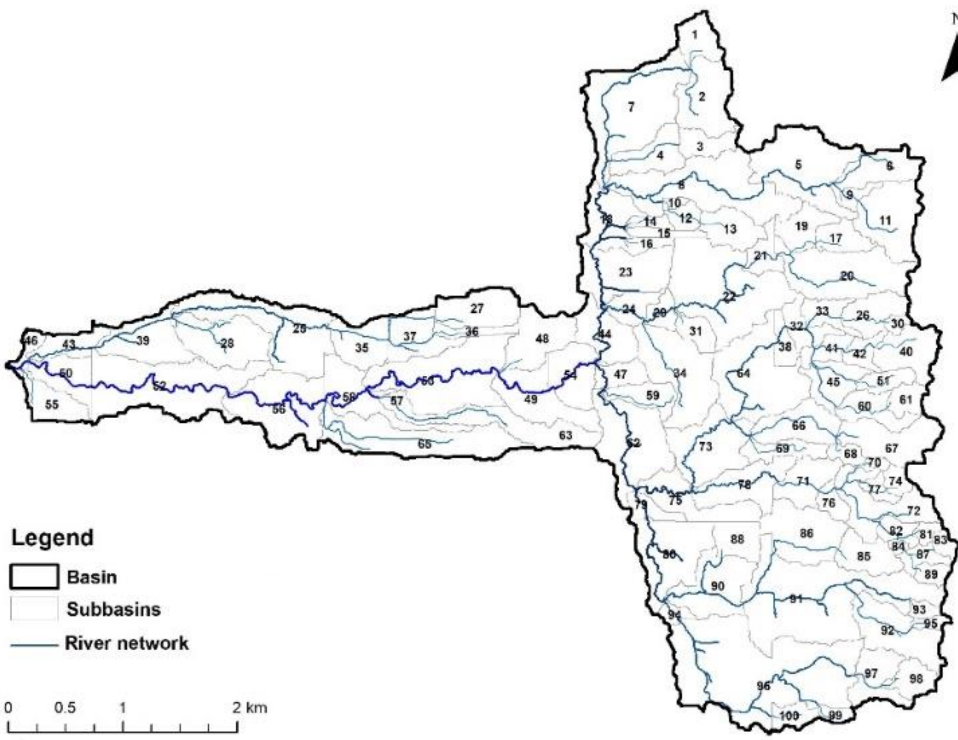

Figure 8. Delineated sub-basins and river network.

3.2.2 Hydrological Response Unit (HRU) Definition

Figure 9 shows how the DEM data was used to make a slope map. The slope map was split into four classes with breaks at 2%, 5%, and 10%. Most of the area in the Gully Creek watershed (42%) has a slope between 2% and 5%, 20% of the area has a slope of less than 2%, 21% of the area has a slope of between 5% and 10%, and 17% of the area has slope exceeding 10%. To keep the differences in land use, soil, and slope across space, a "zero threshold" approach was used, with no threshold values for soil, land use, or slope. This led to the creation of 3733 HRUs. Some researchers, like Strauch et al. (2015), found that using higher threshold values, like 10%, did not make much of a difference in larger watersheds. However, this effect would be more noticeable in smaller watersheds. With this method, the fields in the watershed were better delineated. Accordingly, a zero-threshold approach can be justified, even though it leads to a larger number of HRUs, and consequently greater computational effort.

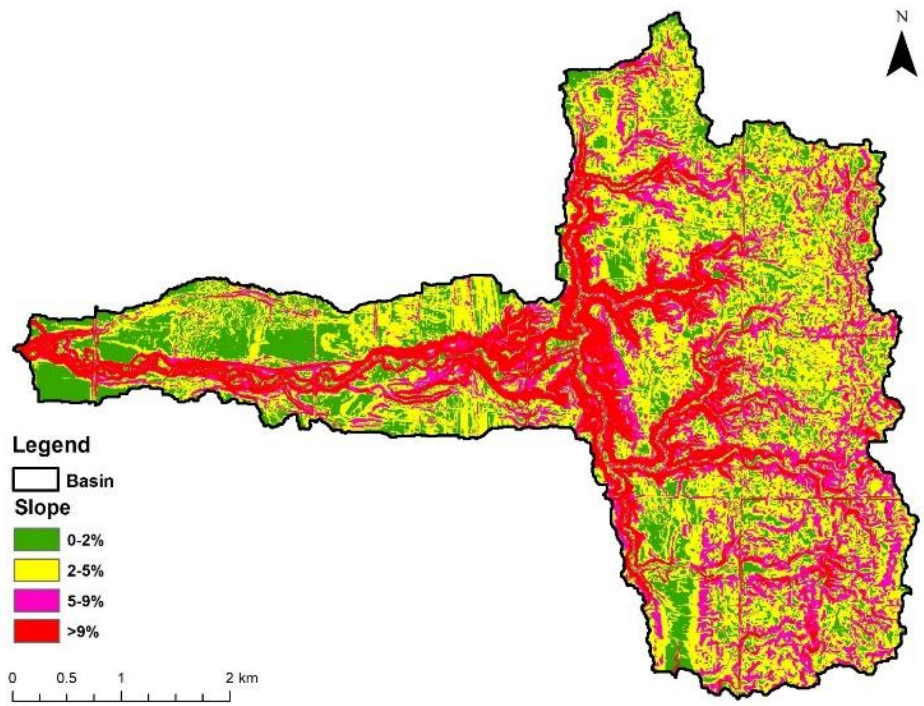

Figure 9. Slope map derived from DEM.

3.2.3 Weather Generator

SWAT accepts the "-99.0" code for missing meteorological data, which is then filled in with "synthetic" or "generated" data based on a weather generator database chosen by the user. The average monthly values that users put into the database are used to estimate missing daily values. For example, SWAT uses the first-order Markov chain model to decide if a day will be wet or dry. It does this by comparing a random number (0–1) generated by the model to the monthly probabilities of wet and dry days that the user has put into the weather database. If the day is labeled "wet," the amount of rain comes from a skewed distribution or a modified exponential distribution (Neitsch et al., 2011a). Most of the time, it is best to use a user-defined database that was put together using data from a nearby station. In this study, one of the weather generators built into SWAT (US First Order) was used. The US First Order weather generator database has monthly weather data for 1040 stations across the US. This data is needed for the SWAT weather generator (U.S.). Given how close our watershed is to the U.S. border, it made sense to use the U.S. First Order weather generator database.

3.2.4 Land and Crop Management

A SWAT model requires various land and crop management data. Once the crops cultivated in each field are determined, other land and crop management parameters are needed, such as the kind and timing of tillage operations, crop planting and harvest dates, and the timing and rates of fertilizer applications. SWAT also requires detailed information about how tillage is applied for each field and each crop grown in that field. SWAT needs to know the month and day of the operation and what kind of tillage operation it is. It also allows one to change the moisture condition II curve number (CN2) for the tillage operation (CNOP). Plant growth is initiated by the SWAT planting process, which is applicable to HRUs where no crops are growing. SWAT requires details about the planting timing (month and day), the kind of plants cultivated there, the most recent CNOP number for the plantation's operation, etc. The relevant crop management properties are assigned for land-use/cover types other than the fields that are cropped. SWAT model fertilizer application includes timing (month and day), kind of fertilizer or manure, amount of fertilizer, and depth of application. This study assumes 90% of the fertilizer to be surface applied. Complete broadcasting indicates 100% fertilizer being used on the surface.

3.2.5 Tile Drainage

This study did not distinguish between systematic and random tile drainage systems because detailed information such as tile length, tile spacing, tile depth, etc., was not available. Both types of tile drainage systems were represented by a simplified approach, suggested by Arnold et al. (1998), which requires the specification of four parameters: (a) depth to surface drain (DDRAIN), (b) time to drain soil to field capacity (TDRAIN), and (c) drain tile lag time (GDRAIN). SWAT's tile drainage technique is based on Hooghoudt and Kirkham (Moriasi et al., 2012). For this research project, tile drainage was simulated for all agricultural fields in the watershed using the SWAT IO documentation's recommended values for depth to drain (DDRAIN), drain tile lag time (GDRAIN), and time to drain soil to field capacity (TDRAIN) reported by Merriman et al. (2018a).

3.2.6 Tillage Operations

SWAT requires land and crop management details, including tillage. The SWAT tillage subroutine redistributes nutrients and residue in the soil profile, affecting yield and transport. Some fields in the designated watersheds are already practicing conservational tillage. SWAT requires the month, day, and kind of tillage operation for each field and operation. It also updates the tillage moisture AMCII curve number (CN2) (CNOP). SWAT's "till.dat" database includes all tillage operations. In the "till.dat" database, a new tillage operation's mixing efficiency and depth of mixing can be defined (Arnold et al., 2011). The Ausable Bayfield Conservation Association (ABCA) provided the tillage practices adopted for each field.

3.2.7 Cover Crops

Cover crops are becoming popular BMPs because they provide numerous benefits, such as reduced erosion, increased soil nutrient uptake, and decreased compaction. Different cover crops (*e.g.*, red clover, cereal rye, etc.) were widely used in the watershed, particularly with winter wheat. Winter wheat is considered a general crop in this study. Furthermore, some may argue that the effectiveness of winter wheat should be considered when calculating cover crop effectiveness, which is not done in this study. Because winter wheat is planted in the autumn, cover crop seeds are typically planted in April, and when winter wheat is harvested in the summer (*e.g.*, July), a good stand of the cover crop remains in the field. The cover crop would stay until fall or the following spring, supplying nutrients to the soils in the form of plant biomass. As a result, some farmers reduce fertilizer application rates for the next crop.

There would be a good stand of the cover crop when the winter wheat is harvested. SWAT, however, restricts crop cultivation to two crops at once. Instead, SWAT allows the transplantation of a crop. Two parameters would need to be specified to do this transplantation in SWAT: (a) the leaf area index at the time of transplantation (LAI INIT) and (b) the biomass at the time of transplantation (BIO INIT). Based on data pertaining to the date of winter wheat sowing and harvest, these parameters (LAI INIT and BIO INIT) were calculated.

3.2.8 Retiring Agricultural Land

The termination of agricultural activities on a piece of land, either for a specific field or field cluster (especially marginal lands) or for a broader area, is referred to as retiring the land. The land is returned to the natural state it was in previously, which was either grassland, pasture, forest, or a combination of these. Because no-tillage techniques, fertilizer applications, or crop harvesting takes place, this is the best-case scenario for the decrease of phosphorus burden in the watershed.

3.2.9 VFS

The VFS are gently sloping bands of native vegetation. Filter strips protect against erosion while also filtering sediment, phosphorus, and other pollutants from agricultural runoff. Because of the low installation and maintenance costs of VFS, as well as their effectiveness in removing pollutants, conservation and regulatory agencies are encouraging their use (Dillaha et al., 1989).

3.3 Definition of BMP Scenarios

The following section describes the scenarios that were tested in the Gully Creek watershed:

3.3.1 Current BMPs

The "Current BMP" scenario includes all the existing BMPs that were in place in the Gully Creek watershed. The majority of BMPs used in the Gully Creek watershed are non-structural. It includes tillage BMPs, namely, no-till and minimum-tillage.

3.3.2 No BMPs

All BMPs from the "Current BMPs" scenario are retired in the "No BMPs" scenario. This will be used to compare the effectiveness of the various BMPs implemented in the model to all other scenarios.

3.3.3 All Fields Min-Till

Minimum tillage was applied to all agricultural fields in the "No BMPs" scenario by modifying the tillage operations in the management file. The tillage operation for soybean is set to "Generic No-Till Mixing," while the tillage operation for other crops is set to "Generic Conservation Tillage." For this scenario, all crop curve numbers (CN2) were reduced by 2 in the tillage operation's curve number (CNOP). Based on the approach used by Merriman et al. (2018a) and Merriman et al. (2018b), parameters BIOMIX.mgt and OVN.hru were changed to 0.4 and 0.2, respectively.

3.3.4 All Fields No-Till

The "All Fields No-Till" scenario switches all tillage activities in the management to the "Generic No-Till Mixing" option, just as the "All Fields Min-Till" scenario is based on the "No BMPs" scenario. In this case, all curve number (CN2) values for the tillage operations in the management file were reduced by 5 for the CNOP. Using both Merriman et al. (2018a) BIOMIX.mgt and OVN.hru were set to 0.5 and 0.3, respectively.

3.3.5 Retire Agriculture Fields (Forest)

The "Retire Agricultural Fields (Forest)" scenario substitutes the FRSD (deciduous forest) management schedule for all agricultural management activities that were previously carried out. Additionally, all agricultural fields had their OVN.hru altered to 0.1, based on the values from the land cover database for FRSD and CN2.mgt adjusted depending on soil group.

3.3.6 Cover Crops after Winter wheat

The "Cover Crops" scenario was employed to test the efficacy of cover crops following winter wheat for phosphorus reduction during the winter months/non-growing season. Red clover was planted on 20 March and harvested the next year on 30 April. LAI INIT was given a value of 0.5, based on the red clover study by Black et al. (2009). The value of BIO INIT was set at 800 kg ha^{-1} in accordance with the findings of Alaru et al. (2017). When the cover crop was harvested, it was designated as having been left on the ground by setting the harvest efficiency (HARVEFF) close to zero and IHV GBM = 0, which indicates that the biomass was harvested and left on the ground.

3.3.7 VFS

The VFS were deployed at the boundary of all agricultural fields in this scenario by activating the.ops file. The following are the parameters and their values for the filter strip operations: According to Merriman et al., VFSI was set to 1, VFSRATIO to 40, VFSCON to the usual 0.5, and VFSCH to 0 (Merriman et al., 2018a).

Chapter 4: Model Calibration

4.1 Flow Calibration

Calibration was performed by keeping three years (2008-2010) as a model warmup period and three years (2011-13) as a model calibration period. The model was calibrated for daily streamflow simulations at GULGUL5 (outlet of subbasin no. 54). Table 6 shows a list of different flow hydrology parameters, such as those related to snow and snowmelt, groundwater, and relative parameters like CN2, SOL K, SOL ALB, SOL AWC, etc., which may have different spatial patterns from HRU to HRU at the field level. So, these parameters were chosen to calibrate the stream flow model. The final values and ranges for these parameters are shown in Table 6. SWAT-CUP (Abbaspour et al., 2007) was used to calibrate the model using the SUFI-2 (Abbaspour et al., 2007) optimization algorithm. SWATCUP was run for 500 simulations with a uniform distribution of parameters based on Table 6's upper and lower limits. If more runs were needed, they were done based on what the SUFI-2 algorithm called "new parameter sets." The Nash-Sutcliffe Efficiency (NSE) and the Percentage of Bias were used as statistical model accuracy indicators for flow calibration and subsequent calibrations (PBIAS). The calculated values for NSE and PBIAS were 0.5 and 24.8 percent, respectively (Table 7 and Table 9). Being between 0.5 and 0.7, the NSE value was deemed satisfactory (Moriasi et al., 2015).

Table 6. Parameters Used in Calibration of Streamflow

Parameter	File Type	Description	Default Value	Model Range	Gully Creek
SMTMP	.bsn	Snow melt base temperature (°C)	0.5	-5 to 5	0
SFTMP	.bsn	Snowfall temperature (°C)	1	-5 to 5	-1
SMFMX	.bsn	Maximum melt factor for snow on June 21 (mm H_2O $°C^{-1}day^{-1}$)	4.5	1.4 to 6.9	5.5
SMFMN	.bsn	Minimum melt factor for snow on December 21 (mm H_2O $°C^{-1}day^{-1}$)	4.5	1.4 to 6.9	5
SNOCOVMX	.bsn	Minimum snow water content that corresponds to 100% snow cover (mm H_2O)	1	0 to 500	15
SNO50COV	.bsn	Fraction of snow volume that corresponds to 50% snow cover	0.5	0.01 to 0.99	0.5
TIMP	.bsn	Snow pack temperature lag factor	1	0.01 to 1	0.4
ESCO	.hru	Soil Evaporation compensation factor	0.95	0 to 1	0.8
EPCO	.hru	Plant uptake compensation factor	1	0 to 1	0.65
CH_N2	.rte	Manning's coefficient for the main channel	0.014	-0.01 to 0.3	0.04
CH_K2	.rte	Effective hydraulic conductivity in main channel alluvium (mm hr^{-1})	0	-0.01 to 500	10
SURLAG	.hru	Surface runoff lag coefficient	2	0 to 24	2
GWQMN	.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm H_2O)	1000	0 to 5000	1000
RCHRG_DP	.gw	Deep aquifer percolation traction	0	0 to 1	0.05
GW_DELAY	.gw	Groundwater delay time (days)	31	0 to 2000	31
GW_REVAP	.gw	Groundwater “revap” coefficient	0.02	0.02 to 0.2	0.04
ALPHA.BF	.gw	Baseflow alpha factor	0.048	0 to 1	0.6
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	750
SOL.AWC	.sol	Available water capacity of the soil layer (mm H_2O mm^{-1} soil)	Varies	-0.1 to 0.1*	0.023
SOL_K	.sol	Saturated hydraulic conductivity (mm hr^{-1})	Varies	-0.1 to 0.1*	0.127
DEP_IMP	.hru	Depth to impervious layer m agricultural fields (mm)	6000	0 to 6000	2100
CN2	.mgt	Initial SCS runoff curve number for moisture condition II	Varies	-0.4 to 0.4*	0.124
DDRAIN	.mgt	Depth to drains (mm); must be >0 to initiate tile drainage	0	0 to 2000	900
TDRADJ	.mgt	Time to drain soil to field capacity (hours)	0	0 to 2000	48
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)

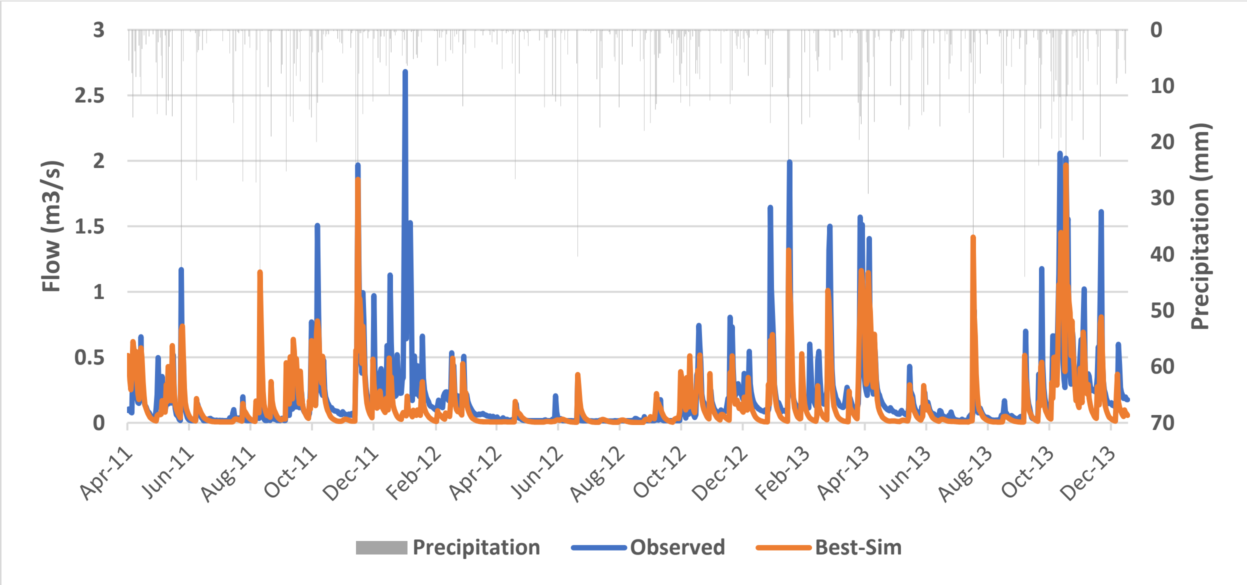

Figure 10. Observed precipitation and comparison of observed streamflow with simulated streamflow during 2011-13.

Table 7. Model Performance for Flow Simulation at GULGUL5

Station	Period	Daily NSE	PBIAS	R^2
GULGUL5	4/15/2011 to 12/31/2013	0.5	24.8	0.53

4.2 Water Balance

During the calibration of the SWAT model, the accuracy of water balance component simulations was checked. Figure 11 shows the water balance components generated by the calibrated SWAT model. Table 8 presents the comparison of water balance components, simulated by the SWAT, using the optimized streamflow parameter set presented in Table 6. Snowfall constituted 8.32% of the total precipitation, about 47.32% of precipitation was converted into water yield, and 52.85% of the precipitation was lost as actual evapotranspiration.

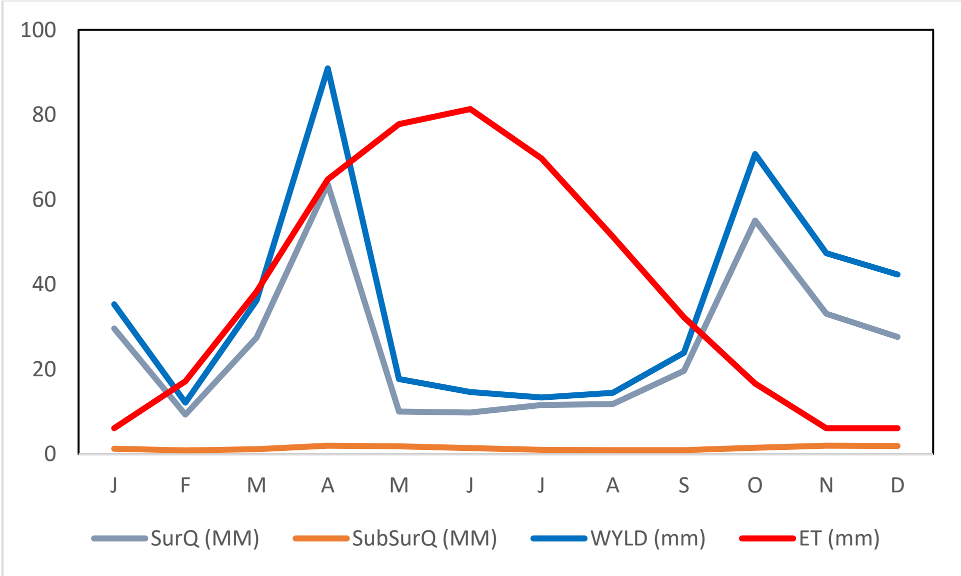

Figure 11. Monthly hydrological budget simulated by SWAT model Note: SurQ: Surface runoff; SubSurQ: Sub-surface runoff; WYLD: Water yield; ET: evapotranspiration.

Table 8. Monthly and annual hydrological budget of the selected watershed as simulated by the best-fit streamflow-related parameter set

Mon	Precipitation (mm)	Snow (mm)	SurQ (mm)	SubSurQ (mm)	WYLD (mm)	ET (mm)
1	60.21	26.03	29.59	1.24	35.31	6.47
2	36.11	21.01	9.29	0.84	12.11	6.1
3	43.78	19.06	27.45	1.15	36.22	17.16
4	88.17	0.26	63.61	1.96	90.92	38.29
5	68.97	0	10	1.83	17.69	64.75
6	72.67	0	9.8	1.39	14.62	77.76
7	82.07	0	11.57	0.98	13.33	81.33
8	67.95	0	11.77	0.92	14.41	69.7
9	97.2	0	19.61	0.9	23.88	51.29
10	138.44	0	55.05	1.48	70.72	32.23
11	68.25	2.02	33.08	1.95	47.35	16.61
12	61.29	5.29	27.6	1.9	42.31	6.07
Annual	885.11	73.67	308.42	16.54	418.87	467.76
%		**8.32**	**34.85**	**1.87**	**47.32**	**52.85**

4.3 Sediment Calibration

After the flow calibration, sediment load calibration was performed. SWAT-CUP was used to calibrate the model by comparing the simulated sediment concentration to the measured sediment concentration. The warmup period was from 2008 to 2010, and the calibration period was from

2011 to 2013. The model was calibrated at a monthly time step (derived from daily values). For the calibration of sediment, sediment concentration data was used. SWATCUP auto-calibration was performed using the selected sediment transport parameters, as shown in Table 9. The comparison of observed sediment with simulated sediment concentration is shown in Figure 12.Table 10 provides the calibration statistics for sediment simulation. Based on the values of PBIAS, NSE, and R, the model's performance was unsatisfactory (Moriasi et al. (2015) in simulating sediment concentration. This was attributed to the insufficient and infrequent availability of sediment data for calibration.

Table 9. Parameters Used in Sediment Calibration

Parameter	**File Type**	**Description**	**Default Value**	**Model Range**	**Gully Creek**
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	0.0016
SPEXP	.bsn	Exponent parameter for calculating sediment reentrained in channel sediment routing	1	1.0 to 1.5	1.7
ADJ_PKR	.bsn	Peak rate adjustment factor for sediment routing in the subbasin (tributary channels)	1	0.5 to 2	1.39
PRF_BSN	.bsn	Peak rate adjustment factor for sediment routing in the main channel	1	0 to 2	0.55
CH_COV1	.rte	Channel erodibility factor	0	-0.05 to 0.6	0.057
CH_COV2	.rte	Channel cover factor	0	-0.001 to 1	0.284
CH_ERODMO (1-12)	.rte	Monthly channel erodibility factor	0	0 to 1	Varies
USLE_K	.sol	USLE equation soil erodibility (K) factor	Varies	-0.1 to 0.1*	-0.087
RES_D50	.res	Median particle diameter of sediment (µm)		1.95 to 2000	1530

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

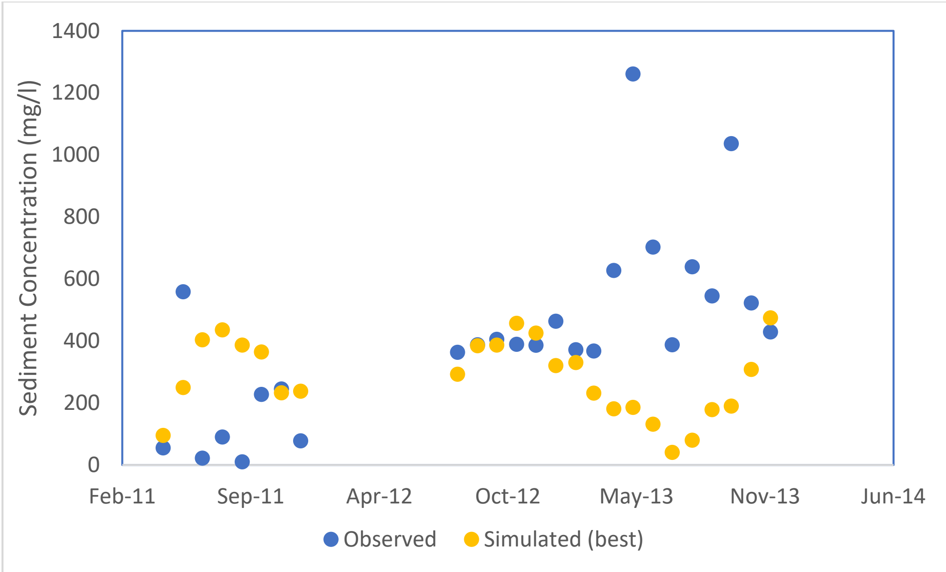

Figure 12. Comparison of observed sediment with simulated sediment loads during the period of 2011-2013.

Table 10. Model Performance for Sediment Simulation at GULGUL5

Station	**Period**	**Daily NSE**	**PBIAS**	**R^2**
GULGUL5	4/15/2011 to 12/31/2013	-0.75	33.8	0.14

4.4 Phosphorus Calibration

After streamflow and sediment calibration, the SWAT model was calibrated for phosphorus using SWAT-CUP, maintaining a warming period of 3 years (2008-2010) and a calibration period of 2 years (2011–2013). Total P output from the SWAT model was compared with the observed data. A suitable parameter range of phosphorus-related parameters was acquired after numerous runs and was used for calibration. The selected calibration parameters used in the Phosphorus calibration are shown in Table 11. Using the measured flow data, the total phosphorus load was computed from the concentration (Figure 13).

Table 11. Parameters Used in Phosphorus Calibration

Parameter	File Type	Description	Default Value	Model Range	Gully Creek
SOL_P_MODEL	.bsn	Soil Phosphorus Model (0=original; 1 = new soil P model)	0	0 or 1	0
P_UPDIS	.bsn	Phosphorus uptake distribution parameter	20.0	Varies	44.29
PPERCO	.bsn	Phosphorus percolation coefficient (10 m^3 Mg^{-1})	10.0	10 to 17.5	14.25
PHOSKD	.bsn	Phosphorus soil partitioning coefficient (m^3 Mg^{-1})	175.0	Varies	143.25
PSP	.bsn	Phosphorus availability index	0.40	Varies	0.22
GWSOLP	.gw	Concentration of soluble phosphorus in groundwater contribution to streamflow from subbasin (mg P L^{-1} or ppm)	-	Varies	1240.04
ERORGP	.hru	Phosphorus enrichment ratio for loading with sediment	0	Varies	2.04

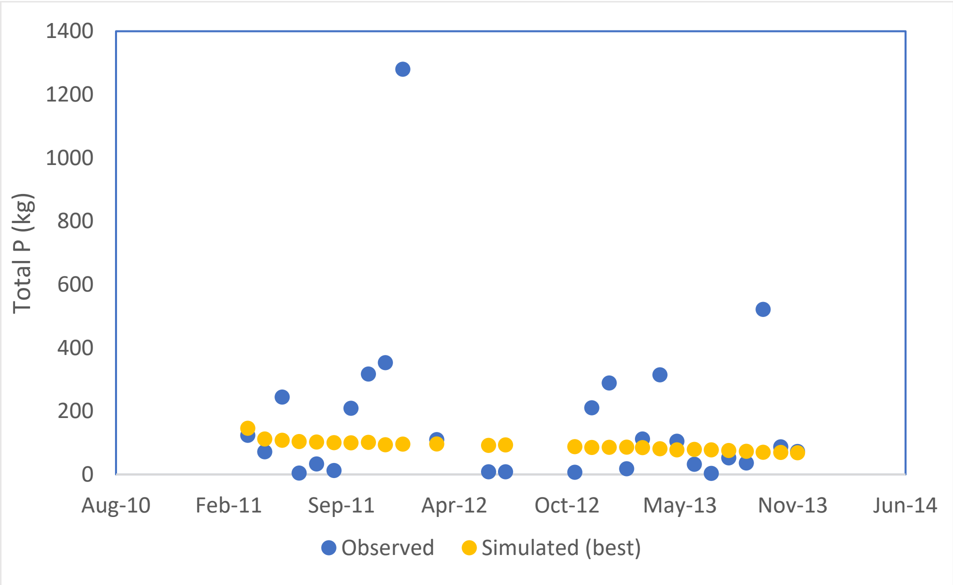

Figure 13. Comparison of observed phosphorus with simulated phosphorus loads during the period of 2011-13.

The calibration statistics are shown in Table 12. Based on the criteria set by Moriasi et al. (2015), with an NSE < -0.1 and the PBIAS > 30%, model performance was unsatisfactory (2015).

Table 12. Model Performance for Phosphorus Simulation

Station	Period	Daily NSE	PBIAS	R^2
GULGUL5	4/15/2011 to 12/31/2013	-0.10	47.3	0.00

4.5 Model limitations

All the water quality data used in the calibration of the model was instantaneous data. Observations were not collected at evenly distributed intervals on days with numerous samplings. As a result of this, the observed data was insufficient for proper model calibration. The number of water quality data points that were available was also limited, and calibration was performed by comparing the continuous results from the model simulation with instantaneously observed data. These factors appear to have resulted in poorer model performance for sediment and Phosphorus simulations.

Chapter 5: BMP Scenarios Results

The calibrated SWAT model was used to evaluate the efficacy of various BMP scenarios in reducing phosphorus loads in the Gully Creek watershed on both an annual and seasonal (growing and non-growing season) basis. The “non-growing season" refers to the time from November to April when most crops are dormant or not growing. The months of May through October are considered the growing season. All possible outcomes in this study were contrasted with the "No BMPs" scenario, detailed in the previous chapter.

5.1 Effectiveness of Potential BMPs

The calibrated model was used to evaluate potential BMPs (Retiring Land scenario, Minimum tillage, No-tillage, Cover crop after winter wheat, VFS). The BMPs were applied in all agricultural fields in the watershed, and the total phosphorus load exported out of the watershed outlet in each scenario was compared with the "No BMP" scenario. Their effectiveness was then computed on various time scales.

5.1.1 Retiring Land Scenarios

This scenario was performed to see the maximum P reduction potential in the Gully Creek watershed. It was done by converting all the agricultural fields to either forest or pasture. Traditionally, retiring land involves reintroducing native flora (trees, bushes, grasses, etc.) to unprofitable agricultural land.

5.1.1.1 “Retire to Forest” Scenario

The “Retire to Forest” scenario showed a significant flow reduction during the growing season up to a maximum annual flow reduction of about 22% (Table 13). The reduction of flow was significantly higher during the growing season. This is expected as forests absorb excess rainwater, preventing runoff and flooding damage. The scenario also showed a substantial sediment reduction (80% - 92%) during the growing season (Table 13). The decrease in sediment load was more significant during the growing season than in the non-growing season.

There was also a significant reduction in P at the outlet. Retiring land is a best-case scenario where all crops, tilling practices, and fertilizers are removed from the watershed. Accordingly, the amount of phosphorus loss is significantly reduced, both seasonally and annually. In the present case, there was a reduction of as much as 95% in total P loss at the outlet (Table 13, Figure 14). The total P reduction was greater during summer and fall than in the winter and spring seasons. In all years of simulation, the relative reduction in organic P is greater than that of inorganic P mineral. On a seasonal scale, the average annual phosphorous reduction at the watershed outlet was 93% during the non-growing season and 88% during the growing season (Figure 14). However, retiring the full watershed to the forest is not a practical or realistic option, given that agricultural activity in this area is a significant component of the region's economy.

Table 13. Effectiveness of the "Retire to Forest" scenario during 2011-2015

"Retire to Forest" Reductions (%)						
Year	**Season**	**Flow**	**SED YIELD**	**P Organic**	**P Mineral**	**P total**
2011	Non-Growing	-6.08	-87.63	-88.94	-72.58	-88.44
	Growing	-35.40	-94.24	-95.95	-80.81	-95.39
	Year	-16.39	-91.31	-91.87	-76.41	-91.35
2012	Non-Growing	-11.98	-88.41	-91.31	-77.90	-90.83
	Growing	-43.51	-93.68	-96.74	-83.34	-96.05
	Year	-19.21	-91.35	-93.96	-81.10	-93.40
2013	Non-Growing	-1.71	-88.84	-90.41	-81.00	-90.12
	Growing	-20.75	-91.58	-93.30	-84.60	-92.94
	Year	-7.87	-90.11	-91.56	-82.71	-91.25
2014	Non-Growing	-7.71	-80.23	-79.32	-69.21	-79.05
	Growing	-14.78	-80.21	-84.01	-55.28	-82.10
	Year	-10.85	-79.95	-80.33	-63.47	-79.73
2015	Non-Growing	-18.38	-92.59	-93.54	-73.42	-92.88
	Growing	-27.00	-92.77	-94.34	-73.42	-93.64
	Year	-22.36	-92.73	-94.07	-73.42	-93.39

* Negative values represent a reduction, whereas positive values represent an increase

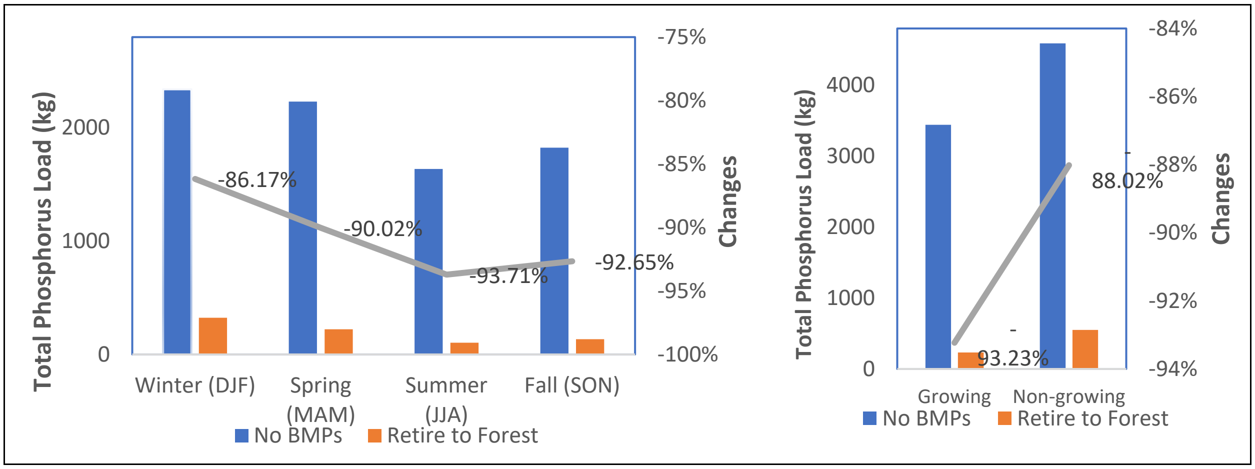

Figure 14. Seasonal and growing/non-growing season annual total P loss changes under the "Retire to Forest" scenario.

5.1.1.2 "Retire to Pasture" Scenario

Except in 2013 and 2014, there was some reduction in flow (Table 14), mainly during the growing season. The precipitation was very high during 2013 (1044 mm) compared to 2014 (864 mm). The average annual sediment yield is not as high as we saw in the "Retire to Forest" scenario, the highest being 81% reduction in 2012. The reason is the excellent land coverage during the non-growing season, which reduces the runoff and eventually controls soil erosion. There is also a significant P (70% reduction in average annual P total) in this scenario but lesser than in the "Retire to Forest" Scenario. As stated earlier, "Retire to Pasture" is a best-case scenario where there is no tillage and not any fertilizers or manures are added to the environment. Also, the P loss from the crop residue is lesser than in the No-BMP scenario. As a result, the average annual reduction of P is around 70% during the growing season and 76% during the non-growing season (Figure 15 and Table 14).The amount of P organic is significantly higher than the P mineral in all the simulated years. Approximately 30 to 65 percent of total soil phosphorus is in organic forms unavailable to plants, with the remaining 35 to 70 percent in inorganic forms (Harrison, 1987; Turner and Engelbrecht, 2011). Dead plant/animal residues and soil microorganisms are organic sources of phosphorus. Soil microorganisms are essential in converting these organic forms of phosphorus into plant-available forms.

Table 14. Effectiveness of "Retire to Pasture" scenario at the watershed outlet during 2011-2015

"Retire to Pasture" Reductions (%)						
Year	**Season**	**Flow**	**SED YIELD**	**P Organic**	**P Mineral**	**P total**
2011	Non-Growing	-3.25	-71.77	-76.67	-67.42	-76.38
	Growing	-7.14	-80.45	-84.01	-69.07	-83.45
	Year	-4.62	-76.53	-79.73	-68.18	-79.35
2012	Non-Growing	1.19	-77.54	-82.71	-75.72	-82.46
	Growing	-18.98	-83.91	-88.39	-78.26	-87.87
	Year	-3.43	-81.09	-85.49	-77.21	-85.13
2013	Non-Growing	-0.17	-79.71	-82.14	-77.00	-81.98
	Growing	8.56	-73.06	-77.99	-73.71	-77.81
	Year	2.66	-76.64	-80.49	-75.44	-80.31
2014	Non-Growing	-1.01	-58.47	-60.10	-57.78	-60.05
	Growing	14.07	68.75	21.65	-7.18	19.74
	Year	5.70	-30.41	-42.52	-36.93	-42.33
2015	Non-Growing	-9.21	-69.14	-72.38	-66.95	-72.21
	Growing	1.77	-50.20	-61.47	-43.19	-60.86
	Year	-4.15	-54.85	-65.09	-50.89	-64.62

* Negative values represent a reduction, whereas positive values are an increase

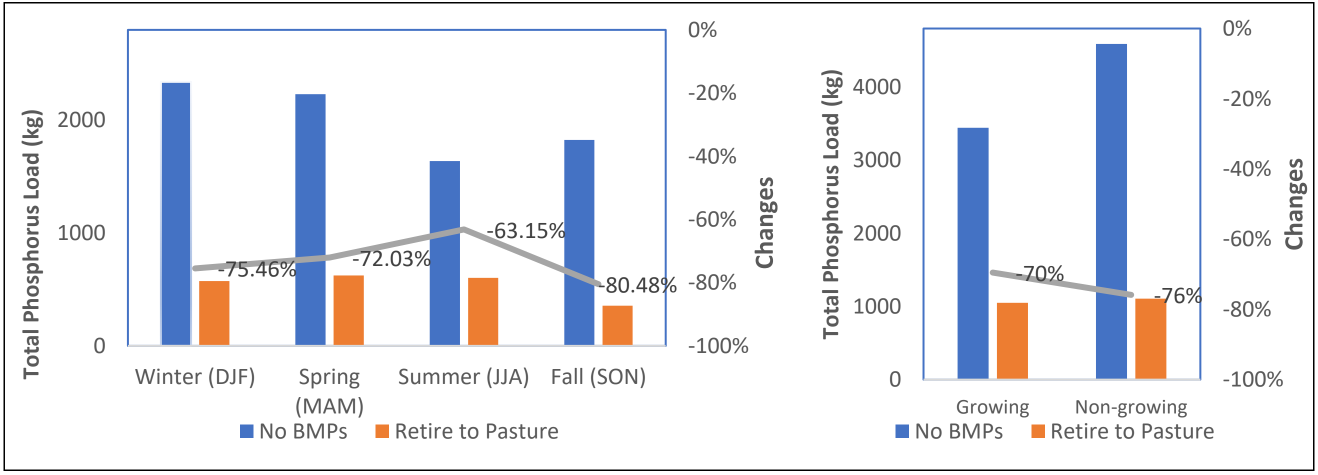

Figure 15. Seasonal and growing/non-growing annual Total P changes under the "Retire to Pasture" scenario

5.1.2 Minimum Tillage Scenario

This scenario was applied to all agricultural fields within the watershed using "All min-till" for tillage operations. Results were compared to the "No BMP" scenario results. Under this scenario, there were some reductions in annual flows (Table 15). The "All Min-Till" scenario's phosphorus losses showed a decline exceeding 16% during the growing season but a negligible one during the non-growing season (Figure 16). The decrease in the quantity of inorganic phosphorus was marginally greater than that of organic phosphorus. This was due to reduced surface runoff, which, in turn, decreased the soil erosion rate and mineral phosphorus transport to the streams. As compared to both “Retire to Forest” and “Retire to Pasture” scenarios, the reduction of P under this scenario was substantially less. This was because only the tillage practices were minimized, but all crops were still grown and received the required fertilizers/manures as usual.

Table 15. Effectiveness of Minimum Tillage scenario during 2011-2015

Min Tillage Reductions (%)						
Year	**Season**	**Flow**	**SED YIELD**	**P Organic**	**P Mineral**	**P total**
2011	Non-Growing	0.24	4.57	6.23	1.32	6.07
	Growing	-1.55	-19.75	-16.63	-14.38	-16.53
	Year	-0.39	-8.57	-3.32	-5.98	-3.41
2012	Non-Growing	0.44	-13.04	-8.74	-9.10	-8.76
	Growing	-14.06	-27.59	-26.20	-21.71	-25.96
	Year	-2.88	-21.15	-17.27	-16.51	-17.24
2013	Non-Growing	0.44	-5.51	-4.76	-6.44	-4.80
	Growing	-3.16	-18.01	-16.70	-11.24	-16.47
	Year	-0.72	-11.29	-9.51	-8.71	-9.47
2014	Non-Growing	-0.17	-1.69	0.08	-2.25	0.00
	Growing	-1.09	-10.42	-8.05	-10.55	-8.21
	Year	-0.58	-2.25	-1.67	-5.67	-1.82
2015	Non-Growing	0.21	-4.94	2.44	-1.25	2.32
	Growing	-4.05	-18.07	-14.69	-13.78	-14.67
	Year	-1.75	-14.85	-9.00	-9.72	-9.04

* Negative values represent a reduction, whereas positive values are an increase

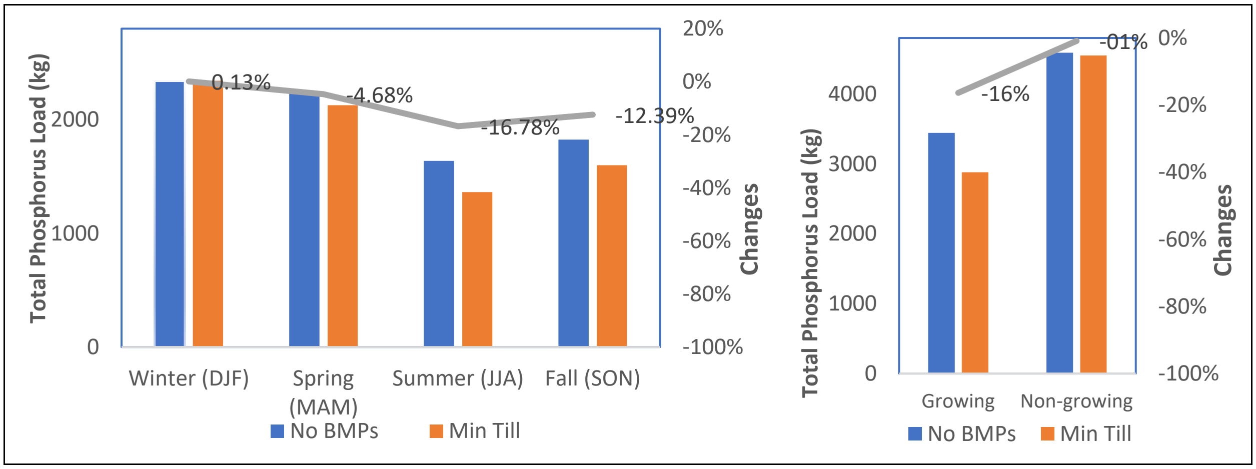

Figure 16. Seasonal and growing/non-growing annual Total P changes under the Minimum Tillage scenario.

5.1.3 No-Tillage Scenario

The no-tillage scenario resulted in a 34% annual reduction in P loss during the growing season and 12% during the non-growing season (Figure 17) compared to the "No BMP" scenario. Unlike the "Min Tillage" scenario, no-tillage showed 18% less reduction during the growing season and 11% less reduction during the non-growing season. This is because fertilizers/manures were applied during the growing season and no-tillage minimized nutrient losses from agricultural farms. The level of reduction was far less than the land retiring scenario, which is to be expected as crops were still grown on the farmlands. Similar to the "minimum tillage" scenario, the "no-tillage" scenario does not show any significant reduction in phosphorus losses compared to retiring land scenarios. The highest reduction in phosphorus load is seen during summer (34%), followed by fall (27%) and spring (23%). There is a slight reduction in flow during the entire period.The sediment yield reduction is much higher than we saw in the minimum tillage scenario.

Table 16. Effectiveness of No-Tillage scenario during 2011-2015

No-Tillage Reductions (%)						
Year	**Season**	**Flow**	**SED YIELD**	**P Organic**	**P Mineral**	**P total**
2011	Non-Growing	0.78	-24.19	-13.55	-9.39	-13.41
	Growing	-2.60	-47.74	-38.04	-30.77	-37.77
	Year	-0.41	-37.09	-23.78	-19.33	-23.63
2012	Non-Growing	1.15	-27.54	-17.70	-17.75	-17.70
	Growing	-30.11	-52.87	-47.88	-42.15	-47.59
	Year	-6.02	-41.67	-32.45	-32.09	-32.44
2013	Non-Growing	1.08	-18.99	-10.47	-11.53	-10.50
	Growing	-6.59	-37.54	-31.31	-23.68	-31.00
	Year	-1.40	-27.57	-18.75	-17.28	-18.70
2014	Non-Growing	-0.07	-13.84	-7.43	-6.01	-7.42
	Growing	-1.80	-29.17	-25.52	-19.02	-25.07
	Year	-0.84	-15.99	-11.32	-11.37	-11.34
2015	Non-Growing	0.16	-29.63	-14.94	-12.23	-14.86
	Growing	-8.35	-42.17	-31.69	-25.65	-31.49
	Year	-3.76	-39.09	-26.13	-21.30	-25.97

* Negative values represent a reduction, whereas positive values are an increase

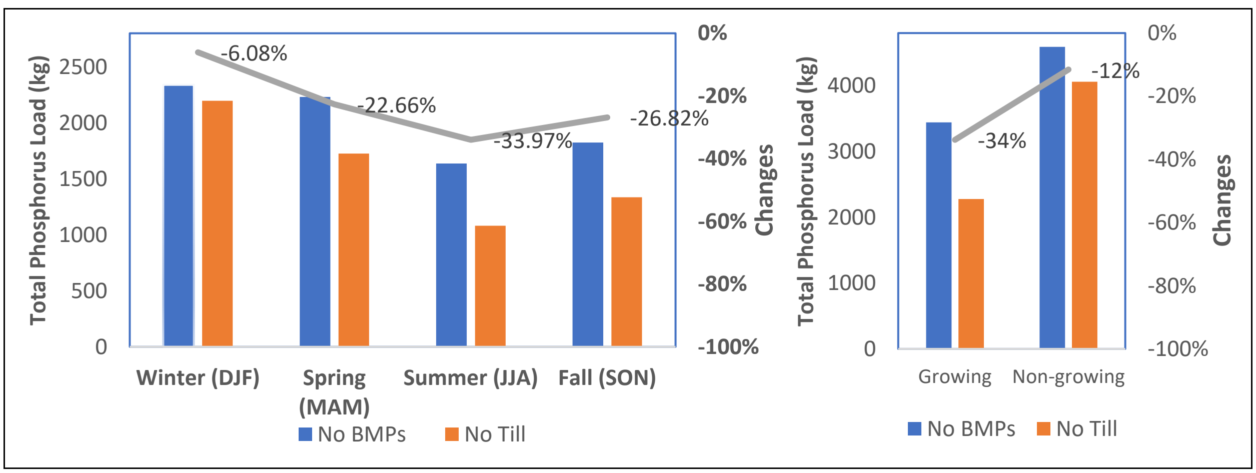

Figure 17. Seasonal and growing/non-growing annual Total P changes under the No-Tillage scenario.

5.1.4 Cover crop after Winter Wheat scenario

As mentioned in section 3.3.6, red clover was chosen for the cover crop BMP. Red clover was planted in early spring and harvested at the end of April of the next year. and Figure 18. Compared with the land retiring scenario, the reduction was significantly lower, and the decline is less compared with the two tillage BMPs. The highest reduction in phosphorus load is seen during spring (29%), followed by summer (21%), fall (3.7%), and winter (3.6%) (Figure 18). This BMP resulted in a 15% decrease in total phosphorus loads during the growing seasons with no change during the growing season and 11% during the non-growing season (Figure 18).

Table 17. Effectiveness of Cover crop scenario during 2011-2015

Cover Crop Reductions (%)						
Year	**Season**	**Flow**	**SED YIELD**	**P Organic**	**P Mineral**	**P total**
2011	Non-Growing	-8.11	-47.58	-43.49	-19.40	-42.75
	Growing	-8.15	-34.57	-27.16	-18.91	-26.85
	Year	-8.12	-39.79	-36.67	-19.17	-36.08
2012	Non-Growing	0.15	-0.72	31.95	31.97	31.93
	Growing	0.20	-2.30	22.19	33.11	22.76
	Year	0.16	-1.60	27.18	32.64	27.41
2013	Non-Growing	0.01	-0.14	8.49	9.07	8.51
	Growing	0.01	0.17	3.62	3.10	3.61
	Year	0.01	0.00	6.55	6.25	6.55
2014	Non-Growing	-3.02	-12.71	-16.38	-16.00	-16.39
	Growing	-14.95	-31.25	-34.70	-35.18	-34.73
	Year	-8.33	-15.54	-20.32	-23.90	-20.46
2015	Non-Growing	-1.55	-49.38	-39.08	-10.66	-38.16
	Growing	-21.91	-42.97	-39.75	-27.75	-39.36
	Year	-10.94	-44.55	-39.53	-22.21	-38.96

* Negative values represent a reduction, whereas positive values are an increase

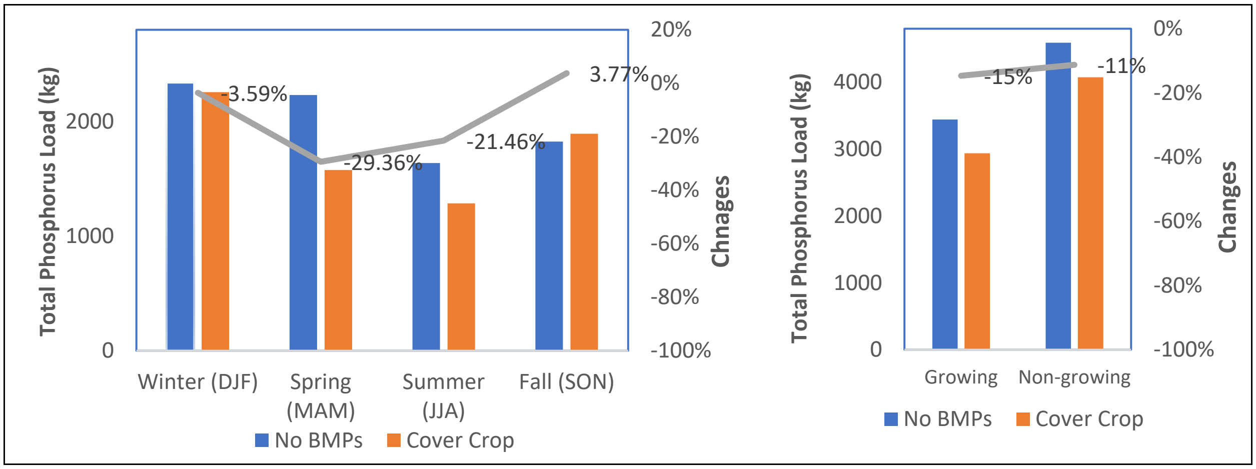

Figure 18. Seasonal and growing/non-growing annual Total P changes under the Cover Crop scenario.

5.1.5 VFS Scenario

This BMP was simulated by activating the .ops file in the SWAT model and applying a VFS on the boundary of all the agricultural fields. Based on the parameters employed, for each unit of filter strip area, there were forty units (VFSRATIO) of seeding area. As a result, the area and width of the filter strips varied depending on the size of the HRU they were applied to. The FSRATIO parameter represents the ratio between the HRU drainage area and the VFS area. As one is reducing the VFS area available for filtering, the more significant the VFSRATIO, the lower the reduction in sediments/nutrient losses. Adopting VFS in the watershed resulted in a reduction of phosphorus load by 62% during the non-growing season and by 60% during the growing season (Figure 19). The reductions in organic phosphorus and mineral phosphorus were much more significant than those under the tillage or cover crops scenarios. VFS utilizes filtration, deposition, infiltration, adsorption, absorption, decomposition, and/or volatilization to remove sediment and other contaminants from surface water runoff. There was a reduction in total phosphorus of about 67%, 64%, 60%, and 52% during fall, spring, winter, and summer (Table 18). There is a significant sediment loss reduction, with an average annual sediment reduction of 69%. It is interesting to note that the flow rate did not change after implementing VFS on agricultural land. So, VFS reduced sediments/nutrients, bacteria, and pesticides but did not affect surface runoff in SWAT.

Table 18. Effectiveness of VFS Scenario during 2011-2015

VFS Reductions (%)						
Year	**Season**	**Flow**	**TSS**	**P Organic**	**P Mineral**	**P total**
2011	Non-Growing	0.00	-69.35	-61.88	-55.47	-61.69
	Growing	0.00	-71.01	-62.22	-52.77	-61.87
	Year	0.00	-70.29	-62.03	-54.21	-61.76
2012	Non-Growing	0.00	-77.37	-67.70	-60.81	-67.47
	Growing	0.00	-69.71	-60.83	-47.97	-60.16
	Year	0.00	-73.08	-64.34	-53.26	-63.86
2013	Non-Growing	0.00	-67.92	-63.79	-60.06	-63.67
	Growing	0.00	-66.05	-61.45	-56.07	-61.23
	Year	0.00	-67.06	-62.86	-58.17	-62.69
2014	Non-Growing	0.00	-64.12	-54.80	-52.55	-54.75
	Growing	0.00	-71.28	-65.04	-50.93	-64.10
	Year	0.00	-65.63	-57.00	-51.89	-56.83
2015	Non-Growing	0.00	-77.36	-67.69	-57.07	-67.35
	Growing	0.00	-64.53	-56.91	-46.57	-56.57
	Year	0.00	-67.63	-60.49	-49.97	-60.14

* Negative values represent a reduction, whereas positive values are an increase

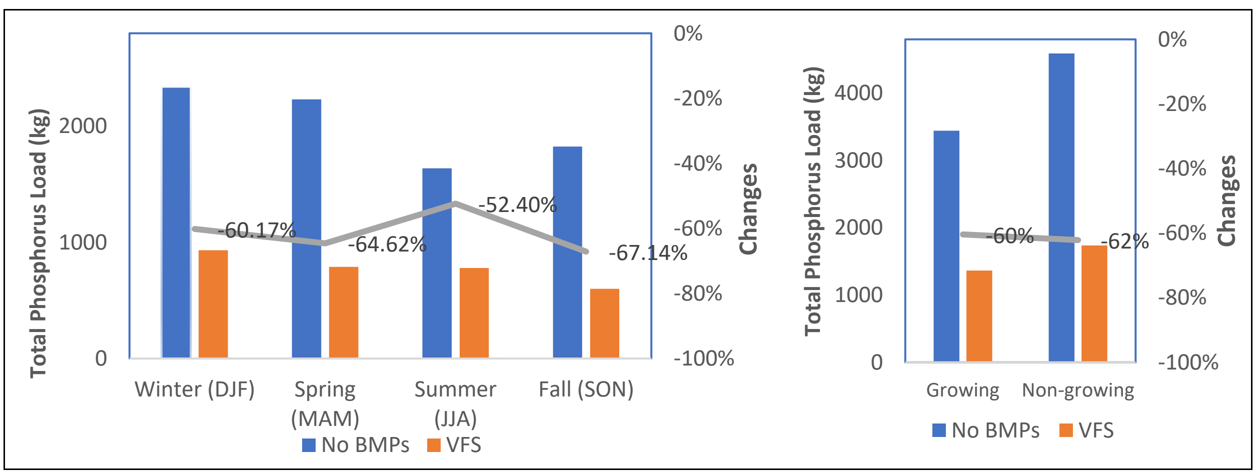

Figure 19. Seasonal and growing/non-growing annual Total P changes under the VFS scenario.

Chapter 6: Summary and Conclusions

In this study, the Soil and Water Assessment Tool (SWAT) was selected as a continuous simulation hydrological and water quality watershed model to evaluate the efficacy of various BMPs in preventing phosphorus loss from a small agricultural watershed. The model was set up using various spatial, meteorological, and farming information data. The model was calibrated using hydrological and water quality data (stream flow, sediment, and total phosphorus concentration). The calibrated model was then used to simulate several selected BMPs to assess their effectiveness in reducing the total phosphorus load exiting the watershed.

The model showed the highest reduction in total phosphorus load in the case of the two land retiring scenarios, viz., “Retire to Forest” and “Retire to Pasture.” Retiring to the forest gives the highest reduction in total phosphorus loss (≈ 90%) as compared to retiring to pasture (≈ 73%). The two-conservation tillage BMPs were effective in reducing phosphorus loads. The No-till BMP resulted in an average annual reduction in phosphorus of about 23%, whereas minimum tillage resulted in an 8% reduction. VFS along the boundary of the agricultural fields had a more significant impact on phosphorus reduction (61%). Cover crop BMP reduced the annual phosphorus loss (13%), whereas, during the spring season, there is a significant reduction in phosphorus loss (29%).

Based on the BMP scenarios examined in the present study, land retirement to either forest or pasture would deliver the most significant phosphorus load decrease. However, retiring lands is also a logistically unfeasible alternative because the agricultural activity is a substantial contributor to the local economy. The application of minimum-till or no-till throughout the whole watershed has the potential to reduce phosphorus losses. However, this could lead to a dependence on herbicides to manage undesirable flora (weeds) and necessitate land maintenance expenditures. The fact that minimum-till retains some of the benefits of conventional tillage while reducing phosphorus losses shows that its application is a viable choice. The effect of cover crops following winter wheat on the lowering of phosphorus loads is negligible, whereas cover crops are substantially more beneficial for nitrogen control. VFS significantly reduced phosphorus levels; however, this approach would the area of land available for crop production, resulting in a financial loss. This would likely result in a lower adoption rate by the farmers.

Caution should be taken when using these results for further study due to the inherent simplifications that a model makes while portraying the real system. The model setup and calibration were also done with limited data. There were some missing values in the daily rainfall data, and the water quality data were scarce. All the observed water quantity and quality data used in model calibration were instantaneously collected.

6.1 Future Recommendations

Based on this modeling work, several recommendations can be made:

i. Create a database of crop and land management for each field based on a long-term survey of farmers. Information such as crops grown, tillage date and type, planting date, fertilizer (mineral or organic) application date and rate, crop harvest date and rate, residue management, and implementation of any BMPs should be collected on an annual basis.
ii. Flow and water quality data at the watershed outlet should be monitored more often.
iii. Obtain stakeholder inputs on BMP selection and implementation.
iv. Selecting and implementing multiple BMPs at a time
v. Identify Critical Source Areas (CSAs) to target BMPs implementation: this will lead to a maximum reduction of phosphorus with minimal cost.
vi. Work on methods that can allocate the best BMP for a given location on the watershed
vii. Testing the model for future climate change scenarios
viii. Evaluate the efficacy of BMPs under changing climatic conditions

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